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Comparison of Projections to Actual Performance in the DOE-EPRI Wind Turbine Verification Program

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COMPARISON OF PROJECTIONS TO ACTUAL PERFORMANCE IN THE DOE-EPRI WIND TURBINE VERIFICATION PROGRAM

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Abstract

As part of the U.S. Department of Energy/Electric Power Research Institute (DOE-EPRI) Wind Turbine Verification Program (TVP), Global Energy Concepts (GEC) worked with participating utilities to develop a set of performance projections for their projects based on historical site atmospheric conditions, turbine performance data, operation and maintenance (O&M) strategies, and assumptions about various energy losses. After a preliminary operation period at each project, GEC compared the actual performance to projections and evaluated the accuracy of the data and assumptions that formed the performance projections.

This paper presents a comparison of 1999 power output, turbine availability, and other performance characteristics to the projections for TVP projects in Texas, Vermont, Iowa, Nebraska, Wisconsin, and Alaska. Factors that were overestimated or underestimated are quantified. Actual wind speeds are compared to projections based on long-term historical measurements. Turbine power curve measurements are compared with data provided by the manufacturers, and loss assumptions are evaluated for accuracy. Overall, the projects performed well, particularly new commercial turbines in the first few years of operation. However, some sites experienced below average wind resources and greater than expected losses. The TVP project owners successfully developed and constructed wind power plants that are now in full commercial operation, serving a total of approximately 12,000 households.

Introduction and Background

The U.S. DOE and EPRI began the TVP in 1992 to evaluate prototype advanced wind turbines and to provide a bridge from development programs to commercial purchases. The TVP is intended to help utilities learn about wind power through first-hand experience, and to build, test, and operate enough new wind turbines to gain statistically significant performance data. Other TVP objectives include verifying the performance, reliability, maintainability, and cost of new wind turbine designs and system components in commercial utility environments; and providing other utilities and stakeholders with information about wind technology, the project development process, and the operation of wind power plants from the perspective of utility owners and operators.

EPRI and DOE selected TVP projects based on site and wind resource documentation, geographic and climatic diversity among selected hosts, evidence of intent to include wind power as a generation resource, the relevance of the project to the future use of wind power, and prospects for sufficient funding to achieve project implementation. Figure 1 shows the turbine configurations and approximate locations of all seven TVP projects, ranging from 0.66 megawatts (MW) at Kotzebue to 34.32 MW at Big Spring. Figure 2 shows a timeline of the projects' operation and TVP reporting periods. With a total installed capacity of 51.98 MW and expected energy of nearly 168.1 million kilowatt hours (kWh) per year, the seven TVP projects together serve approximately 12,000 households.

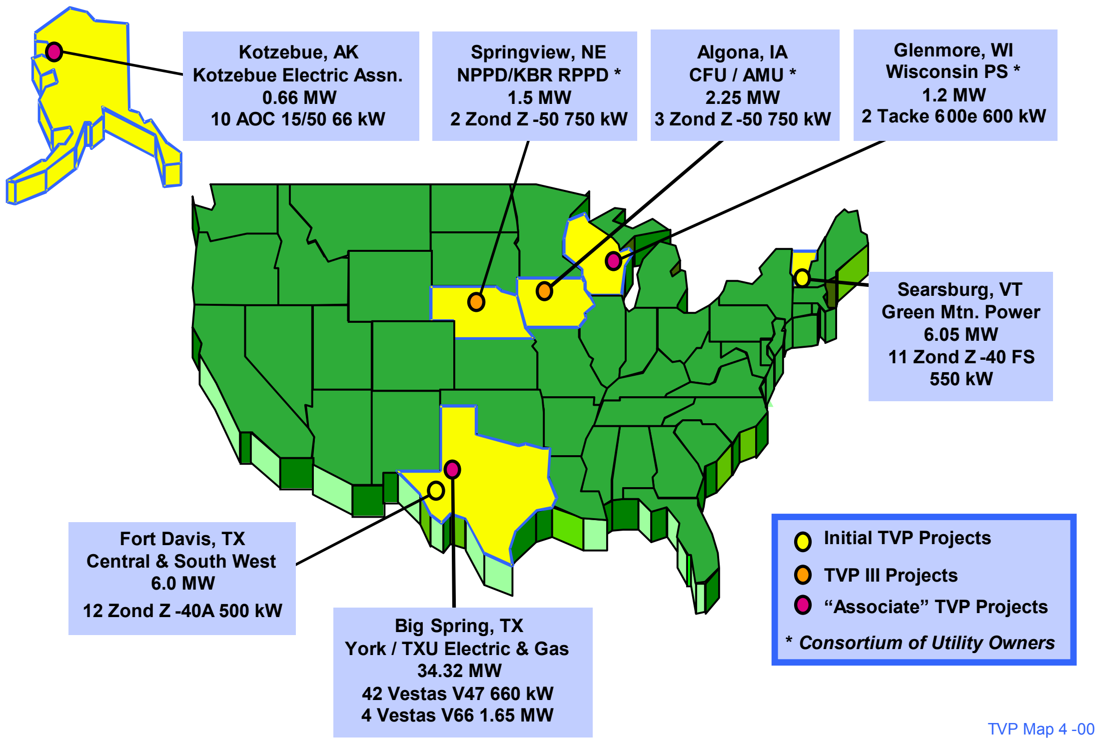

Figure 1. Locations and descriptions of DOE-EPRI wind turbine verification projects

This paper presents turbine production at the seven TVP projects during 1999 compared to historical performance, when possible, and the long-term projected annual output. It also describes the methodology GEC used to develop the projections and loss assumptions. Key factors affecting performance, including the sites' wind resources, the turbines' power curves, and the projects' availability and other energy losses, are examined, and lessons learned are summarized.

Results

Between January and December 1999, the seven TVP projects together produced a total of more than 120.3 million kWh of electricity, which represents a 28.6% capacity factor based on a combined annual average 48.03 MW of installed capacity.[1] The overall calculated TVP system availability, which takes into account all downtime, averaged 91.3% across all projects on a per-turbine basis during 1999.[2] Annual project capacity factors ranged from 10.6% at Kotzebue to 33.9% at Algona; 1999 TVP project availability ranged from 82.8% at Fort Davis to 96.5% at Big Spring.

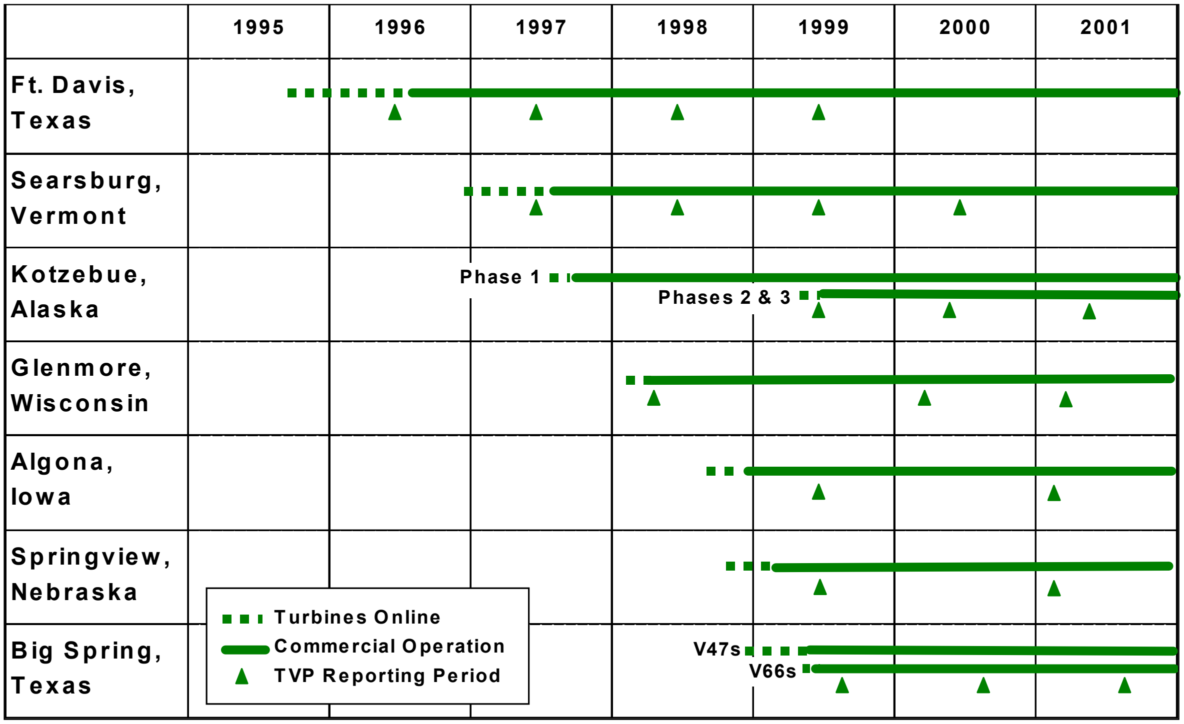

Figure 2. Timeline of TVP projects' installation, operation, and reporting periods

Figures 3 through 5 compare 1999 production to the long-term projection for each TVP project using three different performance measures. Although the Searsburg Z-40FS turbines produced the greatest surplus over the prediction, the Z-50s at Algona produced the highest output per turbine among all of the TVP projects during the 12-month period. A primary reason for lower than predicted production at Kotzebue, Glenmore, and Big Spring during 1999 was the substantially lower wind energy available compared to expectations based on long-term wind resource measurements. Lower than expected turbine availability also decreased production at Fort Davis, Glenmore, and Springview.

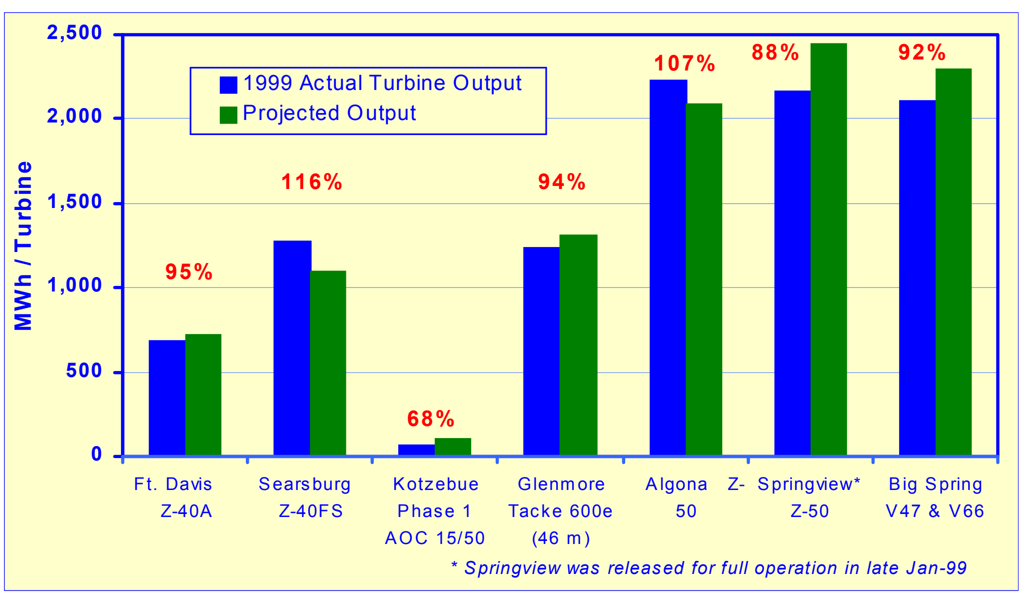

Figure 3. Long-term projected turbine output achieved in 1999

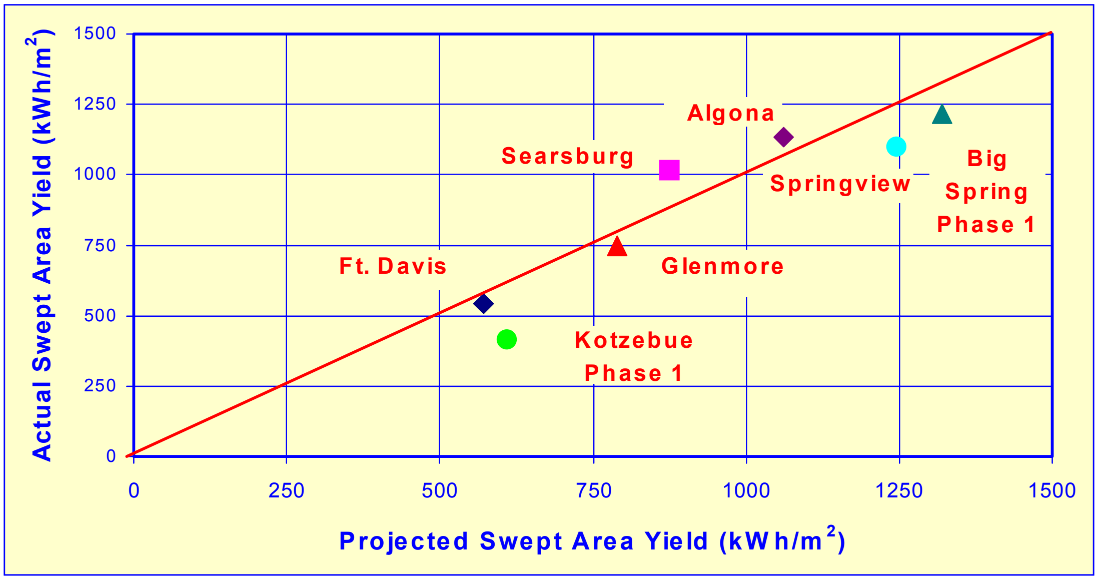

Figure 4. Long-term projected vs. 1999 specific yield

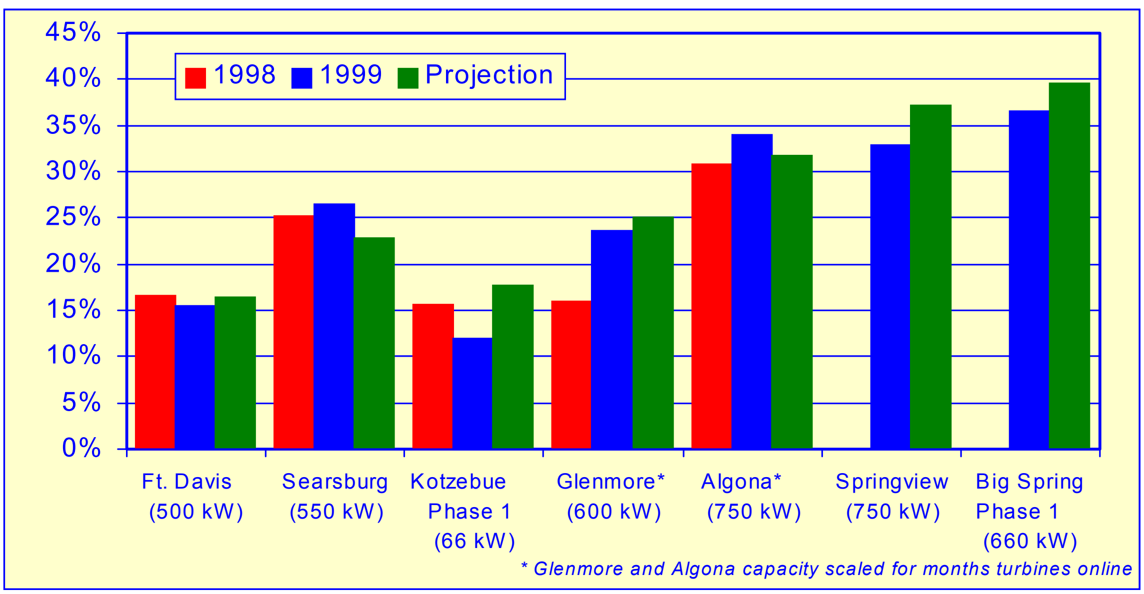

Figure 5. Long-term projected and 1999 actual capacity factors

The wide range of turbine and project sizes included in the TVP presents a challenge for meaningful comparisons on the same scale. Because the turbines' rotor diameters affect the total collection area and therefore the amount of wind energy available for capture, swept-area yield is considered a good way to compare performance between projects of different configurations. The diagonal line in Figure 4 shows where the actual 1999 swept yield is equal to the projection. Most projects were very close, and Vermont and Iowa surpassed the expectation. The variation between projects in specific yield is because some sites have higher average wind speeds than others. The wind resources at Kotzebue and Fort Davis are relatively low, whereas Springview and Big Spring have the most energetic wind resources in the TVP.

The V47 Phase 1 turbines at Big Spring achieved the highest swept-area yield during 1999, and the V66s are expected to achieve the highest swept-area yield over the long-term, based on their specific power rating of 0.48 kW/m^2.

Methods

As TVP's technical support contractor, GEC downloads, processes, and analyzes 10-minute turbine production and meteorological (met) data from Supervisory Control and Data Acquisition (SCADA) systems and other data loggers at each project. Wind direction and wind speeds are typically measured at two and three levels, respectively, with redundant anemometers at hub height. Because of the research nature of the program, the TVP projects are heavily instrumented relative to typical wind power projects of their size.

In cooperation with participating utilities, various energy projections were prepared and published for each TVP project during initial site evaluations and since installation. Significant uncertainty was associated with many of the original projections as they were based on limited wind resource data and early, theoretical power curves for the turbines. Now that substantial operational experience has been gained at most of the TVP projects, GEC has developed a set of new performance projections based on historical site atmospheric conditions, turbine performance data, O&M strategies, and more informed assumptions about energy losses. GEC utilized standard industry procedures to calculate long-term annual expected energy output in a consistent manner.

Figure 6 illustrates the major steps involved in determining net turbine and project energy. For this analysis, GEC used 1999 validated met data scaled to the sites' historical mean wind speed, when possible, compared to local long-term airport wind data. For all projects except Big Spring, GEC developed complete annual met data sets for 1999 following the guidelines developed by the National Renewable Energy Laboratory (NREL) for the Utility Wind Resource Assessment Program (UWRAP)[3] Met data processing methods included validation for sensor accuracy and icing and replacement of missing periods with redundant sensors, adjacent records, or the monthly diurnal average to develop complete annual data sets.

For Kotzebue and Springview, data were not available at hub height for much of the year, so concurrent monthly shear factors were applied to data collected at lower heights. Because the overall data recovery was high and because good relationships were found between the various sensors used at each project, the reconstructed wind speed data sets provide reasonably accurate representations of the wind characteristics at the sites during 1999.

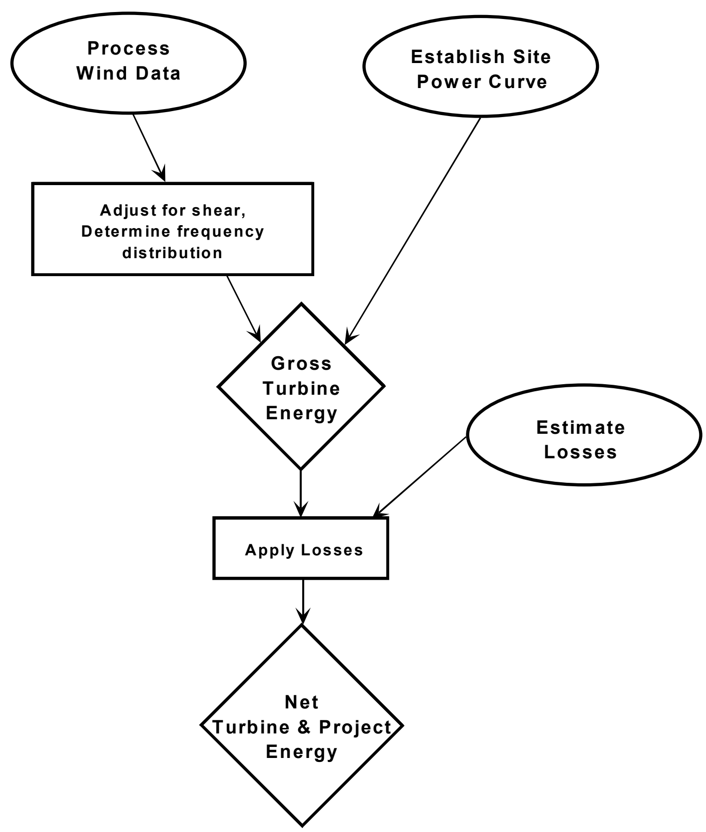

Figure 6. TVP Method for Calculating Performance Projections

Frequency distributions (the hours of occurrence at each wind speed) were calculated in 0.5 meter/second (m/s) bins for the 1999 and long-term scaled data sets. When possible, we used independently measured power curves were used and adjusted to the annual site density, which was determined by long-term annual site temperature and elevation. The frequency distribution (hours in each bin) was multiplied by the site power curve (kW in each bin) to calculate gross energy (kWh). Availability and other loss assumptions were multiplied to determine the cumulative estimated losses and then applied to the gross energy to calculate net turbine energy. Because TVP production is reported from measurements taken at the turbines, projections reported here do not include line losses within the array or to the substation. The predicted project net energy is simply the predicted net turbine energy multiplied by the number of turbines in each project.

GEC developed new loss assumptions for this analysis, shown in Figure 7, based on performance to date and each project's operational strategy. As the only commercially owned facility in the program, Big Spring is expected to have the highest turbine availability over the life of the project. Algona and Springview are also expected to have reliable turbine operation due to conscientious maintenance by the host utilities. Although though the Ft. Davis site operations have been diligent at repairing their turbines, greater availability losses are expected to continue there because of aileron design problems. The Glenmore turbines are a lower priority for the host utility and turbine vendor, which is substantial availability losses.

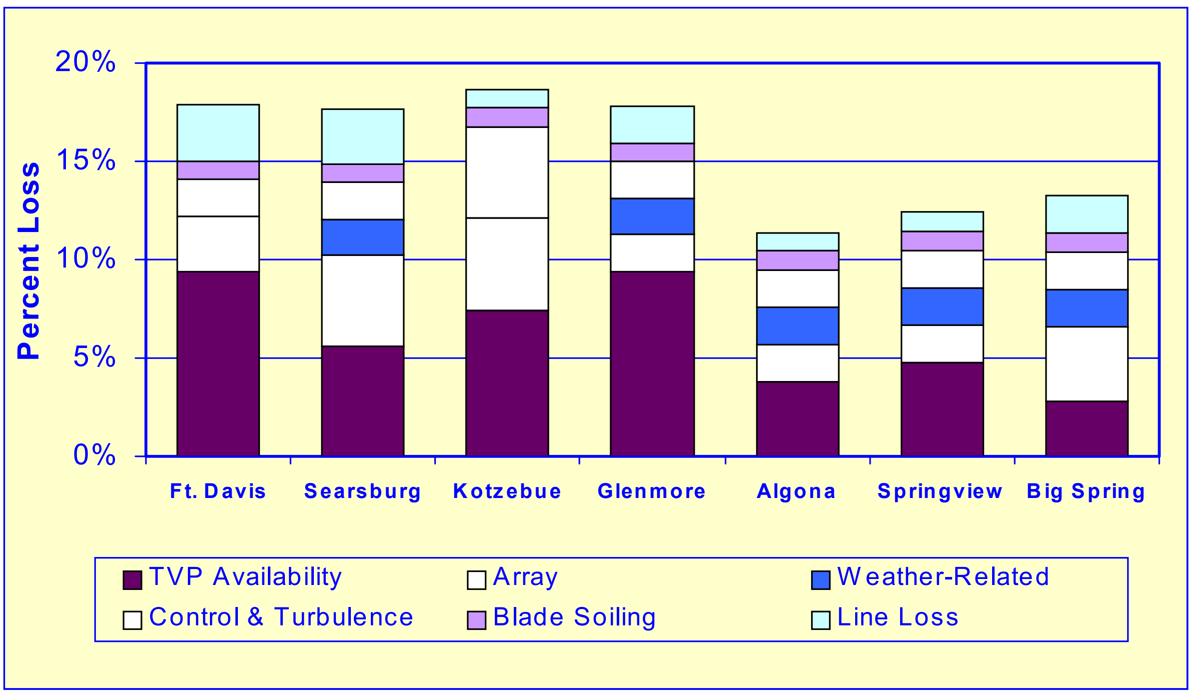

Figure 7. Current TVP loss assumptions

Array, weather-related, control and turbulence, and blade soiling losses were estimated based on turbine layout, design, and site considerations. Fort Davis experiences frequent lightning storms, but an effective mitigation approach has been developed so no additional significant lightning-related downtime is expected in the future. Although Kotzebue has the coldest climate, weather-related losses are not expected to be significant; as very little lightning or ice accumulation on the blades has been experienced. However, substantial continuing control-related losses are expected with the AOC 15/50 turbines at Kotzebue related to "slow start" difficulties coming online during winds just above the rated cut-in speed.

Line loss estimates were based on utility meter measurements for Fort Davis, Searsburg, Kotzebue, and Big Spring, and estimated based on interconnection configurations for Glenmore, Algona, and Springview.

The seven TVP projects came online over a four-year period, so the calendar years used for comparison reflect varied periods of operating experience. Kotzebue's Phases 2 and 3, Springview, and Big Spring turbineswere not fully commercial during all 12 months of 1999, so additional operational data will allow for a more complete performance analysis. Partial data for 1998 for Glenmore and Algona is included for comparison.

Sensitivity Analysis

Wind Resource

TVP evaluations are being conducted in a variety of terrain types including mountains, plains, desert, and coastal tundra; in atmospheric conditions ranging from arid to arctic; and in fairly low to relatively high wind resources. Figure 8 shows the 1998, 1999, and historic hub-height mean wind speed for the TVP sites, as well as historical mean wind speeds adjusted to 40 m (131 ft) for comparison of the sites' wind resources. Note that the average wind speed at the turbines may be different than at the projects' met towers, particularly at sites with complex terrain, such as Fort Davis, Searsburg, and Big Spring,and large numbers of turbines.

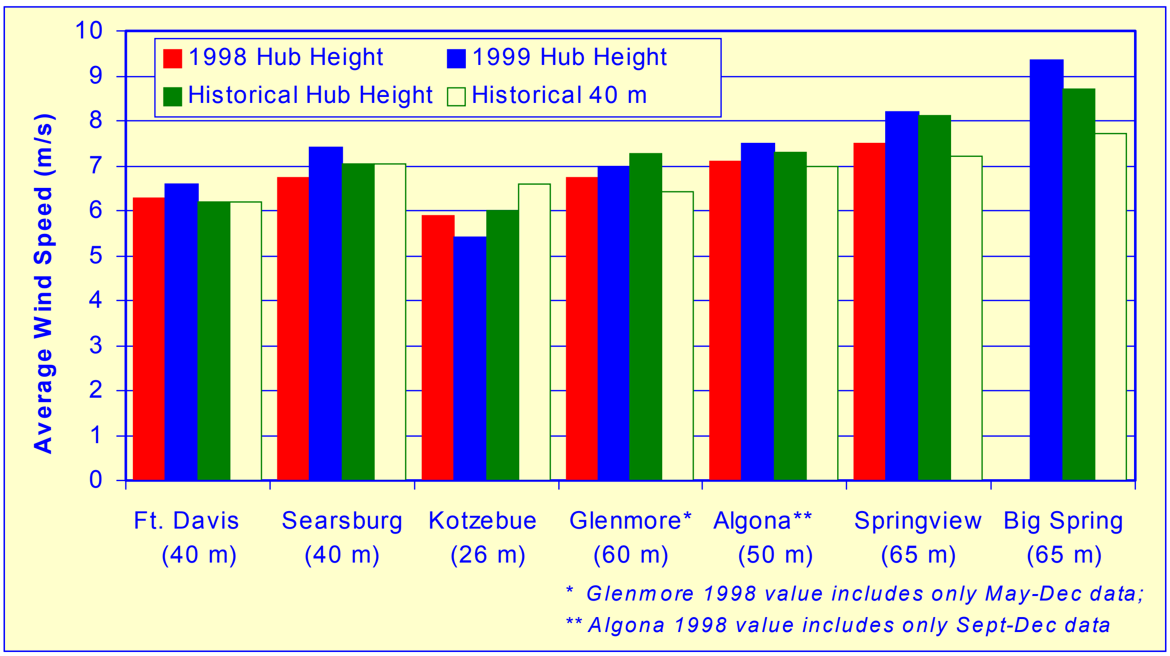

Figure 8. 1999 and Historical Wind Resources at TVP Sites

The 1999 average annual hub height wind speeds ranged from 5.4 m/s (12.1 mph) at Kotzebue to 8.2 m/s (18.3 mph) at Springview. All of the projects except Fort Davis experienced below-average mean wind speeds during 1998, and Kotzebue was the only site with lower winds in 1999 than in 1998. The annual average wind speed at Glenmore was also slightly lower than its long-term estimate, but the 1999 averages at Fort Davis, Searsburg, Algona, Springview, and Big Spring were higher than the expected long-term averages. Fort Davis has the lowest historical average wind speed at 40 m, but Kotzebue has the lowest historical wind speed at hub height (26.5 m). Big Spring has the highest long-term average wind speed, both at 40 m and hub height.

With the 1999 average wind speed 10% below the historical value, Kotzebue experienced the greatest deviation from its expected long-term average. As shown in Figure 9, significantly fewer hours in the high-wind-speed bins resulted in 27% less energy available during 1999 than the historical average.

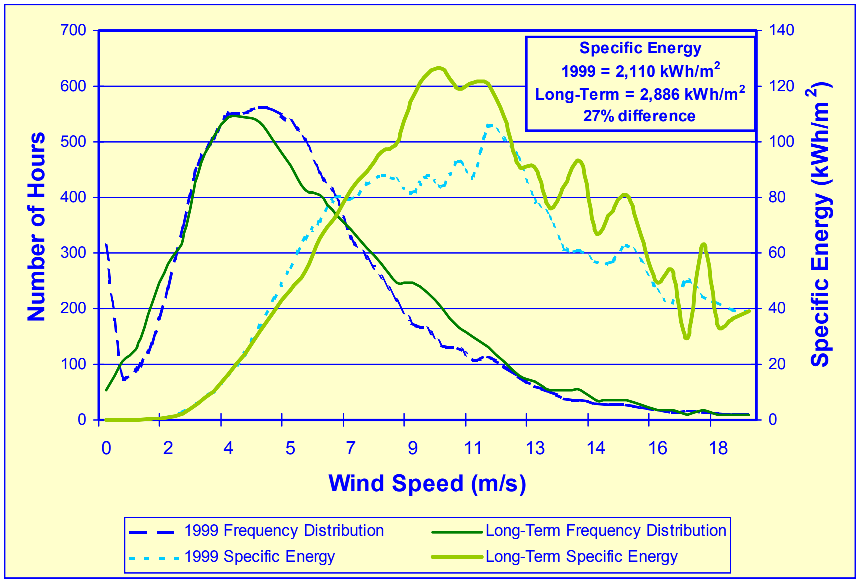

Figure 9. Kotzebue 1999 and long-term wind resource

Power Curve

Turbine power performance has a considerable impact on production. The warranted and measured power curves for Glenmore are shown in Figure 10. Typically, the warranted curve is conservative, resulting in low estimates, but the Tacke 600e measured curve was significantly lower than warranted as the result of blade modifications to reduce vibrations. Unfortunately, the part of the power curve most affected is in the highest frequency wind-speed bins, which causes nearly a 9% energy loss.

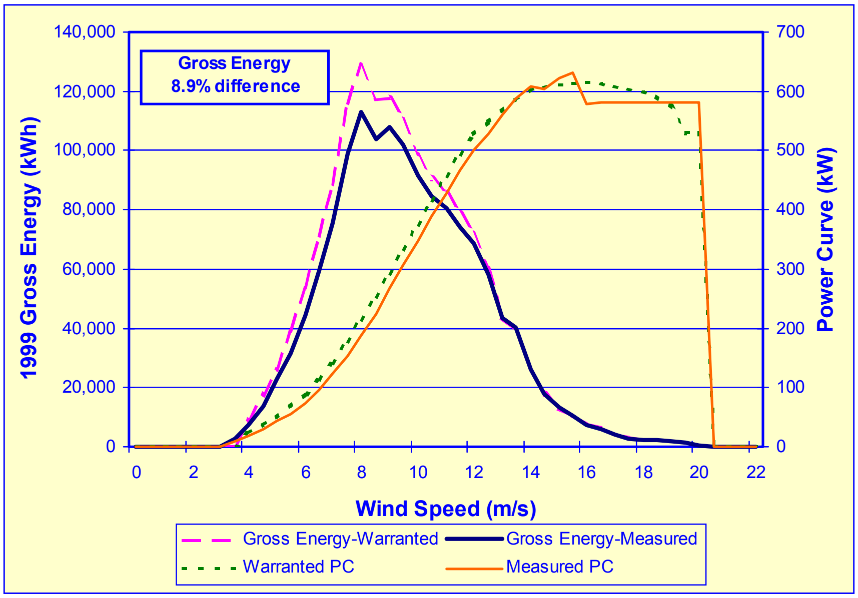

Figure 10. Glenmore measured and warranted power

Availability

To ensure consistency throughout the program, the TVP definition of availability takes into account all downtime experienced by the individual wind turbines in a project and divides the available hours by the total hours in the period. This is a conservative approach, which generally results in greater stated downtime compared to other methods.

Figure 11 summarizes the 1998 and 1999 TVP availability by project and compares the results to long-term estimates. The 1999 calculated TVP project availability ranged from 82.8% at Fort Davis to 96.5% at Big Spring, although data was only available for Big Spring starting in September. In general, the availability was lower during the summer partly due to retrofit work and scheduled maintenance. At the Fort Davis project, aileron failures, inspections, and repairs have caused significant amounts of downtime since the project began operation. Enron is no longer offering turbine models with ailerons, primarily due to the experience gained through this project. Response time to faults has affected availability at Glenmore, and lightning damage to the rotor was a major cause of 1999 downtime at Springview. Availability has improved for the projects online during 1998, and additional improvements are expected. GEC estimated the average long-term TVP availability shown in Figure 11 based on the projects' performance to date and expected future performance based on each project's O&M approach.

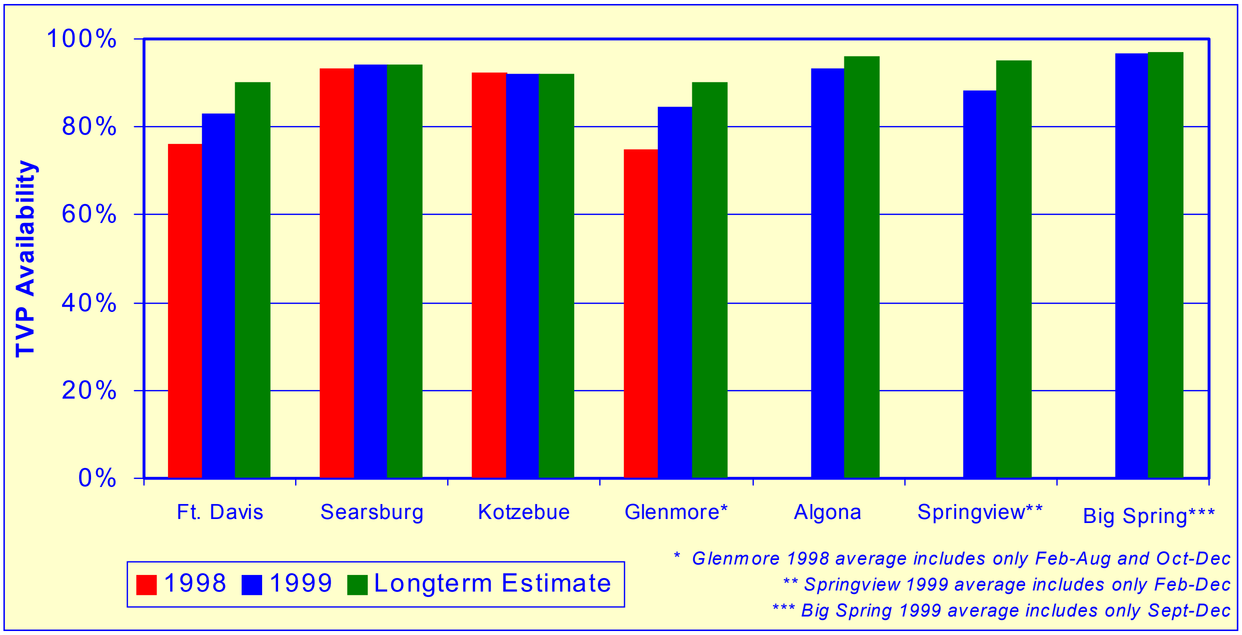

Figure 11. Actual and estimated long-term TVP availability

Other Loss Assumptions

Table 1 shows an analysis of 1999 actual losses compared to assumptions based on the projects' 1999 wind speed frequency distributions and actual availability, as well as the change in the net energy projection from previous estimates. The gross energy predicted for 1999 (A) was calculated based on the 1999 wind-speed frequency distribution and the measured or estimated turbine power curve, and then adjusted with the 1999 actual availability loss (B). The result (C) was compared to the actual 1999 production (D) to estimate the other cumulative losses that were experienced during 1999 (E).

Compared to the current assumptions of other losses (F) described above, Searsburg, Glenmore, and Algona experienced lower than expected array, weather-related, control, turbulence, and/or blade soiling losses; Kotzebue, Springview, and Big Spring experienced more of these losses than expected in the long-term. The change in net energy from previously published projections (G) developed prior to the projects' installation and operating experience are also shown for comparison. Based on this analysis and on additional information on site wind resources and turbine power curves, TVP's current net energy projections are slightly higher than previous estimates for all projects except Kotzebue.

Table 1. Loss Assumptions and Energy Projections

	Ft. Davis	Searsburg	Kotzebue Phase 1	Glenmore	Algona	Springview	Big Spring	
A. 1999 Gross Predicted Energy (MWh/turbine)	965	1,450	98	1,422	2,474	2,858	2,551	6,377
B. 1999 Actual Availability Loss	17%	6%	8%	16%	7%	13%	3%	6%
C. 1999 Predicted Energy Adjusted for Availability (MWh/turbine)	798	1,366	90	1,199	2,302	2,488	2,469	5,994
D. 1999 Actual Production (MWh/turbine)	742	1,276	70	1,239	2,229	2,163	1,924	4,318
E. 1999 Actual Other Losses (C minus D ÷ A)	6%	6%	21%	-3%	3%	11%	21%	26%
F. Current Assumption of Other Losses	6%	10%	11%	7%	7%	7%	9%	9%
G. Change from Previous Energy Estimates	7%	2%	-10%	4%	10%	8%	n/a	n/a

Lessons Learned

Although the facilities utilize pre-commercial and newly commercial machines, their performance is generally on a par with industry expectations worldwide. Significant progress has been made on many of the start-up challenges, and the projects are expected to continue to perform well in the future. The variation in wind speed, including wind shear and the shape of the wind frequency distribution, has the greatest effect on project production; the turbine power curves and availability are also important factors.

The original estimates for Kotzebue and Glenmore were high due to low loss assumptions and high power curves, and the original TVP loss assumptions appear to have been overstated for Algona. This evaluation is a work-in-progress, and additional data will be examined next year. Quarterly Stats Pages are published in the TVP News Bulletin, which are posted on EPRI's website and can be found through the publications link at www.globalenergyconcepts.com.

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[1] Based on dates turbines came on-line during 1999.

[2] Includes Phase 1 turbines only for Kotzebue, February–December 1999 only for Springview, and September–December 1999 only for Big Spring.

[3] Because the Big Spring project is a commercial venture and additional wind projects will likely be developed in the vicinity, detailed historical met data were not made available to the TVP. The project's overall expected energy included in this paper was determined by York Research Corporation, the project's developer and owner.