Texas Wind Energy Forecasting System Development and Testing Phase 1: Initial Testing

Technical Report

Southwest Mesa Wind Project near McCamey, Texas (Todd Spink and DOE/NREL)

Texas Wind Energy Forecasting System Development and Testing Phase 1: Initial Testing

1008032

Final Report, December 2003

Cosponsors
U.S. Department of Energy
1000 Independence Ave., SW
Washington, D.C. 20585

Principal Investigator
J. Cadogan

National Renewable Energy Laboratories
1617 Cole Blvd.
Golden, CO 80401

Principal Investigator
M. Schwartz

FPL Energy
700 Universe Boulevard
Juno Beach, Florida 94306

Principal Investigator
T. Curley

EPRI Project Manager
C. McGowin

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Wind Economics and Technology, Inc.
Ron Nierenberg (consultant)
Risoe National Laboratory
TrueWind Solutions, LLC
Applied Modeling, Inc.

ORDERING INFORMATION

Requests for copies of this report should be directed to EPRI Orders and Conferences, 1355 Willow Way, Suite 278, Concord, CA 94520, (800) 313-3774, press 2 or internally x5379, (925) 609-9169, (925) 609-1310 (fax).

CITATIONS

This report was prepared by

Wind Economics and Technology, Inc.
511 Frumenti Court
Martinez, CA 94553

Principal Investigator
E. McCarthy

R. Nierenberg (consultant)
153 Sacramento Ave.
San Anselmo, CA 94960

Principal Investigator
R. Nierenberg

Risoe National Laboratory
VEA 125, P.O. Box 49
DK-4000, Roskilde, Denmark

Principal Investigator
L. Landberg

TrueWind Solutions, LLC
CESTM, 251 Fuller Road, Suite B220
Albany, NY 12203

Principal Investigator
J. Zack

Applied Modeling, Inc.
206 Black Eagle Ave.
Henderson, NV

Principal Investigator
K. Tran

This report describes research sponsored by EPRI, U.S. Department of Energy, National Renewable Energy Laboratories, and FPL Energy.

The report is a corporate document that should be cited in the literature in the following manner:

Texas Wind Energy Forecasting System Development and Testing Phase1: Initial Testing, EPRI, Palo Alto, CA, U.S. Department of Energy, Washington, D.C., National Renewable Energy Laboratories, Golden, CO, and FPL Energy, Juno Beach, FL: 2003. 1008032.

REPORT SUMMARY

This report describes initial results from the Texas Wind Energy Forecasting System Development and Testing Project at a 75-MW wind project in west Texas.

Background

As of December 2002, the installed wind generation in Texas was about 1100 MW, which represented almost a quarter of the total 4700 MW of installed wind capacity in the United States. Since wind generation is intermittent and not dispatchable, such a large block of wind generation creates a challenge for the ERCOT Regional Transmission Operator in Texas. ERCOT operates the state's electricity grid and must dynamically schedule transmission and other generation resources to respond to varying wind generation and balance total system load and generation. Wind energy forecasting systems are expected to support system operation in cases where wind generation contributes more than a few percent of total generating capacity.

Objectives

To develop and evaluate the forecast accuracy of three meteorology-based wind energy forecasting systems at a Texas wind power plant.

Approach

The host wind plant operator provided access to design, wind resource, wind generation, and turbine availability data for the 75-MW Southwest Mesa wind project near McCamey, Texas, operated by FPL Energy for West Texas Wind Energy Partners, LP.

Risoe National Laboratory, TrueWind Solutions, and Applied Modeling, Inc., each developed automated wind energy forecasting systems for each wind plant based on their respective proprietary *Prediktor*, *eWind*, and *WEFS* wind energy forecasting models. They calibrated the models using historical site data and developed model output statistic (MOS) algorithms to improve forecast accuracy. The resulting wind forecasting systems automatically receive and process regional numerical weather forecasts; generate 48-hour forecasts of the hourly wind speed, direction, ambient temperature, and energy generation; and, post forecasts on EPRI's FTP server. The three developers tested the models by generating twice-daily 48-hour forecasts of hourly wind speed, direction, and energy generation during the period May 1-31, 2002.

Results

In general, the meteorology forecasts at Southwest Mesa were more accurate than either the persistence or climatology forecasts.

Using monthly average wind speed and generation at Southwest Mesa, researchers calculated normalized monthly mean and mean absolute errors between forecast and measured wind speed and generation values for May 2002. Risoe monthly mean wind speed and generation forecast errors for May were respectively –20% and +5% of monthly mean wind speed and generation, and corresponding monthly mean absolute errors were 33% and 51%. For TrueWind, normalized monthly mean errors were –11% and –20% for wind speed and generation, and monthly mean absolute errors were 28% and 40%. For Applied Modeling, mean wind speed and generation errors were –21% and –19%, and mean absolute errors were 30% and 38%, respectively. However, before drawing any conclusions about whether the unique wind resource and topography of Texas significantly affect forecast accuracy, it is necessary to accumulate several months of test data and measure monthly forecast errors during all seasons of the year.

EPRI Perspective

This Phase 1 report presents initial results of an early application of wind energy forecasting models to the unique mesa topography of West Texas. Results indicate that the technology is capable of forecasting wind speed and generation more accurately than simple persistence and climatology forecast models. However, more accurate numerical weather prediction and high-resolution wind flow models are needed to reduce forecast error. Previous related EPRI reports include EPRI TR-112146, a description of the European Union Wind Energy Forecasting Project (1999); EPRI 1000667, a project description and status report (2000); and, EPRI 1007338 and 10007339, describing the Phase 1 and 2 results from the California Wind Energy Forecasting Project (2003). The final results of 12 months of testing at Southwest Mesa will be presented in a subsequent report, expected to be issued in early 2004 (EPRI 1008033).

Keywords

Wind power
Wind energy forecasting

ABSTRACT

As of December 2002, the installed wind generation in Texas was about 1100 MW, which represented almost a quarter of the total 4700 MW of installed wind capacity in the U.S. Because wind generation is intermittent and not dispatchable, the existence of the large block of wind generation in Texas creates a challenge for the Electricity Reliability Council of Texas Regional Transmission Operator (ERCOT RTO), which operates the state's system and must schedule transmission line operations and other generation to respond to changes in wind generation. In addition, the utilities and wind plant operators need to be able to accurately forecast next-hour and next-day hourly wind generation in order to report planned generation of wind energy to the ERCOT RTO.

This report presents the initial results of a project that is developing and testing wind energy forecasting systems at a 75 MW project near McCamey, Texas, which is about 75 miles south of Odessa, Texas. Three wind energy forecasting system developers, Risoe Natgional Laboratory, TrueWind Solutions, LLC, and Applied Modeling, Inc., developed and conducted initial testing of their proprietary forecast systems and evaluated the forecast performance vs. observed data from the wind plant site. This Phase 1 report describes the development and early testing of the three wind energy forecasting systems. The initial forecast performance results for May 2002 are promising and comparable to results from other sites. The monthly mean errors of the wind speed and generation forecasts respectively ranged from -11% to -21% of the monthly mean hourly wind speed (10.2 m/sec) and -20% to +5% of the mean hourly generation (36,406 kW) for the month. The corresponding ranges of the monthly mean absolute errors were 28% to 33% for wind speed and 38% to 51% for wind generation.

Before drawing any conclusions about whether the unique wind resource and mesa topography of west Texas significantly affect forecast accuracy, it is necessary to accumulate several months of testing and measure monthly forecast errors during all seasons of the year. It is anticipated that the full year of forecast testing at Southwest Mesa will be completed in March 2003. The results of the full year of testing will be documented in the Phase 2 report to be issued in early 2004.

ACKNOWLEDGMENTS

Several organizations and individuals provided information to the Texas Wind Energy Forecasting System Development and Testing project and contributed to the production of this report. Valuable input and comments were received from representatives of FPL Energy, National Renewable Energy Laboratory, and EPRI. Rusty Wheeler and Jesse Nevarez of FPL Energy arranged access to the wind plant design data and daily wind resource, generation, and turbine availability data for the Southwest Mesa wind project, and several of their staff members assembled and uploaded the daily data files to the EPRI ftp server. They included Joe Carasco, James Ontiveros, David Gonzalez, Mace Hooley, and Vivian Venegas. Marc Schwartz of the National Renewable Energy Laboratory helped define the protocol for evaluating the performance of the wind energy forecasting systems. Alejandro Jimenez, Marty Mashlakian, and Jon Suemnick of EPRI assisted with processing and conversion of the daily wind resource data files received from the Southwest Mesa wind plant.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1
INTRODUCTION

California hosted the first installations of large-scale wind energy plants in the world beginning in the early 1980s and there are now 12 U.S. states with more than 30 MW of installed wind capacity. As of the end of 2002, California and Texas were the leading states with about 1800 MW and 1100 MW of installed capacity, representing about one third and one quarter of the 4700 MW of installed wind capacity in the U.S.

Because wind generation is intermittent and not dispatchable, the existence of the large block of wind generation in Texas creates a challenge for the Electricity Reliability Council of Texas Regional Transmission Operator in Texas (ERCOT RTO). The ERCOT RTO operates the State's system and must dynamically schedule transmission line operations and other generation to respond to changes in wind generation and avoid creating imbalances between electricity demand and supply. Wind energy forecasting will enable the Texas utilities and wind plant operators better understand and prepare more accurate next-hour and next-day forecasts of wind power generation for the ERCOT RTO.

Wind energy forecasting uses sophisticated numerical weather forecasting and wind plant power generation models to predict the hourly energy generation of a wind power plant up to 48 hours in advance. As a result, it has great potential to address the needs of the ERCOT RTO and the utilities, wind plant operators, power marketers and buyers, and utility system dispatch personnel.

The U.S. Department of Energy's National Renewable Energy Laboratory and EPRI identified wind energy forecasting as a high priority research need in 1998. In response, EPRI initiated a project cofunded by EPRI and the DOE-EPRI Wind Turbine Verification Program to develop and test wind energy forecasting systems in Texas.

As described further below, the Texas Wind Energy Forecasting project was to be developed in two phases:

Phase 1: Initial development and testing of three Wind Energy Forecasting Systems at a wind plant in west Texas.

Phase 2: Continued testing of the three Systems at the west Texas wind plant.

This report describes the results of the Phase 1 development, calibration, and initial testing of three wind energy forecasting systems for data collected during May 2002. The host project site was the 75 MW Southwest Mesa wind project, owned by West Texas Wind Energy Partners, LP and operated by FPL Energy. Two earlier reports present initial and 12-month wind energy forecasting results for two California wind projects (EPRI 1003778 and 1003779, March and July 2003).

Objectives and Scope

The overall objective of the Texas Project is to transfer European wind energy forecasting technology to the U.S. and develop and test three wind energy forecasting systems in parallel to assess the forecast performance and the accuracy of the forecasts vs. observed data from the west Texas wind project.

The results will be of interest to wind plant operators, electric utilities in Texas, and the Energy Reliability Council of Texas Regional Transmission Operator (ERCOT RTO). To the extent possible, this project will identify a reasonable level of the absolute forecast error for wind speed and wind energy generation on an hourly basis over the 48-hour forecast period.

The performance of the three wind energy forecasting systems was evaluated by comparing the forecast and observed wind speed, direction, and energy generation. The system developers are Risoe National Laboratory in Denmark (Risoe); TrueWind Solutions, a New York State partnership (TWS); and Applied Modeling, Inc. a Nevada company. In addition, Ron Nierenberg, CCM and Wind Economics and Technology (WECTEC) provided meteorological support to the Program and prepared the final reports. The National Renewable Energy Laboratory (NREL) will independently assessed the performance of the wind energy forecasting systems

Project Participants and Responsibilities

The Texas project participants include EPRI, U.S. DOE, NREL, the host utility, American Electric Power, the wind plant owner/operator, FPL Energy, Risoe National Laboratory (Risoe), TrueWind Solutions (TWS), Applied Modeling, Inc. (AMI), Ron Nierenberg (RN), and Wind Economics and Technology (WECTEC). EPRI manages the Program on behalf of EPRI and U.S. DOE. EPRI, U.S. DOE, NREL, and other program sponsors also participate in the Program Oversight Committee, which provides technical oversight for the Program.

EPRI is responsible for: (1) overall program management; (2) arranging the wind energy forecast applications with the host wind plant owner/operator; (3) arranging for access to historical wind resource data, wind turbine and met tower locations and characteristics, other site data, and observed hourly wind, energy generation and turbine data at the site; (4) development of file-transfer-protocol (FTP) files on the EPRI FTP file server to receive time-stamped daily wind resource, energy generation, and turbine availability data from the host site and time-stamped twice-daily wind and energy-generation forecasts and performance verification and skill score statistics from the wind energy forecasting contractors; (5) monitor and verify the performance verification statistics delivered by the three wind energy forecasting developers on the password-protected FTP files on the EPRI FTP server during Phases 1 and 2; (6) prepare data files and a letter report summarizing the results for NREL to use in preparation of the independent performance verification report; (7) prepare monthly program reports on project status, priority action items, and schedule; (8) report publication; and (9) participation in Program Oversight Committee.

U.S. Department of Energy (U.S. DOE) is responsible for overall direction of the DOE Wind Program and the DOE funding provided to the project through the DOE-EPRI Wind Turbine Verification Program.

NREL will conduct an independent performance evaluation of the wind energy forecasting program results in collaboration EPRI.

NREL is responsible for (1) review and evaluation of the database of forecast and observed wind and energy generation data and verification statistics data files on the password-protected FTP pages on the EPRI FTP server and the summary data file prepared by the EPRI; (2) preparation of independent performance evaluation reports at the conclusions of Phases 1 and 2; and (3) participation in the Program Oversight Committee.

FPL Energy, the Wind Plant Owner/Operator is responsible for providing the following information to EPRI: (1) the location of the wind plant and a detailed plot plan including specific turbine and met tower locations and a tabular file of the coordinates of each turbine and met tower; (2) design specifics of the wind turbine, including hub heights, power curve, thrust curve, and interconnection points; (3) historical wind speed and wind direction data for the site; (4) feedback on the desired format, method and time of delivery of wind energy forecasts; (5) access to the hourly wind resource, generation, and turbine availability data from the plant by either providing daily or weekly reports via electronic mail, delivering the data to the password-protected FTP files on the EPRI FTP server, or providing daily access to the SCADA system at the site during specified hours of the day (shorter time intervals (10-minute and 30-minute) are also acceptable); (6) feedback on the suitability and use of the forecasts; and (7) participation in periodic project review meetings.

Ron Nierenberg, CCM (RN) is responsible for providing meteorological support and analyses of historical and climatology data for the wind plant site.

Wind Economics and Technology (WECTEC) is responsible for: (1) preparation of wind plant power curves, climatology data, and wind forecast reporting format for the Texas wind project tested in Phases 1 and 2; (2) participation in periodic project review meetings; (3) preparation of final reports at the conclusion of Phases 1 and 2.

Risoe National Laboratory (Risoe) will develop and calibrate a wind energy forecasting system for the Texas wind plant in Phase 1 and operate the system for at least 12 months in Phase 2.

Risoe is responsible for the following scope: (1) selection of the appropriate numerical weather prediction model(s) or technique(s) for predicting the wind speed and wind direction and preparing the wind plant power output; (2) preparation of twice-daily forecasts of the hourly average wind speed and direction and the wind energy generation for hours one through 48 in the future; (3) delivery of the forecasts to EPRI and each respective host site via electronic mail or other method to be specified by EPRI; (4) delivery of the forecast results with a date/time stamp to the password-protected FTP files on the EPRI FTP file server to be provided by EPRI; (5) calculation of performance verification statistics of the forecast and observed values using the

Risoe protocol for specified time frames (e.g. hourly, every 3-hours, every 6-hours, etc.); (6) calculation of forecast skill scores against persistence and climatology for the same time periods; (7) delivery of the results of (5) and (6) at least once per week to the password-protected FTP files on the EPRI FTP file server; (8) preparation of quarterly summaries of forecast verification and skill score statistics in an agreed-upon format; (9) participation in periodic project review meetings; and (10) preparation of final reports at the conclusion of Phases 1 and 2 on the Risoe system results.

TrueWind Solutions (TWS) will develop and calibrate the wind energy forecasting system for the Texas wind plant in Phase 1 and operate the system for at least 12 months in Phase 2.

TWS is responsible for the following scope: (1) selection of the appropriate numerical weather prediction model(s) or technique(s) for predicting the wind speed and wind direction and preparing the wind plant power output; (2) preparation of twice-daily forecasts of the hourly average wind speed and direction and the wind energy generation for hours one through 48 in the future; (3) delivery of the forecasts to EPRIand each respective host site via electronic mail or other method to be specified by EPRI; (4) delivery of the forecast results with a date/time stamp to the password-protected FTP files on the EPRI FTP file server to be provided by EPRI; (5) calculation of performance verification statistics of the forecast and observed values using the Risoe protocol for specified time frames (e.g. hourly, every 3-hours, every 6-hours, etc.); (6) calculation of forecast skill scores against persistence and climatology for the same time periods; (7) delivery of the results of (5) and (6) at least once per week to the password-protected FTP files on the EPRI FTP file server; (8) preparation of quarterly summaries of forecast verification and skill score statistics in an agreed-upon format; (9) participation in periodic project review meetings; and (10) preparation of final reports at the conclusion of Phases 1 and 2 on the TrueWind system results.

Applied Modeling, Inc. (AMI) will develop and calibrate the wind energy forecasting system for the Texas wind plant in Phase 1 and operate the system for at least 12 months in Phase 2.

AMI is responsible for the following scope: (1) selection of the appropriate numerical weather prediction model(s) or technique(s) for predicting the wind speed and wind direction and preparing the wind plant power output; (2) preparation of twice-daily forecasts of the hourly average wind speed and direction and the wind energy generation for hours one through 48 in the future; (3) delivery of the forecasts to EPRI and each respective host site via electronic mail or other method to be specified by EPRI; (4) delivery of the forecast results with a date/time stamp to the password-protected FTP files on the EPRI FTP file server to be provided by EPRI; (5) calculation of performance verification statistics of the forecast and observed values using the Risoe protocol for specified time frames (e.g. hourly, every 3-hours, every 6-hours, etc.); (6) calculation of forecast skill scores against persistence and climatology for the same time periods; (7) delivery of the results of (5) and (6) at least once per week to the password-protected FTP files on the EPRI FTP file server; (8) preparation of quarterly summaries of forecast verification and skill score statistics in an agreed-upon format; (9) participation in periodic project review meetings; and (10) preparation of final reports at the conclusion of Phases 1 and 2 on the Risoe system results.

2

WIND ENERGY FORECASTING BACKGROUND

There is renewed interest in evaluating and developing automated systems to forecast hourly estimates of wind energy production from wind energy facilities. Some Department of Energy (DOE) research in wind speed forecasting occurred during the late 1970s and early 1980s when the development of the MOD wind turbines was underway. However, except in Europe, there has been no significant research activity on this topic. The initial wind forecasting studies funded by DOE and performed by Battelle and others used classical approaches. Standard objective forecasting techniques such as model output statistics (MOS) and semi-objective forecasting techniques such as man/machine interfaces were applied in an attempt to see if both wind speed and direction could be accurately predicted in areas of known wind speed resources. Examples of this work are presented in Carter and Gilhousen (1980), Gilhousen (1979), Notis (1984), Wegley (1980), and Wendell (1978). Some more recent work in the US was presented by McCarthy (1993, 1996) and Oregon State University (1994). Milligan et.al. (1995) authored a study demonstrating that wind speed forecasting and the ability to predict the output of renewable energy facilities would have real economic benefit to a utility.

Research on wind speed forecasting and, correspondingly, the forecast of electricity generation by a wind energy facility are actively pursued in Europe. Dr. Lars Landberg at Risoe National Laboratory and Dr. Simon Watson at the Rutherford Appleton Laboratory have published several recent papers on the application of wind speed forecasting to wind energy facilities (Landberg, 1991, 1994, 1995, 1996; Landberg and Watson, 1992, 1993, 1994). Additional work on this topic has been performed by Soder (1994) and Geerts (1984).

Staff at the Institute of Mathematical Modeling (IMM) at the Technical University of Denmark and ELSAM, a Danish utility company, completed a three-year study on wind power prediction and dispatch of wind energy facilities within ELSAM's service territory. Wind power facilities may produce nearly 20% of the electrical energy demand in ELSAM's service territory during the next 10 years. With the assistance of a grant from the European Union, IMM and ELSAM developed a wind power prediction tool for use in ELSAM's dispatch center (Jensen et.al.1996). The prediction tool provides forecasts of total wind generated electricity for the ELSAM area for 0.5 to 36 hours ahead in half-hourly time steps. The system uses wind measurements and facility power measurements to forecast electricity deliveries.

Expanding from this work, Risoe National Laboratory developed the *Prediktor* Wind and Energy Forecasting Program (Landberg, 2002) that is used in Denmark, Germany, and Spain for routine prediction of wind energy from selected wind plant facilities. In the US, TrueWind Solutions developed the *eWind* wind power forecasting system and used this model to provide forecasts to Southern California Edison (Gilman, et. al., 2001).

3
HOST WIND PLANT AND WIND RESOURCE DESCRIPTION

The host wind plant is the 75 MW Southwest Mesa wind project located on top of a mesa near McCamey and about 75 miles south of Odessa Texas, as shown in Figure 3-1. The Southwest Mesa wind project consists of 107 wind turbines, each rated at 700 kW at rated wind speed, and is operated by FPL Energy for the project owner, West Texas Wind Energy Partners, LP. The wind energy is sold to American Electric Power under a long-term power purchase agreement.

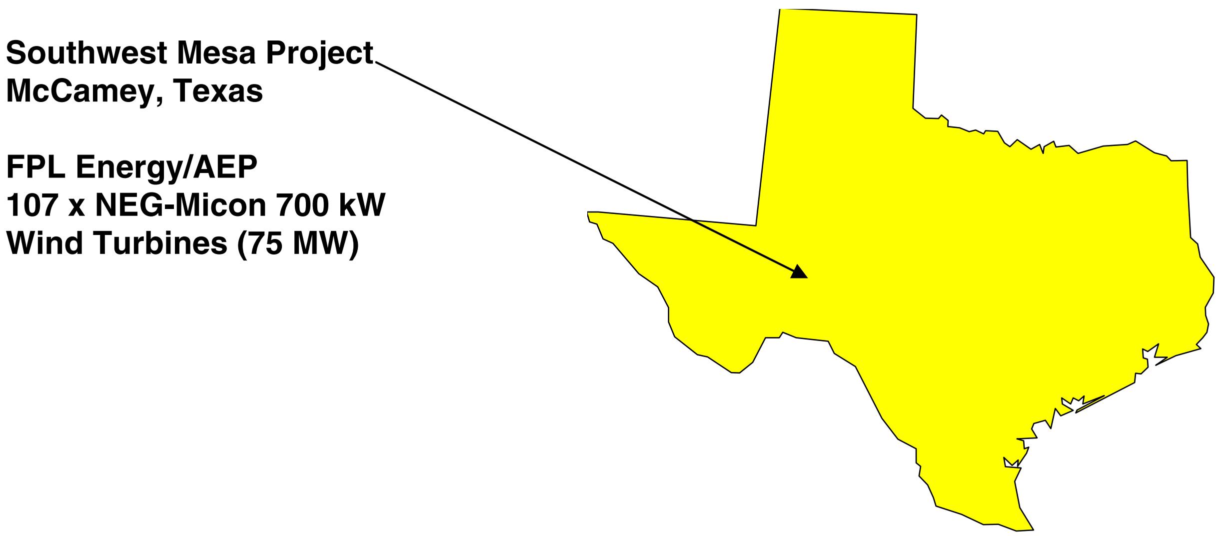


Figure 3-1
Southwest Mesa Wind Plant Location in

Wind Plant Description

The 75 MW Southwest Mesa wind project was installed in 1999 and is owned by West Texas Energy Partners, LP, and operated by FPL Energy. The project consists of 107 wind turbines manufactured by NEG Micon, each rated at 700 kW and mounted on 50-meter tubular steel towers (Figure 3-2). The turbine is an upwind, active-yaw machine and uses a three-blade, fixed-pitch, stall-regulated rotor with a 157.4 foot (48 meter) diameter. Figure 3-3 presents the turbine power curve, with a cut-in wind speed of approximately 6 m/sec, a rated wind speed of 13 m/sec, and a cut-out wind speed of 25 m/sec. The project is located on Southwest Mesa near the town of McCamey, Texas in Crockett County. Figure 3-4 presents a raised relief map of the Southwest Mesa area.

Figure 3-2
NEG-Micon 700kW Wind Turbines at the Southwest Mesa Wind Project

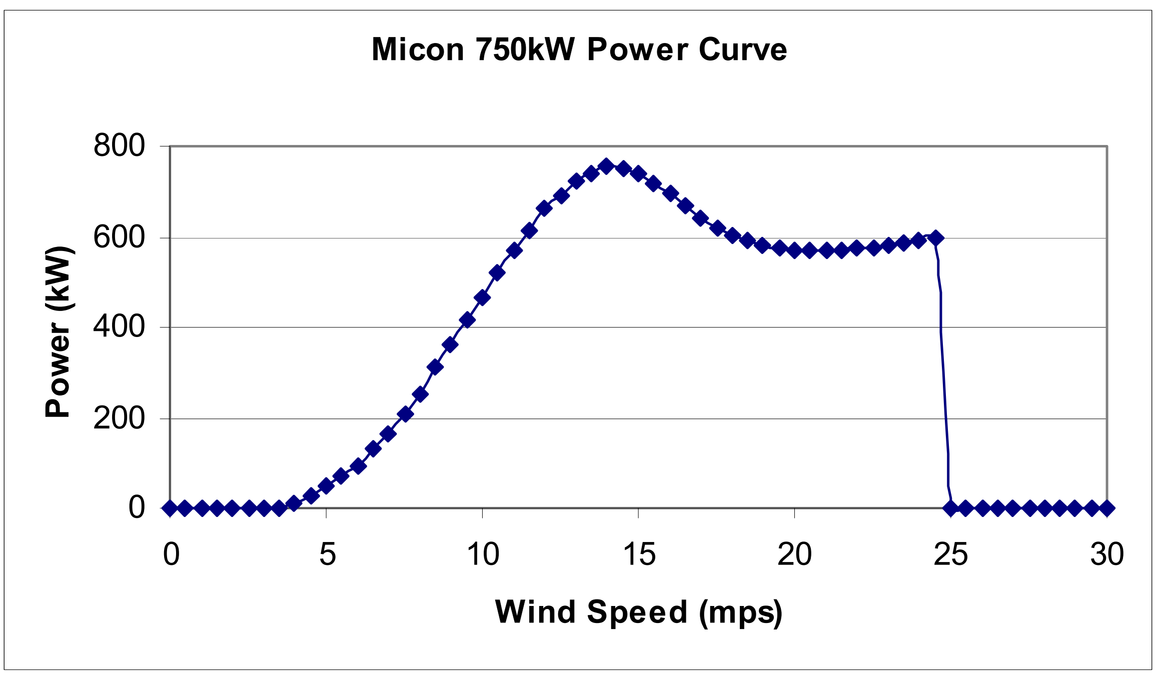


Figure 3-3
NEG Micon 750kW Wind Turbine Power Curve

Daily Wind Resource and Turbine Performance Data

FPL Energy provided daily electronic files containing the previous day's 10-minute wind speed, direction, ambient temperature, and barometric pressure data from the three met towers and generation and availability status data for each of the 107 wind turbines at the site. The daily data files were assembled and posted on the EPRI ftp file server by FPL Energy operating staff and processed by EPRI. Figures 3-5 and 3-6 present partial examples of the daily turbine generation and availability status data files provided by FPL Energy. Each data file contains 144 data records of the 10-min wind resource and generation data and the turbine status codes for the previous day. Turbine status codes equal to zero or 1000 indicate the turbine is available, and all other codes indicate it is unavailable. For example, turbine status code "1047" indicates the turbine is shut down due to curtailment.

Wind Speed

The wind speed forecast evaluation is based on the wind speed measurements at meteorological tower No. 1, 131 feet (40 meters) above ground level. This elevation is slightly below the 50-meter hub height of the NEG-Micon 700kW turbines, but is considered to provide a reasonable estimate of the wind speed at the turbine hub height for predicting power generation.

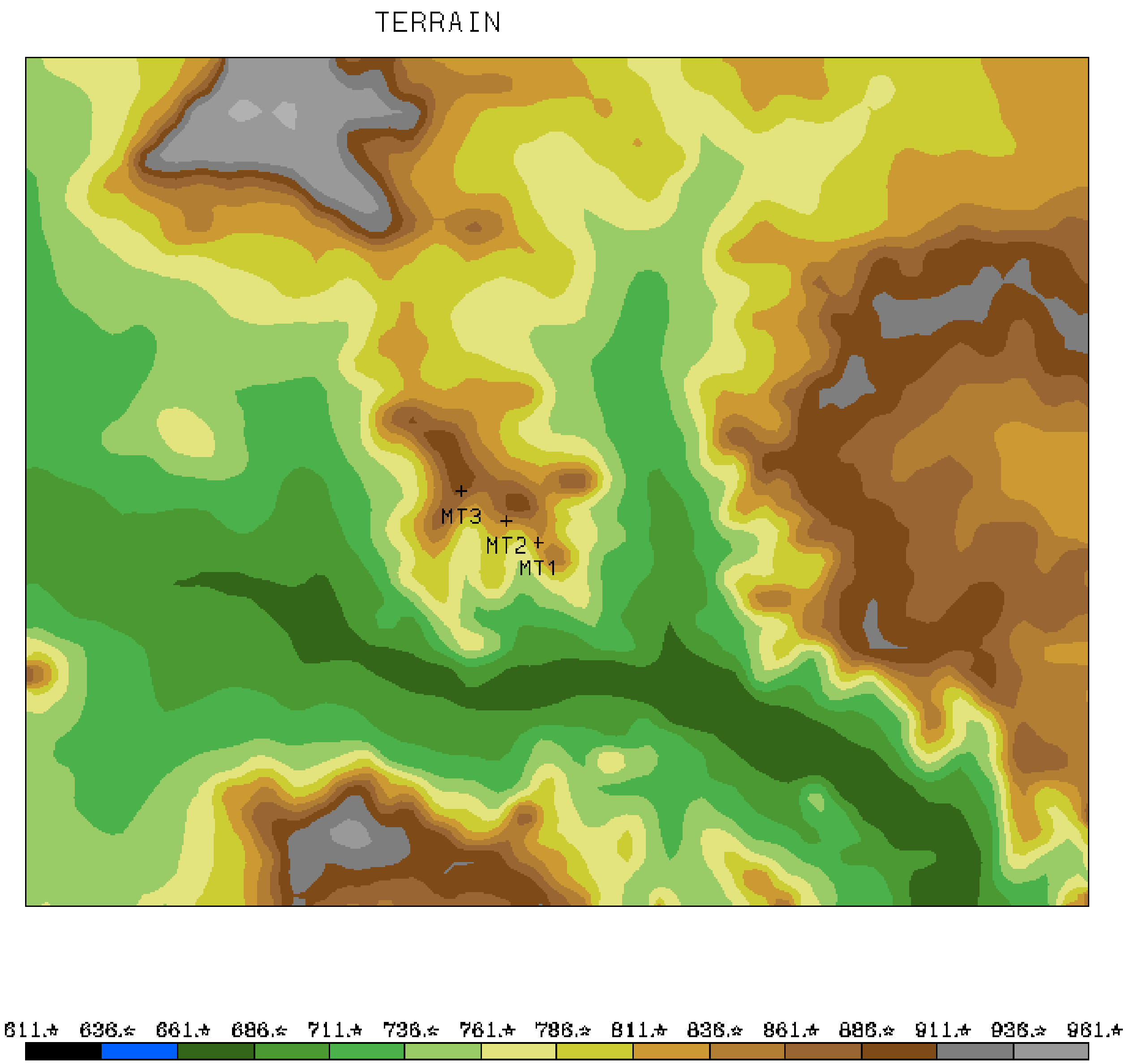


Figure 3-4
Terrain Relief Map of the Southwest Mesa area. The general locations of the three Southwest Mesa meteorology towers are shown (TrueWind Solutions)

Day/Time	A1_kW_ 0212	A2_kW_ 0212	A3_kW_ 0212	A4_kW_ 0212	A5_kW_ 0212	A6_kW_ 0212	A7_kW_ 0212	A8_kW_ 0212	A9_kW_ 0212	A10_kW_ 0212	A11_kW_ 0212	A12_kW_ 0212
7. 00:00	282.9	256.6	234.8	190	254.5	125.3	358	463.6	566.4	587.6	532.1	454.5
7. 00:10	526.1	466.7	459.9	363.8	406.1	195.9	474.3	642.6	657.8	657.3	608.3	535.6
7. 00:20	546.7	475.9	428.9	371.7	427.6	231.8	611.2	617.1	631	620.9	516.7	391.7
7. 00:30	304.5	263.2	224.9	151	202	82.9	581.7	525.2	565.2	505	361.1	270
7. 00:40	471.4	365.4	331.9	247.8	337.2	160	401.2	519.8	554.1	532.3	446.3	370.2
7. 00:50	392.4	331.7	318.9	313.8	395.5	179.1	506.5	551	547	511.2	404.9	353.8
7. 01:00	403.2	444.2	447.9	445.1	526.1	310.2	558.9	608.9	629.5	631.4	523.1	469.4
7. 01:10	330.8	365.2	337.7	384.6	451.7	332.6	613.7	612.7	630.1	637.6	556.2	503.5
7. 01:20	293.6	254.2	361.5	452.4	508.9	315.7	654	634.7	656.6	634.6	580.6	522
7. 01:30	319.3	306.9	331.2	415.1	467.4	277.4	585.6	569.7	586.1	567.4	501.1	451.7
7. 01:40	306	353.1	302.4	329.8	403.2	235.5	632.3	505.2	576.5	627.1	528.7	471.9
7. 01:50	262	281.1	324.8	362	428.3	243.9	586.5	518.7	572.6	573.5	521.4	474.5
7. 02:00	273.3	262.4	264.9	307.4	364.4	257.3	525.1	530	554.4	553.4	522.4	476.4
7. 02:10	195.8	157.9	229.4	268.1	312.3	199.4	394.9	412	455.2	496.5	453.2	410.2
7. 02:20	294.4	267.4	331.6	376.3	404.8	289	388.4	497.8	492.9	482.5	383.1	340.2
7. 02:30	382.3	343.1	323.3	334.9	380.8	233.3	582	575.8	572.8	533.3	498	427.7
7. 02:40	438.3	399.5	442.3	440.3	419	279.4	643.1	721.6	735.4	713.7	600.2	523.2
7. 02:50	386.9	394.5	392.7	405.5	436.7	250.2	664.9	698.4	715	689.6	566.8	476.7
7. 03:00	360.6	313.5	326.5	356.8	337.5	233.6	623.7	638.4	654.8	623.3	532.7	441.8
7. 03:10	313	278.2	292.7	251	253.2	153	639.8	621.1	583.2	500.5	351.3	309.1
7. 03:20	246.6	213	162.9	191.5	223.5	190	580.4	456.5	365.8	318	354.7	373.5
7. 03:30	177.2	177.1	261.9	339.1	437.9	315.1	323.3	261.9	327.5	423.1	638.5	626
7. 03:40	353.6	374.5	346.6	303.4	292	158.1	299.3	499.6	622.5	686.4	747.4	728.7
7. 03:50	228.9	148.6	176.5	195.3	200	142.8	704.7	755.1	763.7	771.2	807.6	811.3
7. 04:00	177	169.9	287.1	308.1	394.2	332.9	729.4	749.7	787.5	787.1	814.6	820.8
7. 04:10	487.4	603.4	629.5	634.3	620.2	541.7	583.2	604.9	710.3	776.7	810.6	808.5
7. 04:20	592.2	599	581.8	567.2	514.3	447.8	642.9	745.9	784.6	781.2	817.9	800.5
7. 04:30	396.1	457.7	380.5	391.4	412.2	416.1	767.8	786.2	796.3	791.7	818.6	801.6
7. 04:40	485.5	535.1	445.4	415.7	457.7	444.5	645.3	740	782.3	782.6	800.6	795.3
7. 04:50	582.2	526.6	493.4	469.5	458	345.6	459.2	632.8	725.2	707.5	762.2	750.1

Figure 3-5
Partial Example of Daily 10-Minute Wind Turbine Generation Data File for Southwest Mesa Provided by FPL Energy

Day/Time	A1_Status code_0212	A2_Status code_0212	A3_Status code_0212	A4_Status code_0212	A5_Status code_0212	A6_Status code_0212	A7_Status code_0212	A8_Status code_0212	A9_Status code_0212	A10_Status code_0212
1. 00:00	0	0	0	0	0	0	0	1000	0	0
1. 00:10	0	0	0	0	0	0	0	1000	1000	0
1. 00:20	0	0	0	0	0	0	0	0	0	0
1. 00:30	0	0	0	0	0	0	0	0	0	0
1. 00:40	0	0	0	0	0	0	0	0	0	1000
1. 00:50	0	0	0	0	0	0	0	0	0	0
1. 01:00	0	1000	0	0	0	1000	0	0	0	0
1. 01:10	0	0	0	0	1000	0	0	0	0	0
1. 01:20	0	0	0	1000	0	0	0	0	0	0
1. 01:30	0	0	0	0	0	0	0	0	0	0
1. 01:40	0	0	0	0	0	0	0	0	0	0
1. 01:50	0	0	0	0	0	0	0	0	0	0
1. 02:00	0	0	0	0	0	0	0	0	0	0
1. 02:10	0	0	1000	0	0	0	0	0	0	0
1. 02:20	1000	0	0	0	0	0	0	0	0	0
1. 02:30	0	0	0	0	0	0	0	0	0	0
1. 02:40	0	0	0	0	0	0	0	0	0	0
1. 02:50	0	0	0	0	0	0	0	0	0	0
1. 03:00	0	0	0	0	0	0	1000	0	0	0
1. 03:10	0	0	0	0	0	0	0	0	0	0
1. 03:20	0	0	0	0	0	0	0	0	0	0
1. 03:30	0	0	0	0	0	0	0	0	0	0
1. 03:40	0	0	0	0	0	0	0	0	0	0
1. 03:50	0	0	0	0	0	0	0	0	0	0
1. 04:00	0	0	0	0	0	0	0	0	0	0
1. 04:10	0	0	0	0	0	0	0	0	0	0
1. 04:20	0	0	0	0	0	0	0	0	0	0
1. 04:30	0	0	0	0	0	0	0	0	0	0
1. 04:40	0	0	0	0	0	0	0	0	0	0
1. 04:50	0	0	0	0	0	0	0	0	0	0

Figure 3-6
Partial Example of Daily 10-Minute Turbine Availability Status File Provided by FPL Energy

Adjustment to 100% Turbine Capability

In order to evaluate the forecast performance vs. the observed data from Southwest Mesa, it is necessary to first adjust the turbine generation data to 100% turbine capability, e.g. each turbine is operating and its generation is consistent with the wind turbine power curve. The procedure described below processes the daily turbine generation/met tower and turbine availability status files provided by FPL Energy and illustrated in Figures 3-5 and 3-6.

The key steps include:

1. For each 10-minute record and each of the 107 turbines, determine the value of turbine data index (0 or 1) as follows: Data index = 0 if any of the following conditions exist: (1) Turbine Status Code does not equal 0 or 1000; (2) both the turbine generation and anemometer wind speed values are zero; or (3) the reported generation is more than 20% below the estimated generation corresponding to the nacelle anemometer wind speed and turbine power curve. Data index = 1 if none of these conditions occur.

2. For individual turbines with data index = 0, the generation is estimated from the anemometer wind speed and the turbine power curve. If the anemometer wind speed is zero or obviously in error, it is estimated from the anemometer wind speed of the adjacent turbine or turbines in the same subgroup of the turbine string, provided the turbine index of the adjacent turbine is equal to one. Turbine string A consists of three turbine groups, A1, A2, and A3, and turbine strings B, C, D, and E each consist of multiple groups. Each turbine group represents a cluster of turbines that are in the same area and are likely exposed to similar wind conditions.

3. Finally the estimated generation for the turbine with index = 0 is compared to the reported generation, and the highest value of the two is used.

4. The adjusted 10-min total generation is the sum of the adjusted generation for the individual turbines.

The results indicate that the total adjusted wind generation is usually within 5% above the reported total generation. The principle exception occurs during high wind periods when the wind plant output is curtailed and the adjusted generation is typically about 20% higher.

Wind Resource Characterization

Table 3-1 presents the typical mean hourly average wind speeds by month for a typical site in the Southwest Mesa area. The highest mean hourly average wind speeds occur from March through October. On an hourly basis, the highest wind speeds occur during the night hours between 8:00 PM and 2:00 AM CST.

Figure 3-7 presents the annual wind rose for the Southwest Mesa site. The predominant wind direction at Southwest Mesa is from the south to southeast.

Table 3-1
Typical Monthly and Diurnal Wind Speeds for Southwest Mesa Site (mph) at 40 m Elevation

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
1	15.4	20.0	27.1	29.5	34.3	36.2	30.3	27.9	25.5	22.7	19.6	13.5	25.6
2	15.2	20.0	27.1	29.1	34.4	35.3	30.5	26.7	25.5	22.3	18.9	13.1	25.2
3	15.1	18.3	27.2	29.0	33.3	34.0	29.6	25.4	25.3	22.0	18.9	13.4	24.7
4	14.4	17.6	26.3	27.9	32.8	33.4	28.7	24.1	24.6	21.8	18.8	13.3	24.0
5	13.9	17.5	25.2	27.2	32.0	32.2	27.5	23.3	23.6	21.0	18.3	13.3	23.3
6	13.9	18.2	25.2	26.5	31.0	31.0	25.8	22.6	22.5	20.2	17.6	12.7	22.5
7	13.8	18.3	24.9	25.7	30.1	29.5	24.1	21.3	21.6	19.7	16.9	12.5	21.8
8	13.6	17.5	24.0	25.1	28.4	27.8	21.1	19.0	20.1	19.3	15.9	12.2	20.5
9	12.6	16.0	21.8	23.9	26.4	25.8	18.0	15.6	17.8	17.9	14.6	12.5	18.7
10	10.3	15.4	20.3	22.7	25.2	25.1	15.8	14.1	16.3	15.9	12.6	12.8	17.4
11	9.6	14.5	19.7	22.8	24.7	25.4	15.8	13.1	15.3	15.6	12.5	12.7	17.0
12	10.1	15.8	20.7	22.7	24.7	26.3	16.3	13.8	16.0	16.1	13.3	13.3	17.6
13	10.9	16.1	21.4	23.6	25.6	27.3	17.7	15.0	16.8	17.0	14.1	13.9	18.5
14	11.8	16.1	22.4	24.0	26.8	28.5	19.5	16.3	18.1	17.2	14.1	14.3	19.3
15	11.5	16.8	22.6	24.3	28.1	30.3	21.2	18.1	19.3	17.6	13.8	14.0	20.1
16	11.5	17.3	23.5	25.4	29.8	31.8	24.3	19.9	20.9	18.2	13.9	13.3	21.1
17	10.8	18.1	23.8	26.2	31.4	33.8	26.7	22.5	21.8	18.2	13.4	11.9	21.9
18	10.7	17.0	24.4	27.3	32.3	35.9	28.8	24.5	22.7	17.6	13.0	11.9	22.6
19	11.7	16.1	24.1	27.8	32.9	36.2	30.5	26.5	23.4	17.6	13.6	11.8	23.2
20	12.2	16.3	24.1	28.3	34.1	36.6	30.8	27.7	24.0	19.3	15.1	12.4	24.0
21	13.7	18.1	25.5	28.5	34.7	37.7	30.8	28.5	25.0	20.4	16.8	13.3	24.9
22	14.3	19.5	26.6	28.5	35.4	37.9	31.0	28.7	26.0	21.4	18.0	13.8	25.6
23	15.1	19.6	27.6	29.3	35.1	37.9	30.9	29.1	26.3	22.0	19.1	13.2	25.9
24	15.0	20.0	28.3	29.7	34.6	37.6	30.6	28.4	26.4	22.4	19.3	13.3	25.9
Mean	12.8	17.5	24.3	26.5	30.7	32.2	25.3	22.2	21.9	19.3	15.9	13.0	22.1

1 meter per second (mps) = 2.24 miles per hour (mph)

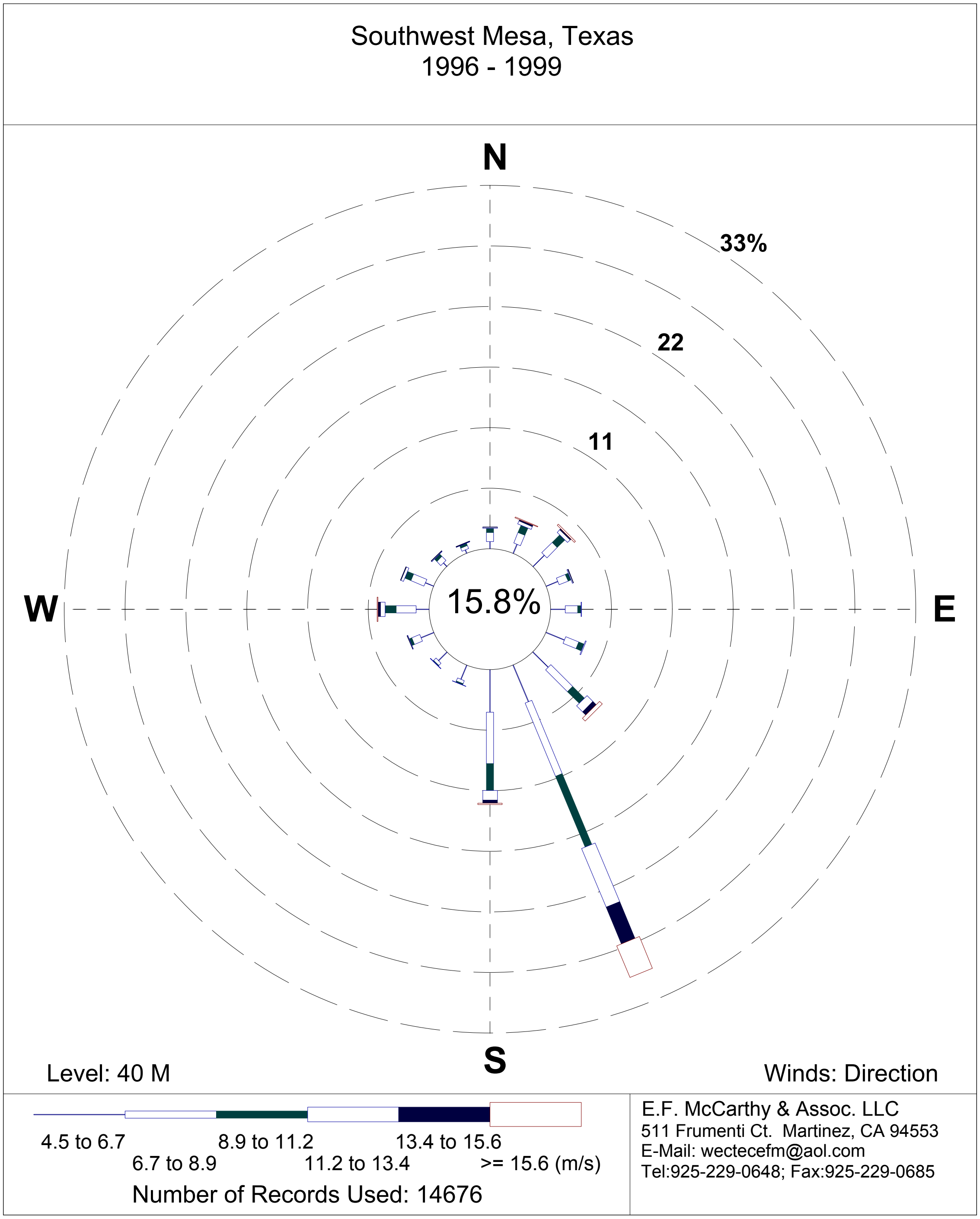


Figure 3-7
Typical Wind Rose in West Texas Mesa Region

Wind Plant Power Curve

Much like the power curve for a single wind turbine, the relationship between the wind speed, wind direction, and the power output of the entire wind plant can be described as a wind plant power curve. This power curve looks at the aggregate energy deliveries of all the wind turbines that make up the wind plant and includes all of the on-site vagaries of topography, array effects, and spacing as a function of wind direction. Figure 3-8 presents the wind plant power curve for a 25 MW wind plant consisting of 83- 300 kW wind turbines. The power curve is a plot of hourly average wind speed versus hourly power production. Each data point represents the aggregated power delivered by a group of wind turbines at a given wind speed and direction.

The preferred source of the wind plant power curve for use in wind energy forecasting is 10-minute or hourly wind energy delivered to the utility interconnection and matching wind speed and wind direction data, measured at the same times.

Alternatively, a wind plant power curve can be constructed using the characteristics of the wind turbine employed in the wind plant, the number of turbines, operating features of the wind plant, and an approximation of losses associated with off-axis wind directions.

The Wind Plant Power Curve defines the relationship between the representative wind speed, the wind direction, and the power output from the wind plant. Table 3-2 illustrates a hypothetical wind plant power curve for a 50 MW wind plant. The power curve is presented as a matrix of wind energy generation as a function of wind speed and wind direction (30-degree sectors).

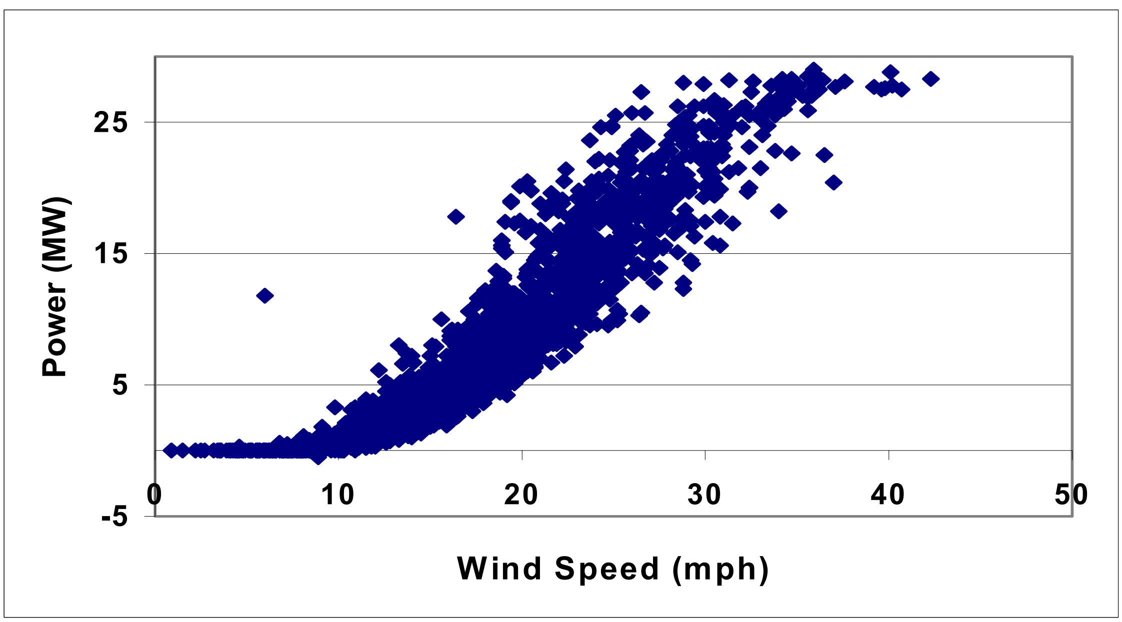


Figure 3-8
Wind Plant Power Curve for 25 MW Wind Plant

The input data required to generate the wind plant power curve include the historical wind speed and wind direction data for the site; a digitized terrain data set for use in the WASP Model; a description of the wind turbine array, including the exact coordinates of each wind turbine and met tower; and the power curve, thrust curve, and hub height of the turbine, and the height of each met tower.

The detailed steps to be followed in the Texas project include:

- Obtain numerical weather forecasts for the region from the National Weather Service or other agency;
- Translate the numerical weather forecast into a specific wind speed and direction forecast at the wind plant site using a meso-scale model of the region;
- Translate the meso-scale forecast into the wind speed and direction forecast at the turbine hub height using physical and/or statistical adjustment factors;
- Calculate the wind energy generation for the array of wind turbines to account for wake turbulence and other losses using the "wind plant power curve" and applying statistical adjustment factors;
- Document and transmit the wind energy forecast to the clients by electronic or hard copy communication;
- Track the performance of the wind energy forecasting model by evaluating the wind speed, direction, and wind energy forecasts vs. the observed data from the site; and
- Develop statistical adjustment factors for (a) the wind speed and direction at hub height vs. the numerical weather forecasts of wind speed and direction improve model performance, and (b) the wind energy generation vs. the forecast generated by the wind plant power curve.

Table 3-2
Hypothetical Wind Plant Power Curve

Wind Generation (MW) vs. Wind Speed and Direction, Hypothetical Site – 50 MW Facility

Wind Direction	Wind Speed (m/sec)							
	0-5	5 – 7.5	7.5 - 10	10 – 12.5	12.5-15.0	15.0 – 25.0	25.0-30.0	>30.0
0	0	5	10	15	20	20	5	0
30	0	7	15	20	30	30	5	0
60	0	10	30	40	50	50	10	0
90	0	10	30	40	50	50	10	0
120	0	10	30	40	50	50	5	0
150	0	7	15	20	30	30	5	0
180	0	5	10	15	30	30	5	0
210	0	7	15	20	20	20	5	0
240	0	10	30	40	30	30	5	0
270	0	10	30	40	50	50	10	0
300	0	10	30	40	50	50	10	0
330	0	7	15	20	30	30	5	0

4
WIND ENERGY FORECASTING SYSTEM DESCRIPTIONS

Three wind energy forecasting systems were developed for the 75 MW Southwest Mesa Wind Project: (1) the *Prediktor* Wind Energy Forecasting System developed by Risoe National Laboratory (2) the *eWind* system developed by TrueWind Solutions, LLC; and (3) the *WEFS* forecasting system developed by Applied Modeling, Inc.. The three forecasting systems are similar in some respects, but use different techniques to forecast the wind speed and direction and wind energy generation. The respective systems are described further in the following sections and in the references.

Risoe National Laboratory - *Prediktor*

Risoe National Laboratory in Denmark has been developing the *Prediktor* physical wind speed power generation prediction model for wind plants over the last five years. Staff at Risoe recognized that there were many areas in Europe, especially in Denmark, where the penetration of wind energy is so great that the fluctuations of the wind energy delivered to the electricity grid affect the control and dispatch of the system.

Two different types of models are used to forecast the wind speed wind generation over the short term, physical models and statistical models. Risoe elected to develop a physical model to predict the output of wind farms. In order to forecast wind plant output at specific times in the future, one must first forecast the wind speed and wind direction and then the wind energy generation. The integration of numerical weather prediction information with an analysis of local effects and the specific characteristics of the wind turbine are the key features of the physical model approach. The key model components include:

- Wind speed and wind direction data from a Numerical Weather Prediction (NWP) model.
- A description of the site (orography, roughness, obstacles).
- A description of the wind turbine (hub height, power curve, thrust curve).

Landberg et. al (2002) provides a complete description of the Risoe model.

Figure 4-1 presents a schematic of the Risoe model. Predictions of wind speed and wind direction from the NWP Model (HIRLAM Wind) are modified using the geostrophic drag law and the logarithmic wind profile to produce an estimate of the surface wind speed and direction. This estimate is then used in the Wind Atlas Analysis and Application Program (WAsP) to generate a local wind speed estimate. The program PARK is then applied to simulate the wake and array effects on the each individual wind turbine. The power production of the wind park is based on the calculated array efficiency for each wind direction sector. In addition, there are local corrections applied to the local wind speed and wind direction and to the estimated power production. Thus, some historical wind resource and the power generation data are used to calibrate the model and improve the accuracy of the forecasts.

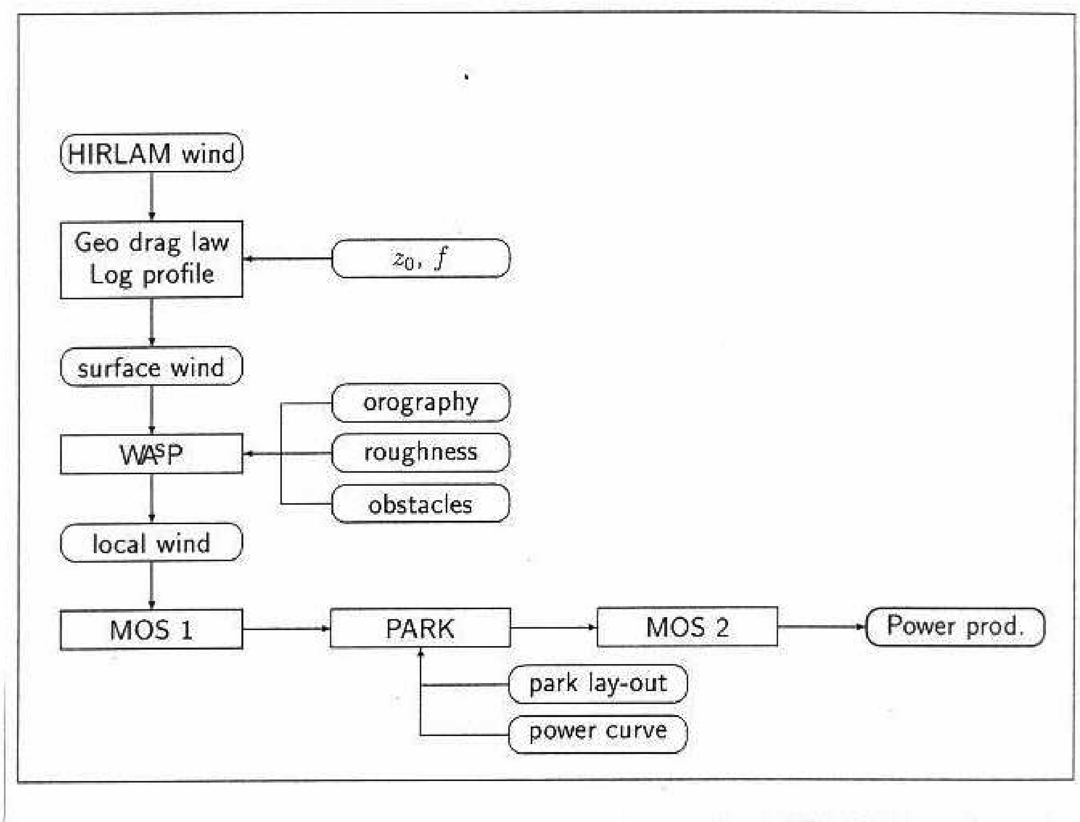


Figure 4-1
Risoe *Prediktor* Model Schematic

Numerical Weather Prediction Data

Numerical weather prediction models use current conditions and past trends to predict the future behavior of the atmosphere. This behavior at discrete time intervals into the future is the first key ingredient of the Risoe Wind Plant power prediction model. The data are usually derived from the regional atmospheric forecasting models from national weather services. They may either be obtained directly from the weather service as point information for the wind farm location or retrieved as grid information from public access ftp-servers. The choice depends on the wind farm and the practice of the weather service.

Surface Wind

The idea behind the physical model is that the predicted wind speed and wind direction from ETA model, which is the wind value specific to a 20 km grid cell, can be transformed using the geostrophic drag law and the logarithmic wind profile. The drag law is expressed as:

$$G = \mu_*/\kappa\ (\sqrt{\ [\ln (\mu_*/f\ z_o)\text{-}A]^2 + B^2} \tag{4-1}$$

where G is the geostrophic wind, equal to the ETA wind speed, μ_* is the friction velocity, κ is the Von Karman constant (0.4), f is the Coriolis parameter, z_o is the roughness length, and A and B are constants (1.8 and 4.5, respectively). The logarithmic wind profile is expressed as:

$$u(z) = (\mu_*/\kappa)\ (\ln (z/z_o)) \tag{4-2}$$

where u(z) is the wind in the surface boundary layer at height z.

WAsP

The wind speed and wind direction calculated from ETA Model is valid for a very large area and must be corrected for local effects. This is done using the Risoe Wind Atlas Analysis and Siting program (WAsP) (Mortensen, et al, 1993). WAsP modifies the local wind field for the effects of obstacles (structures, wind breaks, etc.), the effects of surface roughness and the changes in surface roughness, and the effects of orography. The application of WAsP requires a digitized terrain file, a file of surface roughness and change in surface roughness as a function of the wind direction sector, and an obstacle file, which contains a description of each obstacle, which affects the wind speed.

PARK

To take into account the influence of wakes on the turbine arrays, the PARK Program (Sanderhoff, 1993) is applied. The PARK program requires the wind turbine coordinates, the wind turbine power curve, and the wind turbine thrust curve to determine a wind park efficiency factor by wind direction sector (twelve 30 degree sectors).

Model Output Statistics (MOS)

To correct for effects not explained by the models, Model Output Statistics (MOS) are applied in two stages. In the first, MOS corrections in the form of simple linear functions are applied to the wind speed prediction.

$$y(\text{final, sector}) = y(\text{model, sector})a(\text{sector}) + b(\text{sector}) \tag{4-3}$$

where y(final, sector) is the final wind speed forecast , y(model, sector) is the wind speed prediction from the physical models, and a(sector) and b(sector) are the direction dependent constants of the linear function. The directionally dependency is according to twelve 30 degree sectors.

In the second MOS stage, corrections for any other biases in the model predictions of power output are applied, c is selected such that:

$$P_{MOS} = P_{MODEL} + c \tag{4-4}$$

where c is a constant value (power) not sector dependent

Meteorological Forecast Data Retrieval System

The ETA forecast model operated by NOAA is being used to provide meteorological data. ETA is a numerical weather prediction model, which became operational in the mid-1990s. The model employs 60 vertical layers with a 20-kilometer grid resolution and is run four times each day out to 48 hours in the future. The model grid covers North America from the pole to the Caribbean Ocean. It is operated by National Center for Environmental Prediction (NCEP) in Washington, DC (http://www.erh.noaa.gov/er/bgm/models.htm#ETA).

Output from this model is downloaded automatically by a PERL script. The script runs every 20 minutes and checks for the existence of the latest forecast file at the primary ftp-site. If the forecast file is not present there, it checks a secondary ftp-site as a back up. The forecast files are in the GRIB format and each one is approximately 5MB in size. For every forecast cycle run, 17 files are downloaded; the forecast data has a 3-hour time increment out to 48 hours. From these files, wind and temperature at several heights and locations around the wind farm are extracted for a 60 x 60 km region around the SW Mesa wind farm. The data are written to file for use by the *Prediktor* Power Prediction System.

The retrieval system includes a checking script to help ensure the downloading of forecasts is being carried out and to restart it if for some reason it has stopped. It also has the capability of triggering the Power Prediction System when the appropriate forecast data have been collected.

Power Prediction System

The farm power prediction program is written in C. Input parameters include the forecast wind files, farm attributes, turbines, power curve, etc, and the farms' wind and power parameters derived from statistical models. Due to the large size of the wind farms in this project, the actual physical modeling aspect has been minimized. Such detailed modeling of individual turbine production would have required an extensive set-up period and was considered beyond the scope of this project and was considered as not contributing to the accuracy of the predictions.

The system works by looking up the most recent forecast downloaded for each farm and determining whether a power prediction calculation has been applied to that forecast. If it has not, the program precedes. The way the program is written allows for the modification of the wind farm attributes and the addition of further wind farms. Output from the program is handled by the web-site prediction display scripts.

Meteorological Forecast Data Archive

Each day, an automated PERL script collects the previous day's forecast data, compresses and stores the data in a standard way. This operation has been underway since the collection of forecast data began in August and September of 2001. Such an archive is essential for finding relationships between forecast wind, observed wind and wind farm power output.

Prediction Output and Web-Display

Up-to-date prediction information is posted on password-protected web sites four times a day. A script has been written that checks for the existence of a new power prediction for either the SW Mesa wind farm. If a new power prediction exists, a text file is created that reports what meteorological forecast cycle has been used for this prediction. Other summary information could be written to this file such as time of maximum power output, periods of no power production, extreme winds etc. This file is then sent by FTP to a directory on our web server so that it can be displayed in a text box on the wind farm web site. The script also collates the power prediction data into a power history file. This contains the power predictions for the last three predictions using older meteorological forecasts. These data are used to create a graph of predicted power output against time. The degree of agreement of the power predictions from successive meteorological forecasts can give some indication of the predictability of the wind conditions. The last 8 predictions could be used for this purpose (48-hour lead time, 6 hourly forecasts). The older predictions tend to be less accurate and could therefore be given less weight.

The predicted wind speed and farm output are also written to a file, named a PredFile, in a standard format defined by EPRI. Each time this file is updated it is posted to the appropriate EPRI ftp sites.

Application to Southwest Mesa Wind Plant Meteorological and Power Generation Data

Observed wind speed and direction and individual turbine nacelle anemometer wind speed, power generation, and turbine status data were collected from the EPRI ftp server. The data are provided at 10-minute intervals.

Example Forecast Output

Figure 4-1 presents an example forecast generated by the Risoe Forecast Model. The forecasts are issued four times each day and cover the period from zero hour (0) to 48 hours in advance. Each forecast file is specifically identifies the Wind Plant, the Contractor, the Forecast Issue Time in both Universal or Greenwich Mean Time, the forecast hour interval (every three hours), and the valid time for the forecast. The forecast parameters include wind speed, wind direction, temperature, and power output.

Table 4-1
Example Risoe Forecast issued August 1, 2002

Wind Plant	Contractor	Fcst issued (UTC)	Fcst issued	Forecast hour	Forecast hour (MST)	Wind speed (m/s)	Direction	Temp	Wind Power (kW)
SWM	RISOE	200208010000	200207311900	00	200207311900	8.3	151.5	N/A	31848.4
SWM	RISOE	200208010000	200207311900	03	200207312200	10.1	57.4	N/A	53660.5
SWM	RISOE	200208010000	200207311900	06	200208010100	11.4	148.7	N/A	65114.2
SWM	RISOE	200208010000	200207311900	09	200208010400	11.8	158.1	N/A	71084.0
SWM	RISOE	200208010000	200207311900	12	200208010700	9.2	173.2	N/A	42010.3
SWM	RISOE	200208010000	200207311900	15	200208011000	7.9	188.8	N/A	27684.4
SWM	RISOE	200208010000	200207311900	18	200208011300	5.1	157.2	N/A	12914.0
SWM	RISOE	200208010000	200207311900	21	200208011600	4.5	145.4	N/A	10662.9
SWM	RISOE	200208010000	200207311900	24	200208011900	5.9	140.5	N/A	15245.7
SWM	RISOE	200208010000	200207311900	27	200208012200	11.6	131.4	N/A	69346.7
SWM	RISOE	200208010000	200207311900	30	200208020100	12.3	138.1	N/A	76529.2
SWM	RISOE	200208010000	200207311900	33	200208020400	11.6	148.2	N/A	66417.3
SWM	RISOE	200208010000	200207311900	36	200208020700	8.5	148.3	N/A	32111.3
SWM	RISOE	200208010000	200207311900	39	200208021000	8.3	135.2	N/A	32585.9
SWM	RISOE	200208010000	200207311900	42	200208021300	9.0	122.9	N/A	38801.3
SWM	RISOE	200208010000	200207311900	45	200208021600	9.2	119.9	N/A	40814.5
SWM	RISOE	200208010000	200207311900	48	200208021900	9.7	121.3	N/A	45590.5

TrueWind Solutions - *eWind*

TrueWind Solutions has developed a state-of-the-art system, called *eWind*, to forecast the power output of a wind plant as well as a wide range of meteorological parameters in the vicinity of the plant. The *eWind* system is composed of four basic components: (1) a set of high-resolution three-dimensional physics-based atmospheric numerical models; (2) adaptive statistical models; (3) plant output models; and (4) a forecast delivery system. Figure 4-2 presents a schematic representation of the components of the *eWind* wind power forecast system. The following three subsections provide an overview of the major components of the *eWind* system.

Physics-Based Atmospheric Numerical Models

The physics-based atmospheric models are a set of mathematical equations that represent the basic physical principles of conservation of mass, momentum and energy and the equation of state for moist air. The model's equations are solved on a three-dimensional computational grid. These models are conceptually similar to those used by operational weather forecast centers (such as the National Center for Environmental Prediction (NCEP) in the United States) throughout the world. However, the *eWind* models are run at a higher resolution (i.e. smaller grid cells) and the physics and data assimilation schemes used by the models have been specifically configured for high-resolution simulations for wind power forecasting applications. In the initial configuration of the *eWind* system, a single numerical model known was the Mesoscale Atmospheric Simulation System (MASS) was used to generate the forecasts. MASS is a non-hydrostatic atmospheric model that has been developed and used for a variety of applications by MESO, Inc. (one of the principals of TrueWind Solutions) since 1985.

However, recent research has demonstrated that a composite of forecasts from an appropriate ensemble of simulations from a physics-based atmospheric model is generally superior to a forecast based on one simulation (i.e. one member of the ensemble). There are two fundamental strategies that can be used to generate an ensemble of forecasts. One strategy is to use the same atmospheric model and vary the input data (initial and boundary conditions) within their range of uncertainty. The other strategy is to use the same input data and employ different models or different configurations of the same model. The relative value of either strategy depends upon the sources of uncertainty in the forecast simulations. If a greater amount of the uncertainty is related to the input data, then the strategy of executing a set of simulations by perturbing the input data, will be more valuable in reducing the forecast error. If the uncertainty is mostly related to the model formulation, then the use of a set of models will be more valuable. In practice, the magnitude of the sources of uncertainty varies with location, season, the spatial scale of the forecast and other factors. Therefore, the choice of ensemble must be determined from experience and experimentation. This is typically part of the *eWind* setup procedure for a new forecast application.

TrueWind has extensive experience and expertise with the development and/or use of a number of atmospheric models. In addition to the MASS TrueWind also has implemented several other physics-based atmospheric models from a variety of sources for execution on its computational platforms. The availability of this diverse set of atmospheric models facilitates the use of an ensemble forecast strategy. These models include the FOR*EWIND*, MM5, WRF, COAMPS, workstation-ETA and OMEGA models. Each of these models has unique attributes that can bring additional information to an ensemble of numerical forecast simulations. FOR*EWIND* is a high-resolution boundary layer model that has been developed by TrueWind Solutions. This model is intended to run at very high resolution over a layer extending from the surface of the earth to approximately 3 km while accepting data about the state of the atmosphere above 3 km from another model. The ability to limit the domain to the atmospheric boundary layer permits higher vertical and horizontal resolution to be used in this model while still achieving the execution time required for a forecast simulation to be useful. The MM5 model is a public-domain non-hydrostatic three-dimensional mesoscale model developed by the Pennsylvania State University and the National Center for Atmospheric Research (NCAR). Due to its availability in the public domain, it has been widely used and has become a de facto standard for mesoscale models. It's main strength is that it has been widely used and verified and incorporates a variety of physics formulations from different sources. However, the numerical techniques and data assimilation options are somewhat out of date in the MM5 system. The WRF model is a next-generation atmospheric model currently being jointly developed by NCAR and NCEP. An early version of this model is now available. It incorporates many of the physics routines from MM5 but utilizes more advanced numerical techniques and will ultimately have an advanced data assimilation system. COAMPS is a high-resolution model developed by the U.S. Navy. Its most unique feature is that it models both the oceans and the atmosphere, whereas all of the other models in this group treat bodies of water as a specified (from an external source) lower boundary condition. The workstation-ETA model is version of the National Weather Service's ETA model that has been designed to run on a computer workstation rather than in the supercomputer environment at NCEP. It uses a different vertical coordinate system (ETA) from most of the other mesoscale models. This is especially beneficial in regions of steeply sloping terrain. The OMEGA model is a very unique unstructured adaptive grid model that has been co-developed by SAIC and MESO, Inc. It is the first atmospheric model to use an unstructured grid (i.e. a grid in which the grid cells have no predefined relationship to each other). The unique grid structure permits the use of a continuously variable (in space and time) grid resolution within the model domain and permits the adaptation of the grid structure to geographic (e.g. land-water boundaries) or atmospheric features (e.g. frontal zones). All of these models can currently be executed on computational platforms at TrueWind Solutions. However, it is not cost-effective to run an ensemble of simulations that utilizes all of these models and a variety of initial state perturbations. Therefore, a manageable set of initial perturbation and model configuration strategies are customized for each forecast application. The *eWind* forecasts for a specific site are typically based upon the execution of this customized ensemble of physical model simulations.

Adaptive Statistical Models

The adaptive statistical models are used to build a set of empirical relationships between the output of the physics-based atmospheric models and specific parameters to be forecasted for a particular location. In the Southwest Mesa wind forecasting application, the specific parameters are the wind speed and direction and air density at the location of the wind plant. The role of the statistical models is to adjust the output of the physics-based models to account for sub-grid scale and other processes that cannot be resolved or otherwise adequately simulated by the physical models. Two types of statistical models are currently used in the *eWind* system. The first is a traditional multiple screening linear regression model. The second is a Bayesian neural network model. As with the linear regression approach, this scheme uses a training sample to determine a set of parameters that define the equations that relate the inputs (i.e. the predictors) to the target (i.e. the predictand). The difference is essentially in the form of the functional relationships and the method used to estimate the parameters. The neural network scheme used in *eWind* employs a Markov Chain Monte Carlo training method. This method essentially trains an ensemble of networks by taking many samples from the distribution of the network parameters. These network parameters are the weights and biases that determine the input-to-target function. They are the conceptual equivalents of slopes and intercepts in a linear regression. The distributions used for sampling depend on the training data, the "noise model" (i.e. the assumed distribution of the noise in the data) and the "priors" (additional information provided to the scheme about the expected smoothness of the functions, i.e. the ranges of the network parameters).

Plant Output Models

The third component of the system is the plant output model. This model is a relationship between the critical atmospheric variables and the plant output. It is possible to use either a physical or statistical approach in the formulation of the plant output model. The *eWind* system utilizes only the statistical approach. The *eWind* statistical plant output model can be a fixed relationship derived from a single usually long-term dataset of measured meteorological parameters and the plant energy output or it can be a dynamic relationship derived from recent (e.g. the last 60 days) measured data from the plant. However, even a statistical plant output model can incorporate information about the layout of the plant into the model's framework. For example different sets of relationships may be used for cases in which the wind is blowing parallel to a row of turbines than in cases when the wind is blowing perpendicular to the row.

Forecast Delivery System

The final piece is the forecast delivery system. The user has the option of receiving the forecast information via email, an ftp transmission, a faxed page or on a password-protected web page display.

Application to Southwest Mesa Wind Project

In the Southwest Mesa forecasting application, the *eWind* system was configured to produce two 48-hour forecasts of average hourly wind speed and direction and temperature at Southwest Mesa Meteorological Tower #1 and the total hourly energy output per day. The forecast delivery times were 6 A.M. and 6 P.M. Central Standard Time (CST). Due to the limited resources available for this project, only one physics-based model simulation was executed for each forecast cycle. The *eWind* ensemble forecast method was not employed. The single physics-based simulation per forecast cycle was generated with a two-level nested grid configuration of the MASS model. The outer coarse grid consisted of a 100 by 80 horizontal matrix of grid cells with a grid cell size of approximately 40 km. The inner fine grid was composed of an 80 by 70 horizontal matrix of grid cells with a size of about 10 km. The inner grid was centered on the Southwest Mesa wind plant. The simulations were initialized with the 0-hour (analysis) data from the National Weather Services AVN model. The lateral boundary conditions for the 40 km grid were also extracted from the AVN model's forecast dataset. The

6 AM forecast was based on a MASS simulation initialized with data from the 0000 UTC (6 PM CST of the previous day) AVN forecast cycle. It should be noted that the first hour of the 6 AM Southwest Mesa forecast (i.e. the hour ending at 7 AM CST) is actually the 13th hour of the MASS simulation used to make that forecast. Analogously, the 6 PM Southwest Mesa forecast was based on a MASS simulation initialized with data from the 1200 UTC (6 AM CST) AVN forecast cycle.

The output from the physical model simulation was used as input into the statistical model in a procedure known as Model Output Statistics (MOS). In the MOS procedure used in this project, a rolling dataset of the previous 30 days of physics-based model output data and measured data from the Southwest Mesa plant were used as the training sample for the statistical model. The training process was repeated with the latest training sample as part of each forecast cycle. A set of variables computed from the output dataset of the MASS model simulation was used as the pool of candidate predictors. The wind speed and direction and the temperature at the Southwest Mesa meteorological towers and the average wind speed and direction of all of the nacelle anemometer measurements were the predictands (i.e. quantities to be predicted). A screening multiple linear regression (SMLR) procedure was used to create the statistical prediction equations from the training sample data. The SMLR process sequentially selects predictors from the pool of candidate predictors by assessing the predictive value of each candidate predictor and selecting the best one. After a predictor is selected the process is repeated with the previously selected predictors excluded from the candidate pool. The process continues until either the limit on the number of predictors is reached (to prevent overfitting) or the additional predictor selected in the latest iteration does not add sufficient additional predictive value to the regression equation. Once the regression equation is constructed, it is evaluated with the current values of the predictors to generate a forecast of all of the predictands for all the hours in the current forecast cycle.

The plant output model used in the Southwest Mesa forecast application was based on a fixed statistical relationship between the wind speed and direction and the hourly energy output from the plant. This relationship was constructed at the start of the project through the use of several months of measured wind speed and direction and energy generation data. The data were quality-controlled through the use of a two-step process that included both objective and subjective (manual) procedures. The wind data utilized for the plant output model for the Southwest Mesa forecast application were the average wind speed and direction from the nacelle anemometers. The hourly energy generation forecast was produced by providing the MOS-based predictions of the average nacelle anemometer wind speed and direction to the plant output model.

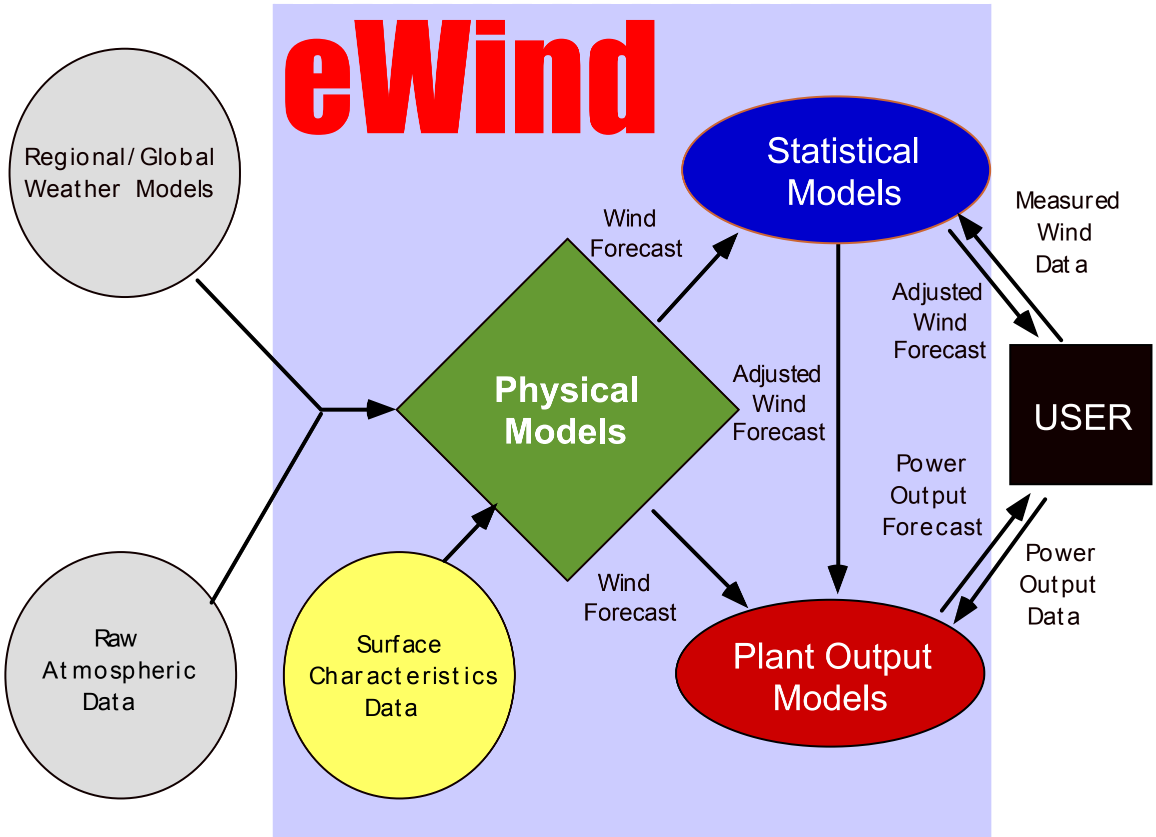


Figure 4-2
A schematic representation of the major components of the *eWind* forecast system

Applied Modeling, Inc.–WEFS

Figure 4-3 is a schematic of the state-of-the-art AMI Wind Energy Forecasting System (*WEFS*) developed by Applied Modeling Inc. *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.

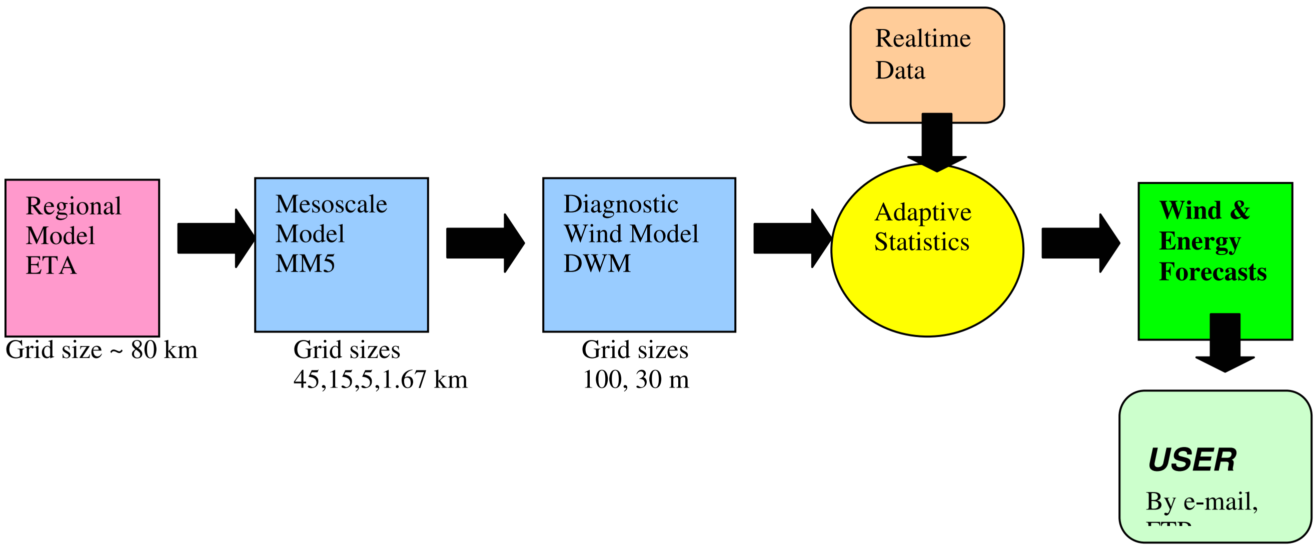


Figure 4-3
Schematic of AMI Wind Energy Forecasting System (WEFS)

Mesoscale Model MM5

The first module of WEFS is a PC-based version developed by Applied Modeling Inc. (AMI) of the advanced, three-dimensional mesoscale model MM5 (Version 3). 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 at the Pennsylvania State University and National Center of Atmospheric Research (NCAR) since the 1970s as a community mesoscale model. 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 in forecasting 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 has 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 the 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 database with a 1-km resolution for use with MM5.

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, accounted for. AMI has 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 wind speed intervals 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 that requires extensive re-calculations due to changes in the forecast models, weather conditions or wind plant configurations.

Forecast Access by Users

Upon their completion, the forecast wind and energy data are sent via e-mail or any other electronic means to the host and other organizations. They can also be uploaded to the host FTP server along with appropriate statistics designed to evaluate the accuracy and skill of the forecasts.

Application to Southwest Mesa Wind Project

Two MM5 forecasts, valid for 48 hours, are generated daily for 00 UTC (1800 CST) and 12 UTC (0600 CST). The MM5 model uses four nested modeling grids as shown in Figure 4-4. 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. Terrain elevations in the outermost domain are shown in Figure 4-3. The first inner domain (domain D02) contains 76 x 76 grid points with a 15 km resolution, and the second inner domain (domain D03) has 46x46 grid points with a 5 km resolution. The innermost domain (domain D04) is centered on the Southwest Mesa plant, and has 34x34 grid points with a 1.67 km resolution.

Initial conditions are generated by interpolating the NCEP ETA analyses to the MM5 grids. Lateral boundary conditions are derived from the ETA forecasts and updated every 6 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. Forecast parameters include hourly averaged wind speed, wind direction, ambient temperature and power output. Table 4-2 shows an example final. Final forecasts are uploaded twice a day to the EPRI FTP server. AMI also maintains a password-protected Web site at http://www.amiace.com that includes graphical displays of MM5 forecasts.

To minimize human errors, the above forecasts, including all model simulations and evaluation, have been completely automated. A Linux PC with dual AMD Athlon microprocessors is used to perform the model simulations.

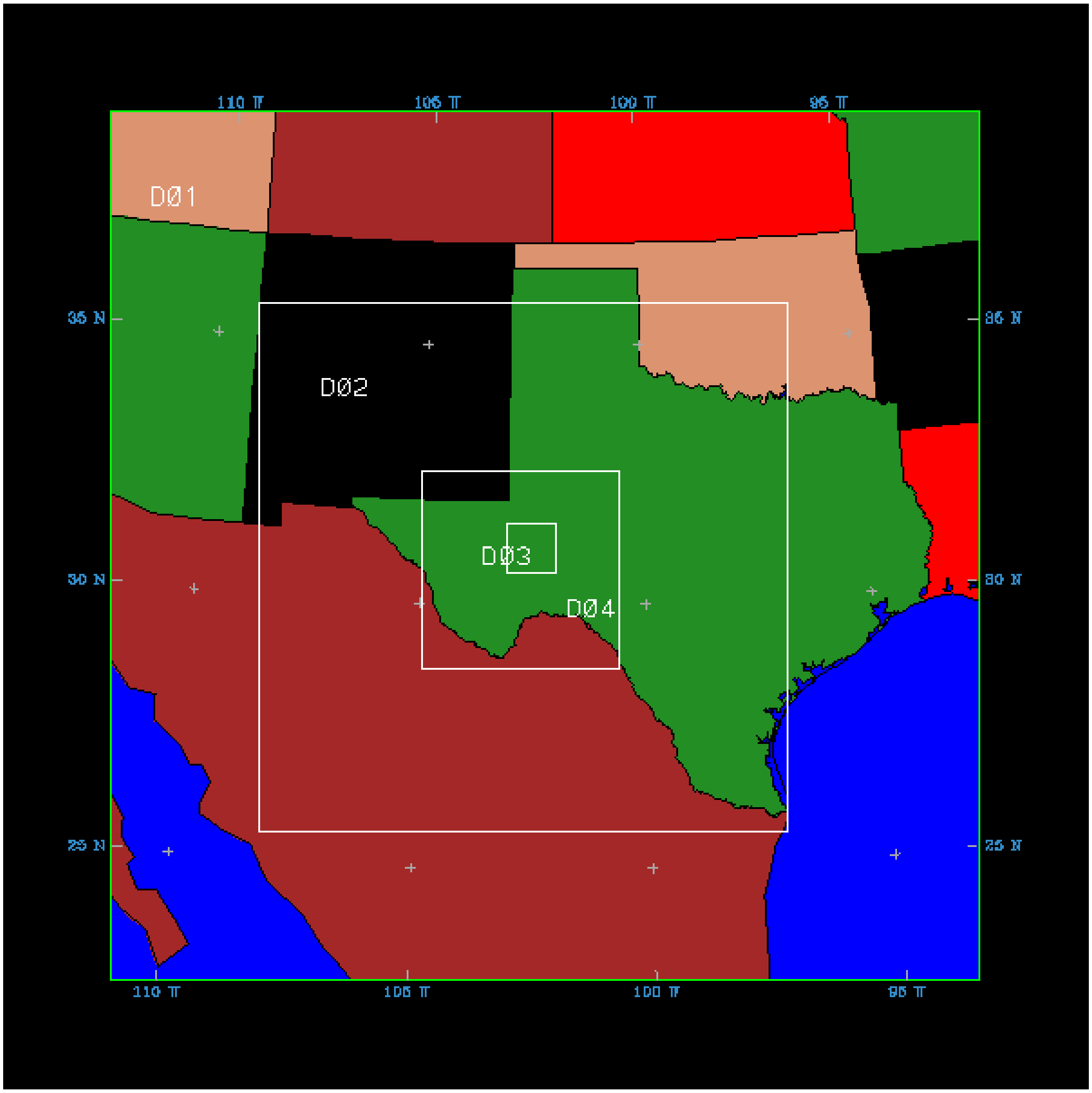


Figure 4-4
MM5 Modeling Grids for the Southwest Mesa Facility. Nested grids use spatial resolutions of 45, 15, 5 and 1.67 km. Innermost grid D04 is centered on Southwest Mesa with a 1.67 km cell spacing

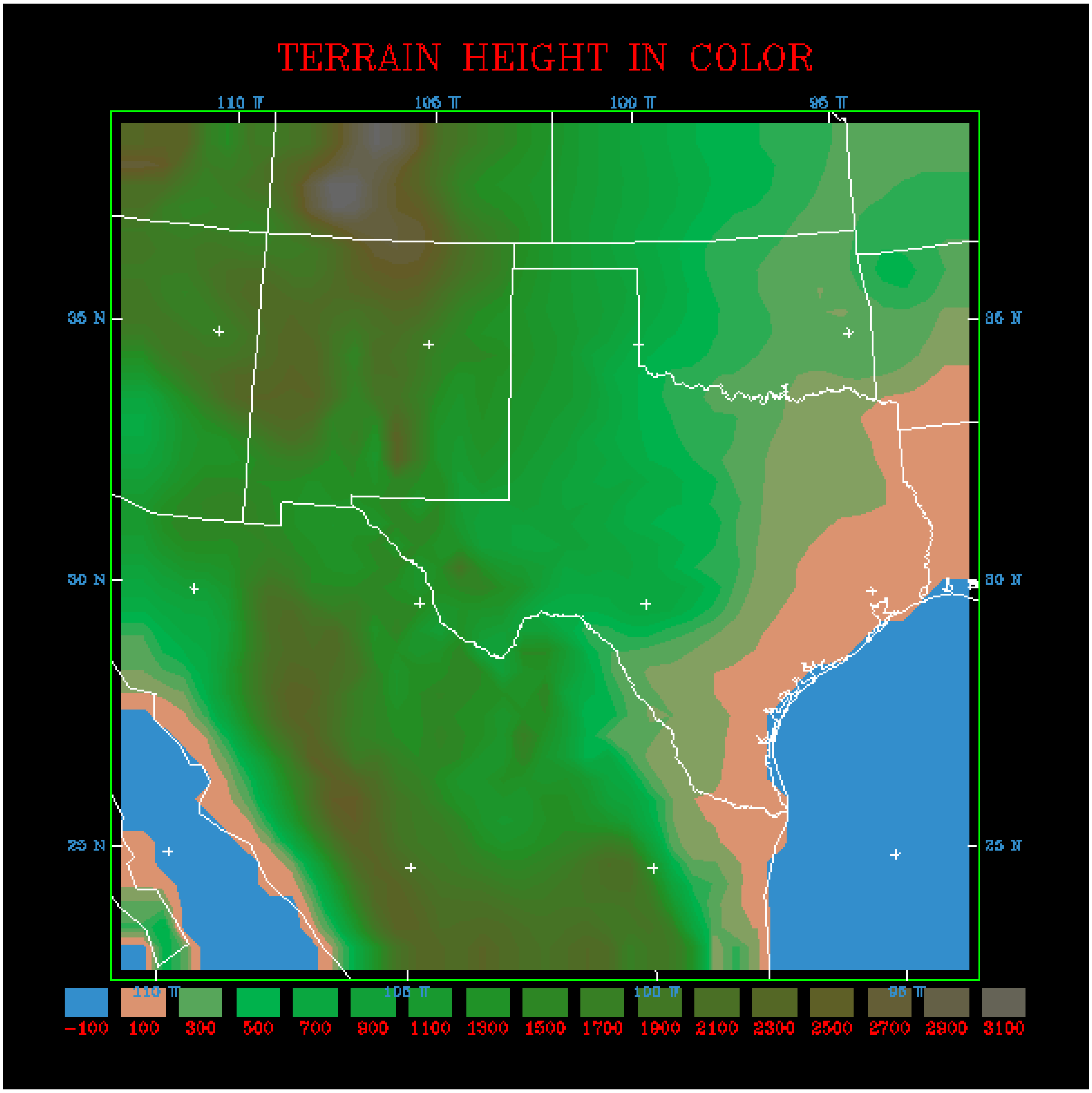


Figure 4-5
Terrain Elevations (m) Around the Southwest Mesa Facility Outermost grid D01 has a spatial resolution of 45 km

Table 4-2
Example AMI Forecast at Southwest Mesa Wind Project

Wind Plant	Contractor	Forecast Issued (UTC)	Forecast Issued (CST)	Forecast Hour	Forecast Time (CST)	Wind Speed (m/sec)	Wind Direction (degrees)	Ambient Temp. (deg C)	Energy Generation (kWh)
SW Mesa	AMI	2002070112	2002070106	1	2002070106	6.8	152	20	12,064
SW Mesa	AMI	2002070112	2002070106	2	2002070107	8	139	19	21,811
SW Mesa	AMI	2002070112	2002070106	3	2002070108	9.4	136	19	34,596
SW Mesa	AMI	2002070112	2002070106	4	2002070109	8.9	138	19	29,386
SW Mesa	AMI	2002070112	2002070106	5	2002070110	7.2	149	20	14,074
SW Mesa	AMI	2002070112	2002070106	6	2002070111	5.5	150	21	6,399
SW Mesa	AMI	2002070112	2002070106	7	2002070112	4	128	24	1,557
SW Mesa	AMI	2002070112	2002070106	8	2002070113	3.6	122	26	702
SW Mesa	AMI	2002070112	2002070106	9	2002070114	4	121	27	1,397
SW Mesa	AMI	2002070112	2002070106	10	2002070115	5	113	27	4,106
SW Mesa	AMI	2002070112	2002070106	11	2002070116	5.4	120	28	5,834
SW Mesa	AMI	2002070112	2002070106	12	2002070117	5.5	122	27	6,504
SW Mesa	AMI	2002070112	2002070106	13	2002070118	6.9	121	27	12,113
SW Mesa	AMI	2002070112	2002070106	14	2002070119	7.9	133	26	20,290
SW Mesa	AMI	2002070112	2002070106	15	2002070120	8.9	139	25	29,893
SW Mesa	AMI	2002070112	2002070106	16	2002070121	10.3	133	24	38,015
SW Mesa	AMI	2002070112	2002070106	17	2002070122	9.5	135	23	36,022
SW Mesa	AMI	2002070112	2002070106	18	2002070123	8	147	23	21,586
SW Mesa	AMI	2002070112	2002070106	19	2002070200	10.3	138	22	37,881
SW Mesa	AMI	2002070112	2002070106	20	2002070201	9.3	145	21	34,340
SW Mesa	AMI	2002070112	2002070106	21	2002070202	9.5	146	21	36,547
SW Mesa	AMI	2002070112	2002070106	22	2002070203	7.9	142	21	20,379
SW Mesa	AMI	2002070112	2002070106	23	2002070204	7	143	20	12,743
SW Mesa	AMI	2002070112	2002070106	24	2002070205	5.6	146	20	7,046
SW Mesa	AMI	2002070112	2002070106	25	2002070206	3.7	152	20	904
SW Mesa	AMI	2002070112	2002070106	26	2002070207	2.4	154	20	0
SW Mesa	AMI	2002070112	2002070106	27	2002070208	2.4	155	20	0
SW Mesa	AMI	2002070112	2002070106	28	2002070209	2	144	21	0
SW Mesa	AMI	2002070112	2002070106	29	2002070210	1.4	144	23	0
SW Mesa	AMI	2002070112	2002070106	30	2002070211	2.1	123	24	0
SW Mesa	AMI	2002070112	2002070106	31	2002070212	4.8	141	25	3,761
SW Mesa	AMI	2002070112	2002070106	32	2002070213	5.8	152	25	7,712
SW Mesa	AMI	2002070112	2002070106	33	2002070214	4.9	24	23	3,574
SW Mesa	AMI	2002070112	2002070106	34	2002070215	4.1	14	22	1,528
SW Mesa	AMI	2002070112	2002070106	35	2002070216	7.1	108	24	12,344
SW Mesa	AMI	2002070112	2002070106	36	2002070217	5.4	92	25	4,650
SW Mesa	AMI	2002070112	2002070106	37	2002070218	1.8	74	23	0
SW Mesa	AMI	2002070112	2002070106	38	2002070219	5.5	6	21	6,051
SW Mesa	AMI	2002070112	2002070106	39	2002070220	7.4	38	20	12,013
SW Mesa	AMI	2002070112	2002070106	40	2002070221	8	67	21	14,286
SW Mesa	AMI	2002070112	2002070106	41	2002070222	6.9	66	22	8,248
SW Mesa	AMI	2002070112	2002070106	42	2002070223	5.1	77	22	3,555
SW Mesa	AMI	2002070112	2002070106	43	2002070300	5.5	118	22	6,243
SW Mesa	AMI	2002070112	2002070106	44	2002070301	8.4	140	22	24,746
SW Mesa	AMI	2002070112	2002070106	45	2002070302	7.6	144	22	17,527
SW Mesa	AMI	2002070112	2002070106	46	2002070303	7.3	142	21	14,714
SW Mesa	AMI	2002070112	2002070106	47	2002070304	8.3	138	21	24,183
SW Mesa	AMI	2002070112	2002070106	48	2002070305	9.2	146	21	32,775

5
WIND ENERGY FORECASTING SYSTEM TEST RESULTS

This chapter describes the metrics used to measure the wind energy forecasting system performance and presents the initial test results of applying the three wind energy forecasting systems to the Southwest Mesa Wind Project near McCamey, Texas. The results address the forecast performance of the Risoe *Prediktor*, TrueWind *eWind*, and Applied Modeling *WEFS* systems described in Chapter 4 vs. observed data from Southwest Mesa during May 2002.

Forecast Performance Evaluation

Wind energy forecasting system performance is measured by how well the forecast hourly wind speed and energy generation track the observed values at the wind project site.

Perhaps the simplest forecast models are those based on persistence and climatology. These models rarely exhibit good skill, but they do form the basis for comparison of forecast techniques. A good forecaster should be able to do better than persistence and climatology overall.

Persistence Forecasts

Persistence forecasts make the simple assumption that the current conditions will persist over the entire forecast period. While this model is simple and can be effective over very short time intervals, the method does not account for any of the physical meteorological processes or allow for any variations in conditions during the forecast period. A persistence forecast is often considered to be a zero-skill forecast and is often used as the basis for assessing other methods. A forecast that performs better than a persistence forecast is considered to exhibit *skill*.

Climatology Forecasts

Climatology forecasts are also simple but they are based on the annual and diurnal variations of the wind resource and other conditions at the project site. However, like persistence forecasts, the forecasts don’t account for the physical process or dynamic changes. A long-term history of conditions is needed to be able to define the climatological mean conditions with a high degree of certainty. However, climatology can provide forecasts of typical conditions at a location that are useful for long term planning and for measuring the skill of meteorological forecasts.

Forecast Performance Metrics

The forecast performance metrics include the mean error between the forecast and observed values (ME), mean absolute error (MAE), the standard deviation of the error (s), and the skill scores vs. persistence and climatology forecasts for each of the forecast hours (hours 1 through 48).

The mean error is:

$$ME = (\Sigma (F_i - Oi))/N$$

where F_i is the ith forecast;

O_i is the corresponding observation, and;

N is the number of forecasts.

The mean absolute error is:

$$MAE = (\Sigma \text{ ABS } (F_i - O_i))/N$$

The standard deviation of the error is:

$$\sigma = \sqrt{} (\Sigma (F_i - O_i - ME)^2)/(N-1)$$

where F_i, O_i, and N_i are the forecast for time i, O_i is the observation for time i, and N is the number of forecasts.

The skill scores compare the monthly mean absolute errors for the meteorology-based forecasts (MAE_M vs. those for persistence and climatology forecasts (MAE_P and MAE_C) as follows:

Skill Score vs. Persistence: $SS_P = 1 - MAE_M / MAE_P$

Skill Score vs. Climatology: $SS_C = 1 - MAE_M / MAE_C$

Initial Wind Energy Forecasting Results – Risoe National Laboratory

As described in Section 4, the Risoe's *Prediktor* forecast system produces forecasts via a multi-step process that employs both physics-based and statistical models. This section describes the initial test results and forecast performance of *Prediktor* for May 2002.

Wind Speed and Energy Forecasts

Figure 5-1 presents the Risoe 48-hour wind speed (top) and wind generation (bottom) meteorology forecasts beginning at 1800 hours on May 18, 2002, together with the corresponding observed data and persistence and climatology forecasts.

The Risoe meteorology forecasts (diamonds) follow the general patterns of the observed wind speed and generation (solid line), and the persistence and climatology forecasts (squares and triangles) fall in the middle of the range. The Risoe wind speed forecast exhibits a negative bias, while the bias present in the wind energy forecast is positive.

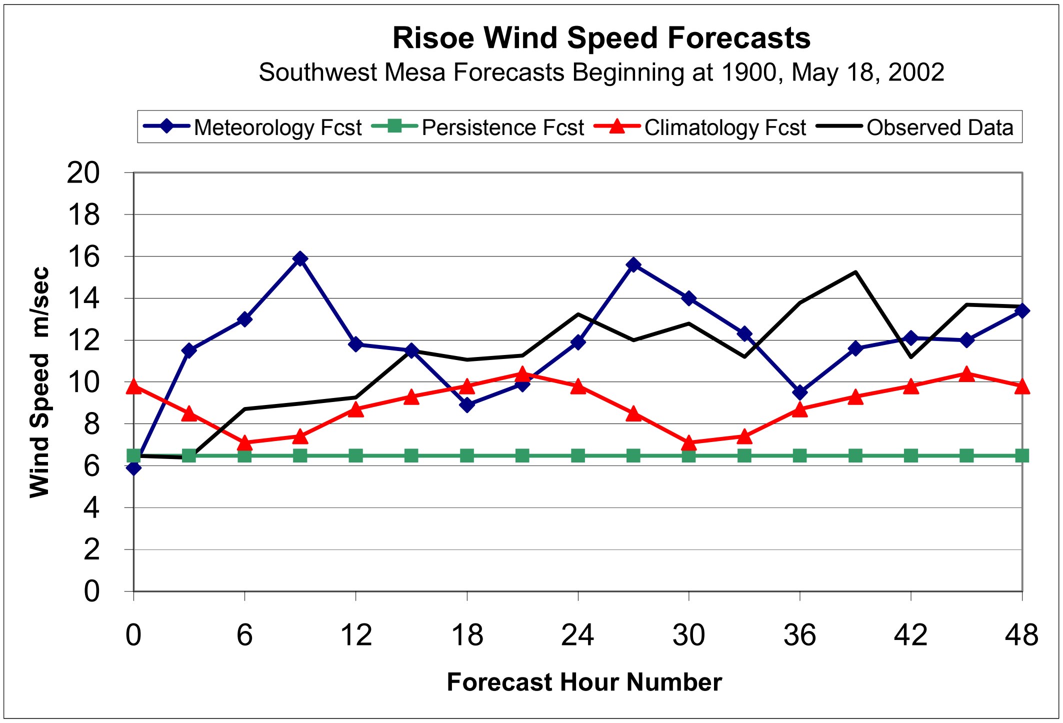
Forecast Performance

Table 5-1 summarizes the monthly performance statistics for the Risoe forecasts at Southwest Mesa for May 2002. The monthly mean errors (ME) of the hourly wind speed and generation forecasts vs. the observed data are –2.1 m/sec and -1727 kW, respectively. The corresponding figures for the monthly mean absolute errors (MAE) are 3.40 m/sec and 18,597 kW. The normalized monthly mean errors of the wind speed and generation are –20.3% and +4.7% of the monthly average hourly wind speed (10.23 m/sec) and wind generation (36,406 kW), respectively. The corresponding figures for the normalized monthly mean absolute errors are 33.2% and 51.1%. The resulting skill scores of the Risoe wind speed and generation forecasts are 6.4% and –5.2% vs. the persistence forecast and 10.5% and 7.1% vs. the climatology forecast. Thus, the wind generation forecasts exhibit higher normalized mean absolute errors and lower skill scores than the wind speed forecasts.

Figure 5-2 presents the mean and mean absolute errors of the wind generation forecasts during May 2002 as functions of the forecast hour number, based on Risoe's four forecasts per day.

Table 5-1
Risoe Forecast Performance Statistics for May 2002

	Wind Speed m/sec	Generation kW
Forecast Error		
Monthly ME (m/sec or kW))	-2.08	1,727
Monthly MAE (m/sec or kW))	3.40	18,597
Normalized Forecast Error		
Monthly ME	-20.3%	4.7%
Monthly MAE	33.2%	51.1%
Average Wind Speed or Gen	10.23	36,406
Monthly Skill Score		
vs. Persistence	6.4%	-5.2%
vs. Climatology	10.5%	7.1%
Wind Forecast Delivery		
Possible Forecasts	62	
Forecasts Delivered	58	
%	93.5%	



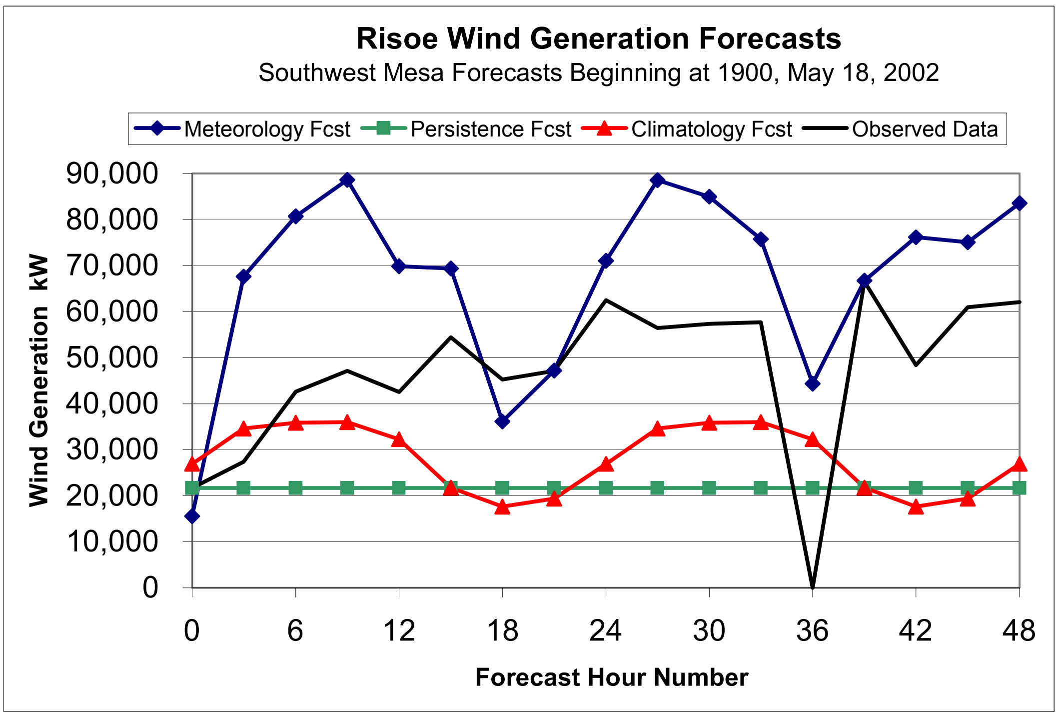


Figure 5-1
Comparison of Risoe 48-Hour Wind Speed and Generation Forecasts at Southwest Mesa with Persistence and Climatology Forecasts and Observed Data, Beginning at 0700 CST, May 18, 2002

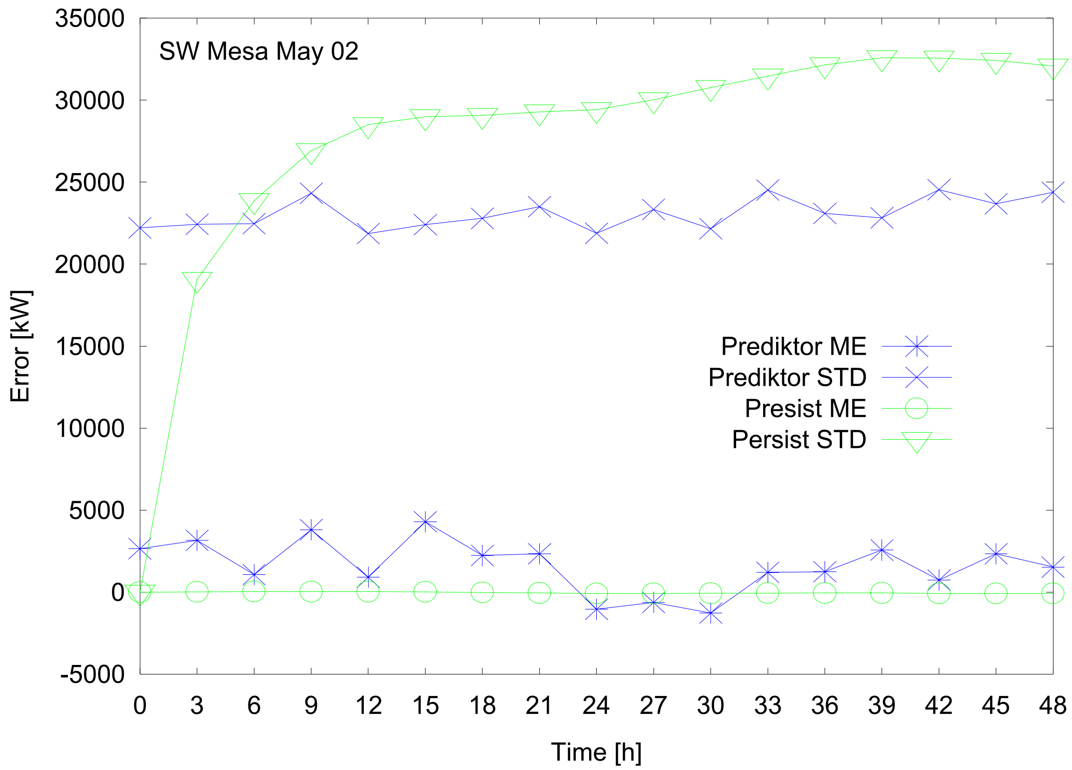
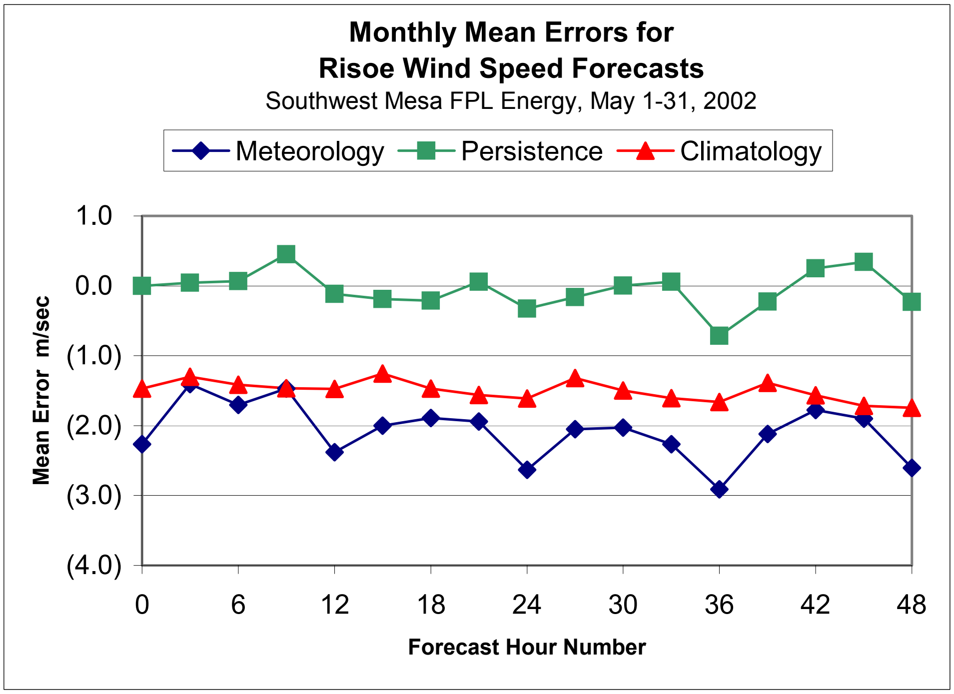


Figure 5-2
Monthly Mean and Mean Absolute Errors of Risoe and Persistence Forecasts of Wind Generation at Southwest Mesa for May 2002

Figures 5-3 through 5-5 present the forecast performance results for the Risoe May 2002 meteorology, persistence, and climatology forecasts, based on two of the four Risoe forecasts each day (0700 and 1900 hours). The figures present the monthly mean errors, mean absolute errors, and skill scores vs. persistence and climatology as functions of the forecast hour number (hours 0, 3, 6, 9,…, 48). The mean absolute errors of the AMI meteorology forecasts cross over and become lower than those of the persistence forecasts beyond twelve hours for both the wind speed and wind energy forecasts.



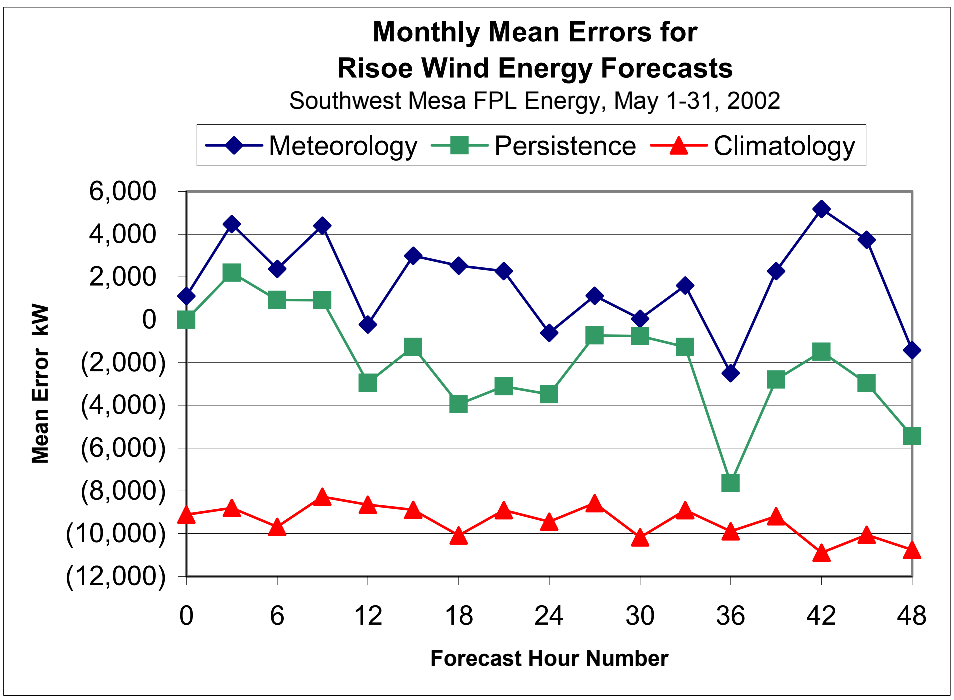
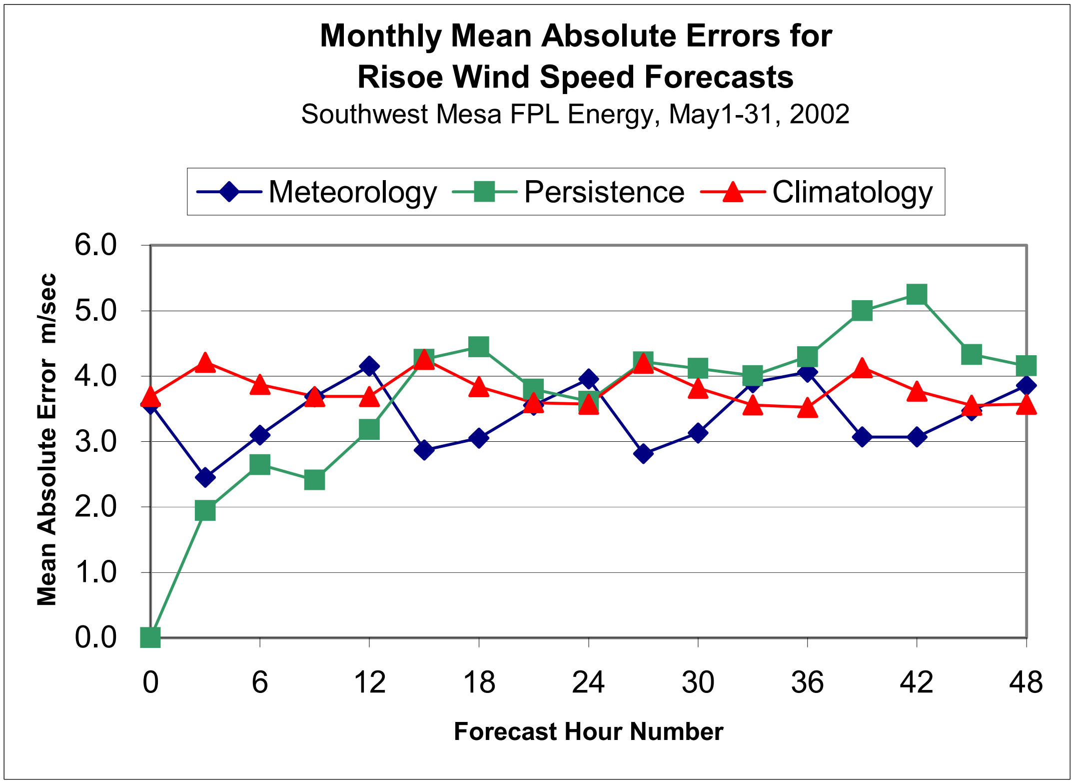


Figure 5-3
Monthly Mean Errors for Risoe Wind Speed and Generation Forecasts at Southwest Mesa, May 2002



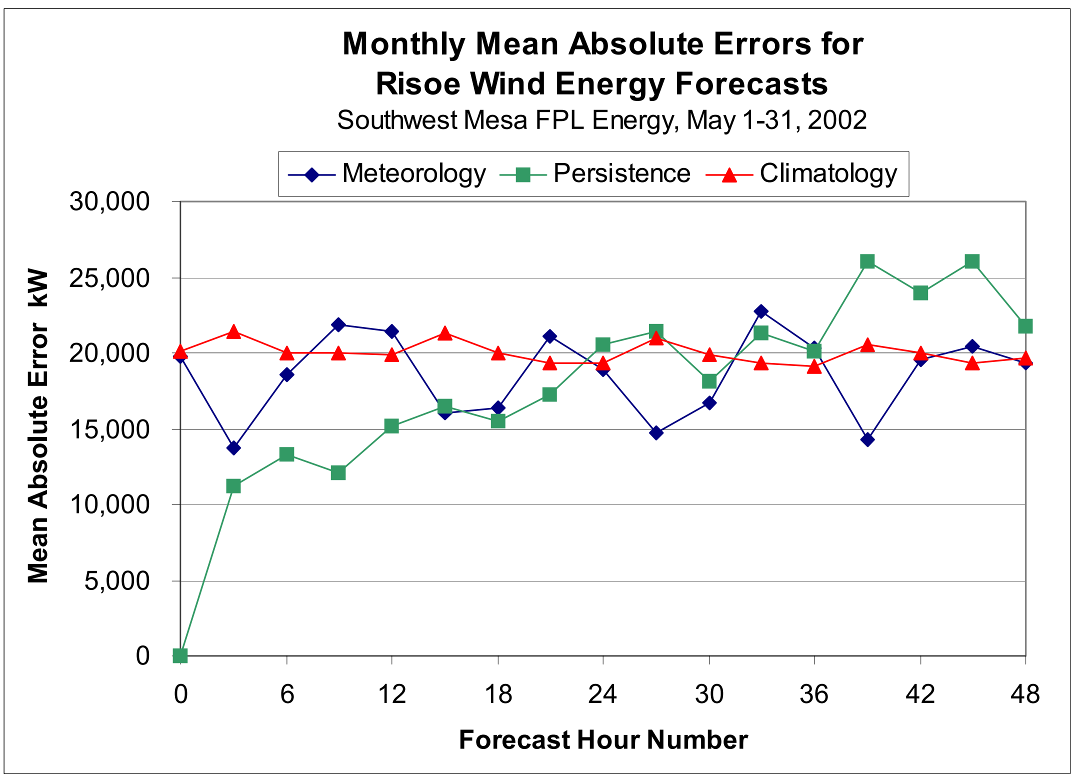
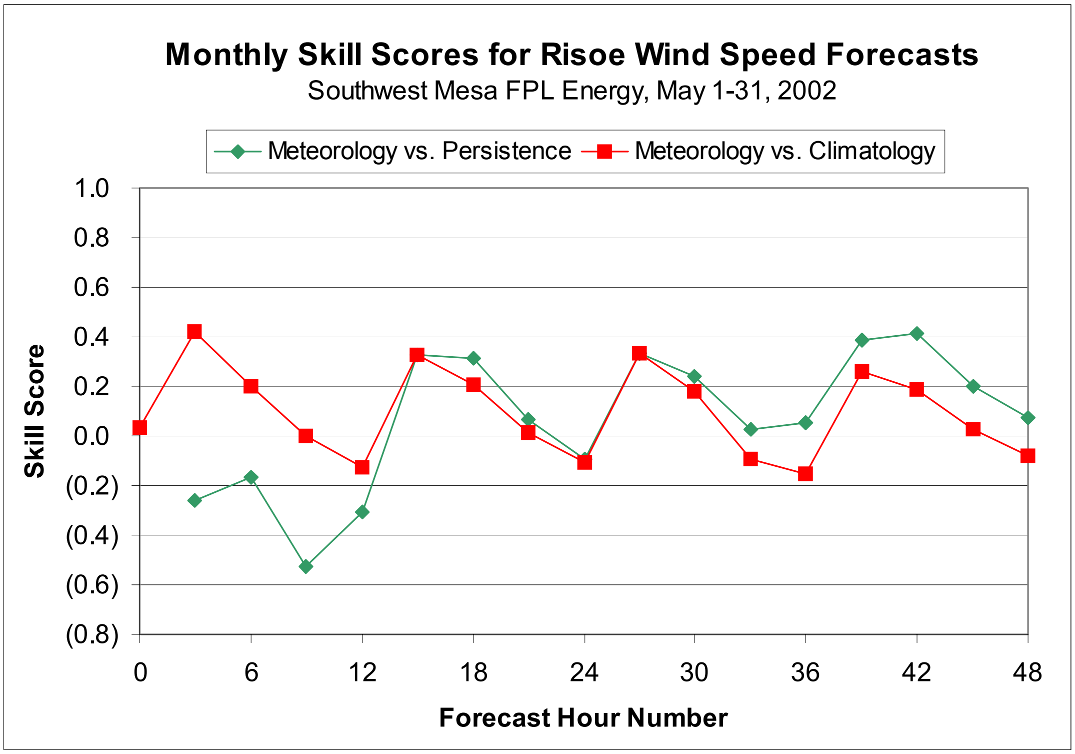


Figure 5-4
Monthly Mean Absolute Errors for Risoe Wind Speed and Generation Forecasts at Southwest Mesa, May 2002



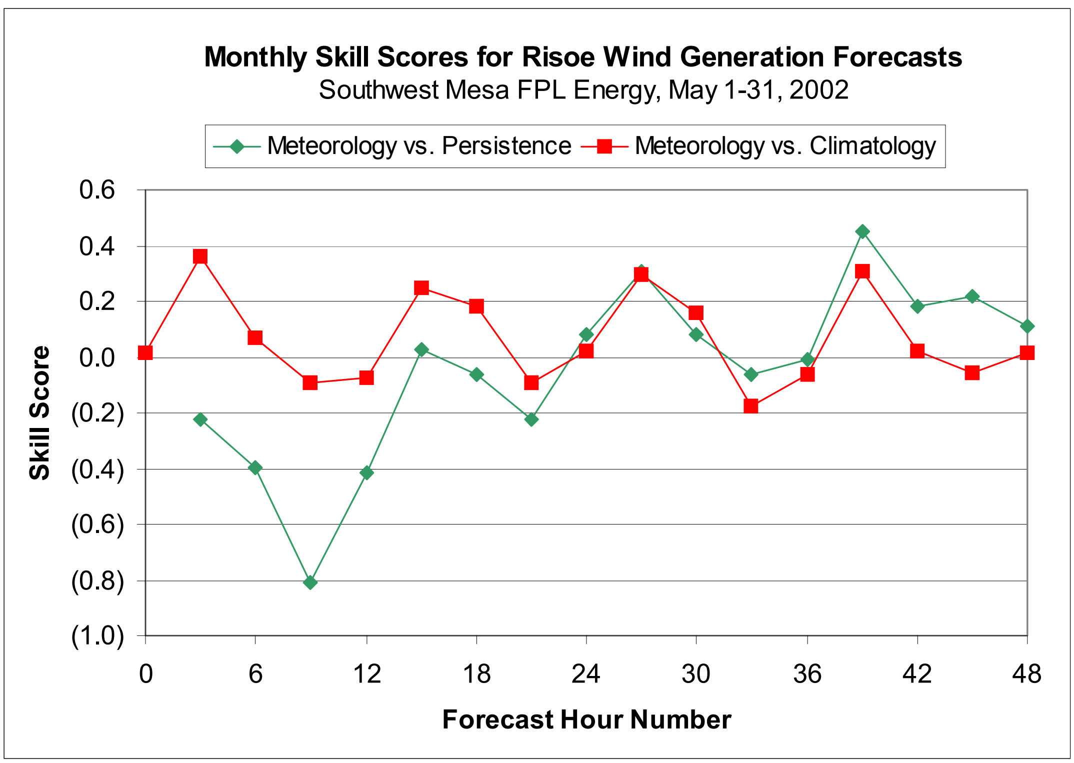


Figure 5-5
Monthly Skill Scores vs. Persistence and Climatology for Risoe Wind Speed and Generation Forecasts at Southwest Mesa, May 2002

Initial Forecasting Results –TrueWind Solutions

As described in Section 4, TrueWind's *eWind* forecast system produces forecasts via a multi-step process that employs both physics-based and statistical models. This section describes the initial test results and forecast performance of *eWind* for May 2002.

The forecast from the morning cycle of May 15, 2002 will be used as an example of the TrueWind forecast process and the typical performance of the forecast system for May 2002. The first forecast hour of this cycle is the hour ending at 7 AM CST May 15. The forecast procedure begins with the execution of an atmospheric simulation with a physics-based atmospheric model. In the configuration of TrueWind's *eWind* forecast system that was employed for the Southwest Mesa forecast evaluation project, a two-level nested grid configuration was used to execute forecast simulations with the MASS model. The outer coarse-resolution grid utilized a grid cell size of about 40 km and covered the region shown in Figure 5–6. This regional simulation used initialization and boundary condition data from the U.S. National Weather Service's AVN model. Figure 5-6 depicts a 21-hour 40 km grid forecast of the mean sea level pressure and the 40 m wind speed and direction for 4 AM May 16 from the morning forecast cycle of May 15. There is a low pressure center predicted to be over the Texas-Oklahoma panhandle area at this time. A trough of low pressure extends southward across western Texas. This trough demarcates the forecasted position of a frontal zone separating drier and slightly cooler air to the west from the warm and moist air to the east. There is a strong southerly flow ahead of this frontal zone and the Southwest Mesa plant is predicted to be on the western periphery of this strong southerly flow of air.

A grid with a cell size of approximately 10 km was embedded within the 40-km grid. The initialization and lateral boundary condition information for the simulation on this grid was extracted from the 40 km simulation. Figure 5-7 shows the area covered by this. The figure depicts a higher resolution version of the same 21-hour forecast fields shown in Figure 5-6. One can easily see the smaller scale wind speed and pressure features that are present in the 10 km simulation but absent from the coarser grid regional simulation. Figure 5-8 depicts the forecast of the same fields for 9 hours (1 PM May 16 or 30 hrs into the forecast period) after those shown in Figure 5-7. A comparison of these two figures indicates that the frontal zone was predicted to move eastward during this period and to be located along a southwest to northeast axis just to the east of the Southwest Mesa wind plant. The strong southerly flow was forecasted to move eastward and the winds in the vicinity of the Southwest Mesa plant are predicted to be significantly weaker and from the west at 1 PM on May 16.

The next step in the forecast process is to use the grid point output from the 10 km simulation as input into a set of equations derived from the *eWind* Model Output Statistics (MOS) module. These statistical prediction equations are derived from a trailing 30-day training sample of measured data from the wind plant and physical model output data. The output from the MOS procedure used in this project was a forecast of the wind speed at each of the three meteorological towers and the average speed of all of the nacelle anemometers. The MOS wind speed forecast for the anemometer on Meteorological Tower No. 1 (MT #1) from the May 15 morning cycle is shown in Figure 5-9. This forecast indicates that the wind speed is predicted to gradually increase to a peak of almost 16 m/s at about 21 hours after the start of the forecast. This corresponds to the strengthening southerly flow of air ahead of the approaching frontal zone in Figure 5-7. The wind speed is then forecasted to sharply decrease to a minimum of about 6 m/s at 30 hours into the forecast period. This forecasted minimum corresponds to the predicted passage of the frontal trough shown in Figure 5-8. The measured MT #1 wind speeds shown in Figure 5-9 indicate that the evolution of the wind speed associated with the approach and passage of this frontal zone during the first 30 hours of the forecast period was quite well predicted. However, after this initial 30-hour period, the May 15 morning forecast is not quite as good. The measured data indicate that the wind speed further decreased to near 4 m/s at 36 hours into the forecast period and then rapidly increased to near 12 m/s about four hour later. The forecast from the morning cycle on May 15 did not predict the continued decrease in wind speed between 30 and 36 hours or the subsequent rapid acceleration of the wind. However, it is interesting to note that the forecast produced the following morning (labeled as "TrueWind+24 hrs") did a much better job of predicting the increase in wind speed during the latter portion of May 16.

The final step in the forecast process is the transformation of the wind speed forecasts to a plant-scale energy generation prediction through the use of a plant output model. The *eWind* system employs a statistical plant output model for this purpose. Figure 5-10 shows the energy generation forecast from the morning forecast cycle of May 15, along with the corresponding persistence and climatology forecasts and the reported energy output for each hour of the forecast period. As one might expect, the quality of this forecast is closely related to the quality of the underlying wind speed forecast shown in Figure 5-9. The energy generation forecast is excellent for the first 36 hours, as it correctly predicts the increasing energy production associated with the strong southerly flow ahead of the approaching frontal system and accurately predicts the rapid decrease in production as the weak pressure gradient associated with the axis of the frontal zone moves across the Southwest Mesa area. However, this forecast fails to anticipate the significant increase in energy production after the passage of the frontal trough. As noted in the previous discussion of the wind speed forecasts, the following morning's forecast does a much better job in predicting the reported increase in energy generation after sunset on May 16.

.

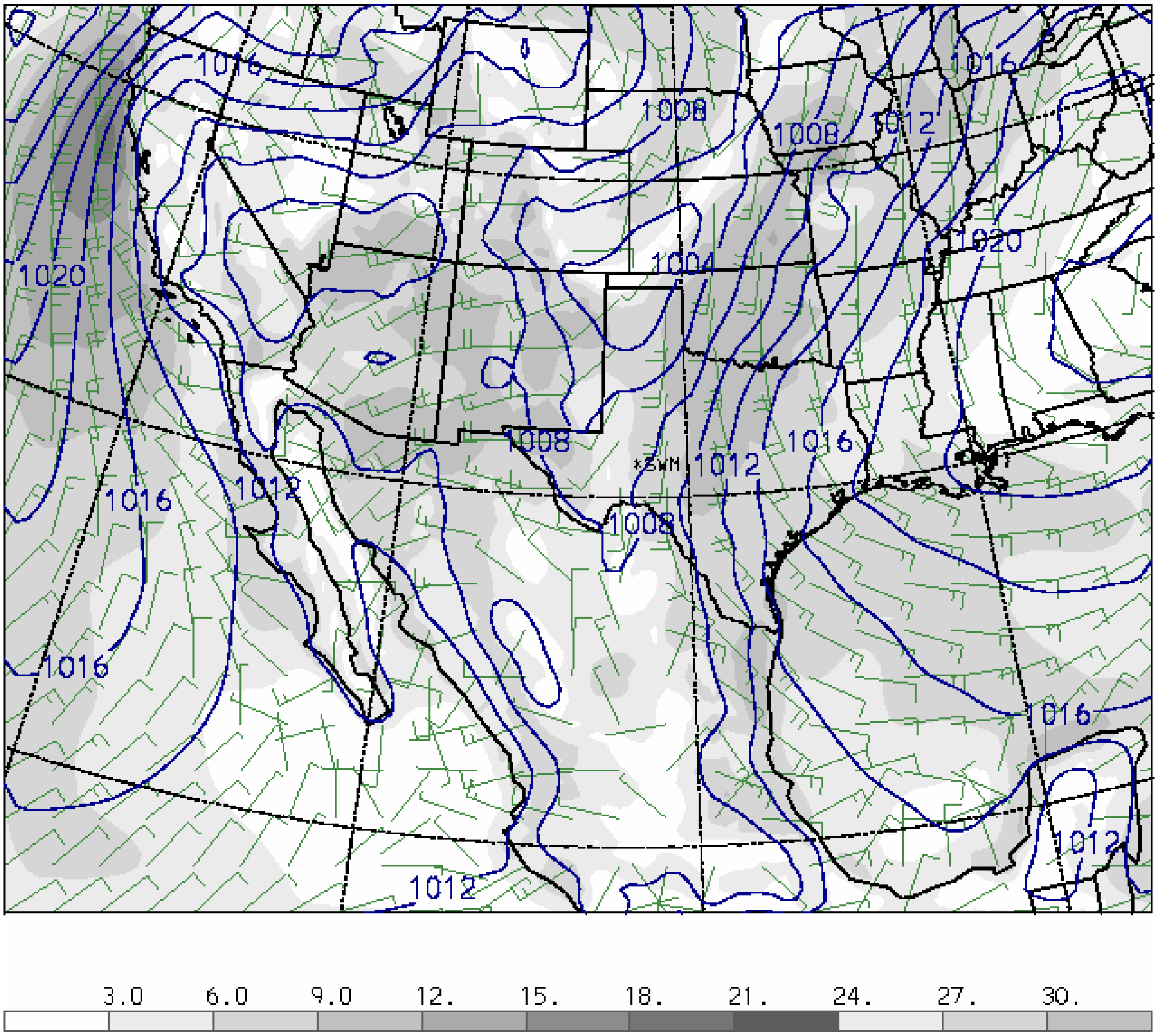


Figure 5-6
A depiction of the 21-hour grid point forecast output for 0400 CST May 16, 2002 from the 40 km grid cell version of physics-based (MASS) model component of TrueWind's *eWind* forecast system. The solid lines are lines of equal mean sea level atmospheric pressure labeled in units of millibars. The barbs depict the wind speed and direction at every 4th model grid point. A full barb represents 5 m/s and a half barb denotes 2.5 m/s. The shading depicts wind speeds at 3 m/s intervals. This forecast was produced on the morning of May 15, 2002. The letters "SWM" denotes the location of the Southwest Mesa wind plant.

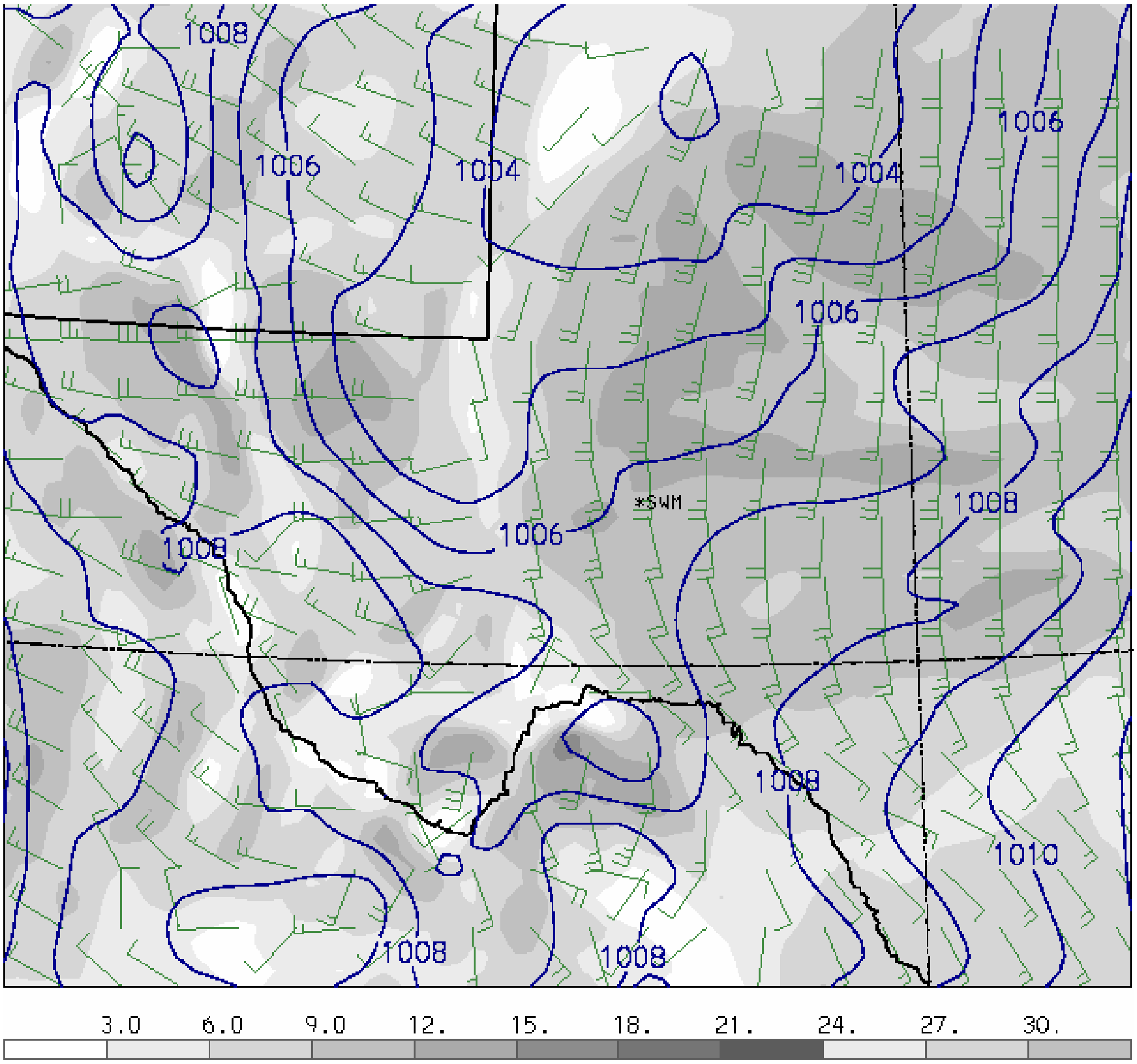


Figure 5-7
A depiction of the 21-hour grid point forecast output for 0400 CST May 16, 2002 from the 10 km grid cell version of physics-based (MASS) model component of TrueWind's *eWind* forecast system. The solid lines are lines of equal mean sea level atmospheric pressure labeled in units of millibars. The barbs depict the 40 m wind speed and direction at every 4th model grid point. A full barb represents 5 m/s and a half barb denotes 2.5 m/s. The shading depicts wind speeds at 3 m/s intervals. This forecast was produced on the morning of May 15, 2002. The letters "SWM" denotes the location of the Southwest MESA wind plant.

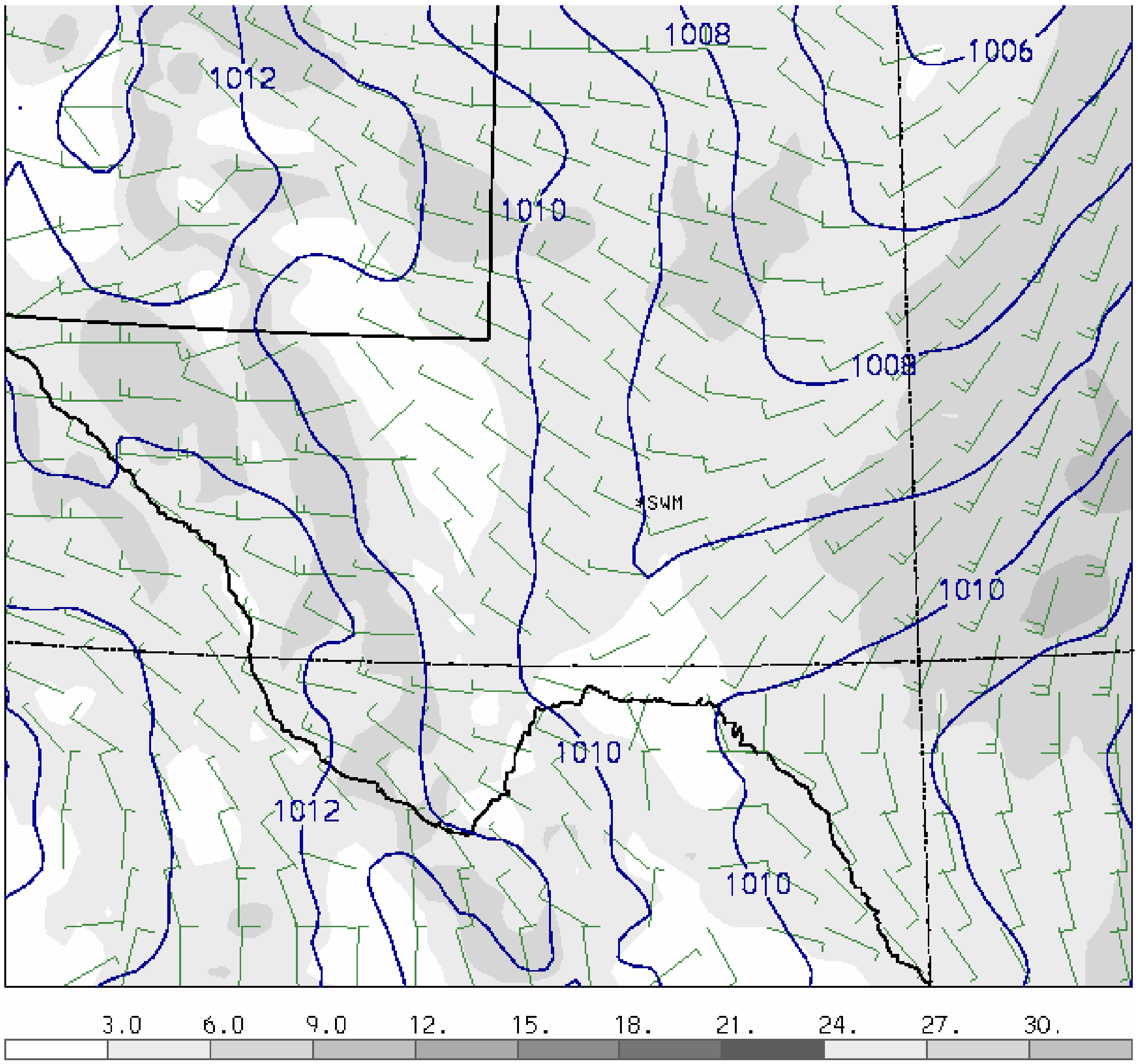


Figure 5-8
A depiction of the 33-hour grid point forecast output for 1300 CST May 16, 2002 from the 10 km grid cell version of the physics-based (MASS) model component of TrueWind's *eWind* forecast system. The solid lines are lines of equal mean sea level atmospheric pressure labeled in units of millibars. The barbs depict the wind speed and direction at every 4th model grid point. A full barb represents 5 m/s and a half barb denotes 2.5 m/s. The shading depicts wind speeds at 4 m/s intervals. This forecast was produced on the morning of May 15, 2002. The letters "SWM" denotes the location of the Southwest Mesa wind plant.

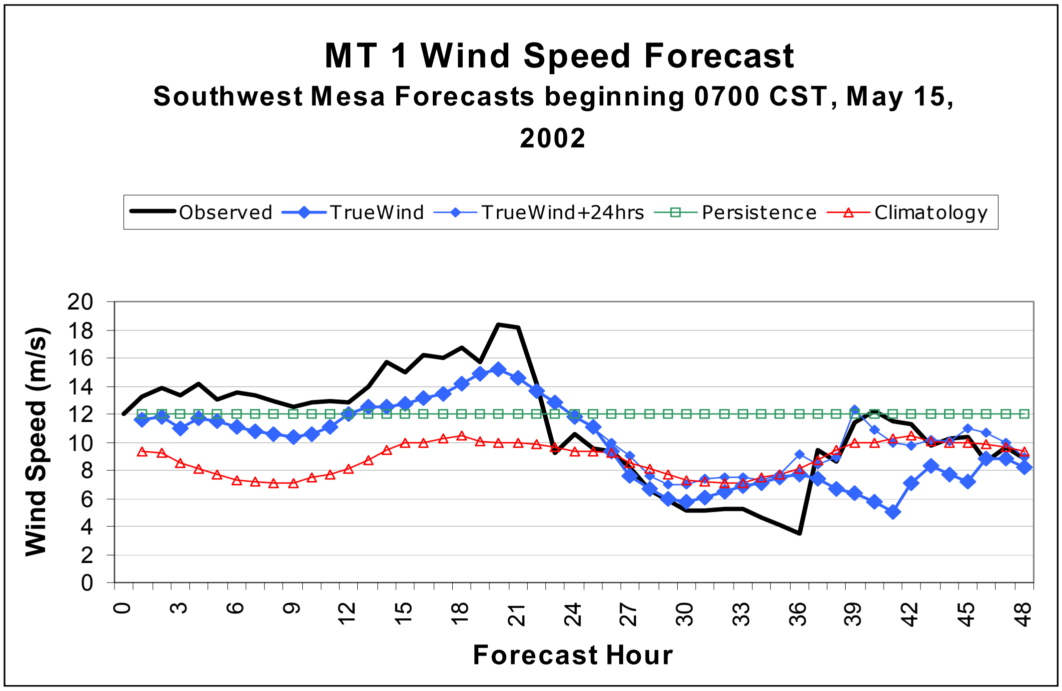


Figure 5-9
TrueWind, persistence and climatology wind speed forecasts and the measured wind speed for MT #1 for the 48-hr period beginning 7 AM CST May 15, 2002. The forecast marked "TrueWind+24hrs" was issued at 7 AM CST on May 16.

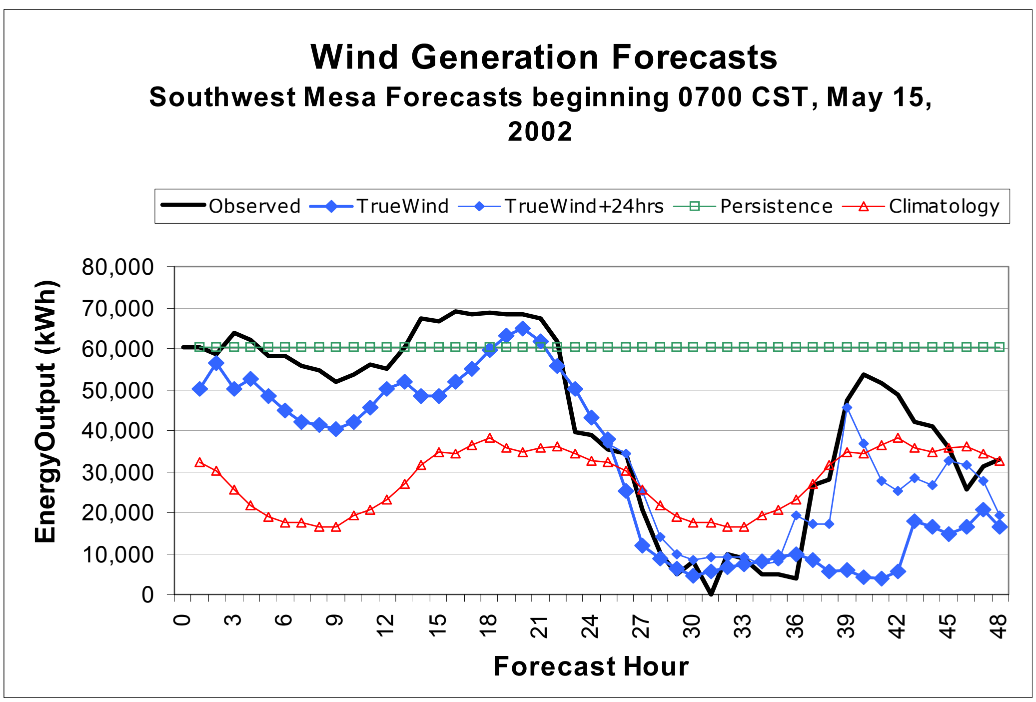


Figure 5-10
TrueWind, persistence and climatology energy generation forecasts and the measured Southwest Mesa energy generation for the 48-hr period beginning 7 AM CST May 15, 2002. The forecast labeled "TrueWind+24hrs" was issued at 7 AM CST on May 16.

Forecast System Performance

This section provides an overview of the performance of TrueWind's energy generation and wind speed forecasts for the Southwest Mesa wind plant for the month of May 2002.

The results are based on a sample that included all forecasts with a first hour in the month of May. TrueWind forecasts were produced for all of the possible forecast cycles during May. Therefore the total number of forecast hours was 31 days multiplied by 2 cycles per day times 48 hours per forecast or 2,976 hours. However, not all of these forecast hours could be verified since measured data was missing for a significant fraction of these hours.

An important issue in the assessment of forecast performance is the quality and consistency of the measured data used to verify the forecasts. One significant issue in this forecast evaluation project was the method used to adjust the energy output to 100% turbine availability and to define the hours for which the data is classified is missing. The adjustment to 100% availability was necessary because all of the forecasts produced in this project were based on an assumption that all turbines were available at all times. Since, in reality, the availability is not always 100%, it was necessary to adjust the reported output to 100% availability to be consistent with the forecasting assumptions. This can be done in a number of ways. TrueWind used the following procedure to adjust the reported output to 100% availability. First, the power was summed from all turbines reporting values greater than or equal to 0 for all 10-minute intervals available during an hour. Next, the number of unavailable turbines during the hour was calculated. If the turbine availability flag was not 0 or 1000,the turbine was counted as unavailable. The average power output for the hour was then calculated by dividing the sum of the power output for the hour by the number of intervals in the hour (normally six) times the number of turbines (107). This average power output was corrected to 100% availability by multiplying by the number of turbines times the number of intervals, divided by the number of turbines times the number of intervals minus the number of unavailable turbines. This procedure also implicitly corrects for missing 10-minute data intervals during an hour.

A different adjustment procedure was used by EPRI. One significant difference between the EPRI and TrueWind procedures was that EPRI's procedure classified the data for an hour as missing if data for any 10-minute interval during the hour was missing. For the month of May 2002 the mean absolute difference between the hourly values calculated by the EPRI method and those calculated by the TrueWind procedure was 1,475 kWh and the mean difference (TrueWind-EPRI) was –939 kWh. The merits of each method can be argued. However, these results indicate that that the performance statistics can be altered by a magnitude as high as 1,000 to 1,500 kWh depending upon one's choice of algorithms to adjust to 100% availability and decide if a particular hour's data is missing. Therefore, differences of that magnitude or less between forecasts are most likely not meaningful.

A second issue is the representativeness and accuracy of the wind speed data measured by the anemometers on the meteorological towers. One can obtain a "feel" for the accuracy and represntativeness of the data by looking at the plant-scale power curve defined by the measured data. Figure 5-11 shows a plant-scale power curve constructed using May 2002 data for the Southwest Mesa plant. There is a large amount of scatter in this "power curve". For example, an 8 m/s hourly average wind speed measured at MT #1 can yield an hourly energy output of

15,000 kWh to 40,000 kWh. This may be an indication that there is a considerable amount of spatial and temporal variability of the wind within the plant area or that some of data is questionable or unrepresentative.

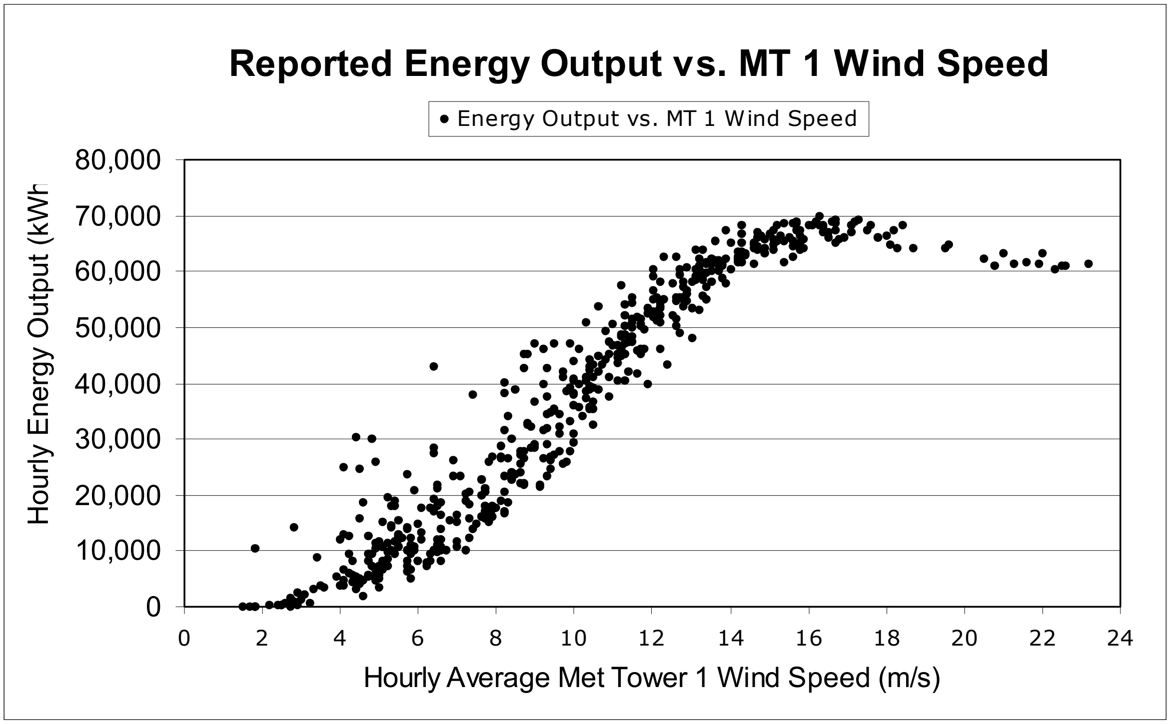


Figure 5-11
The hourly Southwest Mesa energy output vs. the corresponding hourly average wind speeds measured at Southwest Mesa Meteorological Tower #1 for the month of May 2002

Tables 5-2 through 5-5 present the TrueWind forecast performance statistics for the May 2002 . The performance statistics include the mean error (bias), mean absolute error (MAE), the root mean square error (RMSE), the median error, the correlation coefficient between the measured and forecasted values and skill scores with respect to both persistence and climatology. This broad set of evaluation metrics provides a diverse perspective on the TrueWind forecast performance for May 2002.

The monthly performance statistics in Table 5-2 cover all forecast hours and are based on the EPRI verification dataset. The TrueWind wind speed and energy generation forecasts had a substantial negative bias for the month. However, the TrueWind wind speed forecast bias of –1.13 m/s was somewhat less than the bias of –1.52 m/s for the climatology forecasts. This large negative bias for the climatology forecasts indicates that either May 2002 was much less windy than the typical May or that the climatological dataset used as the basis for the climatology forecasts does not provide a good representation of the true average May wind speed at this anemometer site. The TrueWind energy generation forecast bias of –7,226 kWh was also somewhat less than the –8,921 kWh bias recorded for the climatology forecasts. The wind speed forecast MAE of 2.88 m/s was 28.1% of the mean monthly wind speed of 10.23 m/s. The energy generation forecast MAE of 14,446 kWh was 39.7% of the average hourly energy output of 39,406 kWh and 19.3% of the plant's installed capacity of 75,000 kW. As a percentage of installed capacity, this MAE is somewhat higher than the average MAE values obtained for the two California wind plants that were the hosts for the CEC-EPRI California wind forecasting project. However, the Southwest Mesa capacity factor for May 2002 was about 48.5%, which is somewhat higher than that typically seen for wind plants in the EPRI-CEC California forecast project. Thus, although the MAE as percentage of installed capacity was somewhat higher than the typical levels achieved for the California wind plants, the higher capacity factor resulted in a MAE as a percentage of the average output that was actually somewhat lower than the typical values obtained for the California wind plants. Both skill scores for the wind speed forecasts were near 25% while the skill scores for the energy generation forecasts were slightly higher in the 28% to 30% range.

Table 5-2
TrueWind Forecast Performance Statistics for May 2002

	Wind Speed m/sec	Generation kW
Forecast Error		
Monthly ME (m/sec or kW)	-1.13	-7,226
Monthly MAE (m/sec or kW)	2.88	14,446
Normalized Forecast Error		
Monthly ME	-11.1%	-19.8%
Monthly MAE	28.1%	39.7%
Average Wind Speed or Gen	10.23	36,406
Monthly Skill Score		
vs. Persistence	24.9%	29.8%
vs. Climatology	25.1%	28.6%
Wind Forecast Delivery		
Possible Forecasts	62	
Forecasts Delivered	62	
%	100.0%	

Table 5-3 presents a broader set of performance statistics for the energy generation forecasts for the morning and afternoon forecast cycles and the combination of both cycles. These statistics are also for all forecast hours but they are based on the TrueWind verification dataset. There are slight differences between the statistics in Tables 5-2 and 5-3 due to the differences in the verification datasets attributable to the factors noted earlier in this section. Almost all of the performance statistics for the afternoon cycle are slightly worse than those for the morning cycle. These differences are generally insignificant and within the noise range of the verification data but this pattern is consistent with a general tendency for the morning TrueWind forecasts to outperform the afternoon forecasts noted for wind plants at other locations. It is also interesting to note that the RMSE of about 18,300 kWh is about 28% higher than the MAE while the median error of approximately 11,100 kWh is about 22.5% lower than the MAE. The RMSE is much more sensitive to large errors than the MAE while the median error is less sensitive to large errors than the MAE. These statistics indicate that there are a small number of forecasts with large errors that tend to inflate the MAE while the majority of the forecasts have a substantially lower absolute error than that suggested by the MAE statistic.

Table 5-3
TrueWind Energy Generation Forecast Performance Statistics by Forecast Cycle

Wind Generation Forecast Error Statistics May 2002				
Parameter	**Units**	**Morning**	**Afternoon**	**Total**
Reported Hourly Avg.	kWh	36,767	37,615	37,192
Hours Verified	hrs	1,099	1,102	2,201
MAE	kWh	13,949	14,502	14,226
MAE % rated	%	18.60%	19.34%	18.97%
MAE % mean	%	37.94%	38.55%	38.25%
RMSE	kWh	17,911	18,652	18,285
RMSE % rated	%	23.88%	24.87%	24.38%
RMSE % mean	%	48.71%	49.59%	49.16%
Median	kWh	11,137	11,167	11,152
Correlation	non-dim	0.674	0.686	0.680
Skill - Persistence	%	27.34%	23.34%	25.40%
Skill-Climatology	%	30.01%	27.87%	28.93%

Table 5-4 presents an analogous broader set of performance statistics by forecast cycle for the 40 m wind speed forecasts at MT #1. The slight differences in performance between the two cycles have a less consistent pattern than the differences noted for the energy generation forecasts and support the hypothesis that there is essentially no difference in performance between the two cycles for the wind speed forecasts. The RMSE was substantially higher (25%) than the MAE and the median error was somewhat lower (13%) than the MAE. However, the percentage spread among these three statistics for the wind speed forecasts is somewhat less than that for the energy generation forecasts. This is an indication that the energy generation forecasts have more large errors than the wind speed forecasts. This is most likely attributable to the fact that the steep slope of the power curve in the 4 to 12 m/s range tends to magnify the errors in the underlying wind speed forecasts.

Table 5-5 lists the same statistics for the forecasts for three different wind speeds associated with the Southwest Mesa plant. The MT #1 column lists the same performance statistics for the wind speed forecasts for Meteorological Tower # as those in Table 5-3. The column labeled “MT Avg” tabulates the performance statistics for forecasts of the average wind speed for all three Southwest Mesa meteorological towers. The final column, labeled “Nacelle Avg” contains the statistics for the forecasts for the average wind speed of all of the nacelle anemometers. The average speed reported by MT #1 is about 0.5 m/s higher than the average of the speeds from all three anemometers. Obviously, this indicates the average speed of the other two anemometers is substantially lower than that for MT #1. This suggests that the MT #2 and MT #3 anemometers may be more representative of the wind speeds for the Southwest Mesa plant as a whole. This is supported by the fact that the average nacelle anemometer speed is lower than the "MT Avg" value and closer to the average speed of the MT #2 and MT #3 anemometers. However, the nacelle anemometers are often not representative of the free-stream wind speeds because of flow modifications induced by the turbines on which they are mounted.

Table 5-4
TrueWind MT #1 Wind Speed Forecast Performance Statistics by Forecast Cycle

Wind Speed Forecast Error Statistics – May 2002				
Parameter	**Units**	**Morning**	**Afternoon**	**Total**
Reported Hourly Avg.	m/s	10.13	10.27	10.20
Hours Verified	hrs	1,370	1,370	2,740
MAE	m/s	2.83	2.83	2.83
MAE % mean	%	27.98%	27.59%	27.79%
RMSE	m/s	3.53	3.54	3.54
RMSE % mean	%	34.88%	34.50%	34.69%
Median	m/s	2.50	2.40	2.45
Correlation	non-dim	0.671	0.680	0.675
Skill - Persistence	%	28.72%	32.18%	30.48%
Skill-Climatology	%	25.54%	25.68%	25.61%

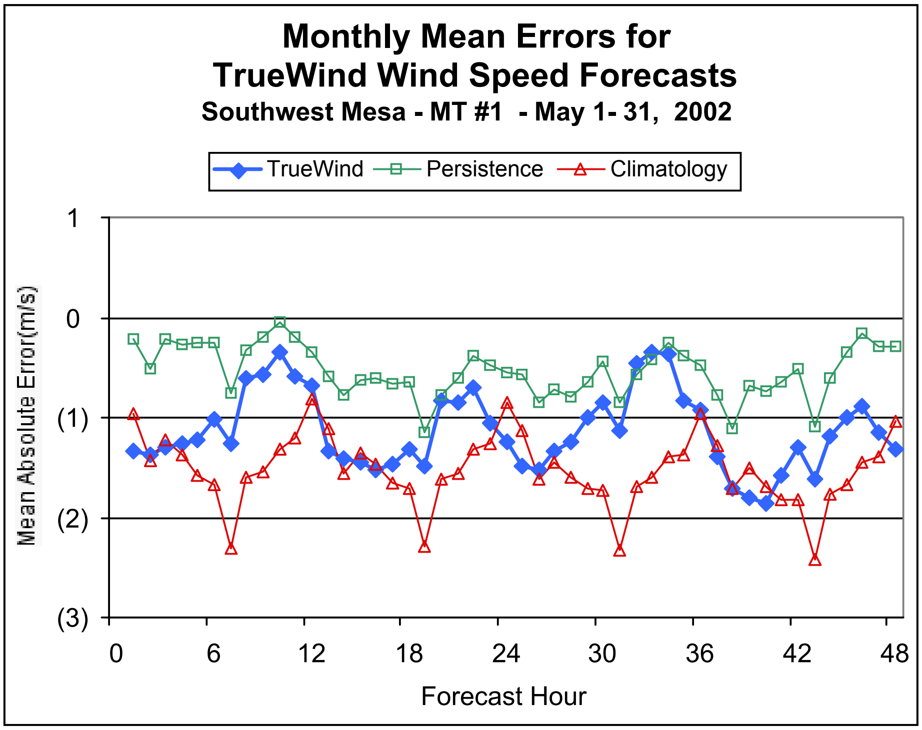
Table 5-5
Comparison of TrueWind Wind Speed Forecast Performance Statistics

Wind Speed Forecast Error Statistics – May 2002				
Parameter	**Units**	**MT #1**	**MT Avg**	**Nacelle Avg**
Reported Hourly Avg	m/s	10.20	9.72	9.39
Hours Verified	hrs	2,740	2,820	2,848
MAE	m/s	2.83	2.72	2.81
MAE % mean	%	27.79%	28.04%	29.94%
RMSE	m/s	3.54	3.45	3.52
RMSE % mean	%	34.69%	35.47%	37.50%
Median	m/s	2.45	2.30	2.40
Correlation	non-dim	0.675	0.659	0.683
Skill - Persistence	%	30.48%	33.27%	31.88%
Skill-Climatology	%	25.61%	26.20%	24.24%

The MAE of the “MT avg” forecasts was about 0.1 m/s lower than that for MT #1. Since the mean speed was lower, the MAE as a percentage of the mean was actually slightly higher. The MAE for the forecasts for the average speed of the nacelle anemometers was the about the same as that for the speed at MT #1 but the percentage error was about 2 percentage points higher because the mean speed was lower. Overall, the differences in TrueWind forecast performance for the different Southwest Mesa wind speed measurements are insignificant (i.e. within the “noise” range) for May 2002.

The bias and MAE by forecast hour for both the wind generation forecasts and the MT #1 wind speed forecasts are presented in Figures 5-12 and 5-13. The corresponding skill scores with respect to persistence and climatology are depicted in Figure 5-14. There is considerable “noise” in the hour to hour bias and MAE values. Much of this is due to the relatively small size of the sample for each hour. The MAE of the energy generation forecasts increases from about 13,000 kWh for the first 6 hours to about 15,000 kWh for the last 6 hours of the forecast period. This represents an average error growth rate of about 50 kWh (0.07% of installed capacity) per forecast hour. Both the wind speed forecasts for MT #1 and the energy generation forecasts outperform the climatology forecasts for all forecast hours. Both forecasts also outperform persistence after 4 hours. The persistence forecasts outperform the TrueWind forecasts for the first 4 hours because no real-time data was available from the wind plant in this project.

Figure 5-15 shows a histogram of the hourly forecast errors for all forecast hours (1-48), and Figure 5-16 shows the corresponding cumulative frequency distribution of the hourly absolute forecast errors. This chart indicates that almost 60% of the absolute errors are smaller than the MAE (19 % of installed capacity).



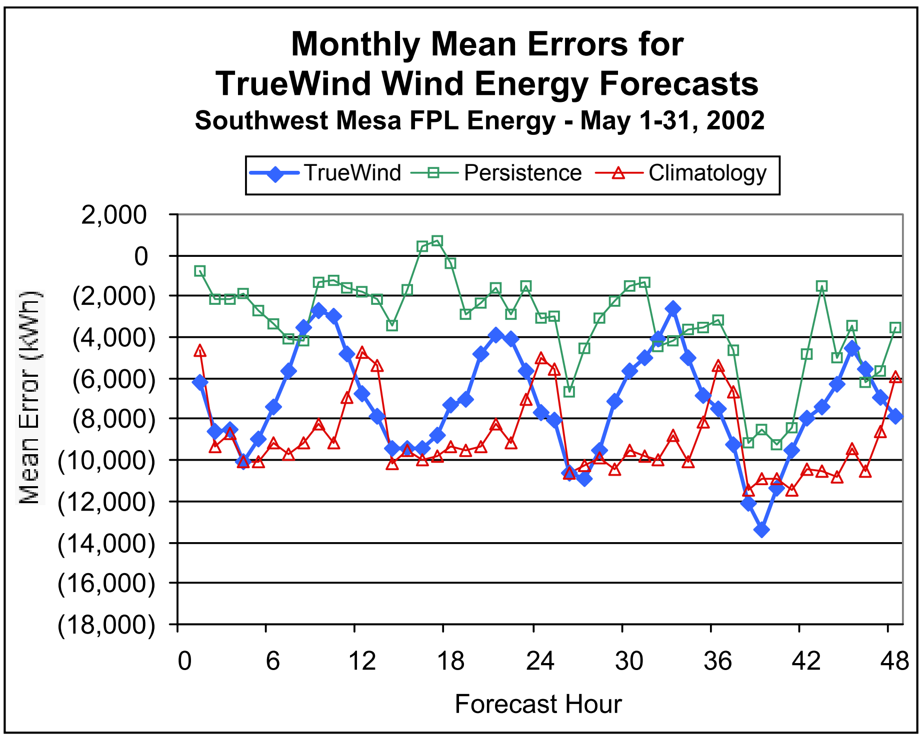
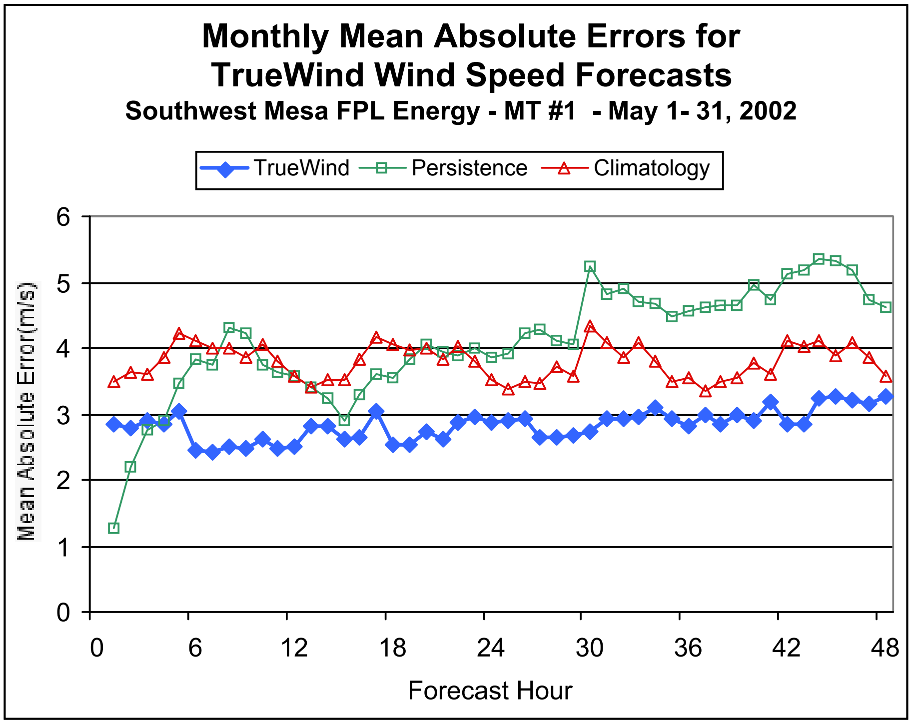


Figure 5-12
A depiction of the MAE of TrueWind's forecasts for the (above) wind speed for Southwest Mesa Meteorological Tower #1 and (below) the total Southwest Mesa energy generation at 100% availability by forecast hour for the month of May 2002.



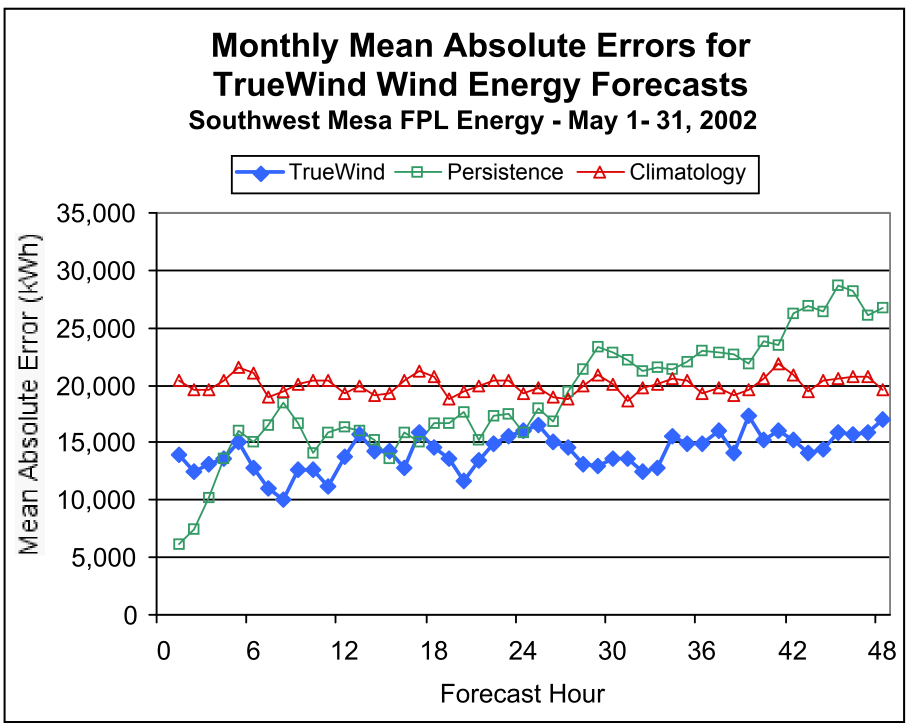
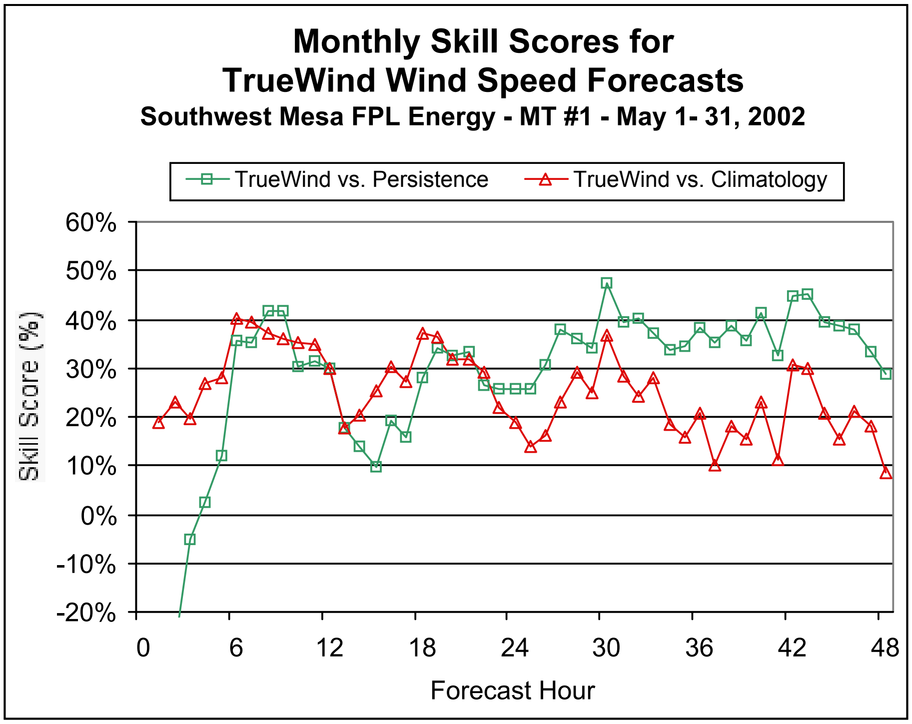


Figure 5-13
A depiction of the MAE of TrueWind's forecasts for the (above) wind speed for Southwest Mesa Meteorological Tower #1 and (below) the total Southwest Mesa energy generation at 100% availability by forecast hour for the month of May 2002.



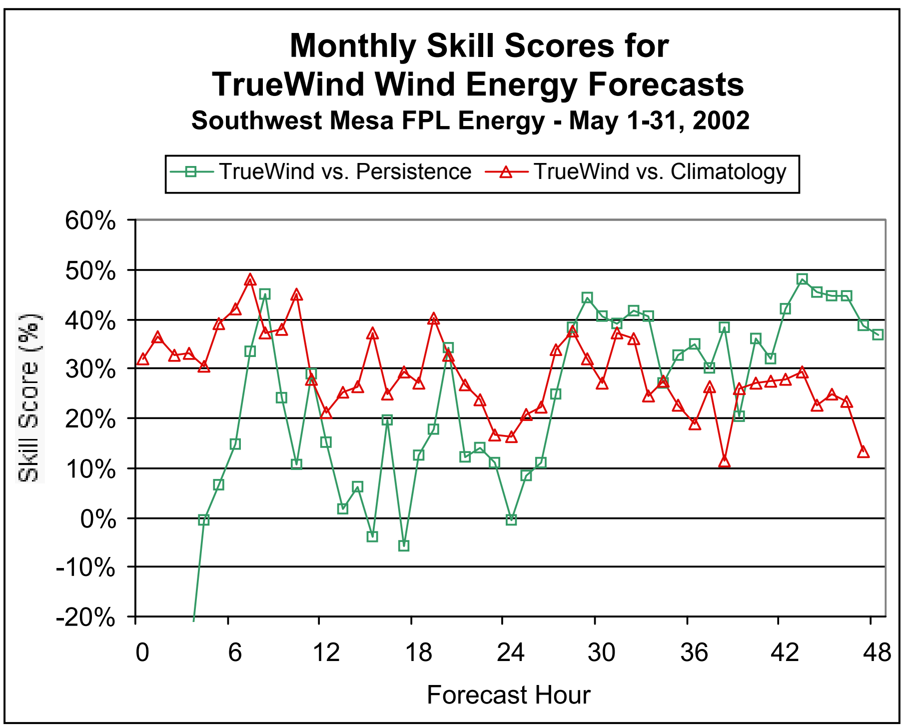


Figure 5-14
A depiction of the skill score with respect to persistence and climatology of TrueWind's forecasts for the (above) wind speed for Southwest Mesa Meteorological Tower #1 and (below) the total Southwest Mesa energy generation at 100% availability by forecast hour for the month of May 2002

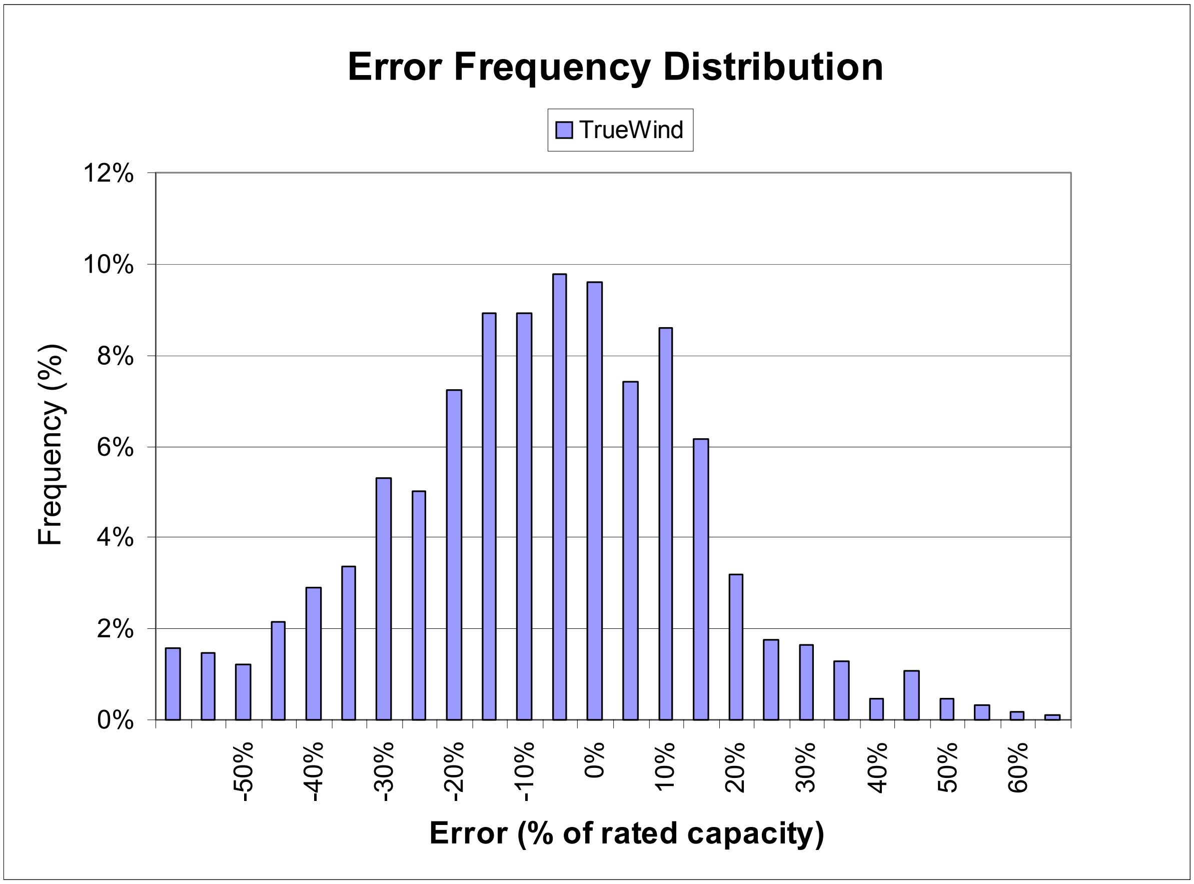


Figure 5-15
An illustration of the error distribution for all hours (1-48) of the TrueWind energy generation forecasts for the Southwest Mesa plant for May 2002. The horizontal axis is the error expressed as a percentage of the plant's installed capacity (75 MW). The vertical axis is the frequency of hours in each error bin. The error bin size is 5% of the installed capacity. The horizontal axis labels denote the upper end of each bin (i.e. 10% represents the bin from 5% to 10%). The left most bin represents all errors less than –60% and the right most bin includes all errors greater than +60%.

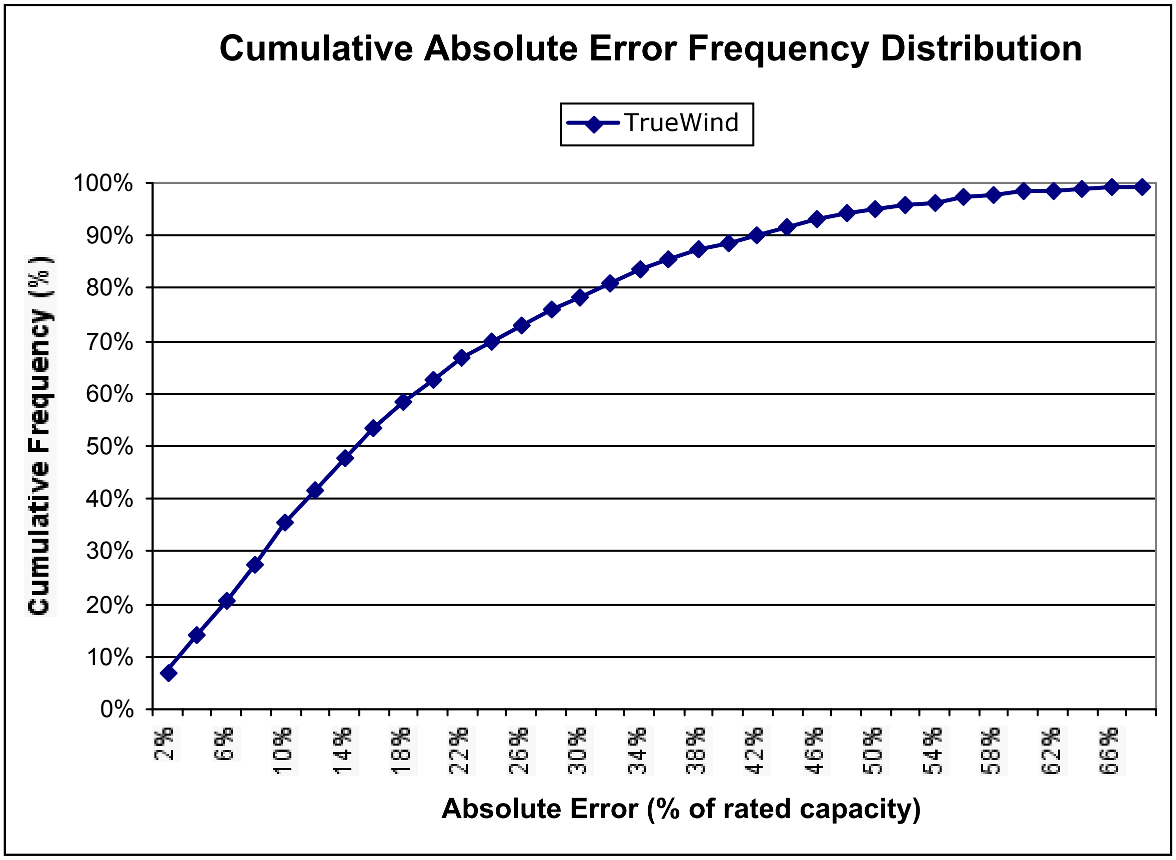


Figure 5-16
The cumulative absolute error distribution for all hours (1-48) of TrueWind's energy generation forecasts for the Southwest Mesa plant for May 2002The horizontal axis is the absolute wind generation forecast error expressed as a percentage of the plant's installed capacity (75 MW). The vertical axis is the cumulative frequency as a percentage of all forecast hours. Thus, a point on the error frequency curve represents the percentage of hours for which the absolute error was less than or equal to the absolute error value on the horizontal axis.

Initial Forecasting Results – Applied Modeling

As described in Section 4, the Applied Modeling's *WEFS* forecast system produces forecasts via a multi-step process that employs both physics-based and statistical models. This section describes the initial test results and forecast performance of WEFS for May 2002.

Figure 5-17 presents the Applied Modeling 48-hour wind speed (top) and wind generation (bottom) meteorology forecasts beginning at 1800 hours on May 18, 2002, together with the corresponding observed data and persistence and climatology forecasts.

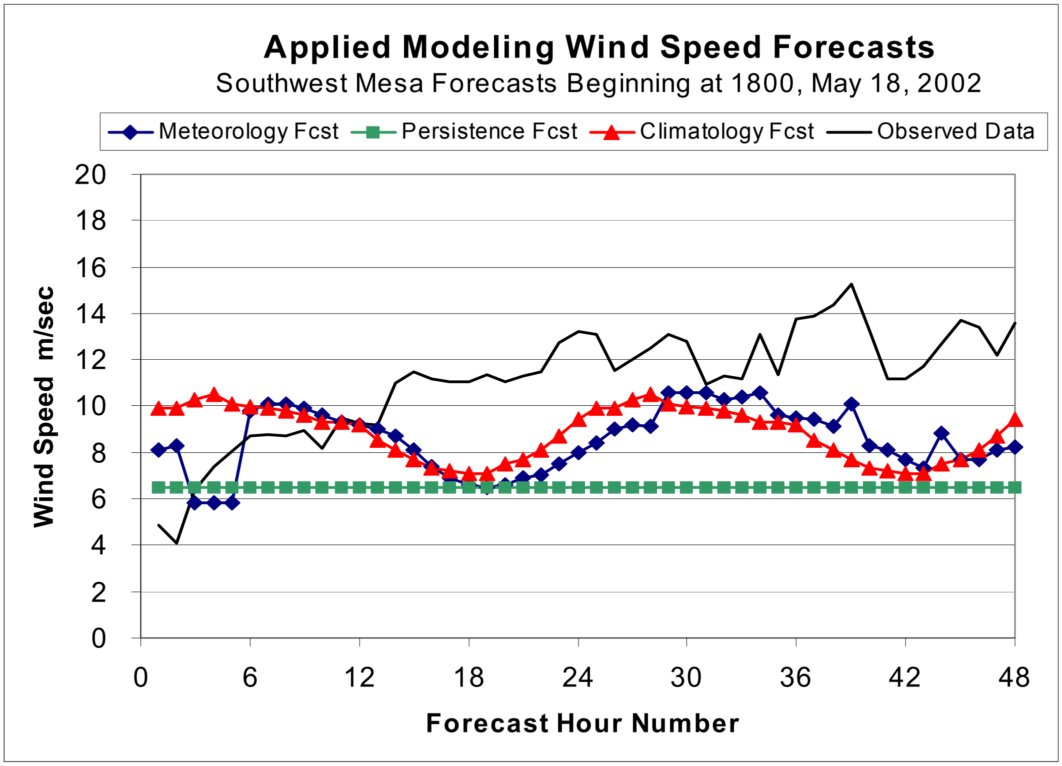
The AMI meteorology forecasts (diamonds) follow the general pattern of the observed wind speed generation (solid line), and the persistence and climatology forecasts (squares and triangles) fall in the middle of the range. The AMI wind speed forecast exhibits a negative bias, while the bias present in the wind energy forecast is lower.

Table 5-6 summarizes the monthly performance statistics for the AMI forecasts at Southwest Mesa for May 2002. The monthly mean errors (ME) of the hourly wind speed and generation forecasts vs. the observed data are –2.11 m/sec and –6,853 kW, respectively. The corresponding figures for the monthly mean absolute errors (MAE) are 3.10 m/sec and 13,983 kW. The normalized monthly mean errors of the wind speed and generation are –24% and –21% of the monthly average hourly wind speed (10.23 m/sec) and wind generation (36,406 kW), respectively. The corresponding figures for the normalized monthly mean absolute errors are 36.0% and 44.4%. The resulting skill scores of the AMI wind speed and generation forecasts are 18.4% and 24.4% vs. the persistence forecast and 16.0% and 28.5% vs. the climatology forecast.

Table 5-6
Applied Modeling Forecast Performance Statistics for May 2002

	Wind Speed m/sec	**Generation kW**
Forecast Error		
Monthly ME (m/sec or kW))	-2.11	-6,853
Monthly MAE (m/sec or kW))	3.10	13,983
Normalized Forecast Error		
Monthly ME	-20.6%	-18.8%
Monthly MAE	30.3%	38.4%
Average Wind Speed or Gen	10.23	36,406
Monthly Skill Score		
vs. Persistence	18.4%	24.4%
vs. Climatology	16.0%	28.5%
Wind Forecast Delivery		
Possible Forecasts	60	
Forecasts Delivered	36	
%	60.0%	

Figures 5-17 through 5-19 present the forecast performance results for the AMI May 2002 meteorology, persistence, and climatology forecasts. The figures present the monthly mean errors, mean absolute errors, and skill scores vs. persistence and climatology as functions of the forecast hour number (1 through 48). The mean absolute errors of the AMI meteorology forecasts cross over and become lower than those of the persistence forecasts beyond three hours for both the wind speed and wind energy forecasts.



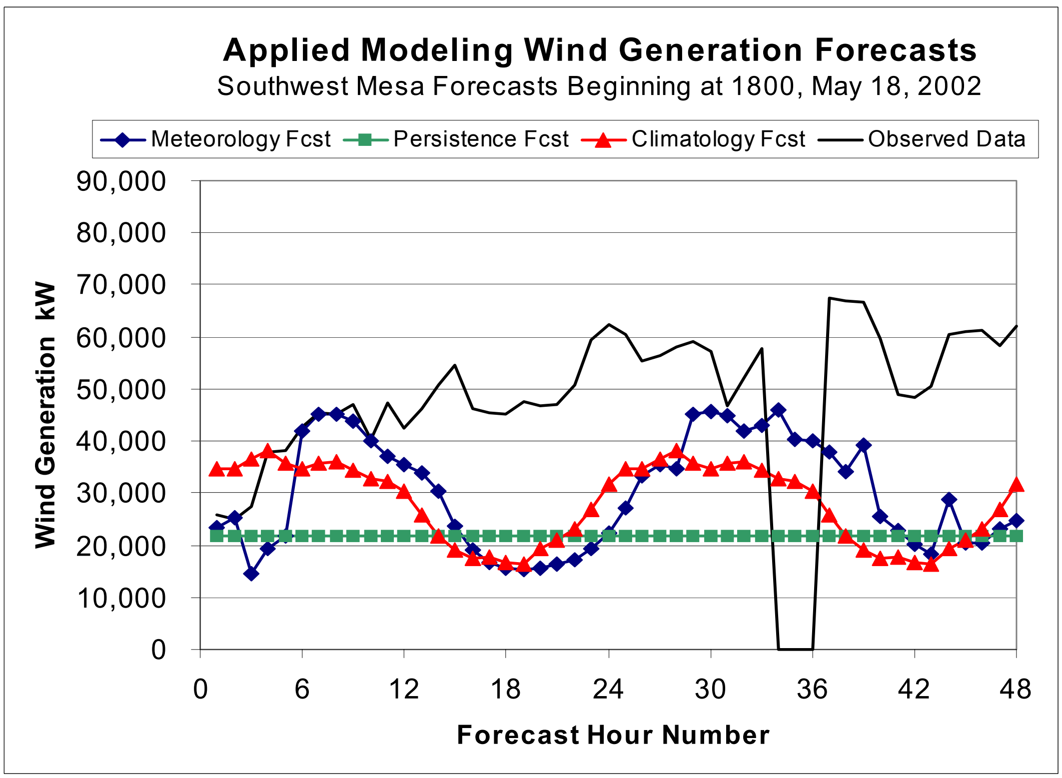
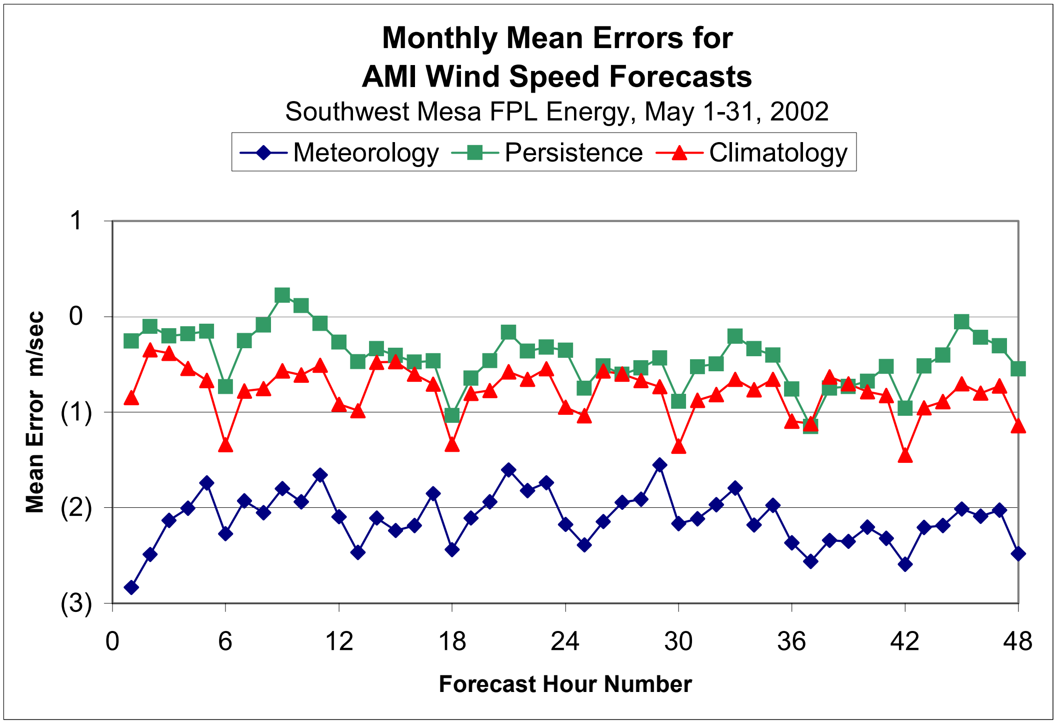


Figure 5-17
Comparison of Applied Modeling 48-Hour Wind Speed and Generation Forecasts at Southwest Mesa with Persistence and Climatology Forecasts and Observed Data Beginning at 1800, May 18, 2002



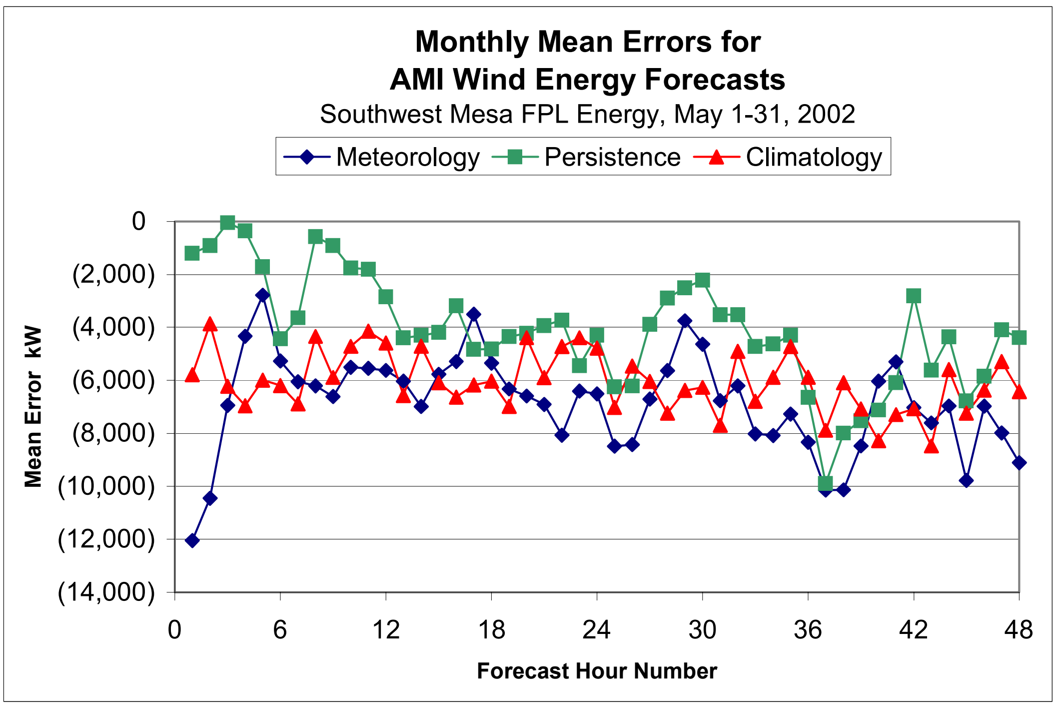
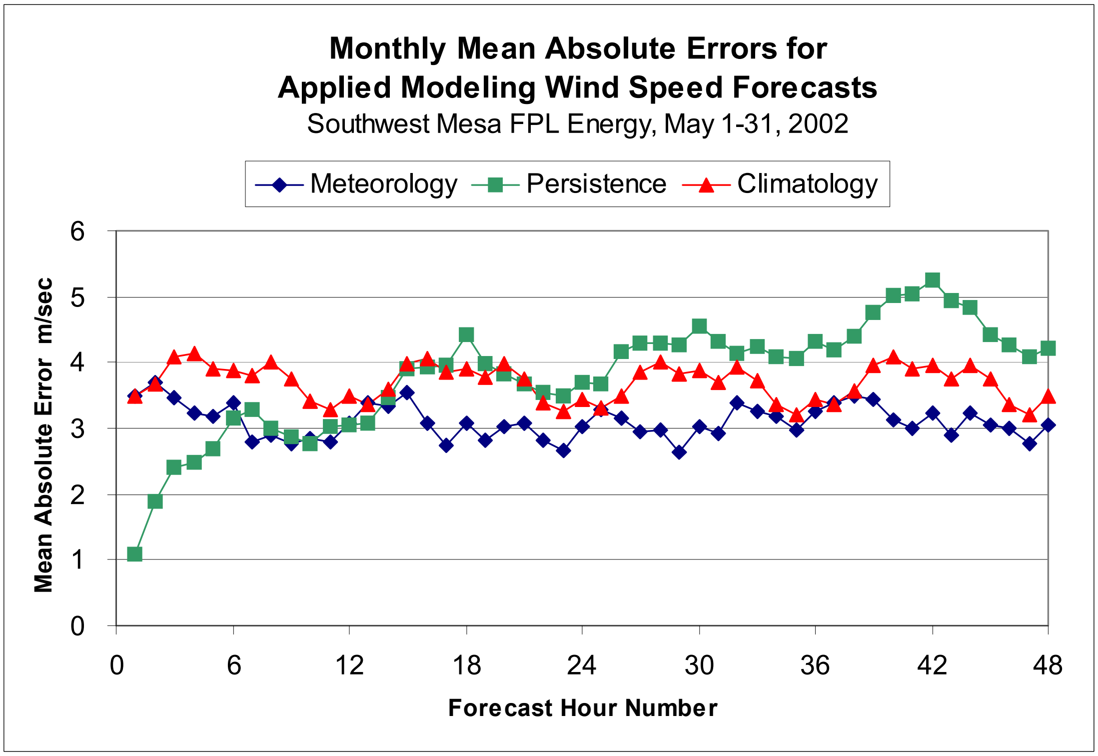


Figure 5-18
Monthly Mean Errors for Applied Modeling Wind Speed and Generation Forecasts at Southwest Mesa, May 2002



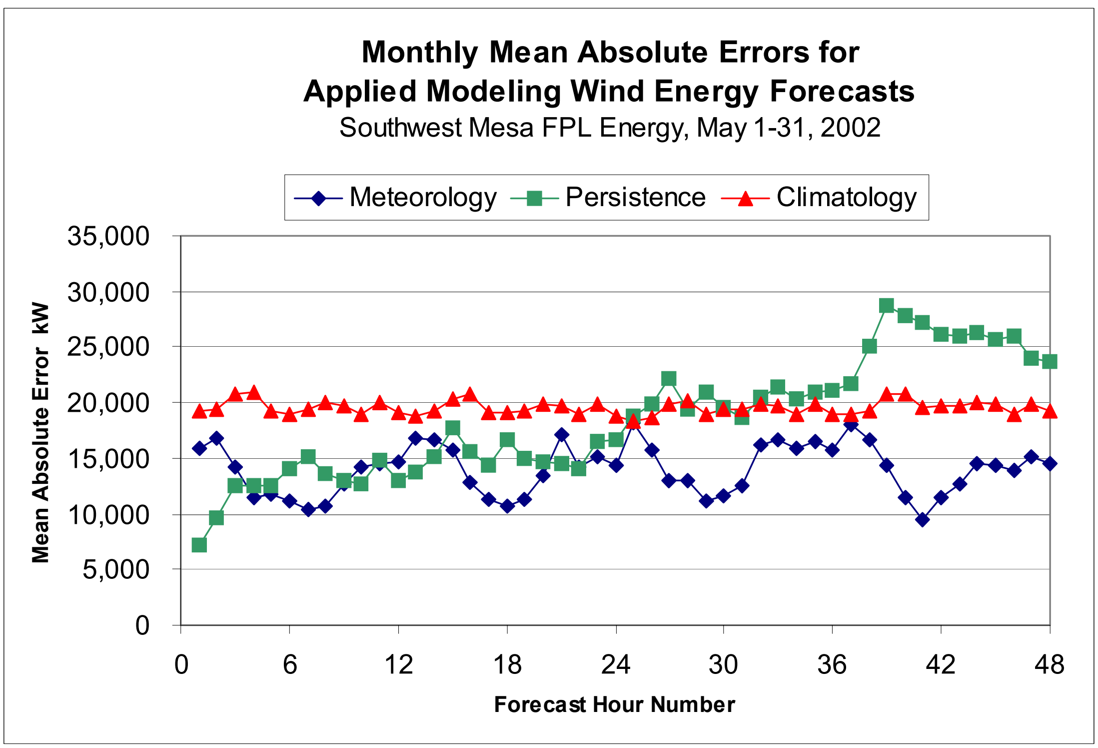
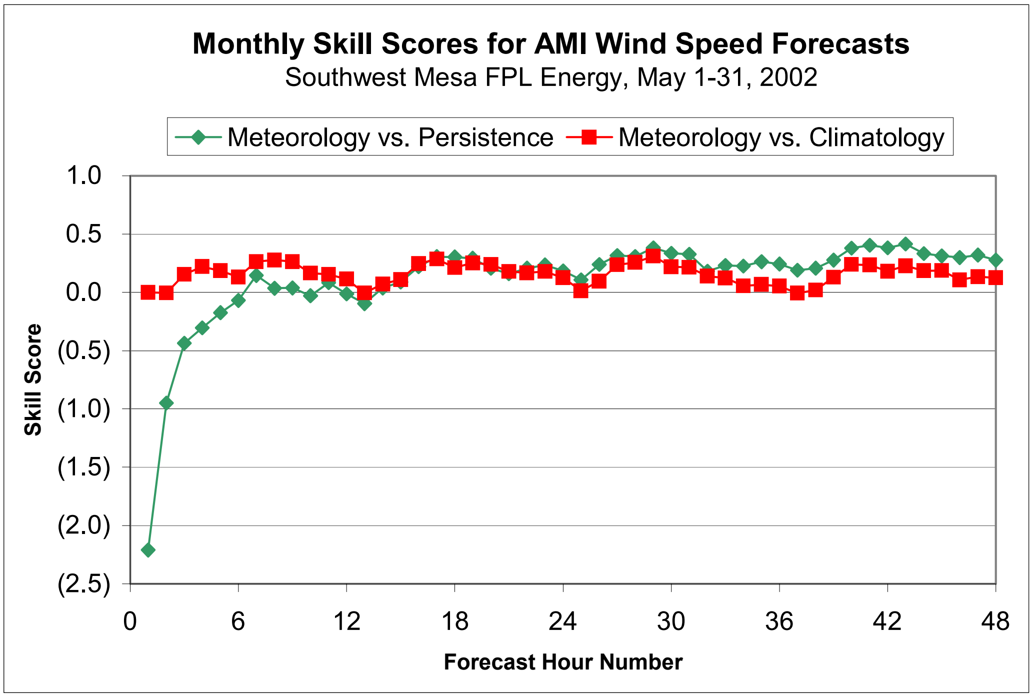


Figure 5-19
Monthly Mean Absolute Errors for Applied Modeling Wind Speed and Generation Forecasts at Southwest Mesa, May 2002



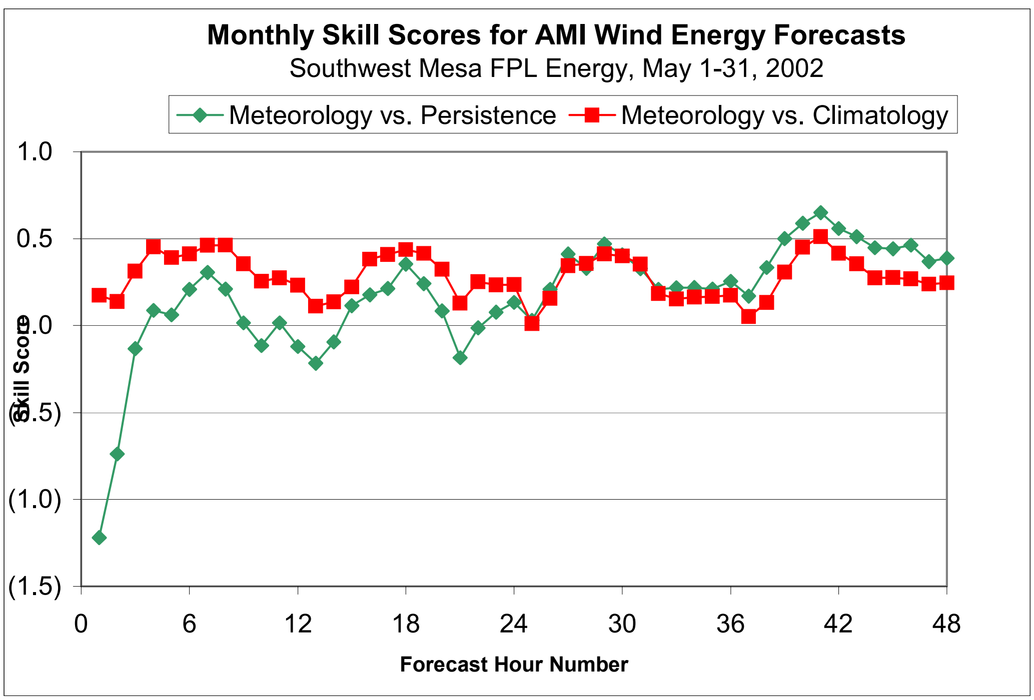


Figure 5-20
Monthly Skill Scores vs. Persistenche and Climatology for Applied Modeling Wind Speed and Generation Forecasts at Southwest Mesa, May 2002

6
CONCLUSIONS

This Phase 1 report describes the development and early testing of the three wind energy forecasting systems developed by Risoe, TrueWind, Applied Modeling at the 75 MW Southwest Mesa wind project near McCamey, Texas. The initial forecast performance results for May 2002 are promising and comparable to results from other sites. The monthly mean absolute errors of the wind speed and generation forecasts respectively ranged from 28% to 33% of the mean hourly wind speed (10.23 m/sec) and 38% to 51% of the mean hourly generation (36,406 kW) for the month. The skill scores of the wind speed forecasts respectively ranged from 6% to 25% vs. persistence and –5% to 30% vs. climatology, while those of the wind generation forecasts ranged from 115% to 25% vs. persistence and 7% to 29% vs. climatology.

Before drawing any conclusions about whether the unique wind resource and mesa topography of west Texas significantly affect forecast accuracy, it is necessary to accumulate several months of testing and measure monthly forecast errors during all seasons of the year.

The full year of forecast testing at Southwest Mesa was completed in March 2003. The results of the full year of testing will be documented in the Phase 2 report to be issued in early 2004.

7
REFERENCES

EPRI Reports

California Wind Energy Forecasting Program Description and Status - 2000: California Energy Commission–EPRI Wind Energy Forecasting Program, EPRI, Palo Alto, CA, California Energy Commission, Sacramento, CA: 2000. 1000667.

California Wind Energy Forecasting System Development and Testing, Phase 1: Initial Testing, EPRI, Palo Alto, CA, and California Energy Commission, Sacramento, CA: 2003. 1007338.

California Wind Energy Forecasting System Development and Testing, Phase 2: 12-Month Testing, EPRI, Palo Alto, CA, and California Energy Commission, Sacramento, CA: 2003. 1007339.

Other References

Barbour, P.L., S.N. Walker, B. Sandmeyer, G. Taylor. An Overview of Wind/Energy Forecasting. Report No. WRC 94-01, Wind Research Cooperative, Oregon State University, April, 1994, 56pp.

Barbour, Philip, S.N. Walker, B. Sandmeyer, and G. Taylor. An Overview of Wind/Energy Forecasting. Wind Research Cooperative Report (WRC) 94-01. April 1994. 56pp.

Brown, B.G., R. W. Katz, A.H. Murphy, Time Series Models to Simulate and Forecast Wind Speed and Wind Power. J. Clim Appl. Met 23:1184-1195, August, 1984.

Brown, B.G., R.W. Katz, A.H. Murphy, and B.A. Peterson, Time Series Models for Simulating Hourly Wind Power. BPA Report 82-10, June 1982.

Carter, G.M. and D.B. Gilhousen. The Potential Impact of Automated Wind Guidance on Wind Energy Conversion Operations. 1980. 13pp.

Curtis, J.C. Statistical Surface Wind Forecasting at Goodnoe Hills, Washington, Master of Science Thesis, Department of Atmospheric Sciences, Oregon State University, 1983.

Geerts, H.M., Short Range Prediction of Windspeeds: A System-Theoretic Approach, European Wind Energy Conference, October 1984, 6pp.

Gilhousen, D.B. Development and Testing of Model Output Statistics for Wind Forecasts at Wind Turbine-Generator Sites. DOE/RL/10064-1, Techniques Development Laboratory, Silver Springs, MD, 1980

Gilhousen, D.B. Development and Testing of Model Output Statistics for Wind Forecasts at Wind Turbine Generator Sites. DOE/RL/10046-1. NWS/NOAA, Silver Spring, MD 20910. 1979. 25pp.

Gilman, B., M. Cheng, J. Issac, J. Zack, B. Bailey, M. Brower. The Values of Wind Forecasting to Southern California Edison. Proceedings of the American Wind Energy Conference, 2001.

Glahn, H.R. and D.A Lowery. The use of Model Output Statistics (MOS) in Objective Weather Forecasting. Journal of Applied Meteorology, 11:1203-11, 1972.

Gustafsson, N. (Ed.), HIRLAM 2 Final Report, Tech. Report No. 9, SMHI S-60176, Norrkoping, Sweden.

Jensen, U.S., E. Pelgrum, H. Madsen, The Development of A Forecasting Model For the Prediction of Wind Power Production To Be Used in Central Dispatch Centres. EU Contract (DG XII) JOU2-CT92-0083, 1995

Landberg, L. Implementing Wind Forecasting at a Utility. In: Proceedings from DWEA 16, pp. 327-331, 1994.

Landberg, L. Implementing Wind Forecasting at a Utility. In: Proceedings from EWEA '94, Thessaloniki, Vol I: 357-360, 1994.

Landberg, L. Implementing Wind Forecasting at a Utility. Submitted to the Seventeenth BWEA Conference, Warwick, United Kingdom, 1996.

Landberg, L. S.J. Watson, J.A. Halliday, and J.U. Jorgensen. Short-term Prediction of Local Wind Conditions. In: Proceedings from ECWEC 93, Travemunde, pp. 677-680, 1993.

Landberg, L. S.J. Watson, J.A. Halliday, J. U. Jorgensen, and A. Hilden. Short-term Prediction of Local Wind Conditions. Report to the Commission of the European Communities. Project JOUR-0091-C(MB). 251pp. 1993.

Landberg, L. Short-term Prediction. In: Proceedings of European Workshop on Wind Energy Integration -- Barriers and Solutions, Aalborg, Denmark. 1995

Landberg, L., Implementing Wind Forecasting At A Utility, Risoe National Laboratory, Denmark. In Proceedings from the Wind Energy R&D Contractors Meeting, Maastricht, p. 69 - 75, 1991.

Landberg, L., S.J. Watson, and J.U. Jorgensen. Short-term Prediction of Local Wind Conditions. In: Proceedings from Wind Energy R&D Contractor Meeting. Alghero, Italy. Commission of the European Communities, DG XII. Ed. G. Caratti and A. Arribas, pp 105-114, 1992.

Landberg, L., S.J. Watson. Short-Term Prediction of Local Wind Conditions. BLM 70:171-195, 1994.

Landberg, Lars, M.A.Hansen, K. Vesterager, W. Bergstrom. Implementing Wind Forecasting at a Utility. Risoe – R-929 (EN), Risoe National Laboratory, Roskilde, Denmark, March 1997.

Landberg, Lars. A Mathematical Look at a Physical Power Prediction Model. Proceedings of the European Wind Energy Conference (EWEC), Dublin, Ireland, October, 1997

Landberg, Lars. A Model to Predict the Power Output from Wind Farms. Proceedings of the American Wind Energy Association (AWEA), Windpower'97, Austin, Texas, June 1997.

Landberg, Lars, M.A. Hansen, K. Vesterager, W. Bergstrom. Implementing Wind Forecasting at a Utility. Risoe – R-929 (EN), Risoe National Laboratory, Roskilde, Denmark, March 2002.

Madsen, (Ed.). Wind Power Prediction Tool in Central Dispatch Centres – Final Report. Commission of the European Communities (DG XII) under Contract No. JOU2-CT92-0083. 1995. 187pp.

Madsen, H. (Ed.). Models and Methods for Predicting Wind Power. Department of Mathematical Modeling, IMM/DTU, Lyngby, Denmark. February 1996, 88pp.

McCarthy, E.F., Understanding the Mechanisms of the Wind Resource: Some Highlights From a Hindcasting Study in California. 1997 ASME Wind Energy Symposium/35AIAA Aerospace Sciences Meeting, Reno, NV, January, 1997.

McCarthy, E.F., Wind Speed Forecasting, Presented at the AWEA Windpower '93 Pre-Conference Seminar--A Primer on Wind Technology for Utilities, San Francisco, California, July, 1993.

Milligan, M.R., A.H. Miller, F. Chapman. Estimating the Economic Value of Wind Forecasting to Utilities. NREL/TP-441-7803, Presented at AWEA Windpower '95, Washington, D.C., March, 1995. 10pp.

Mortensen, N.G., L. Landberg, I. Troen, and E.L. Petersen. Wind Atlas Analysis and Application program (WAsP), Users Guide, Risoe-I-666(EN), Risoe National Laboratory, Roskilde, Denmark, 1993. 133pp.

Nielsen, T.S. and H.Madsen, Using Meteorological Forecasts in On-Line Predictions of Wind Power. IMM Technical Report IMM-REP-1997-31, 1997, 80pp.

Notis, Learning to Forecast Wind at Remote Sites for Wind Energy Applications. 1983

Panofsky, H.A and G.W. Brier. Some Applications of Statistics to Meteorology, College of Earth and Mineral Sciences, The Pennsylvania State University, 1968.

Sanderhoff, P. PARK – User's Guide. A PC-program for calculation of wind turbine park performance. Risoe-I-668(EN), Risoe National Laboratory, Roskilde, Denmark, 1993. 8pp.

Schroder, T.A. and P. A. Daniels. Development of A Wind Forecasting Program For Wind Farm Applications. 1984. 8pp.

Sodar, L. Modeling of Wind Power Forecast Uncertainty. Status Report: Project JOUR-0091-C (MB) Short Term Prediction of Local Wind Conditions.

Taylor, G. J. Michaelson, N. Graham, and J. Shortle. Development of a Wind Forecast Program for Use in Wind Energy Systems. Santa Barbara Softworks, Santa Barbara, CA, 1988.

Wade, J.E., R.W. Baker, and S.N. Walker, Wind Forecasting for Utility Operations, BPA Report 89-30, November 1989.

Watson, S.J., J.A. Halliday, and L. Landberg, 1992. Assessing the Economic Benefits of Numerical Weather Prediction Model Wind Forecasts to Electric Generating Utilities. In: Proceedings of the Fourteenth BWEA Wind Energy Conference. Ed. E.R. Clayton, pp: 291-295,1992.

Watson, S.J., L. Landberg, and J.A. Halliday. 1994: Windspeed forecasting and It's Application to Wind Power Generation. In: Proceedings of the Fifteenth BWEA Conference, Ed. K.F. Pitcher, pp. 63-69, 1993.

Watson, S.J., L. Landberg, J.A. Halliday, Application of Wind Speed Forecasting to the integration of Wind Energy into a Large Scale Power Plant. IEE Proceedings - Gener, Transm. Distrib. 141:4, July, 1994, pp. 357 - 362.

Wegley, H.L. The Development and Evaluation of Wind Forecasts For Wind Energy Applications. Battelle - Pacific Northwest Laboratory. Contract DE-AC06-76ALO 1980.

Wendell, L.L., H.L. Wegley, and M.G. Verholek. Report from a Working Group Meeting on Wind Forecasts for WECS Operations. PNL-2513, Battelle-Pacific Northwest Laboratory, Richland, WA 99352. 1978.

Program:

Renewable Technology Options & Green Power Marketing

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

Printed on recycled paper in the United States of America

1008032

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com