Green Mountain Power Wind Power Project Third - Year Operating Experience: 1999-2000

U.S. Department of Energy-EPRI Wind Turbine Verification Program

Technical Report

Green Mountain Power Wind Power Project Third-Year Operating Experience: 1999-2000

U.S. Department of Energy-EPRI Wind Turbine Verification Program

1000960

Final Report, December 2000

Cosponsors

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

Green Mountain Power Corporation
163 Acorn Lane
Colchester, VT 05446

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

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

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Global Energy Concepts, LLC
Green Mountain Power Corporation
Vermont Environmental Research Associates

ORDERING INFORMATION

Requests for copies of this report should be directed to the EPRI Distribution Center, 207 Coggins Drive, P.O. Box 23205, Pleasant Hill, CA 94523, (800) 313-3774.

Electric Power Research Institute and EPRI are registered service marks of the Electric Power Research Institute, Inc. EPRI. POWERING PROGRESS is a service mark of the Electric Power Research Institute, Inc.

Copyright © 2000 Electric Power Research Institute, Inc. All rights reserved.

CITATIONS

This report was prepared by

Global Energy Concepts, LLC
5729 Lakeview Drive NE, Suite 100
Kirkland, WA 98033

Principal Investigators
T. Lisman
R. Vilhauer
K. Conover
S. Meyer

Green Mountain Power Corporation
163 Acorn Lane
Colchester, VT 05446

Vermont Environmental Research Associates
600 Loomis
Waterbury, VT 05677

Principal Investigator
J. Zimmerman

This report describes research sponsored by EPRI, U.S. Department of Energy, Green Mountain Power Corporation and National Renewable Energy Laboratory.

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

Green Mountain Power Wind Power Project Third-Year Operating Experience–1999-2000: U.S. Department of Energy-EPRI Wind Turbine Verification Program, EPRI, Palo Alto, CA, U.S. Department of Energy, Washington, D.C., Green Mountain Power Corporation, Colchester, VT and National Renewable Energy Laboratory, Golden, CO: 2000. 1000960.

REPORT SUMMARY

The 6.05-MW Green Mountain Power wind power project is located on top of a wooded ridge in the Green Mountains of southern Vermont near the town of Searsburg. This report describes the third-year operating experience at the GMP wind project. The lessons learned in the project will be valuable to other utilities planning similar wind power projects.

Background

In 1992, EPRI and the U.S. Department of Energy (DOE) initiated the Wind Turbine Verification Program (TVP). Program goals are to help electric utility companies gain field experience with wind power, evaluate early commercial wind turbines at several U.S. sites, and transfer experience to the wind power and utility communities. The second wind project implemented under the TVP program is the 6.05-MW wind turbine project owned and operated by GMP at a site near Searsburg, Vermont. The plant consists of 11 Zond Z-40-FS (full span pitch) 550-kW wind turbines. Each turbine has a 40-m diameter three-bladed rotor and a constant-speed turbine generator mounted on a 40-m tubular tower. To withstand the Vermont climate, the turbines have been outfitted with a cold weather package. Project construction was substantially completed in December 1996, and GMP accepted the project in late June 1997.

The Searsburg project development experience is described in a companion report, EPRI TR-109061 (December 1997). The first- and second-year operating experience are described in EPRI TR-111437 (December 1998) and TR-113917 (December 1999), respectively for the periods July 1997 through June 1998 and July 1998 through June 1999. The third year of project operation and the TVP evaluation of the Searsburg project were completed in June 2000.

Objectives

To document GMP’s third year of operating experience, to describe experience gained and problems encountered during the third year of project operation, and to transfer lessons learned to other utilities planning similar projects.

Approach

Project investigators documented third-year operating experience at the Searsburg project, from July 1999 through June 2000. The report describes the project’s annual performance, its operation and maintenance activities, changes from the first and second years of operation, and GMP’s continuing outreach activities.

Results

During the 12-month period, July 1999 through June 2000, the Searsburg wind facility generated over 13.0 million kWh of electricity. This represents a 24.6 % average annual capacity factor based on 6.05 MW of installed capacity. The overall third-year TVP system availability was

86.5%, allowing for all scheduled and forced wind turbine outages. Excluding downtime related to turbine rotor and control system damage due to lightning, tours, and line outages, the availability increased to 90.3%. TVP availability for individual turbines ranged between 63.2% and 96.6%.

Searsburg's third year of operation was marked by generator replacements at two turbines, destruction of a turbine blade by lightning, and an increased incidence of electrical and generator-related faults. However, compared to other TVP projects, response time to faults remained relatively high.

EPRI Perspective

Through 2000, EPRI has issued 17 reports on the project development and operating experience of seven DOE-EPRI Wind Turbine Verification Projects in Alaska, Iowa, Nebraska, Texas, Vermont, and Wisconsin. An important goal of the program is to transfer experience gained in the TVP projects to utilities, wind power developers and turbine vendors, government agencies, and other interested parties so that the lessons learned can be incorporated into future projects. GMP operation reports should be helpful in this regard because they describes negative as well as positive experiences. Information in these reports should help others avoid or reduce the impact of problems similar to those encountered in the program. Future EPRI TVP reports will describe experiences of other projects funded under TVP.

Keywords

Wind power
Wind resource
Performance
Availability
Operations and maintenance

ABSTRACT

The Wind Turbine Verification Program (TVP) is a collaborative effort of the U.S. Department of Energy, the Electric Power Research Institute, and host utilities to develop, construct, and operate wind power plants.

Through its involvement as a TVP host utility, Green Mountain Power (GMP) has developed, constructed, and is now operating a commercial wind power plant. GMP completed construction of its new wind facility near Searsburg, Vermont, in December 1996 and the project was commissioned in June 1997. The facility is situated in a sparsely populated, forested area on privately owned land. The 6.05 MW plant consists of 11 Zond 550-kW Z-40-FS (full span pitch) turbines. As part of the TVP, GMP has successfully completed a three-year performance evaluation program of their wind project.

This report describes the third year of operating experience at the Searsburg TVP wind project. It includes summaries of the wind resource data, energy production, and availability at the site during the third year. The report discusses the operation and maintenance activities and categorizes the downtime experienced by the turbines during the period from July 1999 through June 2000. GMP is evaluating plans for the continuing operation of the wind facility at Searsburg.

ACKNOWLEDGMENTS

Numerous individuals provided information and contributed to the production of this report. Valuable input and comments on draft versions were received from representatives of Green Mountain Power Corporation, the Electric Power Research Institute, the U.S. Department of Energy and the National Renewable Energy Laboratory. John Zimmerman and Martha Staskus of Vermont Environmental Research Associates, Dave Sweet of Enron Wind, Brian Smith of NREL, Chuck McGowin of EPRI, and Tom Hall of the U.S. DOE were particularly helpful in providing suggestions, details and clarification. Alex Compton of Global Energy Concepts helped with assembling information, preparing graphics and the final report. Other GEC staff members also contributed to various sections of the report.

LIST OF ABBREVATIONS

AIAA	American Institute of Aeronautic and Astronautics
ASME	American Society of Mechanical Engineers
AWEA	American Wind Energy Association
C_p	power coefficient
CSW	Central and South West Services
DOE	U.S. Department of Energy
EPRI	Electric Power Research Institute
GEC	Global Energy Concepts
GMP	Green Mountain Power
IEC	International Electrotechnical Commission
Met	meteorological
MTBE	Mean Time Between Events
MTBF	Mean Time Between Failures
NLDN	National Lightning Detection Network
NOAA	National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
RCE	Resource Conversion Efficiency
SCADA	System Control and Data Acquisition
SCR	silicon controller rectifiers
TVP	Turbine Verification Program
VERA	Vermont Environmental Research Association

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1

INTRODUCTION

This report is the fourth in a series of reports documenting Green Mountain Power's (GMP) experience in developing, constructing, and operating a 6.05 MW wind power plant in southern Vermont. The project is part of the Wind Turbine Verification Program (TVP), a collaborative effort of the U.S. Department of Energy (DOE), the Electric Power Research Institute (EPRI), and the host utilities. The objectives of the TVP are to provide a bridge from development to commercial sales of advanced turbines, gain experience with the utility purchase and operation of new wind turbine technology, and communicate that experience to other members of the wind community.

Three previous EPRI reports present additional information on the Searsburg project (EPRI TR-109061, TR-111437 and TR-113917). The first report, published in December 1997, documented the development, installation, and commissioning of the project. The second and third reports summarize operating experience during the first two years of project operation. Extensive background information redundant to the previous reports is not repeated in this report unless appropriate or necessary for comparison purposes.

1.1 Project Background

GMP's Searsburg wind power plant is a 6.05 MW facility using commercial-scale wind turbines. The project consists of 11 Z-40-FS (full span pitch) wind turbines manufactured by Zond Systems of Tehachapi, California, and installed on 40-m tubular towers. Zond Systems was acquired by Enron Corporation in 1997 and was subsequently renamed Enron Wind Corporation. The installed GMP wind turbines retain the Zond name.

The project is located on private property near the town of Searsburg, Vermont. The site is in a heavily-forested section of the Green Mountains, approximately 11 km (7 mi) north of the Massachusetts border. The wind turbines include a cold weather package to address the Vermont climate. The turbine sites are located along a ridgeline in a string stretching approximately 1.2 km (0.75 mi) and at elevations between 823 and 884 meters (2,700 and 2,900 ft) above sea level. Figure 1-1 is a photograph of the site.

Figure 1-1
Photograph of the GMP Wind Power Plant

1.2 Background on the Wind Turbine Verification Program

The objective of the TVP is to provide a bridge between the wind turbine development programs currently underway in the U.S. and utility purchases, and to evaluate commercial, utility-grade wind turbines. The TVP is intended to assist utilities in learning about wind power through first-hand experience and to build, test, and operate enough new wind turbines to gain statistically-significant performance data. A further objective of the TVP is to provide other utilities with information about wind technology and the operation of a wind power plant from the perspective of a utility owner and operator.

EPRI manages the TVP program on behalf of the funding organizations and publishes periodic reports on each of the projects included in the TVP to document the experience. Appendix A presents a list of the TVP reports published by the end of 2000. EPRI and DOE, through its National Renewable Energy Laboratory (NREL), also provide valuable technical and management assistance to the host utilities.

The TVP was implemented in several phases. In 1994, GMP and Central and South West Services (CSW) were chosen to host the first two TVP projects. EPRI and DOE awarded funds to cover a portion of the costs associated with the selected projects based on a number of criteria that demonstrated the ability of the project to help commercialize state-of-the-art wind technology. The projects were also required to be a minimum of 6 MW and use turbines with a substantial U.S. manufactured content.

In 1996, TVP released a solicitation that focused on distributed wind generation projects. The selection criteria required that each project be connected to a distribution line, consist of at least two wind turbines, and have a nameplate rating less than 5 MW. Five proposals were selected for contract negotiation in 1997. Two projects, one in Iowa and one in Nebraska, were installed and began operation in late 1998. The three other prospective projects in Texas, Oklahoma, and New York experienced delays for various reasons and were eventually canceled.

In addition to the projects chosen through the TVP solicitations, three utility wind projects have joined the TVP as “associate projects.” These projects receive limited funding from the program but benefit from the information exchange and technical assistance. In return, the program sponsors receive performance data and other valuable information. The associate projects include the Kotzebue Electric Association’s Wind Power Project in Alaska, the Low Wind Speed Turbine Project in Wisconsin, and the Big Spring Wind Project in Texas.

1.3 Report Objectives and Scope

This report focuses on the third year of operation at the GMP wind power plant. The report addresses the project performance, its operation and maintenance activities, and GMP’s continuing outreach programs. No additional reports are planned on the GMP project because it has reached the end of its three-year evaluation period.

Two goals of the TVP are to verify the performance of wind turbines installed and to transfer the lessons learned to others in the utility and wind industries. The GMP project is the second TVP project to be placed in operation. The GMP Z-40-FS turbines employ full-span pitch control, are mounted on tubular towers, and include cold weather modifications. The GMP project is one of two TVP projects to be installed and operated in a cold climate.

The principle objectives of this report are to summarize the GMP TVP project experience, including project performance characteristics, wind resource data, operating strategy, maintenance activities, and other events of significance that occurred during the third year of operation.

1.4 Report Organization

The report is organized into six sections. Following the introduction, Section 2 describes the wind resource characteristics at the site. Section 3 discusses the performance of the project in terms of energy output and availability during the third year. Section 4 provides additional details on the operation and maintenance activities. Section 5 presents an overview of GMP’s ongoing outreach activities. Section 6 summarizes the conclusions and experience gained during the first three years of operation.

2
WIND RESOURCE CHARACTERISTICS

2.1 Data Collection

During the last two decades, GMP has collected wind resource data from more than a dozen monitoring stations in the vicinity of the project site. GMP installed the first meteorological (met) tower in 1981 and collected data from this and other towers at various locations, at a range of elevations, and for varying time intervals through the present.

In October 1996, GMP installed a 40-m met tower on the project site in a saddle portion of the ridgeline directly upwind of Turbines 6 and 7. GMP intends to collect data from this met tower for the life of the project. The data from this tower are used to evaluate project performance and are the primary source of the wind resource information presented in this report. In addition to the site reference met tower, GMP continues to collect data from a second tower south of Turbine 11.

During construction of the project, Enron installed an unheated anemometer (at approximately 40 m), an unheated wind vane, and a temperature sensor on GMP’s site reference met tower. Data from these additional sensors were recorded by the Zond SCADA system. On July 6, 1999 lightning struck the met tower and Enron’s data collection hardware was irreparably damaged and never replaced. GMP’s logger and calibrated anemometer were also damaged during the lightning storm. The anemometer was replaced and the logger was repaired and returned to service on July 14, 1999. On November 1, 1999, GMP replaced the heated sensor with an upgraded version of the sensor. On May 10, 2000, the tower was again struck by lightning, damaging the logger and heated wind vane. The logger required extensive repair and was not returned to service until July 7, 2000. The damaged heated wind vane was replaced with the unheated wind vane previously used by Enron.

Despite data loss due to lightning damage, a complete annual data set was reconstructed for the reporting period of July 1999 through June 2000 using correlations between the data from the Turbine 6 nacelle anemometer, GMP’s heated anemometer, and the calibrated anemometer used during the power performance test. Although the data are not publicly available, GMP provided data from the heated sensors for project evaluation and reporting purposes. Table 2-1 summarizes the monthly recovery rates of valid data for GMP’s 40-m anemometer and for the nacelle anemometer on Turbine 6. Due to the problems previously discussed, data recovery from GMP’s heated anemometer was much lower than during the first two years. During the first and second years, the data recoveries were 92% and 89%, respectively, compared to 71% during the third year.

Table 2-1
Recovery Rates for 40-m Wind Speed Data – July 1999 to June 2000

Month	Turbine 6 SCADA	GMP Heated Anemometer
July-99	97.5%	75.4%
August	97.9%	78.6%
September	97.4%	100.0%
October	92.2%	100.0%
November	96.6%	0.0%
December	70.4%	0.0%
January-00	47.6%	100.0%
February	78.4%	100.0%
March	97.2%	100.0%
April	93.4%	90.6%
May	89.1%	29.0%
June	98.1%	78.3%
Annual	**88.0%**	**71.0%**

To develop an annual data set, the wind speed records from the heated anemometer and the Turbine 6 nacelle anemometer were first compared and verified for consistency. Erroneous data were removed from the data sets. Wake effect adjustments were unnecessary due to the low occurence of easterly winds.

Data collected from the Turbine 6 nacelle anemometer were used to fill in periods where data were missing from the heated anemometer records. Data were unavailable from all sensors for a few brief periods throughout the year. Data for these periods were reconstructed based on the average wind speed several hours before and after the period of missing data. Because the overall data recovery was high and the recorded values between sensors were well-correlated, the reconstructed wind speed data set provides an accurate representation of the wind characteristics at the site during the third year of operation.

The following sections present an overview of the wind characteristics at the site during July 1999 through June 2000 based on the reconstructed annual data set.

2.2 Wind Speed

Table 2-2 shows the monthly mean wind speeds for the three years of operation at the 40 m level of the site reference met tower. The average annual wind speed from July 1999 through June 2000 was 7.0 m/s (15.6 mph), the same as the annual average wind speed during the second year of operation. Although the average annual wind speeds have been quite consistent since the project began operation, they appear to be approximately 9% lower than the estimated long-term wind speed.

Table 2-2
Mean Monthly Wind Speed

	40 m Wind Speed			
Month	**1997 – 1998 m/s (mph)**	**1998 – 1999 m/s (mph)**	**1999 – 2000 m/s (mph)**	**Long-term m/s (mph)**
July	5.8 (13.1)	6.2 (13.9)	6.1 (13.7)	6.2 (13.9)
August	5.4 (11.9)	4.8 (10.7)	5.0 (11.2)	6.4 (14.2)
September	6.7 (15.0)	6.4 (14.2)	5.2 (11.7)	7.1 (15.8)
October	6.5 (14.6)	7.3 (16.4)	6.7 (14.9)	7.8 (17.4)
November	7.9 (17.8)	7.6 (17.1)	8.1 (18.0)	8.7 (19.5)
December	9.5 (21.2)	8.5 (18.9)	8.2 (18.3)	9.0 (20.1)
January	6.9 (15.4)	8.2 (18.3)	9.6 (21.4)	8.9 (19.9)
February	7.4 (16.5)	7.1 (15.9)	8.6 (19.3)	8.7 (19.5)
March	7.1 (15.8)	8.8 (19.8)	7.4 (16.6)	8.2 (18.3)
April	6.5 (14.6)	7.3 (16.3)	6.8 (15.3)	7.4 (16.5)
May	5.8 (13.0)	5.9 (13.1)	5.9 (13.2)	6.8 (15.3)
June	6.1 (13.6)	5.9 (13.2)	5.9 (13.3)	6.8 (15.3)
Annual	**6.8 (15.2)**	**7.0 (15.6)**	**7.0 (15.6)**	**7.7 (17.2)**

Figure 2-1 shows the monthly patterns of the wind resource, as measured at the reference met tower, during each of the three years of operation. The highest winds occurred in December during the first year of operation, in March during the second year of operation, and in January during the third year of operation. Figure 2-1 also shows the monthly wind speed pattern averaged over the three years of operation and the long-term monthly pattern. The wind speeds during the three years appear to be lower than expected for the long term. Wind speed data collected by the National Oceanic and Atmospheric Administration (NOAA) in Albany, NY, approximately 50 miles from the Searsburg project, exhibits a similar relationship between the averaged monthly patterns for the period July 1997 through June 2000 and the long-term monthly pattern. The Albany long-term pattern is based on over 60 years of observations.

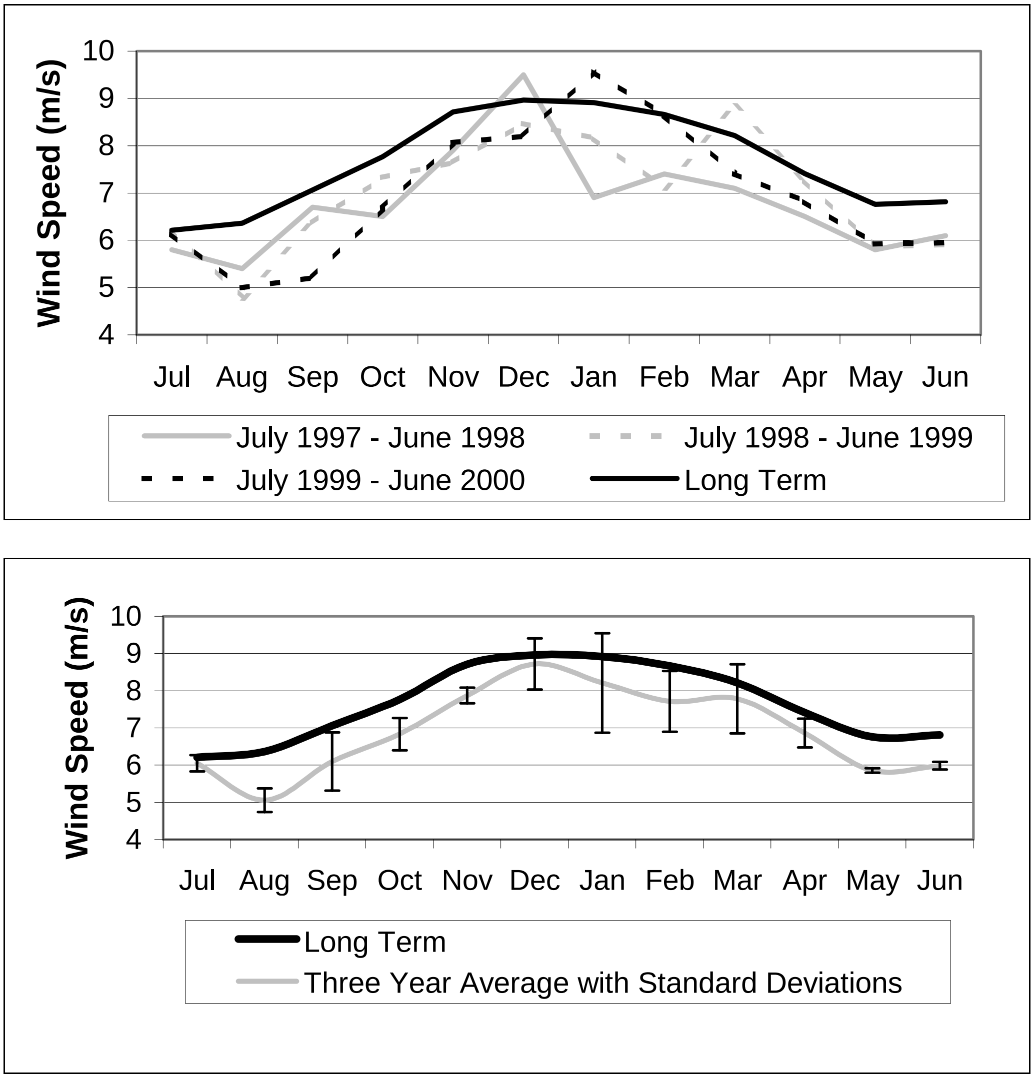


Figure 2-1
Monthly Pattern of the 40 m Wind Speeds

Figure 2-2 shows the average diurnal pattern of the wind resource and the standard deviation of the hourly average wind speed records. The highest winds typically occur late at night and during the early morning hours.

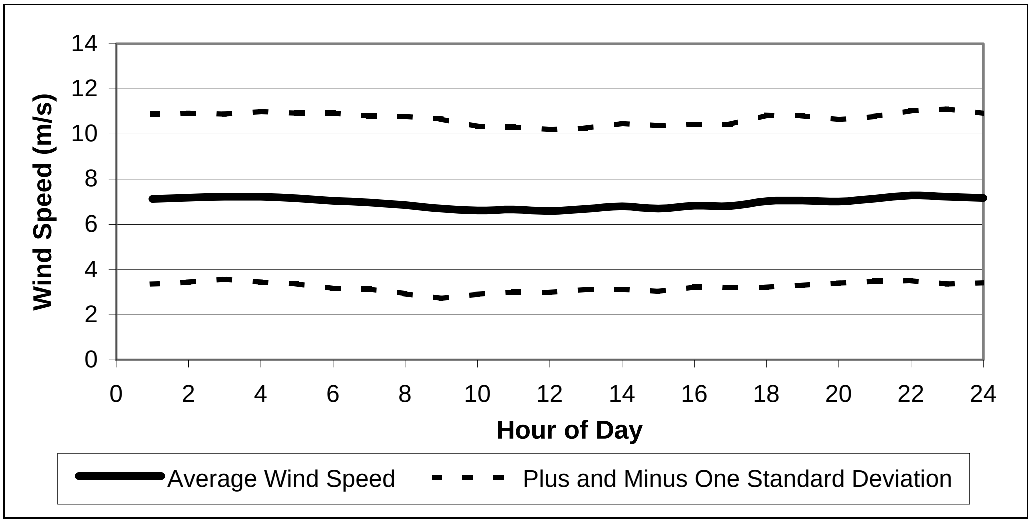


Figure 2-2
Diurnal Pattern of the Wind Resource and Standard Deviation (40 m)

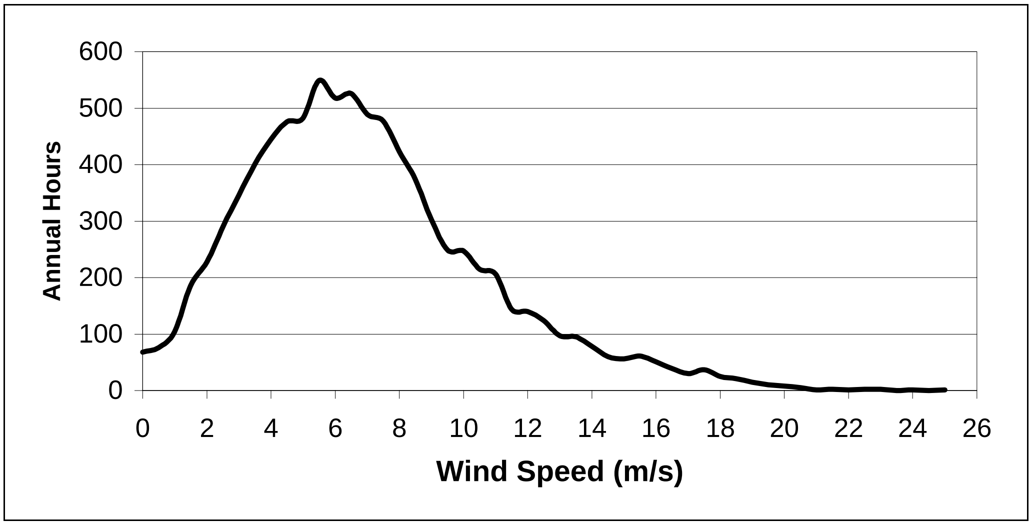
In addition to the monthly and diurnal variations of wind speed at the site, the wind resource varies between each of the eleven turbines. While some variation of wind speed between turbines can be expected at most wind projects, this variation is particularly prevalent at the GMP site due to the complex terrain. The variation in turbine wind speed affects the potential energy output of the turbines and is discussed in Section 3.2.5.

Figure 2-3 presents the wind speed frequency distribution for the Searsburg site during the third year of operation in tabular and graphical format. The distribution of the winds during the third year is similar to the two previous years of operation.

2.3 Wind Direction, Turbulence, and Shear

Although wind direction data were not available for the third year of operation, several years of directional wind analysis confirm predominant westerly winds throughout the year.

Turbulence intensity is a relative indicator of the turbulence characteristics of the wind. GEC has performed historical analysis of site data for wind speeds above the turbine cut-in speed of 4.0 m/s (9.0 mph). The analysis indicates an average turbulence intensity of 0.14 to 0.16. The American Wind Energy Association (AWEA) defines turbulence intensity levels in this range as moderate. While this level is higher than at most of the other TVP sites, it is not uncommon at mountaintop locations in the Northeast.



Bin m/s	Measured Hours	Bin m/s	Measured Hours	Bin m/s	Measured Hours
0.0	68	8.5	374	17.0	30
0.5	76	9.0	303	17.5	37
1.0	104	9.5	249	18.0	25
1.5	186	10.0	247	18.5	21
2.0	228	10.5	215	19.0	15
2.5	290	11.0	206	19.5	10
3.0	346	11.5	144	20.0	8
3.5	401	12.0	140	20.5	5
4.0	445	12.5	124	21.0	1
4.5	476	13.0	97	21.5	2
5.0	482	13.5	95	22.0	1
5.5	549	14.0	78	22.5	2
6.0	518	14.5	60	23.0	2
6.5	526	15.0	56	23.5	0
7.0	489	15.5	61	24.0	1
7.5	477	16.0	51	24.5	0
8.0	423	16.5	39	25.0	1
					8,784

Figure 2-3
Searsburg Wind Speed Frequency Distribution – July 1999 to June 2000

Wind speed data are not collected at multiple heights on the site reference met tower. Therefore, it is not possible to determine the wind shear at the met tower site. The project site is heavily forested with average tree heights of approximately 10.6 m (35 ft). Because the ground cover and immediate topography exerts a drag force on the wind and distorts wind speed readings, shear calculations would not necessarily be indicative of the winds experienced at or above the turbine hub height.

3
PROJECT PERFORMANCE

This section describes the availability and energy production from the GMP TVP project during the third year of operation, July 1999 through June 2000. The total energy produced during the 12-month period was approximately 13,049 MWh. The average TVP system availability, which takes into account all turbine downtime, was 86.5%.

3.1 Availability

Table 3-1 summarizes the energy production and availability for each turbine during the third year of operation. Table 3-2 summarizes the monthly production and availability and compares the results to the first- and second-year performance. The average annual capacity factor was 24.6% based on 6.05 MW of installed capacity. The TVP availability for the third year was 86.5%, down from the 93.9% experienced during the second year. The project availability was the highest during October 1999 at 97.5% and lowest during January 2000 at 58.9%. Turbine 7 achieved the single highest turbine availability for the third year with 96.6%. The lowest turbine availability was on Turbine 10 with 63.2%. During the third year of operation several significant maintenance activities were delayed by harsh weather. Section 4 provides a detailed discussion of project downtime on a monthly and per turbine basis.

There are a number of different ways to define and track availability for individual wind turbines and wind power plants. To ensure consistency between the projects involved, the TVP developed a definition of availability for use in reporting performance statistics for TVP projects. The TVP availability definition accounts for all downtime experienced by the individual wind turbines in a project and divides the available hours by the total hours in the period. For example, in a 100-hour period, a turbine may be shut down for five hours because a site tour is in progress, five hours to repair a component under warranty, and five hours due to a line outage. The TVP would consider 15 hours of downtime in the 100-hour period and report an availability of 85%. Appendix B presents the TVP availability definition.

The TVP availability values presented in Tables 3-1 and 3-2 include hours associated with a number of different activities at the Searsburg project, including lightning-related events, delays in responding to faults during non-business hours, turbine reliability problems, retrofits, scheduled maintenance and routine inspections, trouble-shooting, delays in obtaining parts, line outages, outreach activities (i.e. site tours), and research activities conducted by the TVP.

Table 3-1
Energy and Availability by Turbine – July 1999 to June 2000

WT#	Annual Energy (kWh)	Capacity Factor [1]	Downtime Hours	Swept Area Yield (kWh/m^2)	TVP Availability	TVP Availability Excluding Storm Damage to Rotors and Other Non-Warranty Hours [2]
1	1,181,244	24.5%	1,021	940	88.4%	94.5%
2	1,284,631	26.6%	676	1,022	92.3%	93.9%
3	1,077,509	22.3%	1573	857	82.1%	82.4%
4	1,153,992	23.9%	608	918	93.1%	93.4%
5	1,255,223	26.0%	910	999	89.6%	90.0%
6	1,127,413	23.3%	960	897	89.1%	89.4%
7	1,353,731	28.0%	298	1,077	96.6%	97.1%
8	1,250,126	25.9%	866	995	90.1%	91.1%
9	947,064	19.6%	2,487	754	71.7%	97.3%
10	877,088	18.2%	3,233	698	63.2%	68.9%
11	1,541,411	31.9%	426	1227	95.2%	95.5%
Project	13,049,433	24.6%	13,058	944	86.5%	90.3%

[1] Based on the turbine generator rating of 550 kW.

[2] Excludes 3,713 hours of downtime due to storm damage and other non-warranty events.

During the third year of operation, significant downtime hours are attributed to storm damage on Turbine 9 as well as trouble-shooting and repair related to storm damage of the control systems of other turbines. Hence, Tables 3-1 and 3-2 also show an “adjusted” TVP availability where the downtime associated with repair of storm damage is not considered. A small number of other non-warranted downtime hours due to line outages and site tours has also been removed from this calculation. The availability improves to 90.3% without considering downtime associated with storm damage and other non-warranty downtime.

Table 3-2
Energy and Availability by Month – July 1999 to June 2000

Month	Annual Energy (kWh)	Capacity Factor [1]	Downtime Hours	Swept Area Yield (kWh/m^2)	TVP Availability	TVP Availability Excluding Storm Damage to Rotors and Other Non-Warranty Hours
July 1999	930,908	20.7%	727	741	91.1%	98.8%
August	614,976	13.7%	921	489	88.8%	94.5%
September	647,795	14.9%	270	515	96.6%	97.4%
October	1,228,132	27.3%	209	977	97.5%	97.7%
November	1,551,754	35.6%	544	1,235	93.1%	93.1%
December	1,756,673	39.0%	441	1,398	94.6%	94.6%
January 2000	1,133,995	25.2%	3,365	902	58.9%	65.4%
February	1,223,028	29.0%	1,991	973	74.0 %	83.9%
March	1,077,782	23.9%	2,465	858	69.9%	79.0%
April	808,089	18.6%	1,442	643	81.8%	85.4%
May	1,101,895	24.5%	291	877	96.4%	96.5%
June	974,407	22.4%	393	775	95.0%	97.9%
Annual – 3rd Year (7/99-6/00)	13,049,433	24.6%	13,058	944	86.5%	90.3% [2]
Annual – 2nd Year (7/98-6/99)	14,255,586	26.9%	5,902	1,031	93.9%	96.3% [3]
Annual – 1st Year (7/97-6/98)	11,474,493	21.7%	14,007	830	85.5%	91.2% [4]

[1] Based on the turbine generator rating of 550 kW.

[2] Excludes 3,713 hours of downtime associated with line outages, storm damage, and site tours.

[3] 2nd Year adjusted TVP availability excludes time associated with line outages, tours and research activities.

[4] 1st Year adjusted TVP availability excludes time associated with storm damage to rotors and controllers and a power quality investigation.

3.2 Energy Production

3.2.1 Seasonal and Diurnal Variations

Figure 3-1 shows the monthly variation of energy production, availability, and wind speed at the GMP project during the third year of operation. While the site wind speeds generally are highest during the winter and lowest during the summer, energy production also is affected by turbine availability. Although the highest monthly wind speed occurred in January, the highest monthly energy production occurred in December due to higher availability. During the first and second years, the highest monthly energy production occurred during December and March, respectively. During the reporting period, the lowest monthly energy production occurred during August, while during the first and second years of operation, the lowest months of production were June and August, respectively.

In general the winds are slightly higher in the late evening and early morning. Although there is not a significant diurnal variation on an annual basis, there is more variation during the winter months. While the winter winds drop off somewhat in the afternoon, the average wind speed is still sufficient for the project to continue to produce significant energy throughout the day.

3.2.2 Utility Meter Readings and On-Site Energy Losses

Table 3-3 compares the sum of the energy reported from each turbine and the energy delivered to the grid as determined by the GMP utility meter at the Sleepy Hollow substation. The percentage difference between the meter and the sum of the turbines represents the energy losses (and/or error in measurement) from line and transformer losses in the on-site electrical collection equipment and the energy consumption by the facility. The individual turbine meters are not capable of running "backwards" and therefore do not take into account project consumption during low wind periods. The average energy loss was approximately 3.3%, similar to the previous two years and consistent with experience at other wind projects.

3.2.3 Impact of Icing on Power Output

Based on its experience with operating two test wind turbines in a mountaintop environment in the early 1990s, GMP specified that the wind turbines installed at Searsburg use black-coated rotor blades as a passive method to reduce the impact of icing on performance. Between December and March, below-freezing temperatures combine with periods of high humidity, which can result in rime ice accumulation on the blades. Although ice build up on turbine blades was apparent on several occasions during the third year of operation, noticeable performance degradation generally lasted less than two days.

While icing appeared to affect the project's performance during the first year of operation, its impact during the second and third year was not as apparent. In addition to potential energy loss, icing presents potential safety issues. Access to the turbines is closely monitored and restricted during icing conditions, and GMP has not experienced any icing related safety problems.

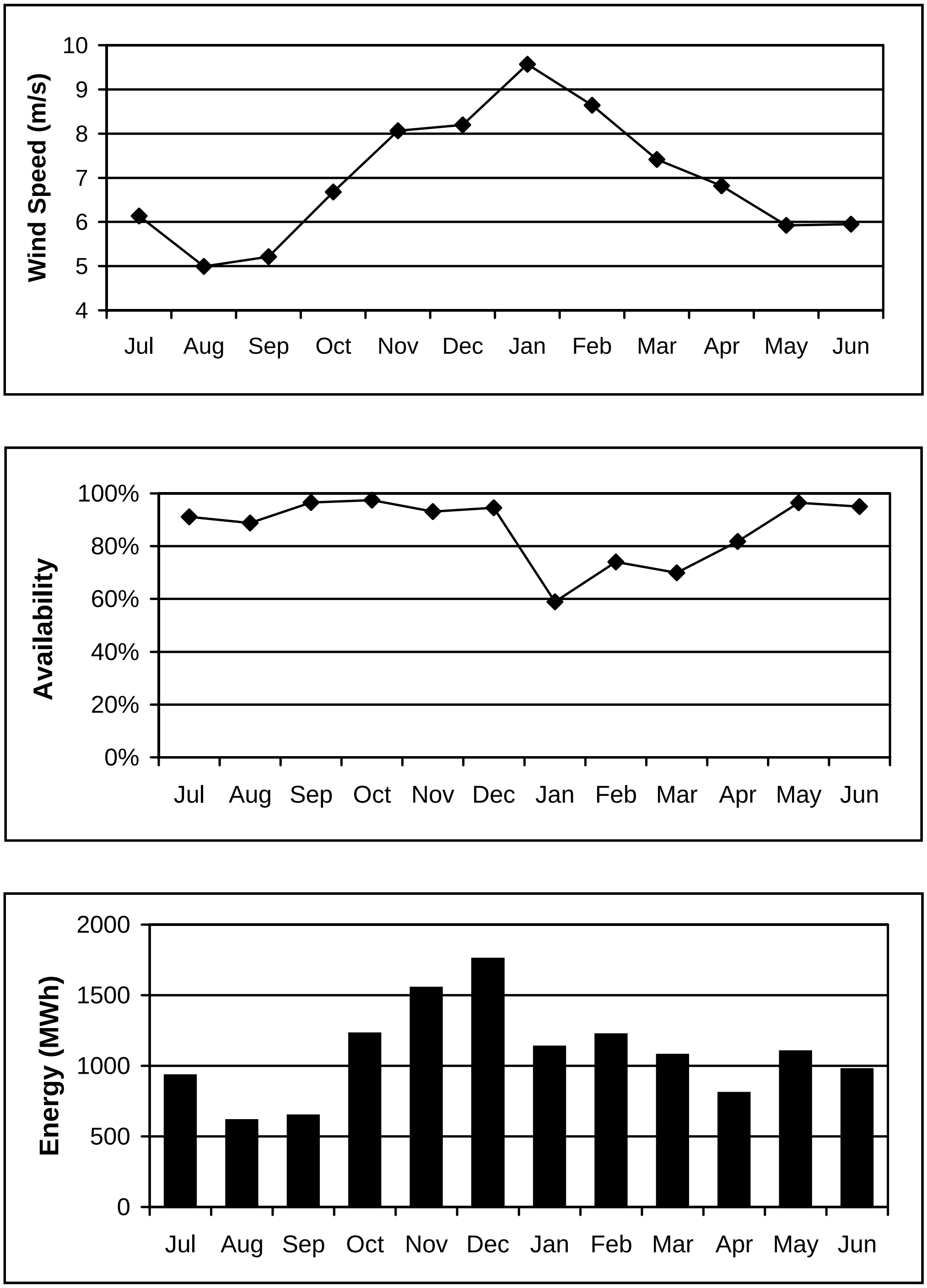


Figure 3-1
Third Year Energy Production, Availability, and Mean Wind Speed

Table 3-3
Meter Readings and Sum of Turbine Readings

Month	Sum of Turbine Energy (MWh)	Metered Energy (MWh)	Percent Loss
July 1999	931	928	0.3%
August	615	590	4.0%
September	648	628	3.1%
October	1,228	1,184	3.6%
November	1,552	1,499	3.4%
December	1,757	1,719	2.1%
January 2000	1,134	1,065	6.1%
February	1,223	1,175	3.9%
March	1,078	1,043	3.3%
April	808	778	3.7%
May	1,102	1,066	3.3%
June	974	949	2.6%
July 1999-June 2000	**13,049**	**12,624**	**3.3%**

3.2.4 Lost Energy due to Downtime

Table 3-4 shows the estimated energy losses during the downtime periods of each month, which is called “lost energy” in this report.[1] The lost energy is calculated using the manufacturer’s power curve at site air density and the estimated hub height wind speed for each turbine during each downtime period. During the third year of operation, the lost energy during downtime periods totaled approximately 2,747 MWh.

The periods with the most lost energy do not necessarily coincide with the periods of the most downtime. Table 3-4 also shows the lost energy for each downtime hour by month. Although November experienced approximately 40% fewer hours of downtime compared to August, estimated lost energy is higher for November than August. Similarly, September downtime is significantly less than July, while the energy lost in September is higher.

---

[1] In reality, the energy is not “lost,” but rather the opportunity to capture the wind energy is lost during periods when the turbines are unavailable to operate.

Table 3-4
Downtime and Lost Energy by Month – July 1999 to June 2000

Month	Downtime Hours	Lost Energy (MWh)	Lost kWh/ Downtime Hour
July 1999	727	83.1	8.7
August	921	118.3	7.8
September	270	88.6	3.0
October	209	49.9	4.2
November	544	203.7	2.7
December	441	96.4	4.6
January 2000	3,365	774.5	4.3
February	1,991	493.4	4.0
March	2,465	455.9	5.4
April	1,442	288.9	0.0
May	291	66.1	5.0
June	393	28.2	4.4
Annual	**13,058**	**2,746.8**	**4.8**

Figure 3-2 shows the actual energy and lost energy due to downtime for each month during the third year of operation. At the GMP site, there also is a significant variation in energy potential between turbines which is discussed further in Section 3.2.5. Section 4 addresses the allocation of lost energy to specific downtime.

3.2.5 Energy Output Variations Between Turbines

Wind speed and energy output vary significantly over the Searsburg ridgeline. Figure 3-3 compares the potential energy (actual plus lost) of the individual turbines. The sum of the actual energy produced and the estimated lost energy during downtime events should approximate the total potential energy. Turbines 8, 9, 10, and 11, which are located on the southwest end of the turbine string and at the highest elevations, have the highest potential energy output. These turbines outperformed the lower-elevation turbines by roughly 15% during the first two years of operations. However, during the third year, Turbines 9 and 10 experienced significant lost energy due to a blade failure and a generator failure, respectively. At the same time, Turbine 11 produced 24% more energy than the average energy produced by the other turbines. The elevation difference between the highest and lowest turbines is 54.9 m (180 ft).

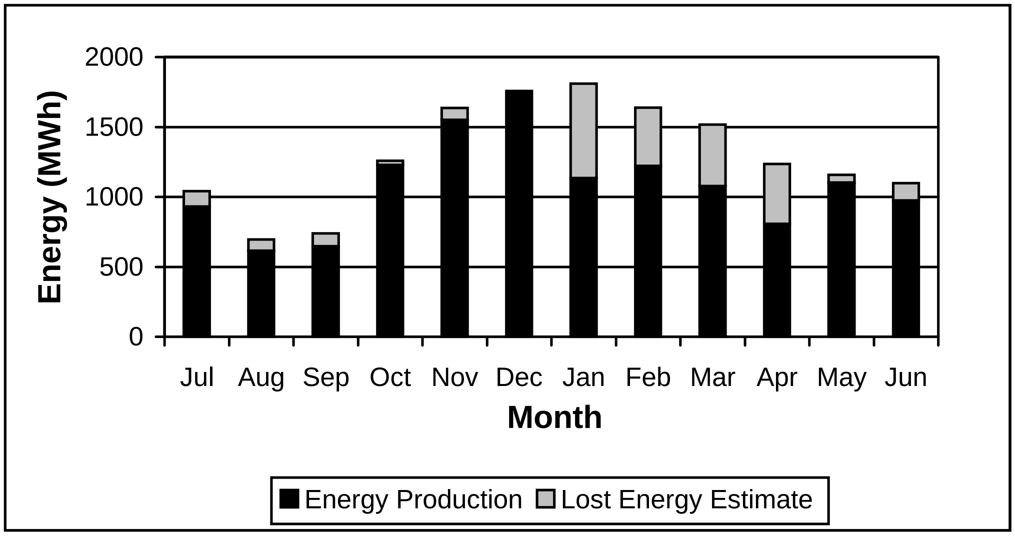


Figure 3-2
Actual and Lost Energy by Month – July 1999 to June 2000

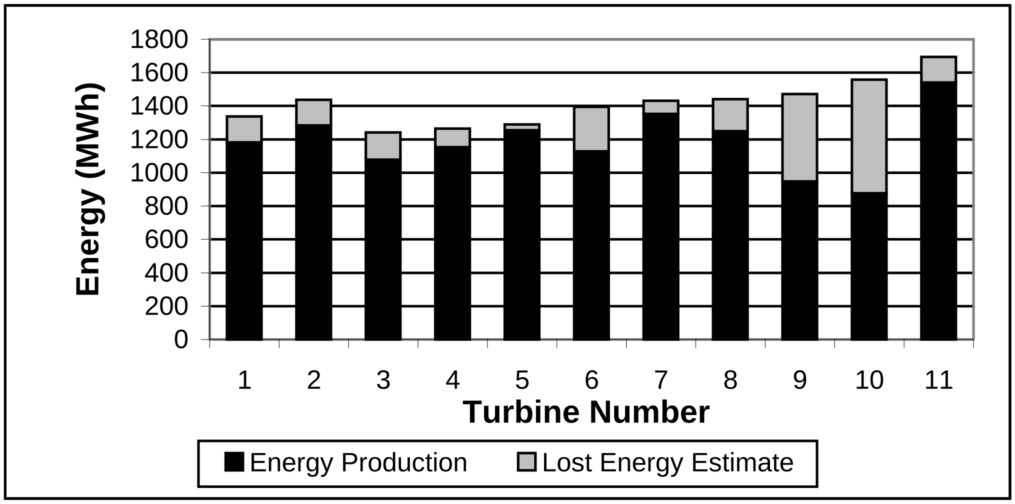


Figure 3-3
Actual and Lost Energy by Turbine – July 1999 to June 2000

3.2.6 Percent Time Generating

On average, the Searsburg turbines generate electricity more than 60% of the time. Figure 3-4 shows the average percentage of time the turbines generated power by month during the second and third years of operation. Individual turbines generated electricity 51% to 75% of the time during the third year, and from 45% to 77% of the time during the second year. The turbine generation time is related to both wind speed and availability.

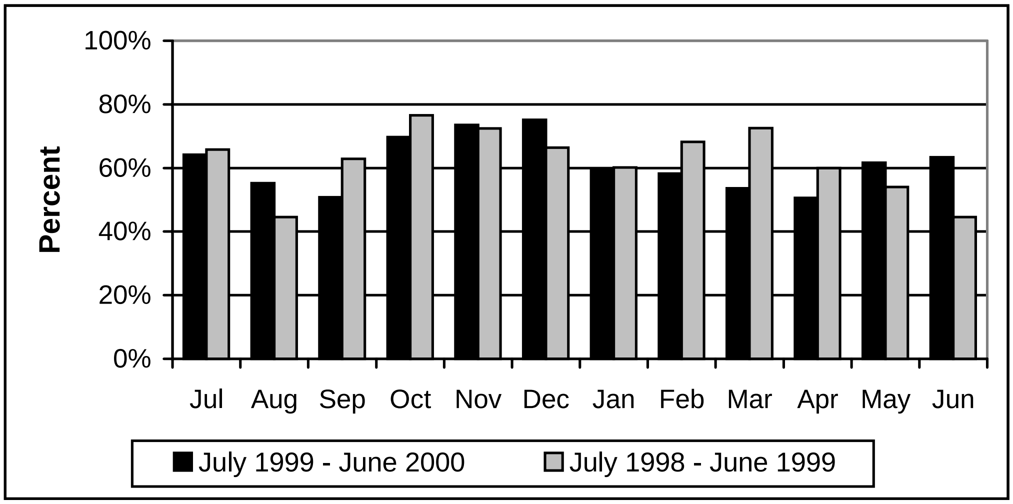


Figure 3-4
Percentage of Time Turbines Generated Power – July 1998 to June 2000

3.2.7 Power Performance Evaluation

Between April 1998 and April 1999, TVP conducted a third-party evaluation of the power performance characteristics of a selected Z-40-FS wind turbine installed at Searsburg. Wind speed and concurrent power were collected from calibrated power transducers and meteorological sensors and processed according to the International Electrotechnical Commission (IEC) Standard 61400-12, *Wind Turbine Power Performance Measurement.*

The performance test generated a measured power curve for comparison against the manufacturer's predicted power curve and to enable baseline production projections for use in evaluating performance. Figure 3-5 presents the results of the power performance test and the uncertainty range within each wind speed bin. The manufacturer's predicted power curve also is shown. Both curves are adjusted to the assumed annual average air density at the Searsburg site (1.196 kg/m^3).

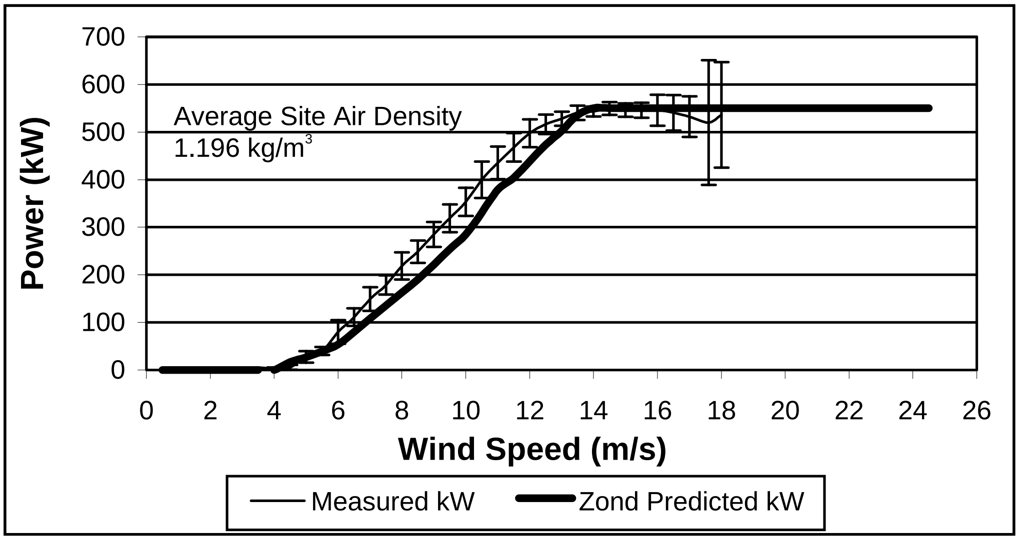


Figure 3-5
Predicted and Measured Power Curves for the Searsburg Z-40-FS

The test results indicate that the calculated power coefficient (C_p) values exceed the Betz limit of 0.59, a theoretical value that defines the maximum power extractable from the wind. With consideration of the uncertainty in the calculations, the lower bound of the range of measured data resulted in more reasonable C_p values. Figure 3-6 shows the measured power coefficient as a function of wind speed, after adjustment to the assumed site density (1.196 kg/m^3).

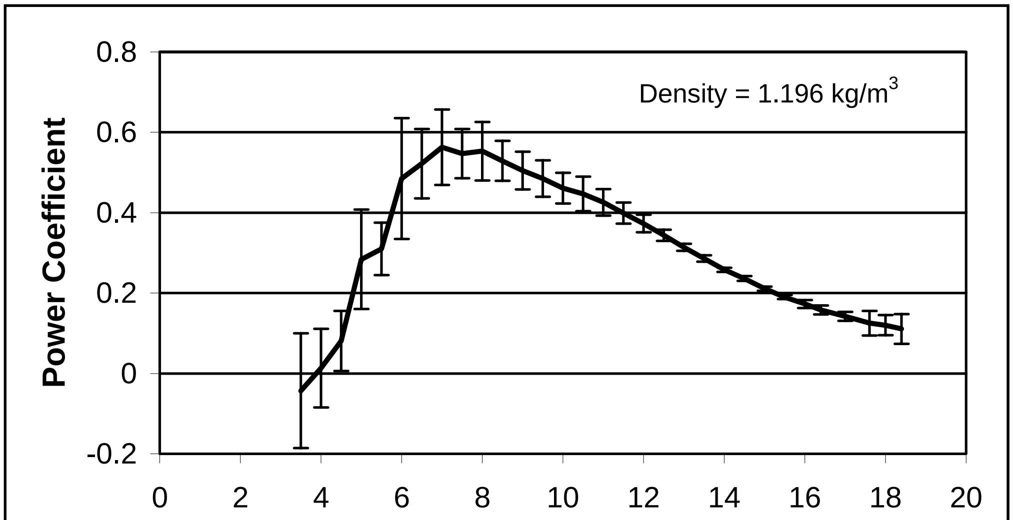


Figure 3-6
Measured Power Coefficient for the Searsburg Z-40-FS

These results generated significant discussion among representatives of GMP, GEC, Enron, NREL's certification test team, and other consultants. The most likely explanation for the high C_p values is errors introduced into the test by the site calibration process. While the test results exceed reasonable limits, it appears that the turbine meets or exceeds the manufacturers power curve. This conclusion is consistent with the performance experience at the site.

Resource conversion efficiency (RCE) measures the capability to convert the energy available in the wind into electrical energy. Figure 3-7 shows the RCE and the power coefficient C_p for the second and third years as a function of wind speed, after adjustment to site density. If the project were 100% available and operated with no losses during a given time period, RCE at each wind speed would be equal to the expected C_p for each wind speed bin during that period. Downtime or other production losses during the time period will reduce RCE relative to the C_p. Figure 3-7 demonstrates that the project was less efficient at higher wind speeds than expected. As discussed in Section 4, the incidence of faults tends to increase with wind speed, so relatively lower RCE values at higher wind speeds are expected. Figure 3-4 also indicates that the project was less efficient during the third year (July 1999 – June 2000) than during the second year (July 1998 – June 1999), which is consistent with the fact that availability was lower during the third year. The unevenness of the RCE charts is probably due in large part to the low resolution of nacelle wind speed data (+/- 0.5 mph) used in the analysis. For this reason, the second-year RCE values below 6 m/s probably are lower than shown in the figure.

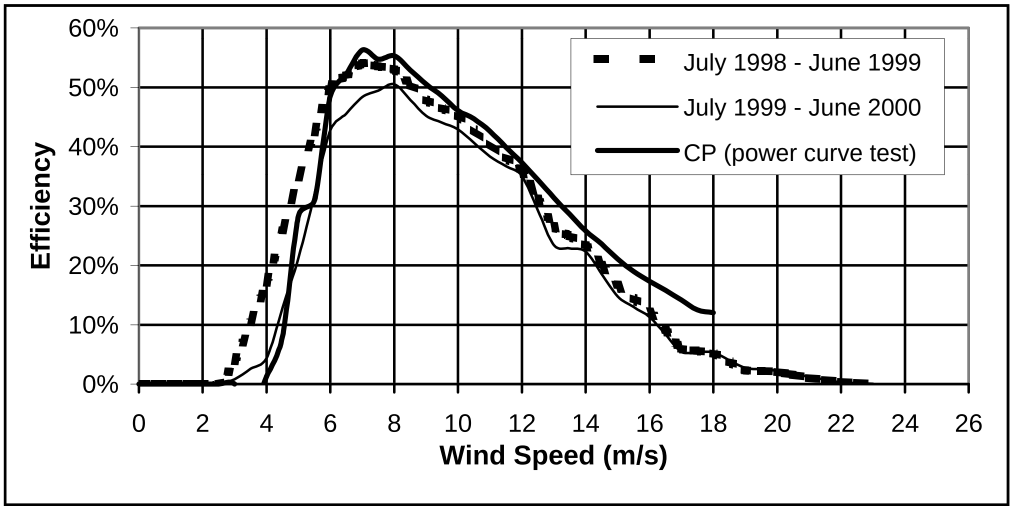


Figure 3-7
Measured Power Coefficient and Resource Conversion Efficiency

4

PROJECT OPERATIONS AND MAINTENANCE

4.1 GMP's O&M Strategy

GMP has an arrangement with Enron to provide all O&M services for the project for the first three years. Enron assumes full responsibility for the project including all preventative maintenance, unscheduled repairs, routine inspections, and operations tasks such as record keeping, inventory tracking, and others. GMP agreed to provide the services of a local technician to provide assistance to Enron's site supervisor on a part-time basis as needed.

An Enron site supervisor works full-time at the project site. Additional Enron technicians are brought to the site to assist with special service activities as necessary. Personnel from GMP's local office in Wilmington are occasionally asked to come to the site when the site supervisor needs to climb a tower. This request generally is for safety reasons rather than to provide assistance with repairs. An entry-level technician also is available to assist the site supervisor.

GMP's initial operating and maintenance plan included providing one of its employees to assist the Enron site supervisor and receive on-the-job training, on at least a half-time basis. However, due to organizational restructuring, GMP was unable to provide an employee. As a result, scheduling of repairs and maintenance has been delayed on several occasions until either a GMP or second Enron representative was available to provide support. In February 2000 Dave Sweet, Enron's site supervisor, attempted to address this staffing problem by hiring an entry-level technician to assist him on a part time basis. Sufficient support continues to be a problem at the GMP project.

4.2 Maintenance Activities and Other Downtime Events

The GMP project experienced a total of 13,058 hours of downtime during the third year of operation. On average, each turbine was down 99 hours per month. Although downtime and availability commonly are used as performance measures in the wind energy industry, it is important to understand that downtime during a low wind period is less significant than equivalent downtime during a high wind period. Unfortunately, the highest wind speeds during the third year occurred in January, the month with the most turbine downtime.

The cause of downtime and the cost to return a turbine to service also are important considerations. For example, 10 hours of downtime due to a fault that is reset without additional action has less impact on the project than 10 hours of downtime due to a repair that requires significant labor, equipment, and parts replacement, assuming the winds are comparable during both periods.

Although labor rates and equipment costs are not available from GMP or Enron, the causes and impacts of downtime have been documented and are discussed in the following sections of this chapter. The downtime is categorized and the impact of events is discussed in terms of hours, frequency, and estimated lost energy if appropriate. As discussed in the previous chapter, the lost energy for each downtime period was calculated for each turbine on an event-by-event basis that considered the actual wind conditions at the site during the time of the event.

4.2.1 Downtime Categories

Figure 4-1 illustrates the total downtime hours by category experienced at the GMP project during the third year of operation by category. The downtime categories are:

- *O&M* – This category includes all trouble-shooting, inspections, adjustments, retrofits, and repairs performed on the turbines, excluding the downtime related to storm damage. It also includes downtime that accumulates while waiting for parts, instructions, or outside services not available on site but required to place a turbine back on line. Downtime associated with the SCADA system is not included in this category if the turbines continued to operate. O&M downtime other than that associated with storm damage accounted for 5,869 hours (45% of the total downtime) and approximately 1,082 MWh of lost energy.
- *Faults* – This category includes only those faults that required a reset with no further action. If a maintenance activity immediately followed a fault, the downtime associated with the fault was combined with the repair hours and the event was included in the O&M category. In some cases, faults are not cleared until after a repair is made or until a second site maintenance person is available to stand by during tower climbing. In these instances, the fault time also was re-classified as an O&M event if sufficient information was available to make that determination. When faults occur in the evening or on weekends, the site operator is notified by the Zond SCADA’s “call-out” feature. In the event that SCADA call-out malfunctions, faults are reset in the morning of the next business day. The response time before the fault was reset is included in the fault category as long as the fault was not followed by repair work. High wind and certain cable twist “soft” faults are not counted as downtime as they are considered a normal part of turbine operation and reset automatically. During the third year of operation, faults accounted for 3,349 hours (26% of the total downtime) and approximately 1,089 MWh of lost energy.
- *Storm Damage* – A lightning storm on January 11, 2000 seriously affected project performance during the first quarter of the year. One blade on Turbine 9 separated from the rotor and the turbine was not returned to service until mid-April due to harsh winter weather conditions that prevented a crane from reaching the turbine. This single event accounted for 2,225 hours of downtime. Turbine 9’s firing board also required replacement before the turbine could be brought on line. Turbine 1 and 10 suffered extensive control system damage due to storms in July 1999. Turbine 1 again suffered extensive control system damage, along with Turbine 2 in June 2000. The July 1999 and June 2000 storms caused some minor control system component failures at other turbines, resulting in minimal downtime. All downtime associated with storm damage during the third year of operation accounted for 3,297 hours (25% of the total downtime) and resulted in an estimated 465 MWh of lost energy.

- *Line Outages* – This category includes time when the entire project was off-line due to a utility line outage at the site. During the third year of operation, line outages accounted for 317 hours, or 2.4% of the total downtime.
- *Other* – This category includes miscellaneous inspections, trouble-shooting, and site tours. For the third year of operation, 226 hours or 1.7% of the total downtime is attributed to this category.

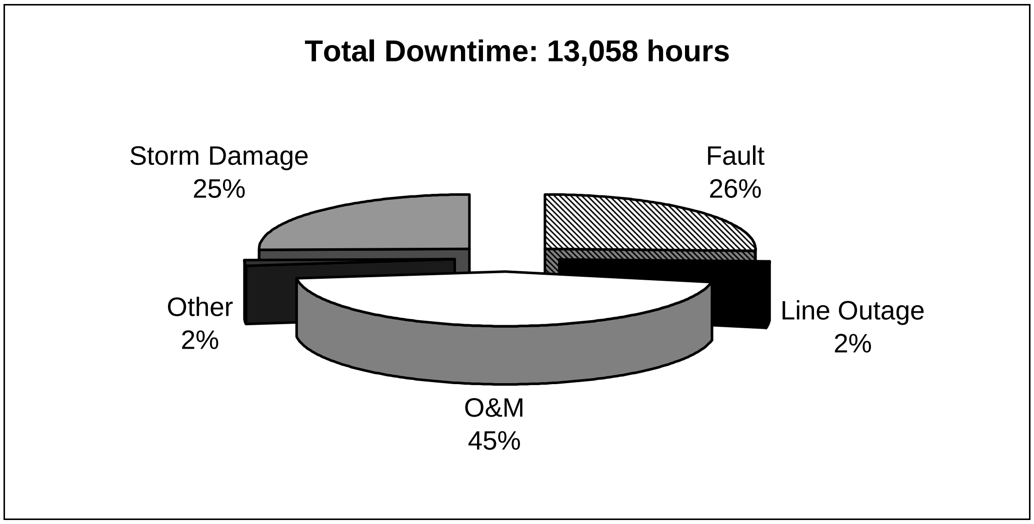


Figure 4-1
Total Project Downtime by Cause – July 1999 to June 2000

Additional analysis of the downtime associated with faults and O&M activities is discussed later in this section.

Figure 4-2 presents the total lost energy by category experienced at the GMP project during the third year of operation. O&M downtime accounts for about 1,082 MWh or 39% of lost energy; faults account for approximately 1,089 MWh or 40%, storm damage accounts for 465 MWh or 17%, line outages account for 65 MWh, and other downtime accounts for 46 MWh. While the downtime hours for faults was significantly lower than the downtime hours from storm damage, more energy was lost during the fault events than from the storm damage because a portion of the storm damage downtime was incurred during the low-wind periods.

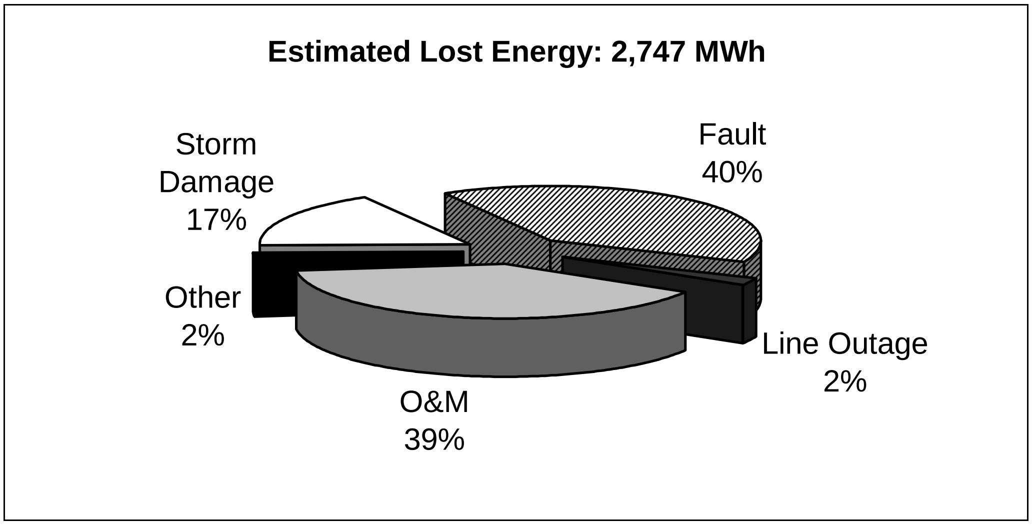


Figure 4-2
Total Lost Energy by Cause – July 1999 to June 2000

Figure 4-3 presents the downtime for each wind turbine by category, excluding the downtime associated with storm damage to Turbines 1 and 9. As shown in Figure 4-3, during the third year of operation, Turbines 2, 7 and 11 experienced less O&M downtime than the other turbines. Turbines 3 and 10 experienced substantially more downtime due to generator failures. Appendix C provides additional information on the specific causes of downtime for each turbine.

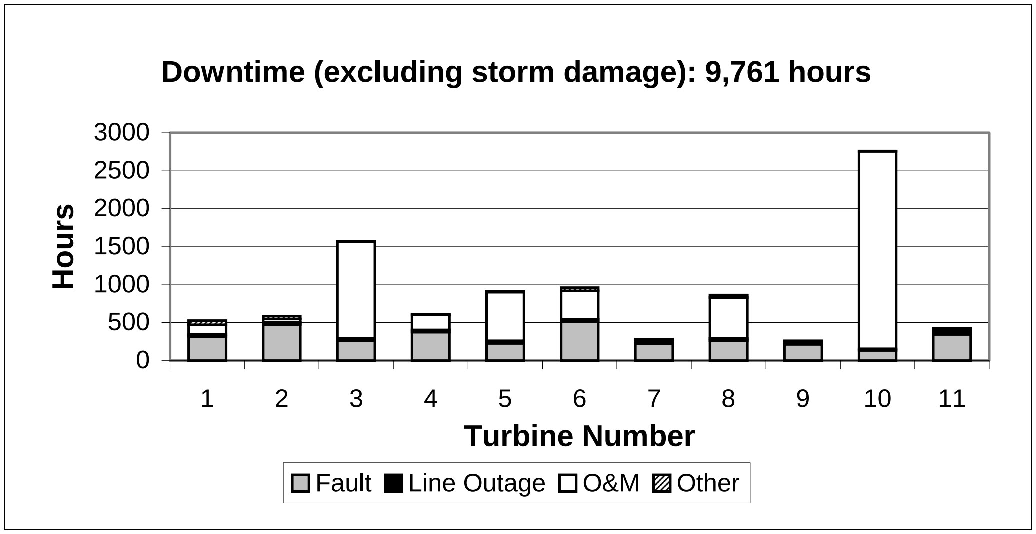


Figure 4-3
Total Project Downtime by Turbine – July 1999 to June 2000

Figure 4-4 presents the monthly average wind speeds and the downtime hours by category for each month, excluding the downtime associated with storm damage. The majority of O&M downtime from January through April is attributed to a generator failure at Turbine 10 that occurred in late December. The fault downtime in January is attributed to electrical and generator-related faults throughout the project as well as hydraulic system faults at Turbines 5 and 6.

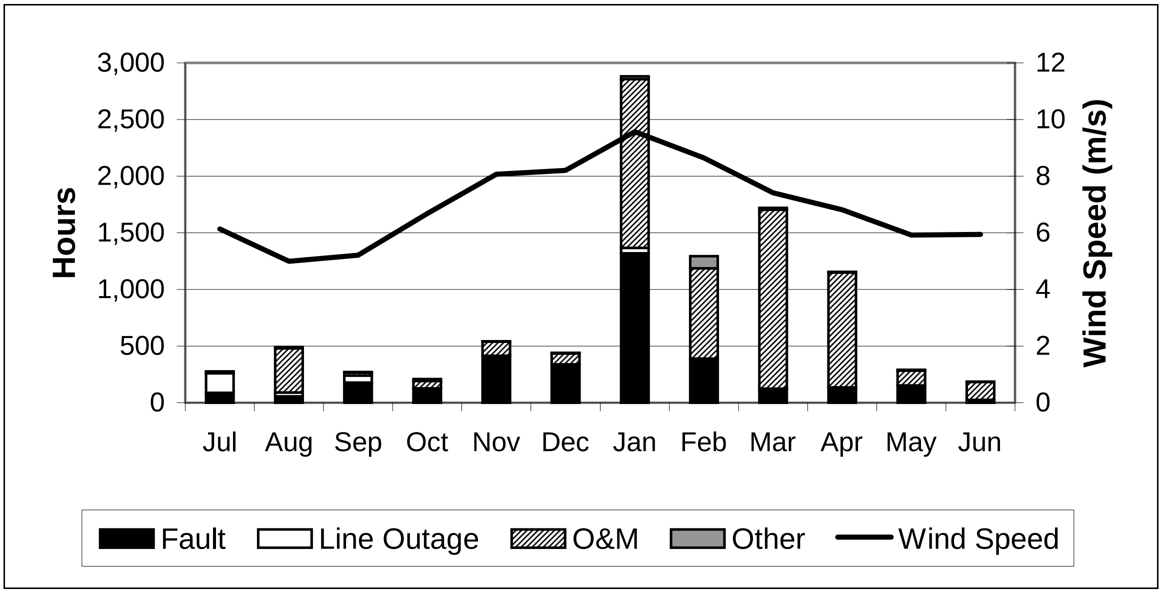


Figure 4-4
Total Project Downtime and Wind Speed by Month – July 1999 to June 2000

4.2.2 Downtime Due To O&M Activities

Figure 4-5 shows a breakdown of downtime included in the O&M category without the downtime related to storm damage. Some general observations on each of the component systems are provided below:

- *Controller system* – During the first three years of operation, firing board malfunctions have plagued the project. Repair or replacement of firing boards occurred at six of the eleven turbines during the first year of operation. Although Enron replaced all firing boards throughout the project during the second year of operation, every turbine experienced downtime related to the firing board assembly, silicon controller rectifiers (SCRs), or SCR cabling during the third year. A controller inspection following the Turbine 3 generator failure revealed significant degradation of the SCR cable insulation at Turbines 1 through 6. This category accounts for 10% of the O&M downtime during the third year.
- *Generator* – Generator failures have impacted availability during the first three years of the project's operation. Following a generator failure in October 1997, the project was shut down while an extensive power quality test was conducted to determine the cause of the failure as well as the reason for the high incidence of electrical and generator-related faults. The project experienced another generator failure in April 1999. During the third year, two more

generators failed. The Turbine 10 generator failed in December 1999 and the Turbine 3 generator failed in March 2000. These two generator events account for 28% of the total downtime and 63% of the O&M downtime during the third year.

- *Hydraulic System* – 52% of the hydraulic system O&M downtime during the third year was due to a failing hydraulic accumulator at Turbine 8. An intermittent electrical connection at the hydraulic manifold on Turbine 5 and replacement of hydraulic pumps on Turbines 3 and 6 account for the majority of the remaining hydraulic downtime. This category accounts for 17% of the O&M downtime during the third year.
- *Other* – The majority of the remaining 563 hours of O&M downtime is attributed to the replacement of the latches on the nose cone hatch of Turbine 5. Scheduled maintenance was performed on all turbines in November 1999 and June 2000 and accounts for most of the remaining downtime in this category. “Other” O&M accounts for less than 10% of the total O&M downtime.

Appendix C presents additional information on the types and timeframe of O&M downtime at the project during the third year of operation.

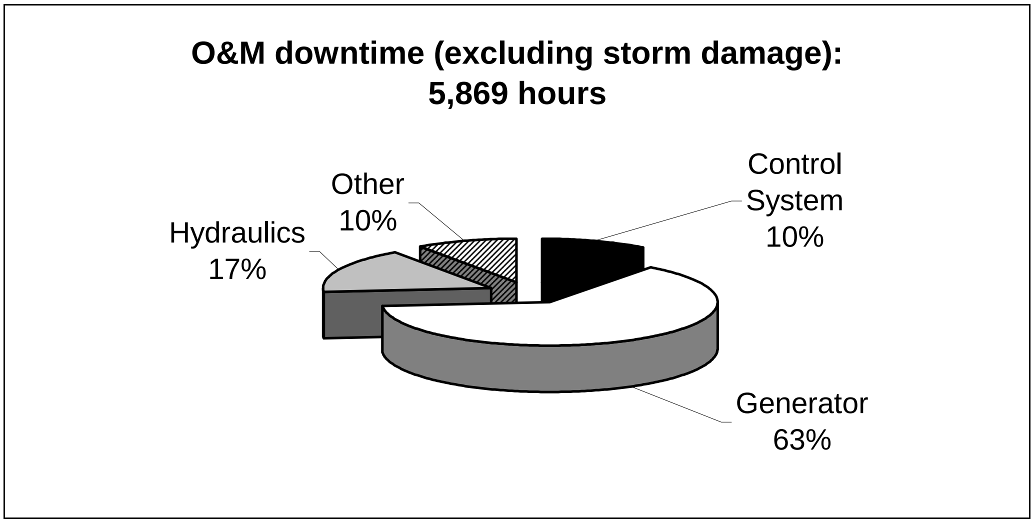
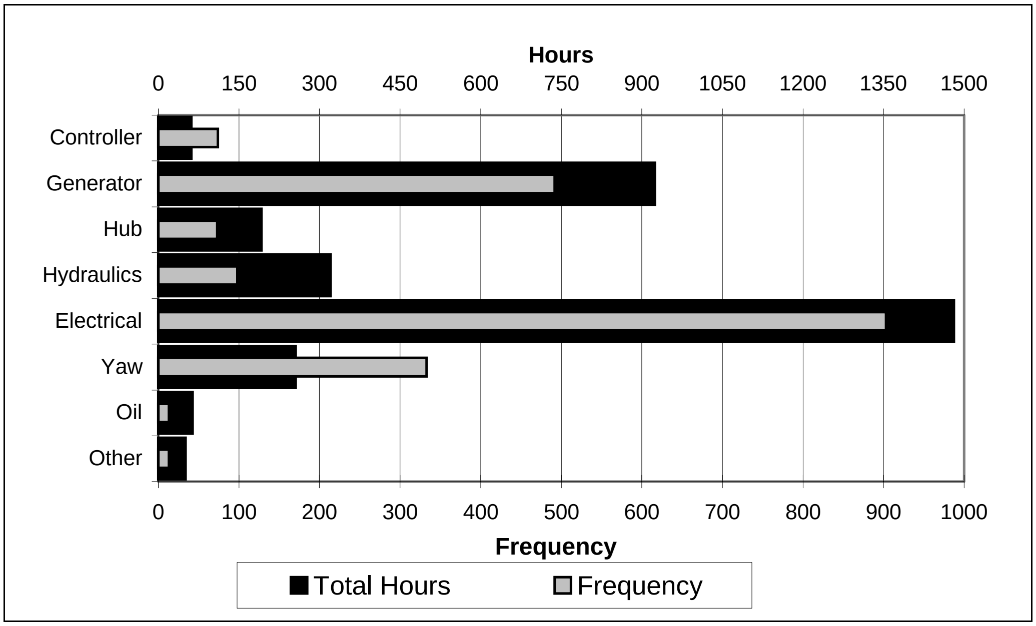


Figure 4-5
Third Year O&M Downtime by Major Turbine Components

4.2.3 Downtime Due To Faults

Faults accounted for 26% of the total downtime during the third year of operation. Figure 4-6 shows the frequency, total faulted hours, and average duration of the faults by type. As previously noted, the faults in this category are only those “nuisance” faults for which the site operator takes no action other than to reset the turbines. The act of resetting a turbine requires only a small fraction of an hour; therefore, most of the hours in this category represent the time it took for the operator to become aware of the fault condition and respond with a reset action.



Fault Type	Number of Faults	Total Hours	Average Duration (hours)
Controller	74	61.3	0.8
Generator	492	924.2	1.9
Hub	73	191.8	2.6
Hydraulics	98	320.7	3.3
Electrical	903	1,481.2	1.6
Yaw	333	255.4	0.8
Oil	13	63.8	4.9
Other	13	50.7	3.9
TOTAL	**1,999**	**3,349.1**	**1.7**

Figure 4-6
Fault Frequency and Duration by Type – July 1999 to June 2000

Figure 4-7 compares the occurrence of faults to the annual wind speed distribution at the site. Generator- and electrical-related faults tend to occur simultaneously during high wind periods, making accurate classification difficult. However an effort has been made to separate generator and electrical faults for this report. As shown in Figure 4-7, approximately 44% of the total fault downtime is attributed to electrical faults such as over-line voltage on the collection circuit. This does not include line outages, which are included in a separate downtime category. The cause of these electrical faults remains unclear. The project experienced more downtime due to electrical faults during the third year than during the second year.

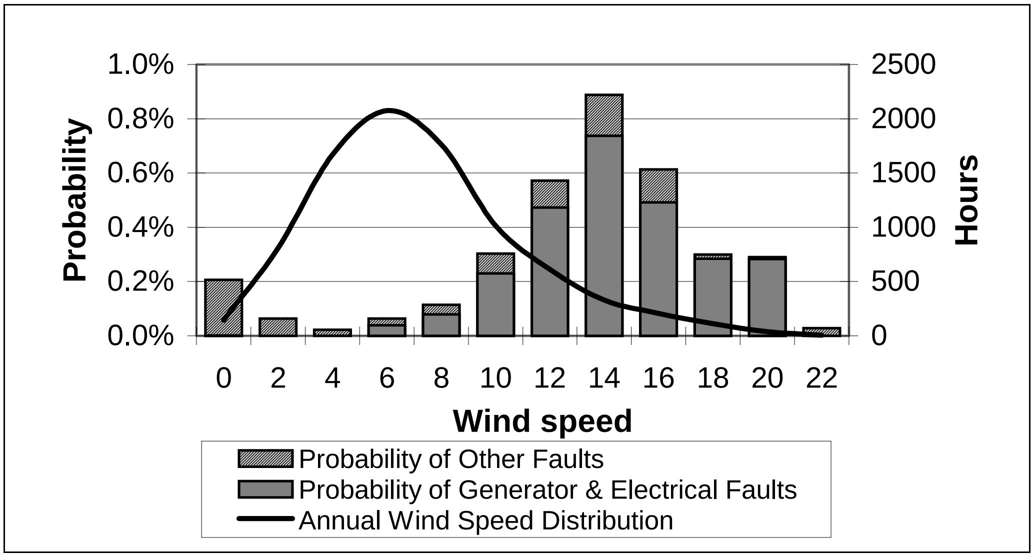


Figure 4-7
Fault Probability by Wind Speed

GMP has speculated that the turbines' controllers may be detecting power quality abnormalities on the site's 12 kV collection circuit that occur when one or more of the other turbines come on line, shut down, or experience significant changes in power output.

Generator over-speed and generator over-current faults account for roughly 28% of the fault downtime during the third year of operation. A project-wide firing board retrofit was conducted during the second year of operation to reduce problems during turbine cut-in and cut-out and to address generator over-speed faults. In spite of this, the number of generator-related faults increased about 21% and resulted in over twice as much downtime due to generator faults as was experienced during the second year of operation.

As mentioned previously, electrical- and generator-related faults tend to occur during high wind periods. They often occur at the same time, usually as over-line voltage and generator over-current, or over-line voltage and generator over-speed faults. Figure 4-7 shows the probability of fault occurrence by wind speed during the third year of operation. The annual wind speed distribution also is shown. Figure 4-8 illustrates the relative impact of different types of faults on energy production. Generator and electrical faults resulted in an estimated 835 MWh of lost energy during the third year of operation. During this period, the estimated energy loss due to these faults exceeded the estimated energy loss associated with lightning damage or generator failures. The project experienced 2,568 hours of electrical- and generator-related faults during the first year of operation. During the second year, these faults accounted for only 1,169 downtime hours (less than half of the first year). However during the third year, the project incurred 2,405 downtime hours due to these faults. Together, electrical- and generator-related faults account for 18.6% of the total downtime during the project's first three years of operation.

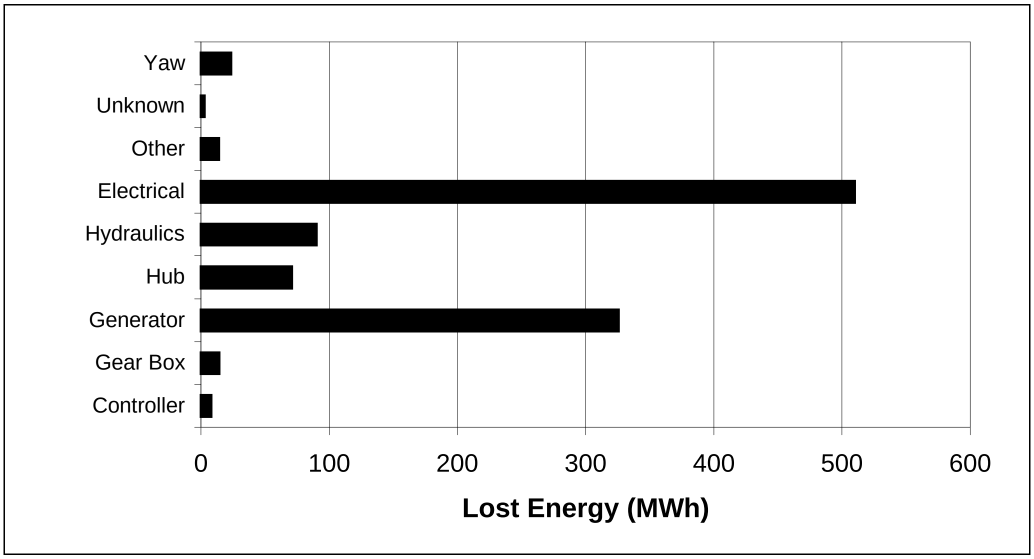
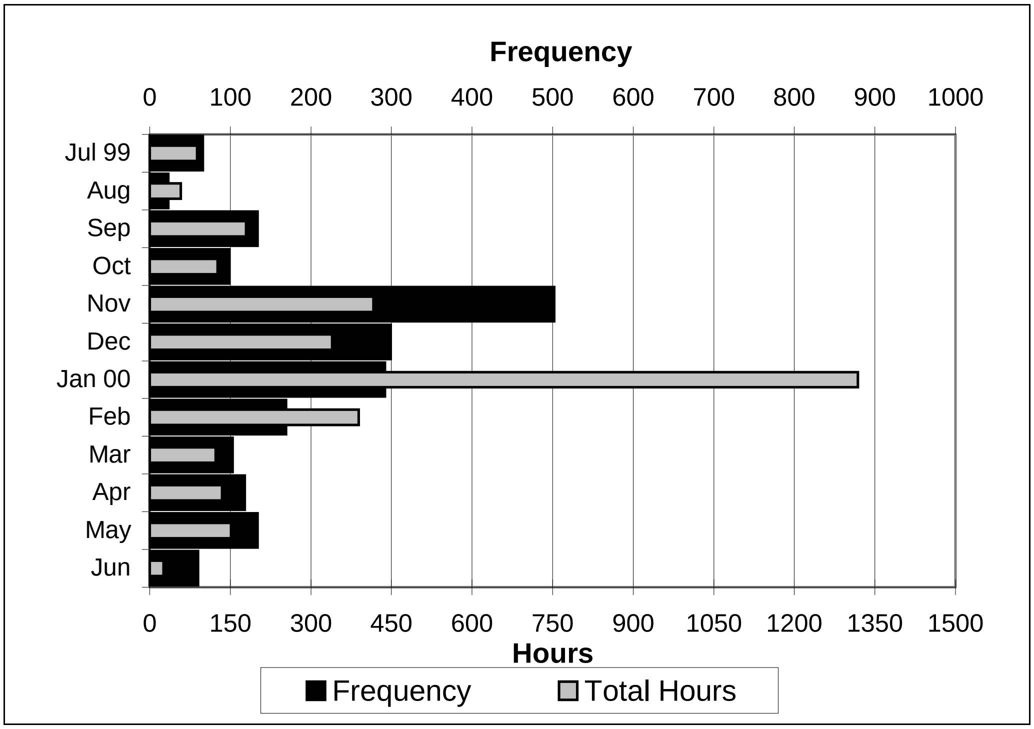


Figure 4-8
Estimated Energy Loss Due to Faults

The majority of hydraulic faults occurred on Turbines 5, 6 and 8 in January and February. An intermittent electrical connection at Turbine 5’s hydraulic manifold caused erroneous faults, while Turbines 6 and 8 suffered low hydraulic accumulator pressure. The accumulators of both turbines were recharged, however Turbine 8 was unable to maintain pressure and continued to experience low hydraulic pressure faults for the remainder of the reporting period. The frequency of hydraulic faults was decreased by approximately 25% during the third year of operation compared to the second year. The reduction is attributed to a hydraulic oil cooler retrofit installed on all turbines in April 1999, which addressed the overheating of the hydraulic fluid during winds greater than 14 m/s (31 mph). The excessive faults in January and February preceded genuine component failures or maintenance events while many of the faults during the first and second years resulted from overheated hydraulic fluid. Figure 4-9 shows the frequency, total faulted hours, and average duration of faults by month. Hydraulic faults resulted in an estimated 93 MWh of energy loss during the third year of operation.



Month	Number of Faults	Total Hours	Average Duration (hours)
July 1999	66	88.0	1.3
August	23	57.7	2.5
September	134	179.2	1.3
October	99	126.2	1.3
November	502	416.5	0.8
December	299	339.7	1.1
January 2000	292	1318.4	4.5
February	169	388.9	2.3
March	103	123.0	1.2
April	118	134.7	1.1
May	134	151.4	1.1
June	60	25.6	0.4
Total	**1999**	**3349.1**	**1.7**

Figure 4-9
Third Year Fault Frequency and Duration by Month

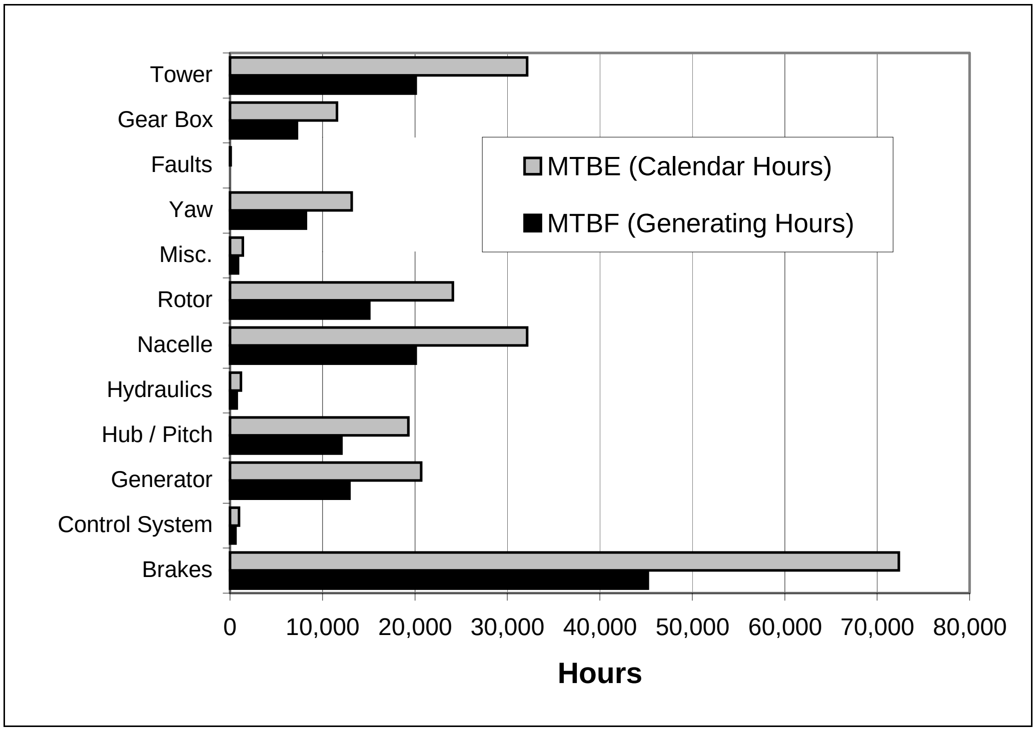
During the third year of operation the number of yaw faults more than tripled from the second year. However, yaw faults were reset quickly and tend to be associated with very low energy losses. Yaw system faults, primarily rotation errors and yaw motor overload, occurred throughout the year. Rotation errors occur during sudden wind direction changes when the turbine rotor begins to spin backwards because the winds are blowing from behind the turbine. Both the generator and the yaw faults appear to be related to the turbulent conditions at the site. Appendix C provides additional information on the types and timeframes of faults at the project during the third year of operation.

As shown in Figure 4-9, the longest response times and the largest number of faults occurred during January, the month of the highest winds. The site supervisor was at a training course for a week during January, which contributed to the high downtime hours for that month. In addition to the high downtime hours in January, the SCADA call-out feature experienced problems throughout the year and often would not notify site personnel when turbines were faulted. As a result, personnel often were not aware of faults that could have been reset remotely during the evenings or weekends. During the third year each turbine faulted an average of 15 times per month for an average of 1.7 hours per fault. During the second year the average downtime per fault was 1.2 hours.

4.3 Turbine Reliability

Wind turbine reliability can be measured by the mean time between unscheduled maintenance events. When based on turbine generation time, this calculation is used to represent the principal measurement of reliability known as mean time between failures (MTBF). When based on calendar hours, it is known as mean time between events (MTBE). A failure is defined as any unscheduled maintenance event including inspections, testing, faults, and repairs; line outages are not counted. Between June 1997 and July 2000, the turbines generated electricity 62.5% of the time, or a total of 180,848 generating hours. Figure 4-10 shows the MTBF and MTBE for each turbine component, the fault category, and the overall project for the first three years of operation.

During the three-year period, the total project MTBF was 35 hours and the total MTBE was 57 hours. In other words, each turbine experienced a fault or O&M event every 35 hours of generation and every 57 calendar hours; on a project-wide basis, an event of some type occurred every 3.2 generating hours and every 5.2 calendar hours. Each turbine experienced a fault on average every 43 hours of generation. The higher values in Figure 4-10 indicate increased reliability as more time passes between events. Therefore, in spite of the serious nature of the blade and generator failures, reliabilities of these components on a daily basis are much higher than that of the control system. The generator MTBF of 12,918 hours and MTBE of 20,667 hours indicate that a generator event occurred at the project five times during the three years. On average, a control system event occurred every three and a half days (961 hours/24 hours in a day/11 turbines).



System	**Number of Unscheduled Maintenance Events**	**Mean Time Between Failures (Generating Hours) [1]**	**Mean Time Between Events (Calendar Hours) [2]**
Brakes	4	45,212	72,336
Control System	301	601	961
Generator	14	12,918	20,667
Hub/Pitch	15	12,057	19,290
Hydraulics	248	729	1,167
Nacelle	9	20,094	32,149
Rotor	12	15,071	24,112
Misc.	211	857	1,371
Yaw	22	8,220	13,152
Faults	4,241	43	68
Gear Box	25	7,234	11,574
Tower	9	20,094	32,149
Overall Total	**5,111**	**35**	**57**

[1] Sum of turbine generating hours (180,848 hours)/Number of failures at the project

[2] Calendar hours (26,304 hours) x 11 turbines/Number of failures at the project

Figure 4-10
Mean Time Between Failures and Events – July 1997 to June 2000

4.4 Lightning Impacts and Mitigation Activities

Over 25% of the total downtime experienced in the third year of operation was related to lightning damage to the rotor of one turbine and control systems of several others. Over the first three years of operation, 24.3% percent of the total downtime has been attributed to lightning damage.

In 1998, the TVP initiated a lightning mitigation program for the GMP project. In a collaborative effort, GMP and Enron retained independent consultants from McNiff Light Industry and Lightning Technologies, Inc. to assess damage and survey the current lightning protection system at the site. The consultants developed recommendations to improve the lightning protection, including grounding variable pitch controller cabinets to gearboxes; attaching flash tube-type surge suppressors to hydraulic transducers and proportional valves; terminating over-braid shielding on transducer and proportional valve cables; and grounding lightning rods to the generators. In 1999 Enron developed a blade conductor retrofit for their Z-750 series turbines, and has worked toward the development of a similar retrofit for the Z-40 FS turbines at Searsburg. The blade conductors are intended to prevent the type of rotor damage that occurred at Turbines 4 and 7 in May 1998 and again at Turbine 9 in January of 2000. No additional protection has been installed or mitigation efforts made at the Searsburg site to date.

The project was hit by two lightning storms in July 1999, which caused considerable control system damage to Turbines 1 and 10, minor control system damage to Turbines 7 and 9, intermittent SCADA system communication loss, and a 15-hour project-wide line outage. In January 2000 a direct strike destroyed one blade of Turbine 9. Turbines 1 and 2 suffered moderate control system damage due to a lightning storm on June 25, 2000.

According to the National Lightning Detection Network (NLDN) database, the Searsburg area is at risk of 1.5 strikes/km^2/year, one of the higher areas of risk in New England. This corresponds to a strike of risk of 0.9 strikes/year to a turbine located somewhere on the site.[1] Documented lightning-related damage to turbines and to equipment located at the long-term met tower indicates lightning strikes occurred at least 3.3 +/- 1.5 times per year during the first three years of operation. The project is sited on a mountaintop, and therefore may experience more storm activity than is normal for the surrounding area.

4.5 Other O&M Experience

During periods of high winds when several turbines fault at the same time, the SCADA call-out feature malfunctions occasionally and does not alert the site supervisor to reset faults during non-business hours. As previously discussed, this was more of a problem during the third year of operation and is partially responsible for the increased fault response time. However, both the SCADA computer and SCADA software are expected to be updated soon.

---

[1] *Lightning Activities in the DOE-EPRI Turbine Verification Program*. WindPower 2000 Proceedings, AWEA, Palm Springs, CA May, 2000

During the first two years of operation, access to the site in the winter months was less of a problem than expected. However, during the third year of operation, winter weather delayed repair of Turbine 9’s rotor and replacement of Turbine 10’s generator by several months.

5

PUBLIC EDUCATION AND OUTREACH ACTIVITIES

During the third year of operation, GMP continued to promote wind energy through various outreach activities with the local community and at the state and national levels. GMP continues to host site tours for schools, government and citizen groups. GMP representatives have participated in several industry conferences and meetings to discuss their experiences.

Figure 5-1
Site Tour of Searsburg Wind Power Facility

This past year GMP conducted site visits for several state and local planning commissions and select boards from New York, Massachusetts, and Connecticut. Martha Staskus of VERA continues to work with groups interested in renewable energy sources, specifically wind power.

Interest in wind power development in the Northeast continues to grow in response to recently implemented state mandates for electric suppliers to include specified minimum amounts of renewable generation in their retail sales. The availability of state-based economic incentives for new renewable energy generation has also spurred interest in wind power development.

Since mid-1997, Walton Congdon, a retired science teacher, has assisted as a visitor guide at the site. He answers questions from school groups and members of the public who visit the turbines during open houses. On March 14, 2000 over 40 students from several regional colleges toured the project.

GMP continues to promote the project through programs such as Education Days where schools organize field trips to bring students to the site to learn about the project first-hand. Education Days attracts approximately 100 students from the primary grades through regional community colleges to tour the site.

In May 2000, at the annual conference of the American Wind Energy Association (AWEA), GMP received an award recognizing their “pioneering vision and leadership” as host of the 6.05 MW Searsburg wind facility. During the conference, John Zimmerman of VERA participated in a panel discussion on the TVP lightning experience and represented GMP at a program-wide TVP participants’ meeting.

GMP continues to distribute a 12-page newsletter, *Wind Power News*, on the project. *Wind Power News* has reported GMP’s wind power experience and other related activities since 1992. Although the last publication occurred in December 1998, back issues of the newsletter are still in demand. Copies of GMP’s “Harnessing the Power in the Wind,” are available at the information kiosk located at the entrance to the site and also remain in high demand.

While the site is closed to the public most of the year to protect sensitive wildlife habitat, a pull-off area constructed at the base of the site access road allows those driving by the project site to stop and acquire general information about the project and view the turbines from a short distance. GMP’s concern for the protection of wildlife has included monitoring of the bear habitat at the project site. Prior to construction of the project, a wildlife expert studied the bear activity in the area. Mitigation steps were taken to minimize the impact of construction and operation to the bear habitat. For instance, site tours are not conducted during bear mating season or when the cubs are young. The wildlife expert recently reassessed the bear activities and determined that bear movement has not been changed during the three years of operation.

6

CONCLUSIONS

Through its involvement in the TVP, GMP has successfully developed, constructed, and is now operating a wind power plant in Searsburg, Vermont. During the third year of operation, the project energy production and availability were lower relative to the earlier years. During the second year, significant progress was made in overcoming many of the start-up challenges, and the project performance improved from the first year. During the third year, the project faced new challenges, including significant storm damage to several turbines, difficulty obtaining personnel support, and harsh weather conditions that delayed completion of necessary repairs.

During the third year, GMP has been undergoing some internal restructuring and considering various options for the future of the wind power project. With the growing green-power market in the Northeast, the wind project is expected to continue operation, but the ownership, power sales arrangements, and ongoing operating strategy are unclear.

Lightning mitigation activities could substantially improve the performance of the project. Several cost-efficient modifications have been recommended and are expected to significantly improve the protection of the control system electronics, sensors, and turbine generators at the GMP site. Enron is developing a blade conductor retrofit that would provide an increased level of blade protection against lightning damage.

In the past, GMP has provided support personnel to the project when a second technician was required to assist the full-time Enron site supervisor. With the closing of the GMP office in Bennington, local support has not been available and has resulted in maintenance delays. During the third year of operation, Enron flew a maintenance technician to Vermont to assist the site supervisor with scheduled maintenance activities. Enron recently hired an entry-level technician to support the site supervisor and hopes to improve O&M response time.

When the project was under development, GMP was concerned about the effect of rotor icing on project performance. Although rotor icing can dramatically reduce project performance for short periods of time, it appeared to have minimal impact on overall annual energy production during the second and third year of operation.

The SCADA computer experienced an increase in SCADA call-out malfunctions, which contributed to the increased downtime during the third year of operation. Other than the call-out feature, the SCADA system operated successfully during the reporting period, and no serious or lasting communication problems occurred.

Analysis and evaluation of the first three years of operating experience at the Searsburg wind facility has provided the project participants with a valuable database of information that can be used to guide future activities. As GMP continues beyond the end of the TVP project, TVP sponsors are working with representatives from GMP and Enron to evaluate options for continued operation of the Searsburg facility. The TVP performance evaluation activities identified significant issues affecting the project operation. Continuing improvements can be made, but few new issues of significance surfaced during the third year.

GMP continues to use the experience gained through the project development and first three years of operation to educate the surrounding community, state and national interest groups, and their own staff on the challenges and benefits of renewable energy. These efforts have been a positive influence on the acceptance and implementation of future wind energy projects in the region.

The TVP continues to make progress towards the goal of providing a bridge for turbine development programs to commercial purchases of wind turbines. Utilities and turbine manufacturers are obtaining valuable experience in wind power plant development, operation and maintenance, and technology transfer. The lessons learned through the TVP in the Searsburg project will be passed on to other projects in which EPRI and DOE have a management role and to the rest of the wind and utility industries through continuing outreach activities.

A

APPENDIX A – TVP-RELATED DOCUMENTS

EPRI Reports

Wind Turbine Verification Project Experience: 1999, EPRI 1000961, December 2000.

Big Spring Wind Power Project First Year Operating Experience: 1999-2000, EPRI 1000958, December 2000.

Project Development Experience at the Big Spring Wind Power Project, EPRI TR-113919, December 1999.

Lessons Learned at the Iowa and Nebraska Public Power Wind Projects, EPRI 1000962, November 2000.

Project Development Experience at the Iowa and Nebraska Distributed Wind Generation Projects, EPRI TR-112835, December 1999.

Kotzebue Wind Power Project First Year Operating Experience: 1999-2000, EPRI 1000957, December 2000.

Project Development Experience at the Kotzebue Wind Power Project, EPRI TR-113918, December 1999.

Wisconsin Low Wind Speed Turbine First and Second Year Operating Experience: 1998-2000, EPRI 1000959, December 2000.

Wisconsin Low Wind Speed Turbine Project Development, EPRI TR-111438, December 1998.

Green Mountain Power Wind Power Project Third Year Operating Experience: 1999-2000, EPRI 1000960, December 2000.

Green Mountain Power Wind Power Project Second Year Operating Experience: 1998-1999, EPRI TR-113917, December 1999.

Green Mountain Power Wind Power Project First Year Operating Experience: 1997-1998, EPRI TR-111437, December 1998.

Green Mountain Power Wind Power Project Development, EPRI TR-109061, December 1997.

Central & South West Wind Power Project Third Year Operating Experience: 1998-1999,
EPRI TR-113916, December 1999.

Central & South West Wind Power Project Second Year Operating Experience: 1997-1998,
EPRI TR-111436, December 1998.

Central & South West Wind Power Project First Year Operating Experience: 1996-1997,
EPRI TR-109062, December 1997.

Central and South West Wind Power Project Development, EPRI TR-107300, December 1996.

DOE-EPRI Wind Turbine Verification Program TVP MI-112231 Status Report, 1998.

Building Community Support for Local Renewables and Green-Pricing Projects
EPRI TR-114203, 1999.

NREL/AWEA WindPower Published Papers

Central & South West's 1998 Operations and Maintenance Field Experiences. B. Givens, Central & South West Services. Presented at WindPower 1999.

Characterizing Wind Turbine System Response to Lightning Activity: Preliminary Results. McNiff, B.; LaWhite, N.; Muljadi, E. Collection of the 1998 ASME Wind Energy Symposium Technical Papers Presented at the 36th AIAA Aerospace Sciences Meeting and Exhibit, 12-15 January 1998, Reno, Nevada. New York: American Institute of Aeronautics and Astronautics, Inc.(AIAA) and American Society of Mechanical Engineers (ASME); pp. 147-156; NICH Report No. 25563. 1998.

Comparison of Projections to Actual Performance in the DOE-EPRI Wind Turbine Verification Program. H. Rhoads, J. VandenBosche, T. McCoy, A. Compton, Global Energy Concepts, LLC, B. Smith, National Renewable Energy Laboratory. 14 pp.; NICH Report No. CP-500-28608. Presented at WindPower 2000.

CSW Small Wind Farm Operating Experience 1996 – 1998. W. Marshall, Central & South West Services, Inc. Presented at WindPower 1998.

Development and Plans for the Kotzebue Wind Power Plant. B. Reeve, Kotzebue Electric Association, and E. Davis, Wind Energy Consulting & Services. Presented at WindPower 1998.

Distribution Line Power Quality Experience with the Nebraska Distributed Wind Generation Project. M. Hasenkamp, Nebraska Public Power District. Presented at WindPower 2000.

DOE-EPRI Distributed Wind Turbine Verification Program (TVP III). C. McGowin and E. DeMeo, Electric Power Research Institute, S. Calvert and P. Goldman, U.S. Department of Energy, B. Smith, S. Hock and R. Thresher, National Renewable Energy Laboratory. Presented at WindPower 1997.

DOE-EPRI Wind Turbine Verification Program (TVP). C. McGowin, EPRI, T. Hall, U.S. Department of Energy and B. Smith, National Renewable Energy Laboratory. Presented at WindPower 1998.

EPRI/DOE Wind Turbine Performance Verification Program. Calvert, S.; Goldman, P.; DeMeo, E.; McGowin, C.; Smith, B.; Tromly, K. 6 pp.; NICH Report No. CP-440-22486. Presented at Solar Energy Forum 1997.

Green Mountain Power's Searsburg Project. B. Ralph, Green Mountain Power Corporation. Presented at WindPower 1999.

Green Mountain Power's 6-MW TVP Wind Project in Searsburg, Vermont. J. Zimmerman, Green Mountain Power Corporation. Presented at WindPower 1998.

Iowa TVP III Project. T. Wind, Cedar Falls Utilities. Presented at WindPower 1999.

Lightning Activities in the DOE-EPRI Turbine Verification Program. T. McCoy, H. Rhoads, T. Lisman, Global Energy Concepts, LLC, B. McNiff, McNiff Light Industry, B. Smith, National Renewable Energy Laboratory. 14 pp.; NICH Report No. CP-500-28604. Presented at WindPower 2000.

Nebraska TVP III Project. M. Hasenkamp, Nebraska Public Power District. Presented at WindPower 1999.

Power Performance Testing Activities in the DOE-EPRI Turbine Verification Program. J. VandenBosche, T. McCoy, H. Rhoads, Global Energy Concepts, LLC, B. McNiff, McNiff Light Industry, B. Smith, National Renewable Energy Laboratory. 15 pp.; NICH Report No. CP-500-28589. Presented at WindPower 2000.

Program on Lightning Risk and Wind Turbine Generator Protection. Muljadi, E.; McNiff, B. National Renewable Energy Laboratory 8 pp.; NICH Report No. CP-440-23159. 1997.

"Projects-at-a-Glance" Summaries of Projects Within the DOE-EPRI Wind Turbine Verification Program. K. Conover, S. Meyer, H. Rhoads, S. Simon, K. Smith, J. VandenBosche and R. Vilhauer, Global Energy Concepts, LLC. Presented at WindPower 2000.

Review of Operation and Maintenance Experience in the DOE-EPRI Wind Turbine Verification Program. K. Conover, J. VandenBosche, H. Rhoads, Global Energy Concepts, LLS, B. Smith, National Renewable Energy Laboratory. 13 pp.; NICH Report No. CP-500-28620. Presented at WindPower 2000.

TU/York Big Springs Project. L. Herrera, TU Electric. Presented at WindPower 1999.

Wind Farm Generation Impact on a Small Municipal Utility System. T. Wind, Wind Utility Consulting. Presented at WindPower 2000.

Wisconsin Low Speed Wind Turbine Project Development Experience. J. VanCampenhout, Wisconsin Public Service Corporation. Presented at WindPower 1998.

Other TVP Resources

Joint Utility Wind Interest Group/Turbine Verification Program/Wind Powering America Technical Workshop. 2000.

TVP News Bulletins. Global Energy Concepts. 1999-2000.

B

APPENDIX B – TVP AVAILABILITY DEFINITION

There are a number of different ways to define and track availability for individual turbines and wind power plants. To ensure consistency among the projects involved in the program, the TVP developed a definition of availability to be used for reporting on performance statistics throughout the program. The TVP definition of availability takes into account all downtime experienced by the individual wind turbines in the project and divides the available hours by the total hours in the period.

For each turbine, the TVP availability is:

% Turbine Availability =

{[H-(Downtime Hours for turbine)]/H} X 100%

where *H* is the number of hours in the period and *Downtime Hours for Turbine* accounts for all downtime experienced by the turbine during the period of interest (i.e., week, month, year-to-date, or 8760 hours for an annual period).

For a wind power plant, the TVP availability is:

% Wind Power Plant Availability =

{[(H X N)-(Sum of the Downtime Hours for N Turbines)]/(H X N)} X 100%

where *H* is the number of hours in the period and *N* is the number of turbines in the project.

Although the above definitions use “hours” in the calculation, it is important to collect data that shows the turbine status (i.e., available or unavailable) on a time interval of 10 minutes or less so that fractions of an hour can be included in the availability calculation.

The TVP availability includes downtime caused by different events including:

- research activities;
- testing;
- delays in responding to faults;
- public relations (i.e., site tours);
- turbine maintenance and retrofit activities;

- scheduled maintenance and routine inspections;
- trouble-shooting;
- delays for parts or equipment;
- line outages; and
- force majuere events.

There are several other availability definitions that exclude some of these events. Although these approaches are intended to serve a specific purpose, the TVP uses the *TVP Wind Power Plant Availability* definition to ensure consistency among the projects.

C

APPENDIX C – O&M AND FAULT DOWNTIME BY MONTH

As discussed in Section 4.2.2, the following tables show breakdowns of downtime caused by O&M of turbine components and faults during the Searsburg project's third year of operation.

O&M and Storm Damage Downtime

System	Jul-99	Aug-99	Sep-99	Oct-99	Nov-99	Dec-99	Jan-00	Feb-00	Mar-00	Apr-00	May-00	Jun-00	Grand Total
Control System	456.8	435.7	14.7	25.2	1.7	69.1	221.2	40.7	191.0		3.8	224.8	1684.6
Gear Box		34.5				0.5						9.7	44.7
Generator			4.3			20.3	744.0	696.0	1300.7	952.2			3717.5
Hydraulics			4.5	33.5	41.8		521.8	59.5	82.0	61.5	126.8	58.0	989.5
Inspection					0.5								0.5
Nacelle		334.8		0.5									335.3
Rotor							485.0	696.0	744.0	286.0			2211.0
Scheduled Maintenance					61.5	2.0						71.2	134.7
Unknown		13.8		4.0	18.8	2.3		0.2	5.5	1.0			45.6
Yaw				2.5									2.5
Grand Total	456.8	818.8	23.5	65.7	124.3	94.3	1972.0	1492.3	2323.2	1300.7	130.7	363.7	9166.0

Fault Downtime

System	Jul-99	Aug-99	Sep-99	Oct-99	Nov-99	Dec-99	Jan-00	Feb-00	Mar-00	Apr-00	May-00	Jun-00	Grand Total
Controller	0.5	25.8	2.5	0.8	1.8	9.8	8.8	7.7	1.3	0.5	1.5	0.2	61.3
Generator	27.7		53.5	46.0	178.2	108.6	322.8	59.2	48.2	56.2	23.7	0.3	924.2
Hub			13.2	23.8	22.8	10.1	87.8	25.2	4.3	4.2	0.3		191.8
Hydraulics	0.0	0.7	0.7	2.0	0.3	0.7	106.7	151.8	19.7	4.0	30.4	3.8	320.7
Line	51.8	26.7	80.3	31.9	192.1	155.9	699.4	117.6	25.7	56.5	43.4		1,481.2
Yaw	8.0	4.5	26.8	21.0	13.5	40.7	27.5	11.0	23.8	10.0	47.5	21.1	255.4
Oil			2.2	0.7		14.0	44.5				2.5		63.8
Other					7.7		20.8	16.5		3.3	2.2	0.2	50.7
Grand Total	88.0	57.7	179.2	126.2	416.5	339.7	1,318.4	388.9	123.0	134.7	151.4	25.6	3,349.1

Targets:

Wind Power Development Support

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

1000960

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