REGULATION REQUIREMENTS FOR WIND GENERATION FACILITIES

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Analytical Approach

This paper documents an evaluation of power system regulation impacts related to multi-turbine wind generation facilities.[1] As a result of varying wind conditions, wind facilities generate varying amounts of electricity. From a grid operations perspective, other generation resources must offset an unanticipated change in output. The purpose of the study was to quantify the amount of regulation services that would be typically required to support a wind generation facility on a grid system.

Data was collected from the Lake Benton II wind facility in Minnesota on a 1-second interval basis. For ORNL analysis needs, NREL supplied the data to ORNL on an averaged 30-second interval basis. Included in the data provided were a time-stamp, wind speed, and power output levels from four separate interconnection points, labeled in this report as A, B, C, and D. As shown below, each interconnection point has a different number of wind machines connected to it.

Interconnect Point	**A**	**B**	**C**	**D**
Number of wind generators	30	39	14	55
Nameplate capacity rating, MWe	22.5	29.25	10.5	41.25

For purposes of evaluating system regulation impacts, a data analysis frequency of two minutes was selected.[2] This rate was felt to be appropriate as the output levels of generating units assigned to regulation service typically respond at about this rate. This data rate is obtained by averaging four 30-second data points for each 2-minute data point for all the power and wind data.

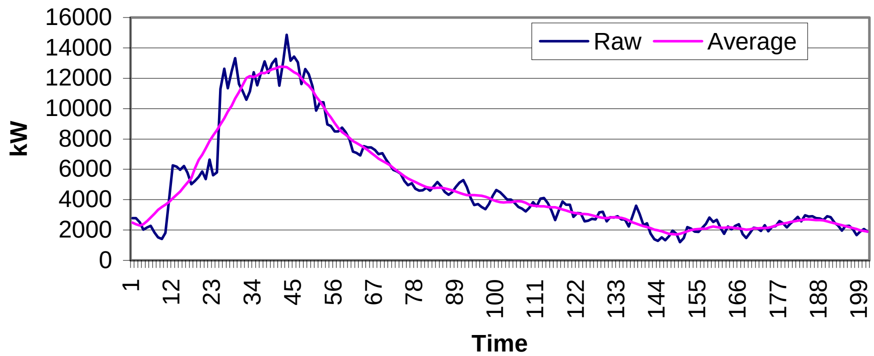
The raw data exhibits a great deal of variability. One of the challenges of this analysis was to allocate this variability to the various dispatch levels typically found in a multi-unit grid system (e.g. base load, intermediate (load following), rapid response (regulation)). An analytical procedure that is useful in this allocation process is the moving average. In this procedure, the moving average serves to segregate the raw data such that a portion of the output variation is allocated to regulation and the remainder, as determined by the average values, is assumed to be related to slower response services (i.e., load following). The selection of a width of the moving average (i.e., the number of data points included in the average) is somewhat arbitrary. However, as discussed in a prior ORNL report (ORNL/CON-474), the choice of width influences the

[1] Work sponsored by the Office of Power Technologies within the Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy.

[2] The selection of a 2-minute frequency is the result of prior research by Kirby and Hirst. *Customer-Specific Metrics for the Regulation and Load-Following Ancillary Services,* Brendan Kirby and Eric Hirst, ORNL/CON-474, January 2000.

allocation fractions. This is apparent when one considers the limiting case of a one-point average. As the resulting average, which in this case is equal to the raw data, is intended to represent services other than regulation (e.g., load following), all variability is therefore assigned to something other than regulation. As one chooses wider moving averages (i.e., more data points in the average), more of the raw variability is allocated to regulation. In this analysis, a 30-minute moving average has been utilized. In a 30-minute moving average, data that fall within a 15-minute window on either side of the time point of interest are averaged and associated with that central data point. This averaging "moves" from point to point in the data set to create a smoothed set of data that tracks the general rise and fall of output from the facility with an average ramp rate, in this case, of less than 1 MW/minute. Subtracting this average from the raw data for each time point produces the regulation portion of the total output variation. A plot of an example portion of the data is shown below to illustrate the averaging technique.

Figure 1. Example Wind Output Data



Description of Typical Analysis Outputs

Wind facility data has been analyzed on a month-to-month basis[3]. Once a data set of regulation-related values for a given month was generated, various statistical processes were used to characterize the regulation requirements of the facility. One of the first observations was that the regulation data conformed to a normal (Gaussian) distribution[4]. Figure 2 shows the high degree of symmetry around the mean for a typical selection of the regulation data. Statistical characterization of the data was developed for each month, as shown in Table 1 for the month of June 2000. Of particular interest is the fact that the mean regulation requirement is essentially zero. This is expected, given the averaging technique employed to create the regulation data. Operationally, this implies that regulation energy requirements net to zero over the long run. What must be provided, therefore, is capacity that can support short-term output swings.

[3] An evaluation of typical behavior of the wind facility on an hourly basis is provided in a later section of the report.

[4] Treating regulation as a statistical function is consistent with utility grid operations in which demand and generation variations at this frequency (i.e., 2-minute periods) are assessed on a statistical basis (i.e., there is not a market clearing and individual accounting for variations at this short frequency).

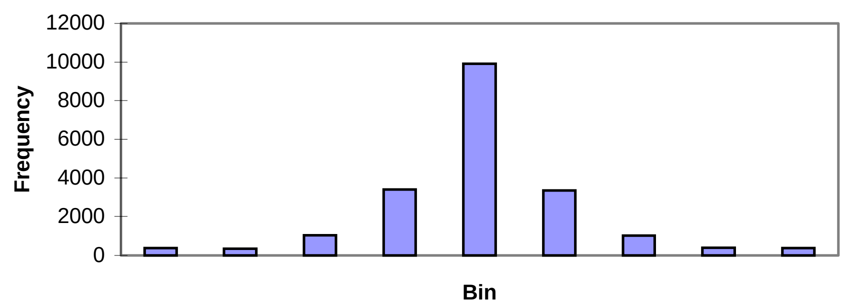


Table 1. Statistical Analysis Results for June 2000

	A	*B*	*C*	*D*	*Total*
No of machines	30	39	14	55	138
Mean	0.3	0.1	-0.1	0.6	0.9
Standard Error	5.4	5.9	2.6	6.9	13.9
Median	-0.9	-2.2	-1.2	-1.7	-8.2
Mode	0.0	0.0	0.0	0.0	0.0
Standard Deviation	763.4	842.9	372.3	985.3	1975.4
Sample Variance	582839.5	710407.9	138611.5	970823.2	3902177.2
Kurtosis	15.7	16.1	10.6	21.0	19.5
Skewness	-0.1	0.0	0.2	-0.6	-0.5
Range	18847.6	18667.9	6804.4	26658.3	49141.5
Minimum	-9991.0	-9906.4	-3204.3	-16688.4	-27840.2
Maximum	8856.6	8761.5	3600.1	9969.9	21301.3
Sum	6321.1	2176.6	-2515.4	13072.2	19052.7
Count	20222	20222	20222	20222	20222

The amount of capacity needed to support the regulation behavior of the wind facility can be determined by the standard deviation of the data. Given its Gaussian nature, 99% of the output variation can be described by 3 times the standard deviation (i.e., 3-sigma). For this paper, we are assuming that the regulation requirement is defined as the variation contained within 3 standard deviations of the regulation data. Statistically, less than one-half of one percent of the variations would fall outside such a definition. Using the data from the four interconnects and the total of the facility, plots of regulation capacity needs versus rated generation capacity were constructed, as shown in Figure 3 for the month of June 2000. Another means of displaying the regulation requirements is on a percent of rated capacity basis, which is shown in Figure 4.

As shown in Figure 4, the relative amount of regulation support required decreases as the number of wind machines included in the sample increases. This is not unexpected. Similar behavior was found in an earlier study of German wind facilities[5]. When wind turbines are scattered in a large area, not all turbines will encounter the same wind speed at the same time, and as a result, power output at each turbine varies. The result of connecting many turbines at independently

[5] Bernhard Ernst, *Analysis of Wind Power Ancillary Services Characteristics with German 250-MW Wind Data*, NREL/TP-500-26969, November, 1999.

fluctuating power levels is that the variation of combined output is less than the variation of any equivalent single turbine. The 138 turbines at Lake Benton II are arranged along a northwest to southeast diagonal line about 17 km (10.6 miles) long. As the operation of the turbines is not synchronized, their outputs do not rise and fall at the same time. When a wind gust sweeps through the site, it reaches some turbines sooner than others.

Figure 3. Regulation Requirements - June 2000

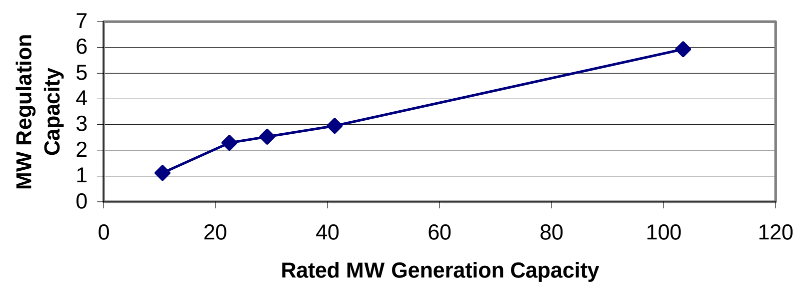
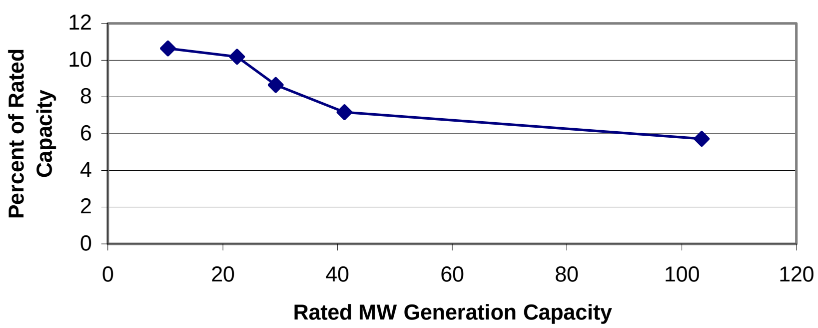
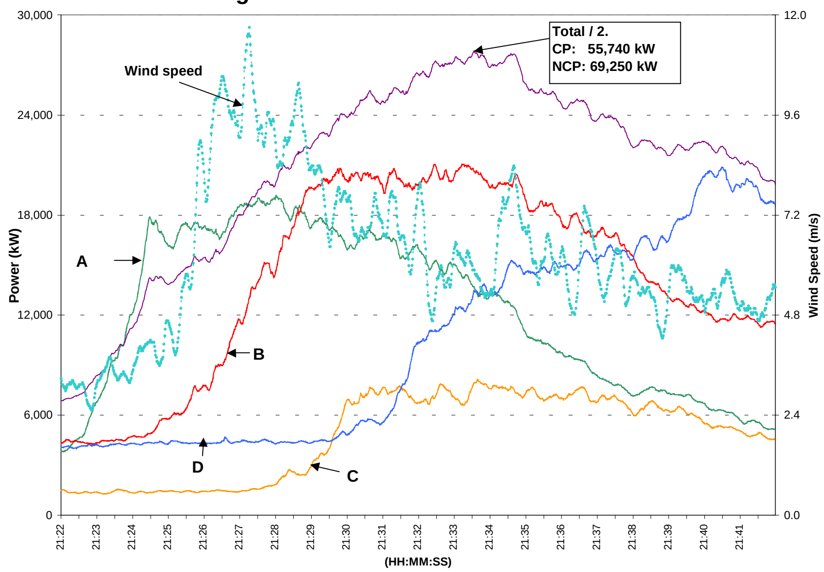


Figure 4. Percentage Regulation Requirements - June 2000



A simple example of this effect is given in Figure 5, which shows the details of a gust and power surge in a 20-minute window for a summer day in 2000 plotted with 1-second power data from the four interconnection points and their sum. The graph shows that although the outputs from all four grid-interconnection points generally follow the wind speed, they are not locked in exact step. The effect of wind turbine separation is clearly seen. Power at the interconnection point **A** rises first, followed by **B**, **C**, and then **D** interconnection. The entire plant reaches a peak output of 55.74 MW at 21:33:33, although output power from **D** interconnection point does not reach its peak until about 7 minutes later at 21:40:29. The peak gust recorded at interconnection point **B** is about 11 m/sec during this period. The peak at interconnection **D** occurs about 16 minutes later than **A**'s first peak. This sequential timing corresponds well with the straight-line distance of 10.8 km between the **A** and **D** interconnection points. The noncoincidental peak during this 20-minute period (the sum of the four individual peaks in the period) is 69.25 MW (if the same gust would have hit all turbines at the same instant). However, the turbines are scattered, and it takes time for the gust to sweep through them. When power from the last group of turbines (**D** interconnection point) begins to rise, power from the first group of turbines (**A** interconnection point) has already begun to drop. As a result, the coincidental peak during this 20-minute period is only 55.74 MW.

Figure 5. Local Peak Power Details



As a result, the turbines are neither totally independent nor totally synchronized with wind behavior. An indication of the degree of interdependence of the wind generators can be obtained by evaluating the covariance or correlation of the regulation requirements of each of the interconnections to each other. As shown in Table 2, there is a positive correlation among each of the interconnections, which therefore increases the resulting total variance and its related regulation requirement.

Table 2. Correlation Coefficients for Interconnection Points – June 2000

	A	*B*	*C*	*D*
A	1			
B	0.384	1		
C	0.135	0.472	1	
D	0.061	0.195	0.297	1

Summary of Results by Month

The primary measure of regulation impact in this study is the standard deviation of the regulation data. Table 3 provides a summary of the standard deviation of the regulation data on a monthly basis for each interconnection point and the total facility. Also included is the standard deviation of the short-term (2-minute) wind variations, which will be discussed below.

Table 3. Standard Deviation of Regulation Data (kilowatts)

Month	**A**	**B**	**C**	**D**	**Total**	**Wind (m/sec)**
March 2000	562.3	634.3	353.8	770.3	1432.8	0.4950
April 2000	728.7	825.1	425.4	1010.3	1915.8	0.5846
May 2000	671.1	860.6	472.3	955.3	1735.6	0.6036
June 2000	763.4	842.9	372.3	985.3	1975.4	0.5874
July 2000	499.5	588.2	252.2	721.6	1398.0	0.4613
August 2000	523.8	643.1	288.0	784.2	1443.5	0.4267
September 2000	642.9	832.2	336.4	940.1	1692.2	0.4552
October 2000	558.7	776.3	306.9	812.5	1527.0	0.4039
November 2000	486.6	699.8	293.9	770.2	1482.1	0.4515
December 2000	531.9	703.6	286.0	774.0	1529.9	0.4858
January 2001	543.3	763.8	261.0	746.8	1612.9	0.3907

Based on the standard deviations shown in Table 3, regulation requirements for a stand-alone wind facility, expressed as a percent of nameplate capacity, were developed and are presented in Table 4 in order of ascending capacity. As discussed in the prior section, the requirement is based on a 3-sigma deviation width, which would encompass 99% of the regulation variability. It is worth noting that corresponding stand-alone regulation requirements for typical steel mill operations is on the order of 20 percent of their peak load.

Table 4. Stand-Alone Regulation Requirements (% of nameplate capacity)

Month	**C** (10.5 MW)	**A** (22.5 MW)	**B** (29.25 MW)	**D** (41.25 MW)	**Total** (103.5 MW)
March 2000	10.1	7.5	6.5	5.6	4.2
April 2000	12.2	9.7	8.5	7.3	5.6
May 2000	13.5	8.9	8.8	6.9	5.0
June 2000	10.6	10.2	8.6	7.2	5.7
July 2000	7.2	6.7	6.0	5.2	4.1
August 2000	8.2	7.0	6.6	5.7	4.2
September 2000	9.6	8.6	8.5	6.8	4.9
October 2000	8.8	7.4	8.0	5.9	4.4
November 2000	8.4	6.5	7.2	5.6	4.3
December 2000	8.2	7.1	7.2	5.6	4.4
January 2001	7.5	7.2	7.8	5.4	4.7
Average	9.5	7.9	7.6	6.1	4.7

As shown in Table 4, the regulation requirements vary from month-to-month within a fairly narrow band. One possible explanation of the cause of this variability could be a similar variability pattern with respect to wind speed. Using the standard deviation of the wind speed given in Table 3, the correlation of regulation requirements to wind variability was examined. As shown in Table 5, a high correlation was found between wind variability and power output variability (as represented by the wind facility regulation requirements). Consistent with this correlation is the higher variability in wind speed during the spring season and the corresponding higher regulation requirements during that period, as shown in Tables 3 and 4.

Table 5. Correlation Of Wind Variation With Regulation Requirements

Interconnect	**A**	**B**	**C**	**D**	**Total**
Correlation Coefficient	.857	.790	.490	.765	.710

Hourly Analysis

Electricity consumption and prices vary dramatically throughout the day. Energy markets typically clear hourly. Ancillary service requirements for individual customers and for the power system as a whole vary hourly as well. To facilitate integration of wind into electricity and ancillary service markets, it is useful to examine how regulation requirements and energy production vary over time frames that are shorter than a month.

As expected, there is considerable range to both energy production and regulation. Figure 6 provides a view of three days where it can be seen that the regulation requirement and energy production requirements are related but not completely coincident. The relationship between energy production and regulation requirement is further explored in Figure 7 where the regulation requirement is plotted against the energy production for all 744 hours in the month. This plot shows significant scatter. Fitting a curve to the data does show some pattern, however. As might be expected the regulation requirement tends to be slightly higher in the middle of the energy production range than it is at either very low or full production. This might be expected because there is very little output variability when the wind is not blowing. Similarly, once the wind machine has reached full output, it can not produce more output even if the wind increases. So the regulation requirement tends to be highest at mid-energy production.

Figure 6. Three Days of Hourly Energy and Regulation
January 2001

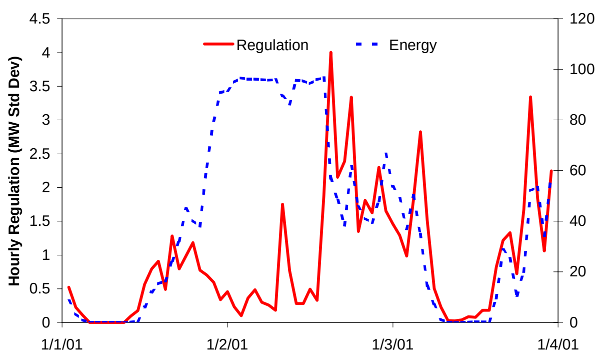
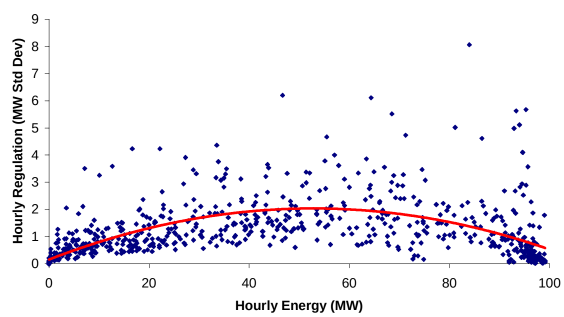


Figure 7. Regulation and Energy Correlation
January 2001



It is also instructive to examine how persistent the regulation requirement is. Figure 8 presents a regulation duration curve. It shows that regulation requirements are high for a relatively short amount of time. Contrast the wind regulation duration curve with Figure 9, which presents similar curves for a steel mill, a set of nonindustrial loads, and an entire utility. The steel mill and the other conventional loads present regulation burdens that are much more uniform; they are constantly requiring compensation by regulating generators. Wind plant regulation requirements appear to be more sporadic.

Figure 8. Energy & Regulation Duration
January 2001

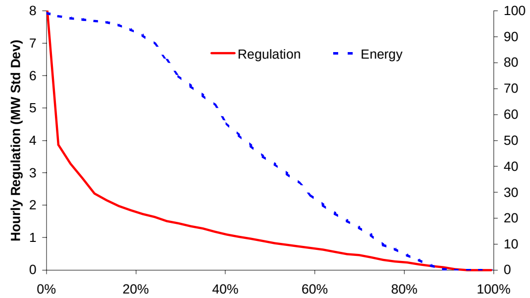
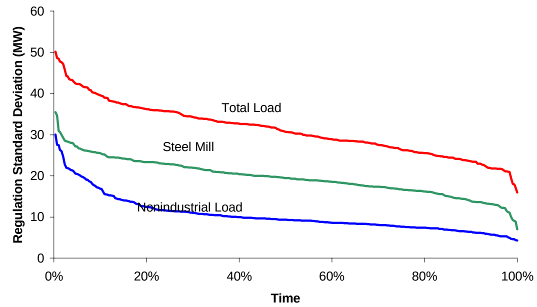


Figure 9. Load Regulation Requirement



Impact of the Utility Grid on Wind Regulation Requirements

It is important to note that the discussion to this point has evaluated wind output variability and its regulation requirement in isolation (i.e., as though there were no other sources of variation on a utility grid). Of course, regulation requirements have their origins in load variation. This section will consider wind facilities and their regulation requirements when included as part of a utility grid where regulation needs due to load variations are present.

It was stated earlier that for variables that are statistically independent, the standard deviation of the combination of the variables is the square root of the sum of the squares of the individual deviations. It is certainly reasonable to assume that the short-term variability of wind output is independent of the short-term variability in the overall consumption of electricity (i.e., demand or load) on a utility grid. Therefore, the regulation requirement for a system that includes a regulation requirement for load and a separate requirement due to wind generation can be expressed as the square root of the sum of the squares of the individual deviations[6]. An equivalent statement is that the total variance is equal to the sum of the individual variances. Mathematically,

$$\sigma^2_{\text{Total}} = \sigma^2_{\text{load}} + \sigma^2_{\text{wind}}$$

The relative contribution of each source term to the total is defined by the ratio of contributing variance to total variance, such that

Wind regulation requirement = wind contribution fraction x total regulation requirement

$$\text{Wind regulation requirement} = [\sigma^2_{\text{wind}}/\sigma^2_{\text{Total}}] \times 3\sigma_{\text{Total}} = 3\sigma^2_{\text{wind}}/\sigma_{\text{Total}},$$

where the regulation requirement is defined here as three times the standard deviation.

[6] Allocating system regulation requirements when the individual variances are statistically *dependent* is more difficult, but a method for doing so has been developed by ORNL. *Customer-Specific Metrics for the Regulation and Load-Following Ancillary Services*, Brendan Kirby and Eric Hirst, ORNL/CON-474, January 2000.

Of interest here are the relative sizes of the contributing variances. If the load variability is very large relative to the wind variability, the fraction of the total variability related to the wind becomes small. As an example consider a utility with a peak load of 2,300 MW, a load variance of 1000.3 MW^2, and a corresponding standard deviation of 31.6 MW. Using data from Table 3, a 100 MW wind facility has a standard deviation of 1.5 MW and a variance of 2.25 MW^2. The total variance of the combination of the load and wind facility is 1002.55 MW^2. The standard deviation of the total is 31.7 MW. Using the formula given above, the regulation requirement due to the wind facility variation is 3 x 2.25 / 31.7 MW or 213 kW. In contrast, the stand-alone regulation requirement for a 100 MW wind facility is 4.7 MW, as shown in Table 4.

As an integrated part of a utility grid, the portion of the system-wide regulation requirement related to the operation of a wind facility (i.e., the contribution of the wind facility to the total regulation requirement) will be determined by the relative magnitudes of the wind facility short-term variance and the existing grid short-term variance (excluding the wind facility impacts).

Cost to Provide Regulation Service

As stated earlier, the net energy flow for regulation over a sufficient period of time (e.g., hours) is zero. Therefore, the primary support requirement is to have capacity available that can compensate for the short-term variations of the aggregated system (loads, conventional generators, and wind plants). Regulation service is generally provided by generation units that can respond quickly. The cost to provide regulation service for a wind facility will depend upon whether the service is being provided under a regulated or deregulated market.

For a regulated market, a first-order approach to the cost of regulation support can be determined by the cost of the capacity needed to support the wind facility's share of the system's regulation requirements (since energy nets to zero). The *stand-alone* regulation requirements for the wind facility (with no grid integration), expressed as a percentage of nameplate capacity, were given in Table 4. Assuming a 4.7 percent requirement for a 100 MW wind facility, the necessary capacity would be 4.7 MW. Using a gas-turbine plant as an example "capacity resource", a new gas-turbine capital cost is approximately $350/kWe. The equivalent cost for 4.7 MW of gas-turbine capacity would be $1.645 million.[7] Relative to the nameplate capacity of the wind facility, the regulation requirement would be $1.645 million per 100 MW or $16.45/kW of wind capacity. For planning and evaluation in a regulated environment, this cost could be assumed to be an added component of the initial capital cost of a proposed wind facility. The regulation cost can also be expressed on a per unit of output energy basis (i.e., $/MWh). Assuming a 20 percent fixed charge rate[8] and a 30 percent average annual capacity factor for a wind facility, the corresponding cost for regulation on an energy basis would be $1.25/MWh.

However, as shown in the previous section, when a wind facility is integrated into a grid system, the resulting fractional contribution to total system regulation requirements is a function of the

[7] Even in the regulated environment the capital cost of the unit providing regulation is only part of the total cost. Since the regulating unit has to be on-line and partly loaded to provide regulation any fuel cost differential (gas vs. coal for example) for the regulating unit is attributable to regulation, for example. Still, the capital cost is often the major component and provides a good first estimate.

[8] A fixed charge rate amortizes a capital investment over the number of years used for economic recovery. In this case, a 20 percent fixed charge rate is consistent with a 10-year capital cost recovery and a 10 percent real cost of money.

size of the grid system relative to the wind facility capacity. Using the utility example given earlier, which has a peak load of 2,300 MW, the wind-related regulation requirement is only 213 kW for a 100 MW wind facility. This would result in a regulation burden of less than $1 per kW of wind nameplate capacity. On a corresponding energy basis, as discussed in the previous paragraph, the cost for regulation when integrated into a grid system would be less than $0.06/MWh of wind generation.

In a deregulated environment, the unit cost of providing regulation service will most likely be determined by hourly auctions in the marketplace (i.e.,$/MW-H). The price of this service will likely vary on an hourly basis and will depend upon the supply and demand for regulation itself. But the price also depends upon the opportunity costs that result from the regulating generator's lost opportunities to sell energy and other ancillary services. As a result, the cost of providing regulation service for a given hour would be the product of the unit price for that hour times the system-integrated amount of regulation capacity needed during that hour. Defining the contractual amount of regulation to be purchased by (or allocated to) each source of regulation burden is subject to interpretation and transaction rules that have yet to be developed. However, one method to determine a regulation allocation would be to use the standard deviation of the 30 two-minute regulation values that comprise a given hour. If the regulation requirements for both the wind facility and all other regulation sources (e.g., short-term load fluctuations) are individually known, then the proportion of the total regulation requirements related to the wind facility can be determined using a vector-allocation method described in Kirby-Hirst (2000)[9]. The wind facility would then pay for its proportional contribution to the hourly system regulation cost. If load variation is considered to be independent of wind generation variation, the regulation burden due to wind can be expressed as $\sigma^2_{wind}/\sigma^2_{Total}$. In the case of the utility example used earlier in the paper, the proportion of the system regulation requirements due to wind would be 2.25/1002.55 or 0.22 percent.

Summary

This paper has evaluated the operational impacts that a wind generation facility may have on the regulation requirements of an electric utility grid system. An analysis of data from a 100 MW wind facility has shown that the regulation burden on a percentage basis is inversely proportional to the size of the wind facility (i.e., number of machines). When integrated into a utility grid, the regulation burden due to the wind facility is influenced by the relative magnitude of the pre-existing variation (e.g., regulation burden due to loads). In cases where the variation of the wind facility output is small relative to the pre-existing grid load variation, the regulation impact of the wind facility will be quite small.

[9] Brendan Kirby and Eric Hirst, *Customer-specific Metrics for the Regulation and Load-Following Ancillary Services*, ORNL/CON-474, January 2000.