Long-Term Wind Power Variability

Y.H. Wan

NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Technical Report
NREL/TP-5500-53637
January 2012

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NATIONAL RENEWABLE ENERGY LABORATORY

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1 Introduction

The National Renewable Energy Laboratory started collecting wind power data from large commercial wind power plants (WPPs) in southwest Minnesota with dedicated dataloggers and communication links in the spring of 2000. Over the years, additional WPPs in other areas were added to and removed from the data collection effort. The longest data stream of actual wind plant output is more than 10 years.

The resulting data have been used to analyze wind power fluctuations, frequency distribution of changes, the effects of spatial diversity, and wind power ancillary services [1–6]. This report uses the multi-year wind power data to examine long-term and shorter-term wind power variability, and provide an overview of the results.

2 Data Sources

Output data from four WPPs are used in this report because the data quality is better for longer periods at these locations. Data from other sites have larger gaps (more missing data) or are available only for shorter time periods. Table 1 lists the name, location, plant capacity and data available period for each of the four WPPs.

Table 1. Locations, Capacities and Available Data of WPPs

WPP Name	Location	Plant Capacity	Data Available
Lake Benton (LB)	Minnesota	104 MW	2000-2010
Storm Lake (SL)	Iowa	113 MW	2001-2010
Blue Canyon (BC)	Oklahoma	75 MW	2003-2010
Trent Mesa (TM)	Texas	150 MW	2004-2010

All data except for Blue Canyon are in 1-second time series. Blue Canyon data are in 1-minute time series [7]. The hourly data are derived from the raw 1-second and 1-minute data streams by averaging them over 3600 seconds or 60 minutes. All four original data streams contain gaps ranging in length from a few minutes to several days because of equipment failures and interruptions in communication links. In addition, the data show that sometimes the outputs from the WPPs would change abruptly (in one or two seconds) or within a very short period (within one minute). These changes were large in magnitude—greater than 15% of the WPP's nameplate capacity. Such a sudden change could be the result of forced outages within or without the WPP (equipment failures or the transmission line outages) and curtailment operations. Because we do not have corresponding wind speed information or operations records of the WPP, it is not possible to identify the causes of these sudden changes in plant output and separate them from changes caused by naturally occurring wind speed changes. No modifications were attempted to the data when the sudden changes occurred. However, when calculating the statistics of wind power step changes (the differences from one hour to the next), only continuous data points (i.e., consecutive data points with continuous time stamps) were included, so that all changes in power level due to data gaps were excluded from the calculation.

3 Inter-Annual Variability of Wind Power

Wind speed fluctuates continuously, and as a result, the power from a wind turbine or plant varies. Short-term fluctuations in wind power are stochastic in nature, but distinctive patterns exist for longer-term fluctuations. For this report, short-term wind power variations mean fluctuations of average wind power from one hour to the next. Longer-term variations of wind power mean changes in daily, seasonally, and yearly WPP productions. Short-term wind speed changes with duration from several seconds to several minutes, such as turbulence and gusts, will manifest as the ramping of turbine or plant output power in varying degrees. Longer-term changes in the underlying wind conditions will result in inter-annual, seasonal, monthly, and diurnal variations of output power levels. For example, the meteorological inter-annual oscillations such as El Niño/La Niña Southern Oscillations could contribute to the wind power inter-annual variations observed in the available data during the 2000-2010 period. This report only focused on the available wind power data itself. Future efforts will link the wind power data to other meteorological and weather data sets and analyze in more detail the correlation between WPP production and meteorological inter-annual oscillations or other quasiperiodic climate patterns.

Figure 1 shows yearly production at Lake Benton from 2000 to 2010. The actual outputs are normalized to the average value of this period.[1] The annual production at this plant ranges from a low of 82% of the average to a high of 113% of the average. The inter-annual variation is relatively large; the highest production year produced 38% more energy than the lowest production year during this period. Outputs from this WPP do not seem to show a periodic pattern. This could be because there were not enough data to establish a definitive pattern or long-term trend.

[1] The actual production values of these WPPs are not used to protect the business-sensitive information of the plant owners.

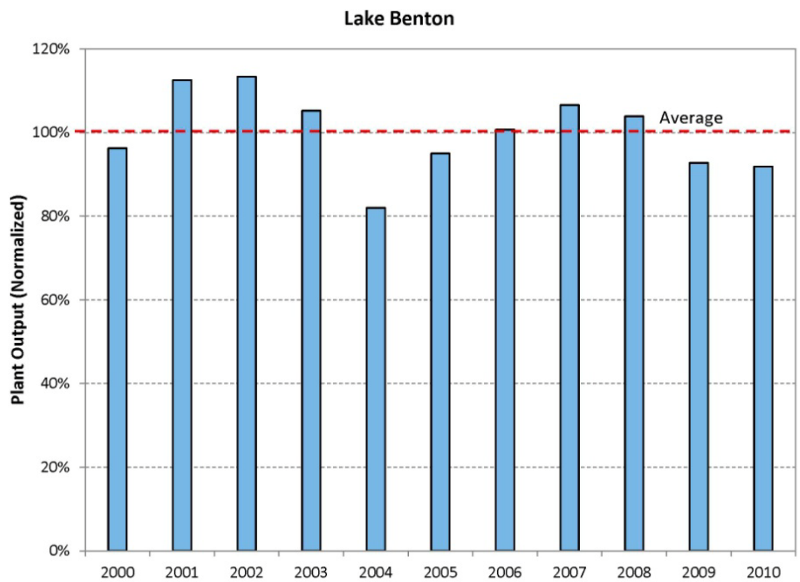

Figure 1. Inter-annual variation of wind energy from Lake Benton

Figure 2 plots normalized annual production of the four WPPs. Because of the plant size differences, the annual production values are normalized to the respective sites' nameplate capacities for easier comparison.

Traces in Figure 2 again suggest that inter-annual variations of wind energy production can be significant. Despite the fact that wind energy production can be relatively high at one plant but relatively low at others in the same year, some features can still be identified. For example, geographic locations can be detected from these annual output traces. The traces of Blue Canyon and Trent Mesa bear some resemblance to each other because these two WPPs are relatively close to one another. Traces of Lake Benton and Storm Lake have similar shapes for the same reason.

Although there are no common features or patterns in the annual wind energy production plots over the period when data were available, there are slight differences in the individual plant behaviors. Trent Mesa, with a standard deviation value of 13% of its 8-year average (2003–2008), had the most inter-annual variation among the four WPPs. During this period, the highest-production year produced 47% more energy than the lowest-production year. Blue Canyon, with a standard deviation value of 8% of its 7-year average, had the least inter-annual variation. The highest production year produced 29% more energy than the lowest production year at Blue Canyon. However, by and large, these four WPPs experienced similar inter-annual variations in annual energy production.

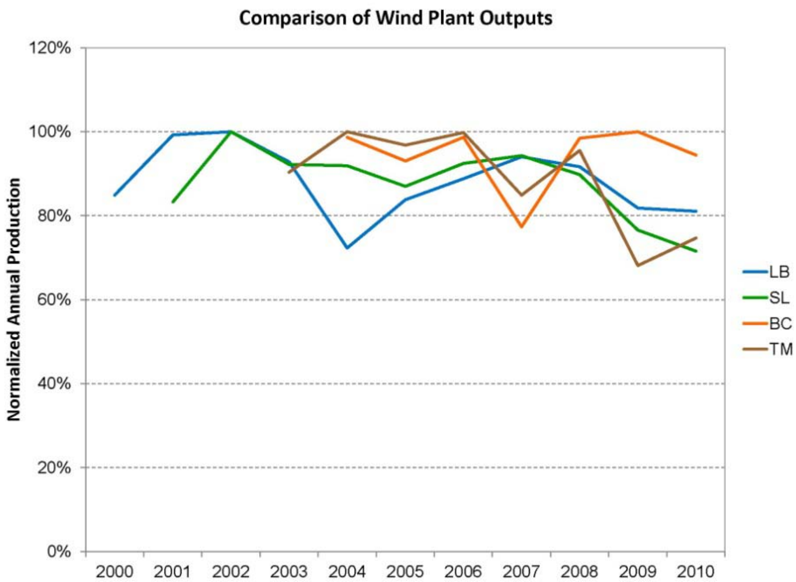

Figure 2. Normalized annual outputs from four WPPs

4 Monthly Variability of Wind Energy

The monthly production at these four plants shows readily discernible patterns during the 11-year period. Figure 3 shows monthly wind energy production at Lake Benton from 2000 to 2010 and significant monthly variations in wind power. The production from the highest month was more than three times more than the production from the lowest month. Even in the same year, the production of the highest month could be almost three times more than the production of the lowest month. For the same month, the changes from one year to the next could also be significant. For example, production during February 2002 was more than twice the production during February 2010.

However, the most distinctive feature of Figure 3 is the consistent low production (dip in the traces) during the summer months of June, July, and August at this location. Average wind production during spring and winter months was fairly constant through the years. During summer months, the production was only about 64% of that of the winter months, on average. Although production during summer months was much lower than during the spring and winter months, production variations (differences between the highest and the lowest) for summer months are generally smaller (i.e., they are more constant). In fact, low production during summer months generally held true for other WPPs in the middle part of the continental United States. Figures 4, 5, and 6 show the monthly wind energy productions from Storm Lake, Blue Canyon, and Trent Mesa. It is obvious they are all subject to similar weather patterns. February and May are the two months with the most variability in wind energy production.

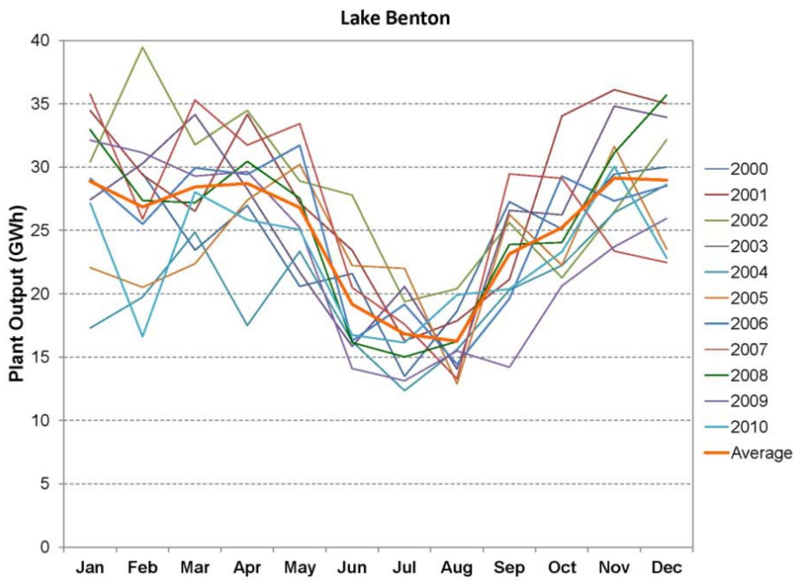

Figure 3. Monthly wind energy production from Lake Benton

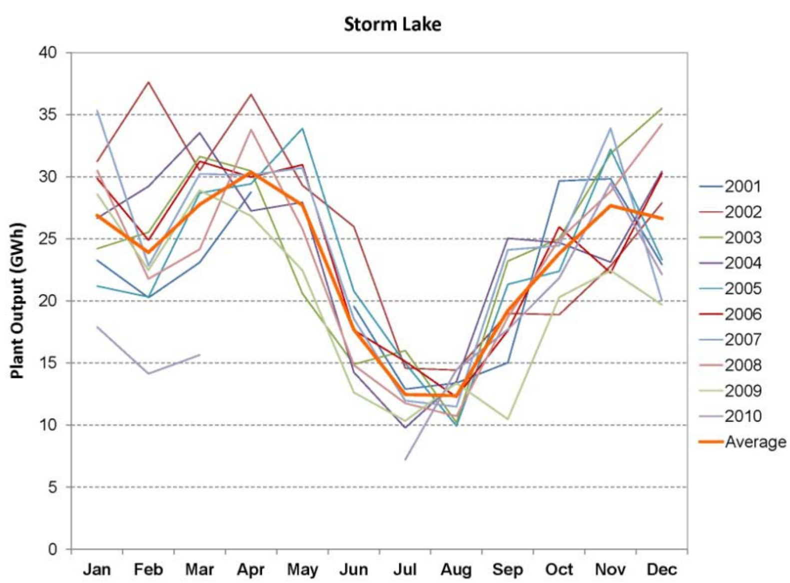

Figure 4. Storm Lake monthly production

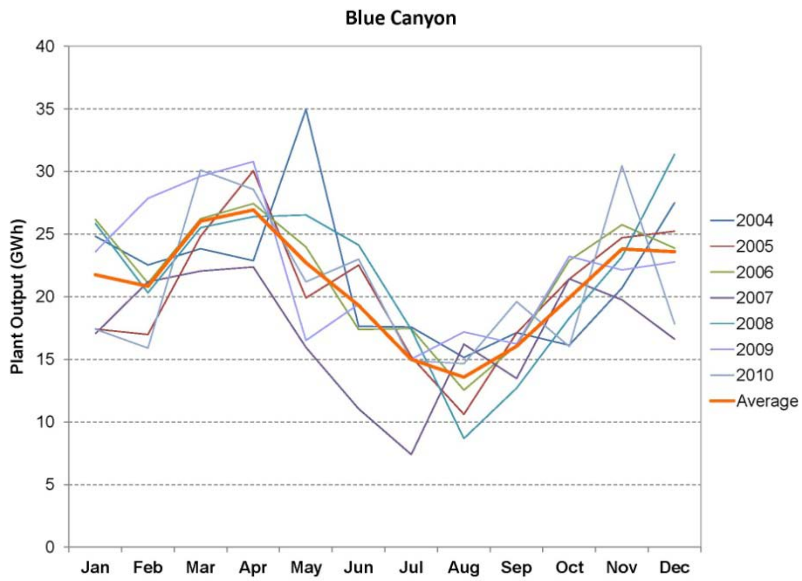

Figure 5. Blue Canyon monthly production

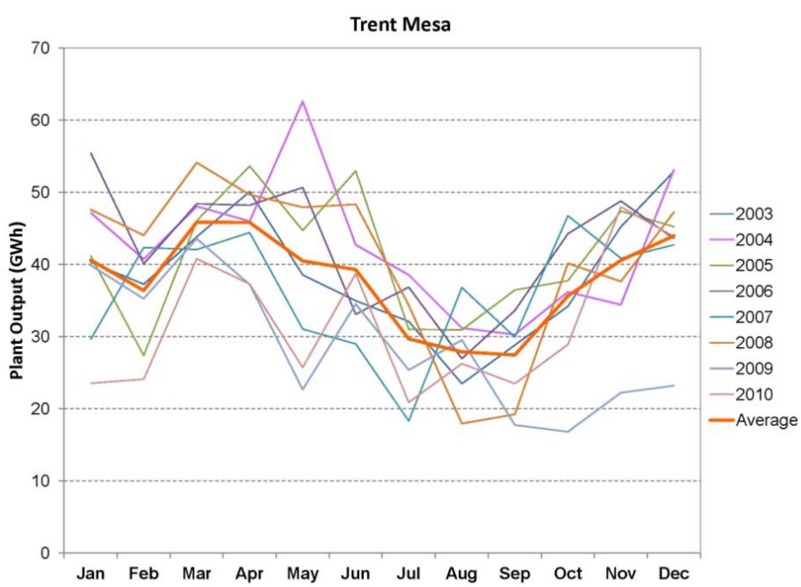

Figure 6. Trent Mesa monthly production

Figures 7, 8, 9, and 10 show hourly average wind power by month from Lake Benton, Storm Lake, Blue Canyon, and Trent Mesa during 2004. Similar plots for other years are in appendices A, B, C, and D. The purpose of these plots is to see if there is a common diurnal pattern throughout the year. Figures 7 through 10 and similar plots of other years reveal that, on a 24-hour cycle, average wind power will dip during early evening hours (6:00 to 7:00 p.m.), especially during summer months. This low will be more prominent the further south the wind plant is located. At Lake Benton, the average hourly wind power over the entire year (the thick red trace in Figure 7) shows a relative high point in early morning (5:00 a.m.) and a relative low point in early evening (6:00 p.m.). However, this pattern does not exist in every month. Individual monthly traces of hourly average wind power at Storm Lake also do not have a consistent pattern throughout the year. On average, Storm Lake wind power is slightly higher during early morning hours. During the early summer months of May and June, the pattern even reverses itself (higher wind power around midday).

The diurnal pattern becomes much clearer at WPPs located farther south. Wind power from Blue Canyon and Trent Mesa—two WPPs more than 1,100 km and 1,300 km to the south—exhibit distinctive diurnal patterns for every month of the year. The additional profiles of other years in appendices A, B, C, and D show that the diurnal patterns of individual WPPs are very consistent throughout the years.

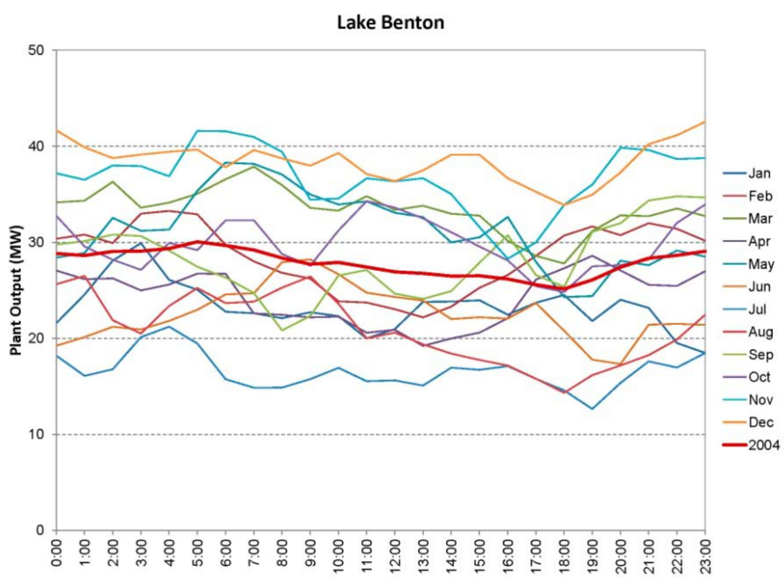

Figure 7. 2004 average hourly wind power profiles by month from Lake Benton

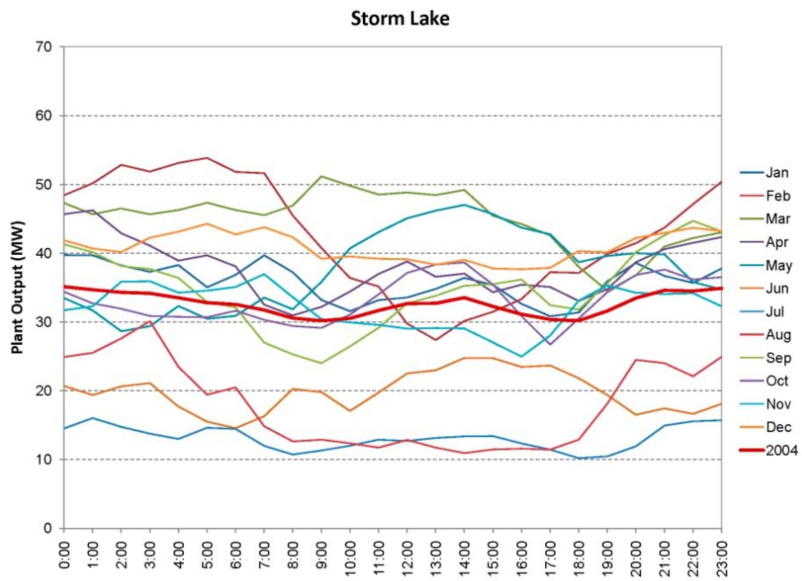

Figure 8. 2004 average hourly wind power profiles by month from Storm Lake

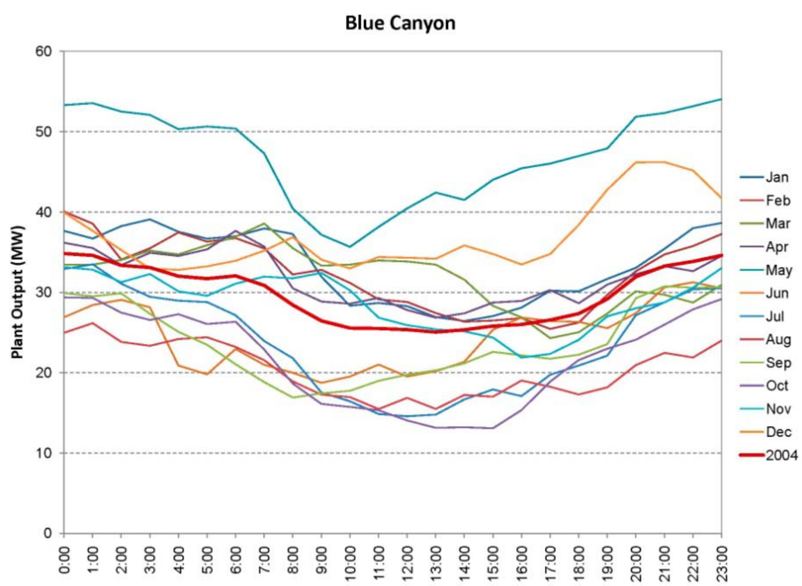

Figure 9. 2004 average hourly wind power profiles by month from Blue Canyon

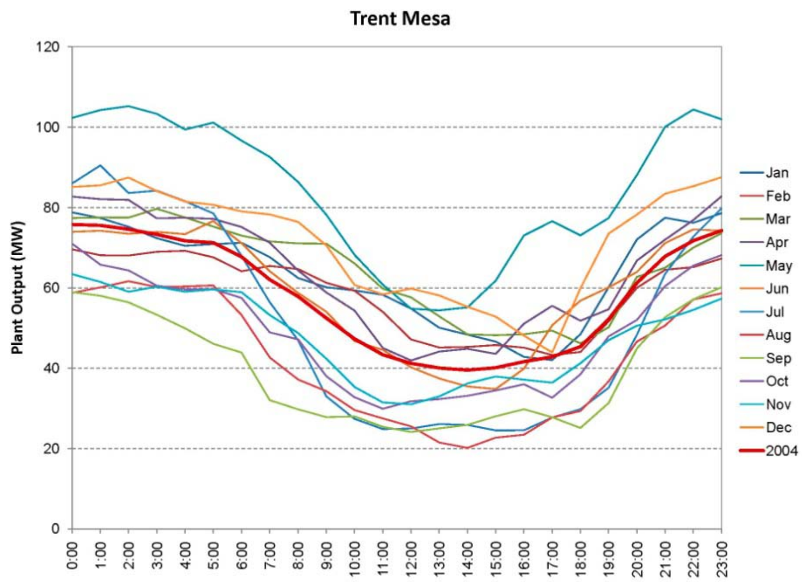

Figure 10. 2004 average hourly wind power profiles by month from Trent Mesa

5 Shorter-Term Variations

Wind production at these four WPPs has shown significant inter-annual variation and distinguished seasonal and diurnal patterns, but the shorter-term behavior of wind power was fairly consistent. One way to gauge short-term wind variability is to compare the coefficients of variation (COV) of wind power. COV is defined as the ratio of standard deviation value to the mean (average) value. If wind speeds were used, the resulting COV is referred to as turbulence intensity, and it is a measure of wind turbulence. Turbulence intensities are directly related to the surface roughness of the ground (i.e. grassland, forest, urban, etc.) and the atmospheric stability [8]. Turbulence intensity generally increases with increased surface roughness, as the wind advects horizontally along the surface. Furthermore, turbulence can be generated through vertical advection (i.e. convection) in a stable or unstable atmosphere. Additionally, turbulence intensity generally decreases with height within the atmospheric boundary layer, due to the reduced influence of surface roughness.

Table 2 lists yearly COV calculated with daily wind production over the entire year of these four WPPs.

Table 2. Yearly COV Values Based on Daily Wind Energy Productions[a]

	LB	SL	BC	TM
2000	0.7			
2001	0.7	0.7		
2002	0.6	0.7		
2003	0.7	0.7		0.6
2004	0.6	0.7	0.7	0.6
2005	0.7	0.7	0.7	0.6
2006	0.7	0.7	0.6	0.6
2007	0.7	0.7	0.8	0.7
2008	0.7	0.7	0.6	0.6
2009	0.8	0.8	0.6	0.7
2010	0.8	0.8	0.7	0.7

[a] Blanks in the table indicate missing data.

Table 3 lists yearly COV calculated with hourly average wind power over the entire year of these four WPPs.

Table 3. Yearly COV Values of Hourly Wind Power

	LB	SL	BC	TM
2000	0.9			
2001	0.8	0.9		
2002	0.8	0.9		
2003	0.8	0.9		0.8
2004	0.9	0.9	0.8	0.8
2005	0.9	0.9	0.9	0.8
2006	0.9	0.9	0.8	0.8
2007	0.9	0.9	1.0	1.0
2008	0.9	0.9	0.8	0.9
2009	0.9	1.0	0.8	1.0
2010	1.0	1.0	0.9	0.9

The COV values in the tables are higher than the typical turbulence intensity values of wind speed [9]. Wind power data were used in the calculation and the available wind power is proportional to wind speed cubed [10]. Values in Table 3 are higher than values in Table 1 because hourly wind power will show more variability than daily energy (8,760 data points compared with 365 data points). The shorter-term variability of the outputs from these four WPPs is consistent throughout the years, as indicated by the near-constant yearly COV values. The higher values of a particular year are generally correlated to low energy production of that year (Figure 2). Lower production implies lower mean wind speed for the year and thus relatively higher variability.

Table 4 lists monthly COV values calculated with the average hourly wind power of Lake Benton. Figure 11 is a plot of the values in Table 4. Similar tables of COV values for other WPPs are in appendix E. At finer resolution, the seasonal variability of wind power begins to appear. Again, higher COV values are associated with lower wind energy production months. The traces in Figure 11 are almost the reverse of Figure 3, which shows monthly productions at Lake Benton. However, Figure 11 shows that the yearly patterns are still fairly consistent.

Table 4. Hourly Wind Power Variability by Month at Lake Benton

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Jan		0.8	0.8	0.8	0.8	1.0	0.8	0.7	0.8	0.7	0.9
Feb	0.7	0.7	0.6	0.7	0.7	0.9	0.7	0.8	0.9	0.7	1.1
Mar	1.0	0.8	0.8	0.7	0.8	0.8	0.8	0.7	0.9	0.9	0.9
Apr	0.8	0.7	0.7	0.8	1.0	0.7	0.8	0.7	0.7	0.7	0.9
May	0.9	0.8	0.8	1.0	0.8	0.7	0.7	0.7	0.8	0.9	0.9
Jun	0.8	0.9	0.8	1.1	0.9	0.9	1.1	0.9	1.1	1.0	1.0
Jul	1.2	1.1	0.9	0.9	1.1	0.9	1.0	1.0	1.2	1.2	1.3
Aug	0.9	0.9	0.9	1.1	0.9	1.0	1.1	1.2	1.1	1.0	1.1
Sep	0.8	1.0	0.8	0.7	0.9	0.8	1.0	0.7	0.9	1.2	0.9
Oct	0.9	0.7	1.0	0.8	0.8	0.9	0.8	0.8	0.9	1.0	1.0
Nov	0.8	0.7	0.8	0.6	0.7	0.7	0.8	0.9	0.8	0.9	0.8
Dec	0.8	0.7	0.7	0.6	0.7	0.9	0.8	1.0	0.6	0.8	0.9

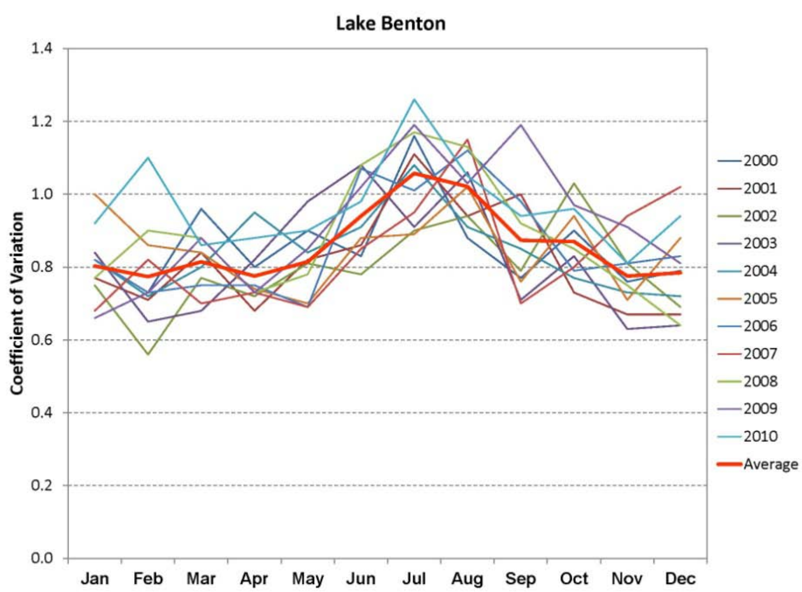

Figure 11. Monthly COV of wind power at Lake Benton

Short-term fluctuations of wind power can also be examined with the statistics of step changes (the differences of wind power levels from successive measurements). The hourly average power outputs of these four WPPs were used to calculate the step changes and their standard deviations for each month and for the entire year. Table 5 shows the yearly standard deviations of the hourly step changes. The actual values were normalized to the nameplate capacity of the respective WPPs to eliminate the size bias and enable easy comparison.

Table 5. Standard Deviation of Hourly Power Level Changes (Normalized to Plant Nameplate Capacity)

	LB	SL	BC	TM
2000	0.08			
2001	0.07	0.06		
2002	0.07	0.07		
2003	0.07	0.07		0.08
2004	0.07	0.07	0.08	0.08
2005	0.07	0.07	0.08	0.08
2006	0.07	0.07	0.08	0.08
2007	0.07	0.06	0.07	0.08
2008	0.07	0.06	0.08	0.09
2009	0.07	0.06	0.08	0.08
2010	0.07	0.06	0.07	0.08

The values in Table 5 indicate that the characteristics of short-term wind power fluctuations do not change much. The climate pattern may change from one year to the next, which will result in mean wind speeds being high or low and thus change wind energy production, but the nature of wind as seen from the point of short-term variations (fluctuations) remains the same.

6 Summary and Conclusions

The wind power data from WPPs in different parts of the country suggest that one can expect relatively large inter-annual changes. The climate and regional weather pattern are the driving forces behind wind and wind plant outputs. Changes in climate and weather patterns will be reflected in the longer-term performance of WPPs. In this respect, wind power is similar to hydropower, especially run-of-the-river type, in that there are high energy production (wet) years and low energy production (dry) years. The available data show that during the highest production year, total wind energy from the same WPP can be almost 40% higher than the annual production of the lowest production year. The available data do not appear to be enough to establish a long-term pattern or trend.

However, shorter-term variations of wind power appear to be less than longer-term variations. The data show that distinctive seasonal and diurnal patterns are persistent over the years independent of the overall annual wind energy production.

For even shorter-term variations, such as power level from one hour to the next, changes of wind power levels become a stochastic process with a very narrow range of standard deviation values around its respective mean. The magnitudes of these mean and standard deviation values are functions of the size of the WPP. Larger WPPs obviously have bigger changes, but the relationship with size is not linear [3] because the spatial diversity of wind speeds within a large WPP will reduce the variability of the plant output relative to a single wind turbine or a small WPP with fewer wind turbines. However, when those mean and standard deviation values are expressed in terms of the installed capacity of the WPPs, they are almost constant on an annual basis (as shown in Table 4). It can be concluded that short-term wind power fluctuations do not exhibit year-to-year variability.

7 References

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Appendix A: Average Hourly Wind Power Profile of Lake Benton

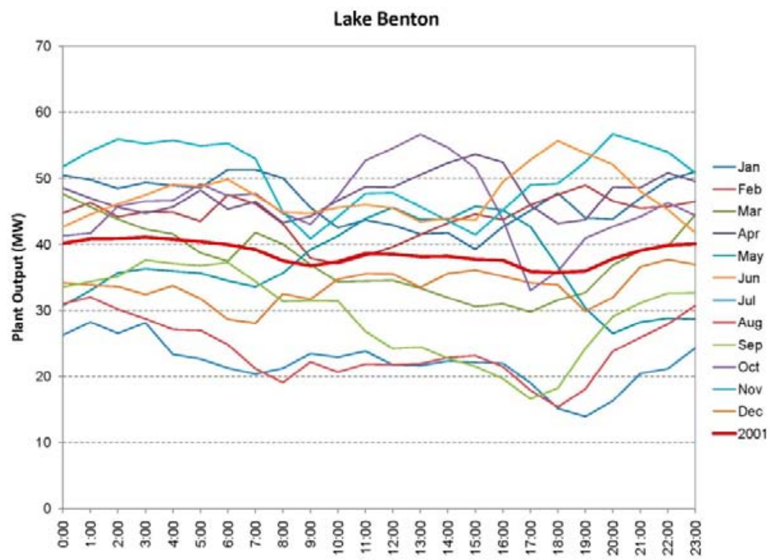

Figure A-1. 2001 average hourly wind power profiles by month from Lake Benton

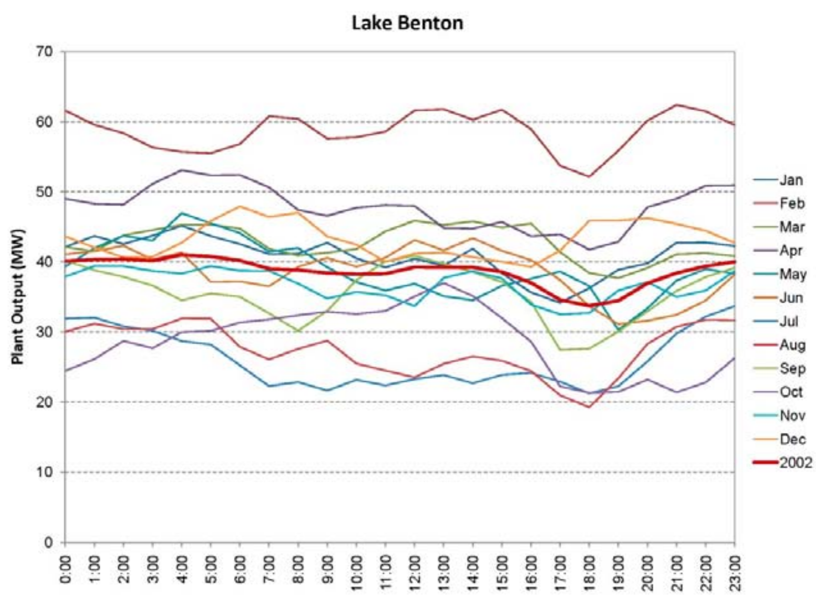

Figure A-2. 2002 average hourly wind power profiles by month from Lake Benton

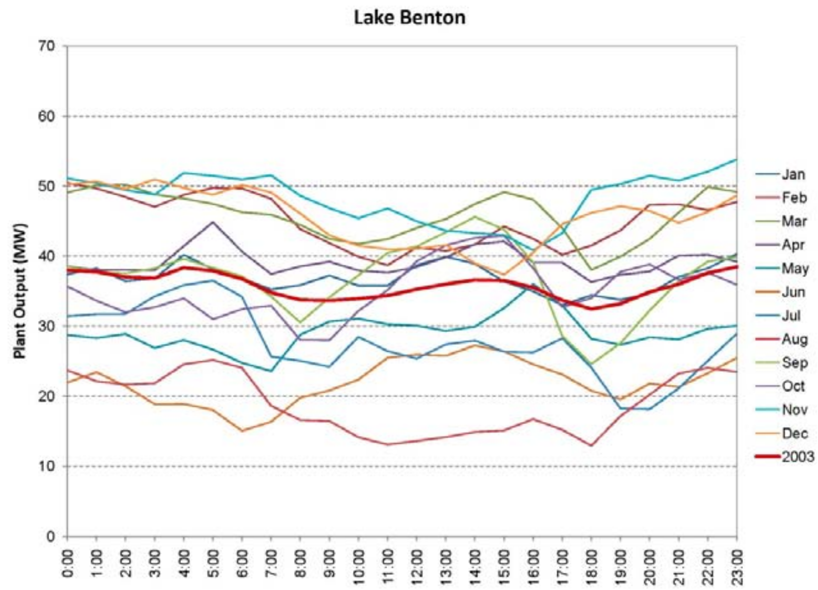

Figure A-3. 2003 average hourly wind power profiles by month from Lake Benton

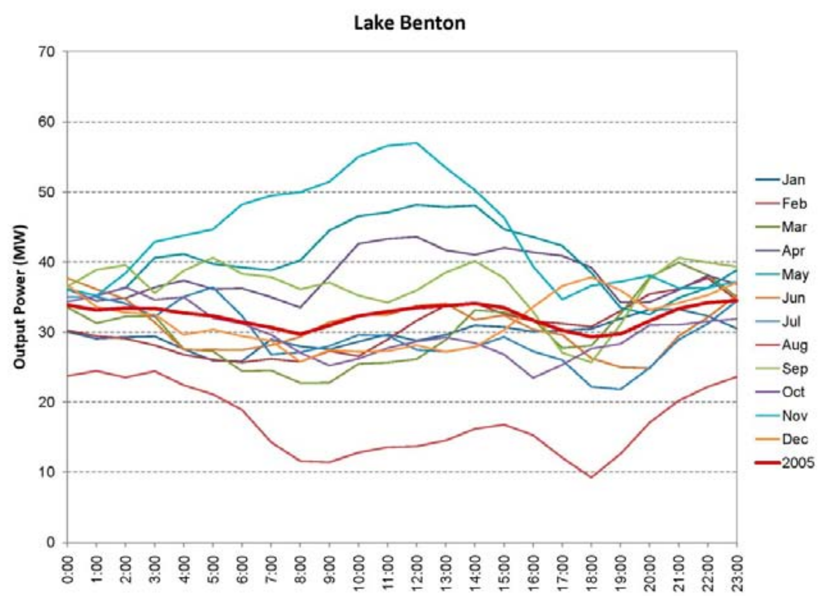

Figure A-4. 2005 average hourly wind power profiles by month from Lake Benton

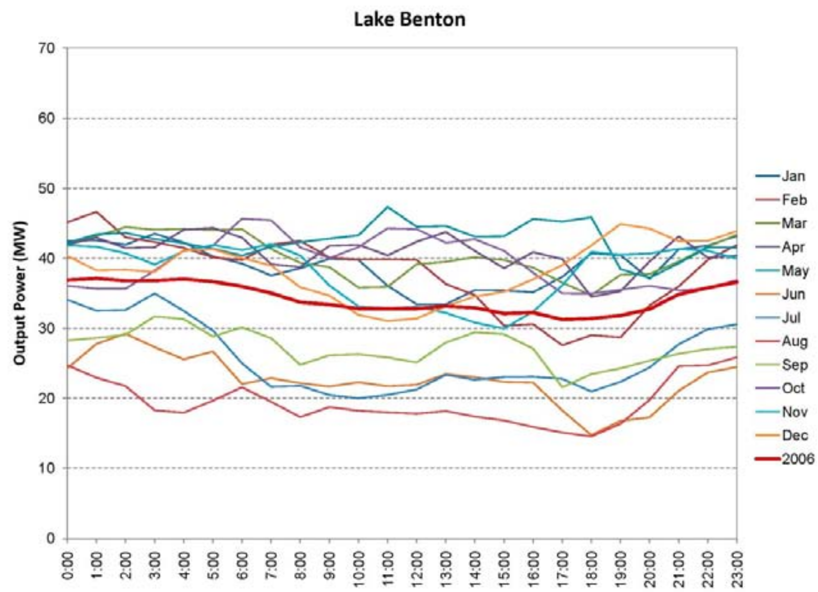

Figure A-5. 2006 average hourly wind power profiles by month from Lake Benton

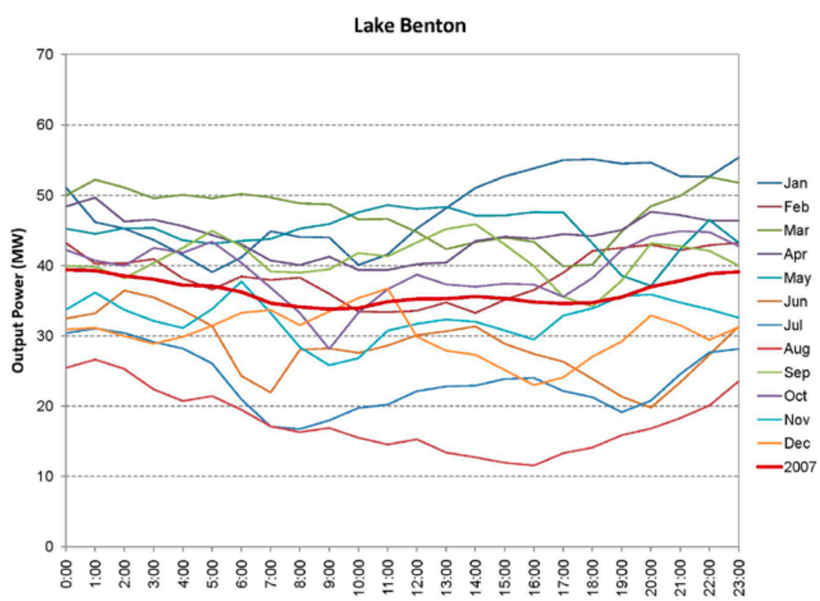

Figure A-6. 2007 average hourly wind power profiles by month from Lake Benton

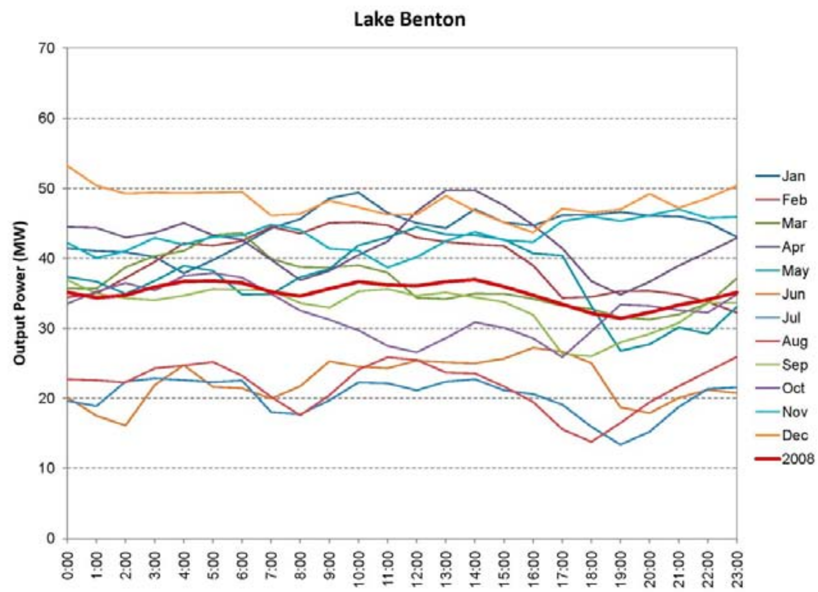

Figure A-7. 2008 average hourly wind power profiles by month from Lake Benton

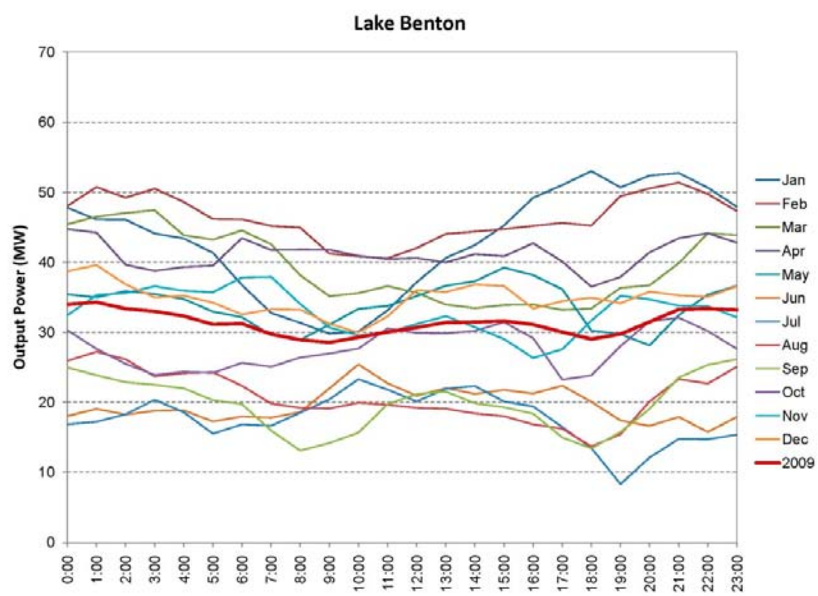

Figure A-8. 2009 average hourly wind power profiles by month from Lake Benton

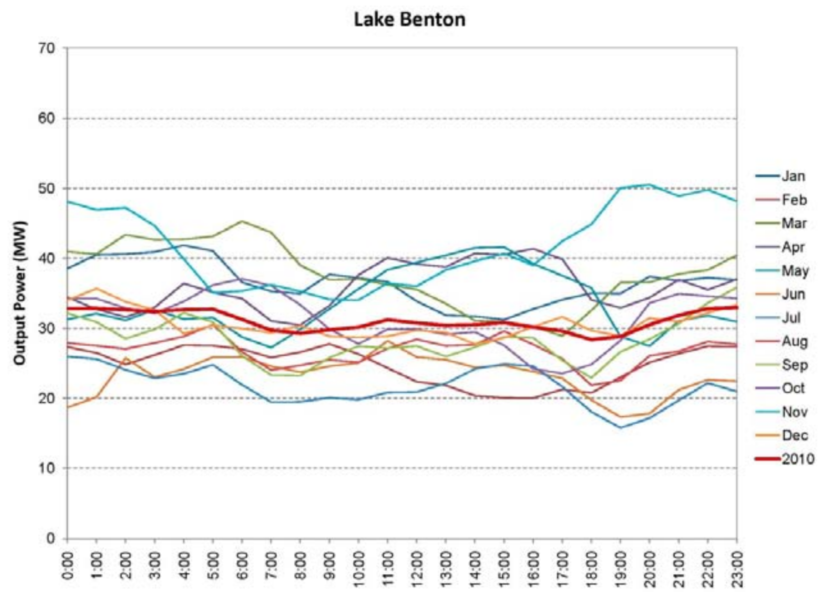

Figure A-9. 2010 average hourly wind power profiles by month from Lake Benton

Appendix B: Hourly Average Wind Power Profile of Storm Lake

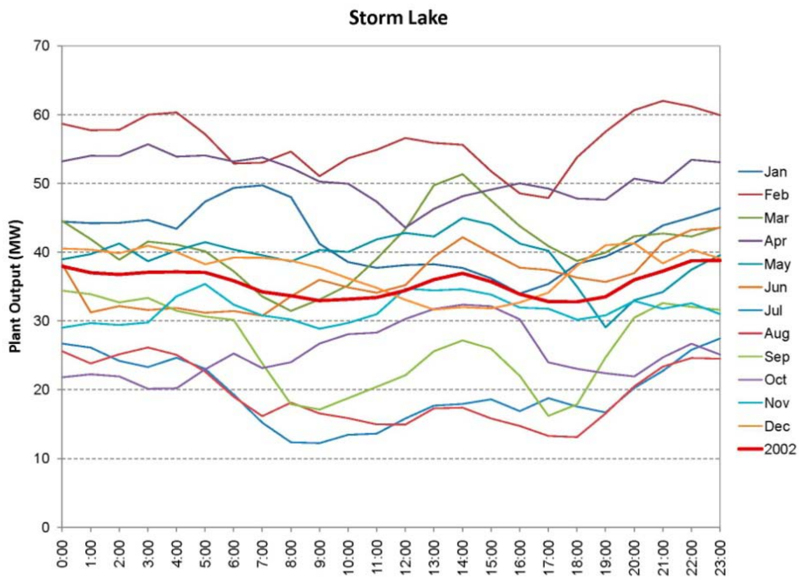

Figure B-1. 2002 average hourly wind power profiles by month from Storm Lake

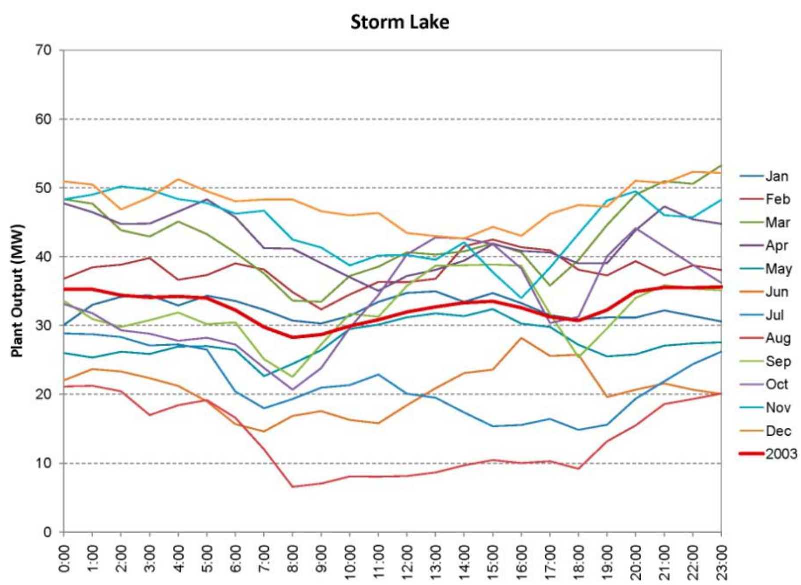

Figure B-2. 2003 average hourly wind power profiles by month from Storm Lake

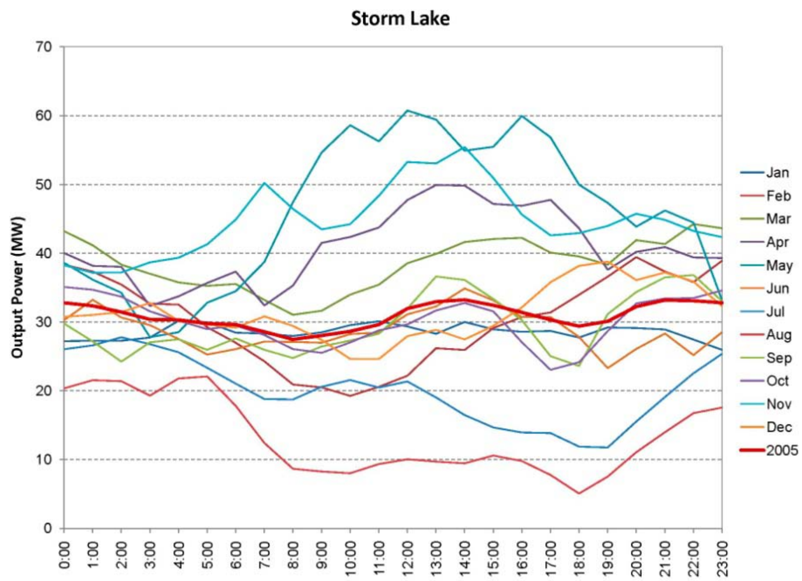

Figure B-3. 2005 average hourly wind power profiles by month from Storm Lake

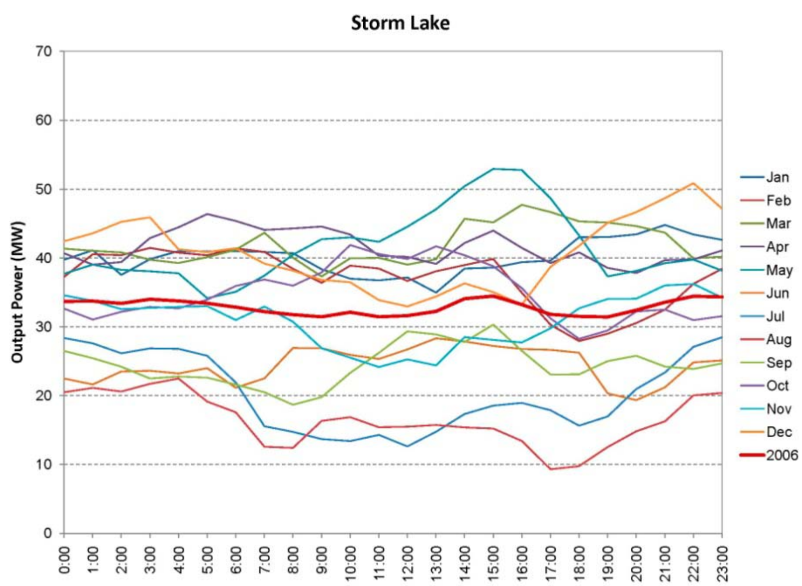

Figure B-4. 2006 average hourly wind power profiles by month from Storm Lake

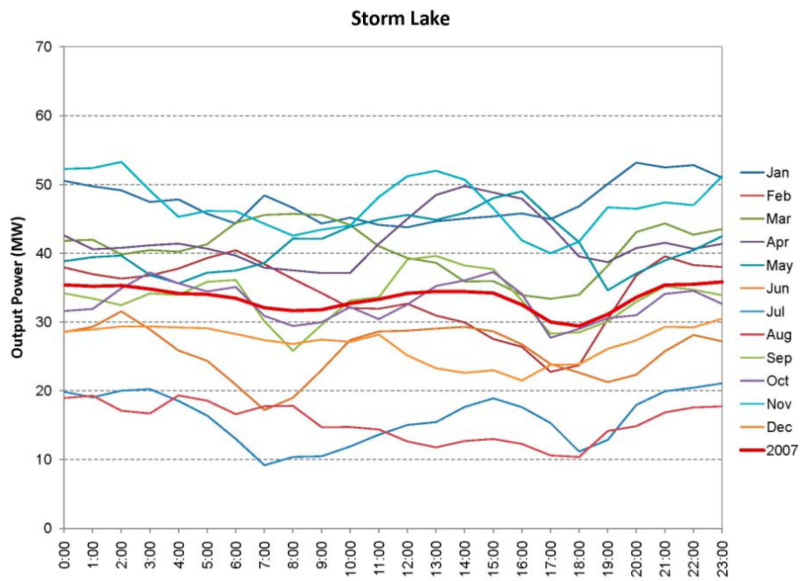

Figure B-5. 2007 average hourly wind power profiles by month from Storm Lake

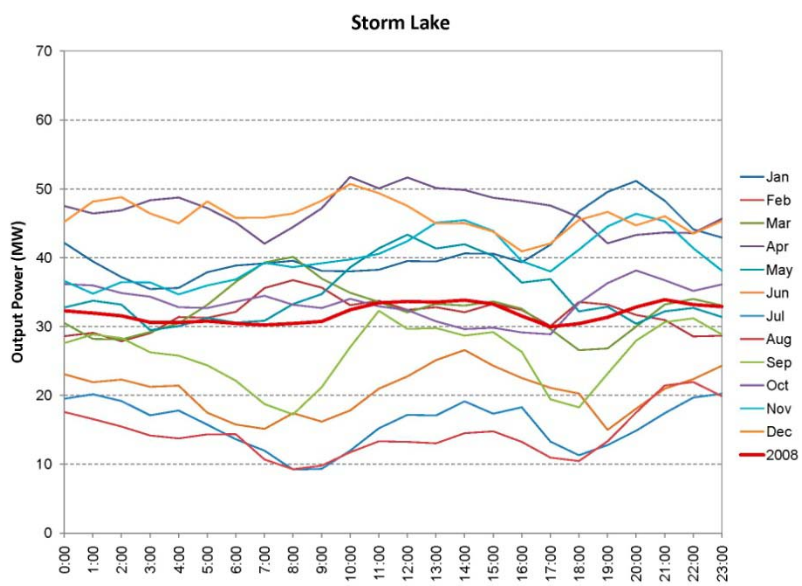

Figure B-6. 2008 average hourly wind power profiles by month from Storm Lake

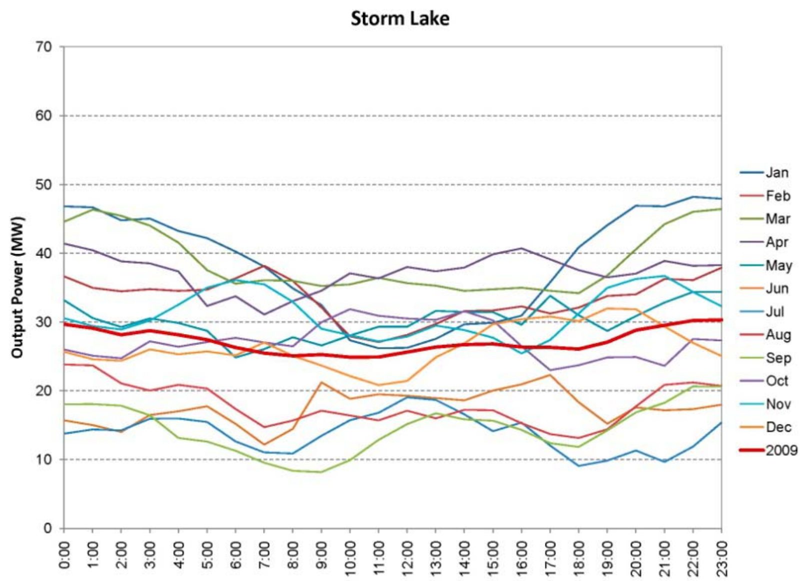

Figure B-7. 2009 average hourly wind power profiles by month from Storm Lake

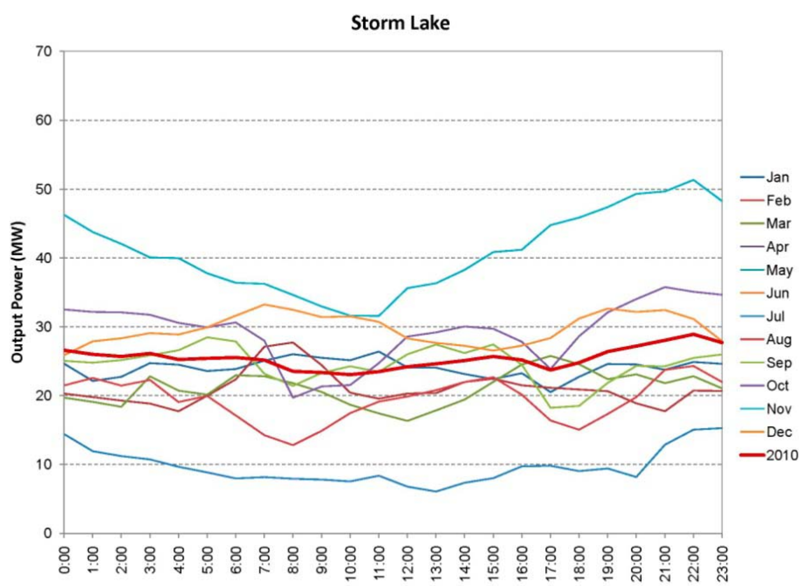

Figure B-8. 2010 average hourly wind power profiles by month from Storm Lake

Appendix C: Hourly Average Wind Power Profile of Blue Canyon

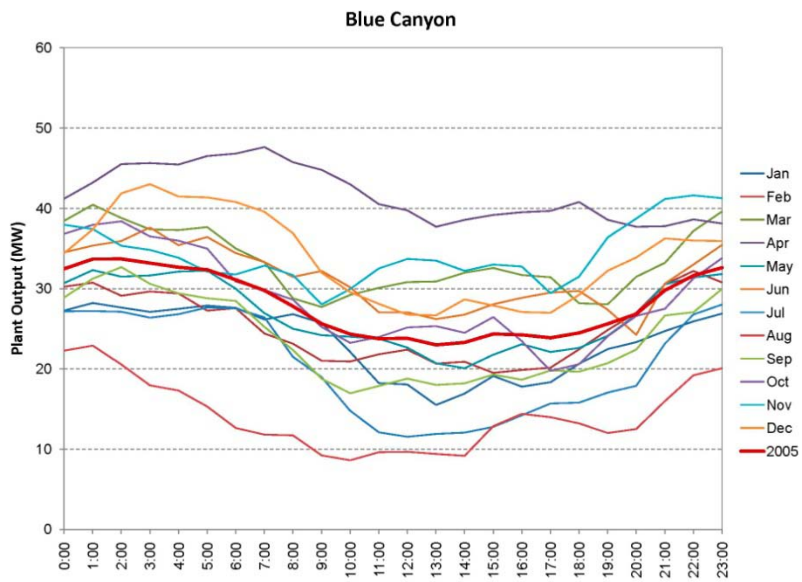

Figure C-1. 2005 average hourly wind power profiles by month from Blue Canyon

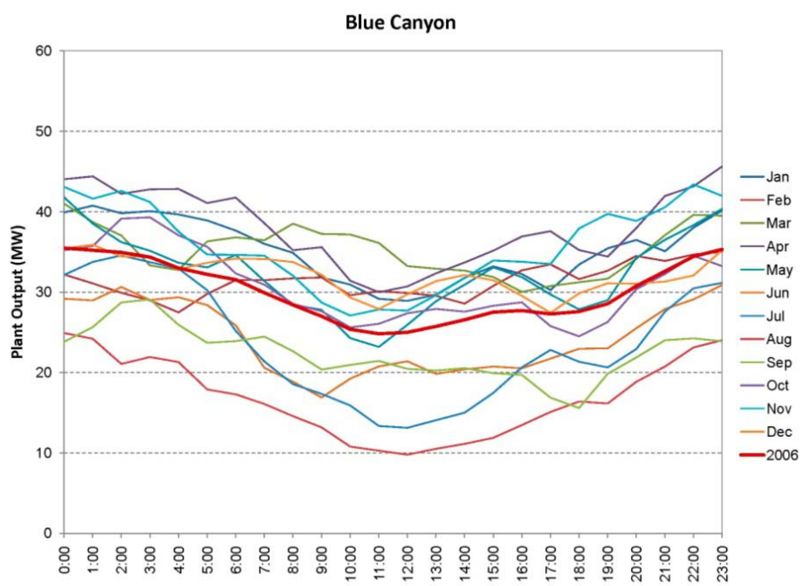

Figure C-2. 2006 average hourly wind power profiles by month from Blue Canyon

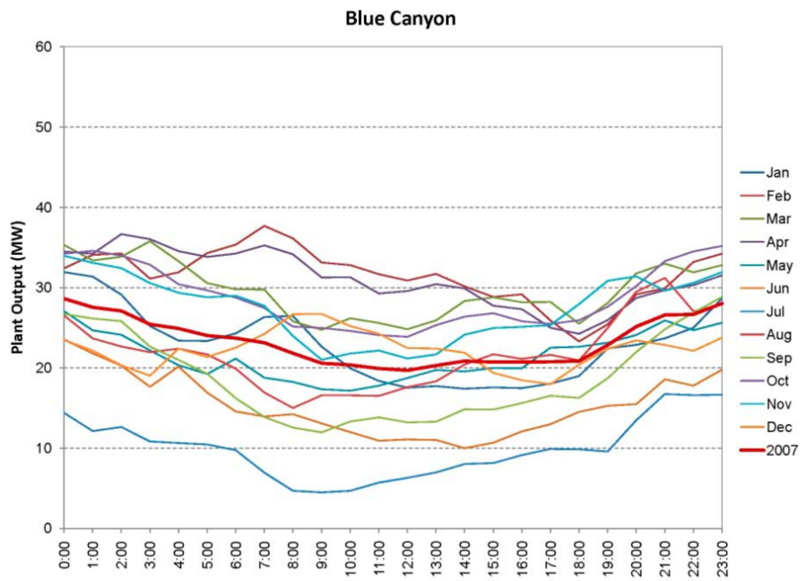

Figure C-3. 2007 average hourly wind power profiles by month from Blue Canyon

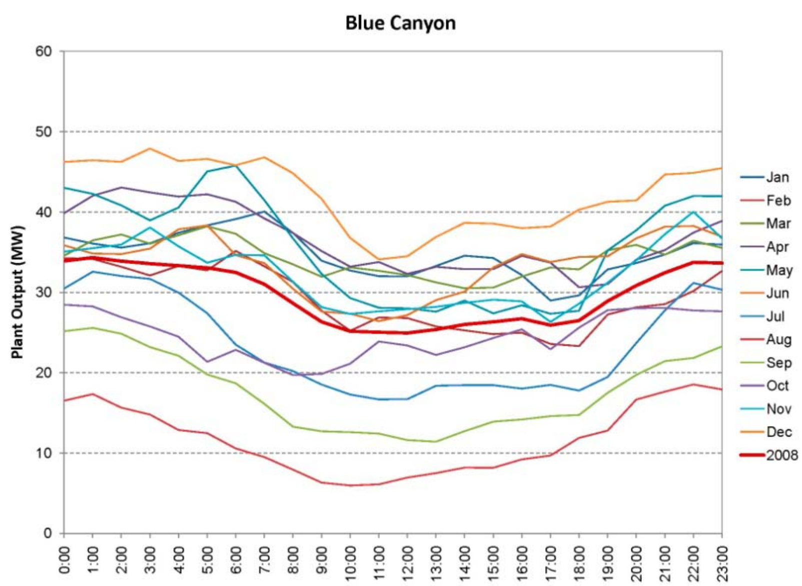

Figure C-4. 2008 average hourly wind power profiles by month from Blue Canyon

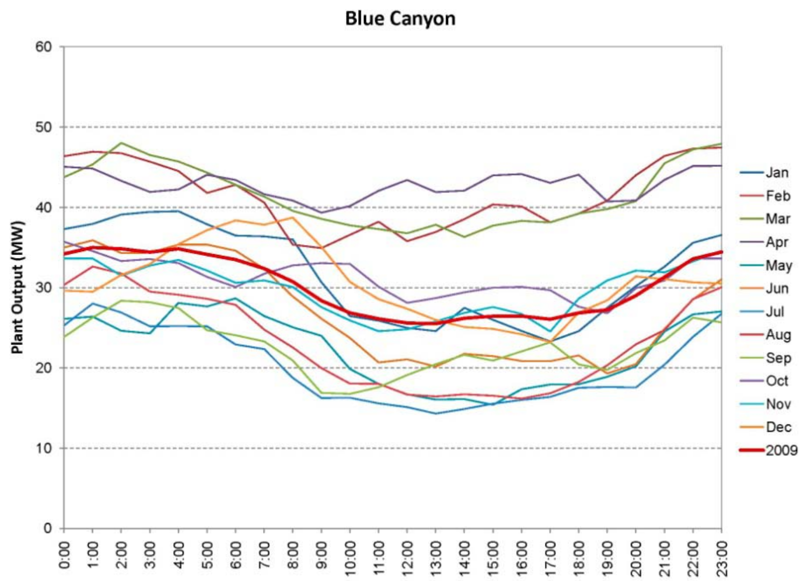

Figure C-5. 2009 average hourly wind power profiles by month from Blue Canyon

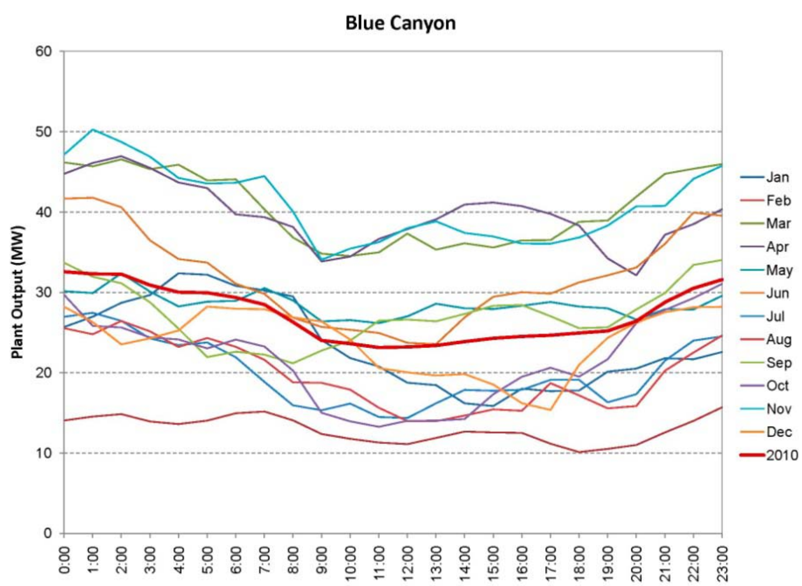

Figure C-6. 2010 average hourly wind power profiles by month from Blue Canyon

Appendix D: Hourly Average Wind Power Profile of Trent Mesa

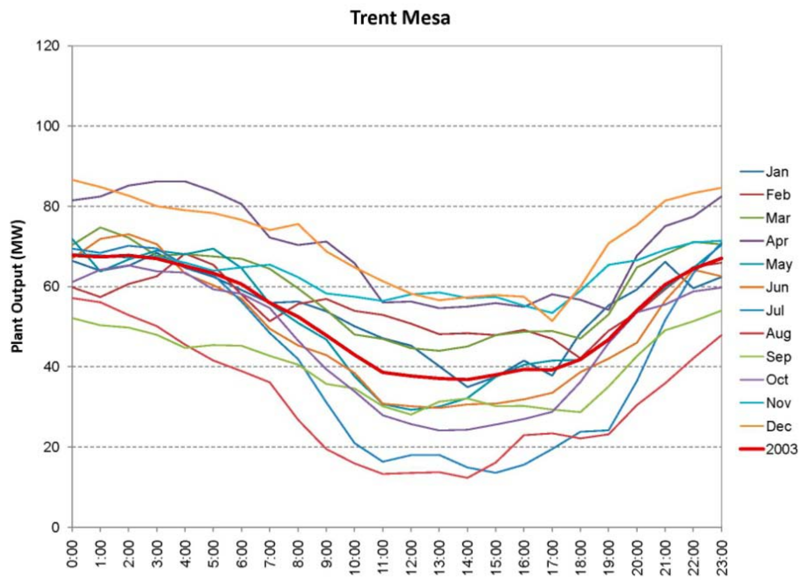

Figure D-1. 2003 average hourly wind power profiles by month from Trent Mesa

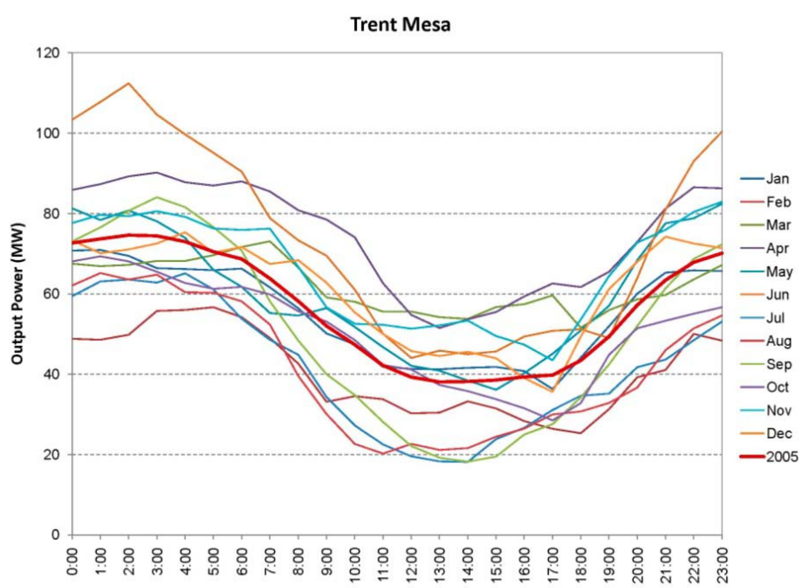

Figure D-2. 2005 average hourly wind power profiles by month from Trent Mesa

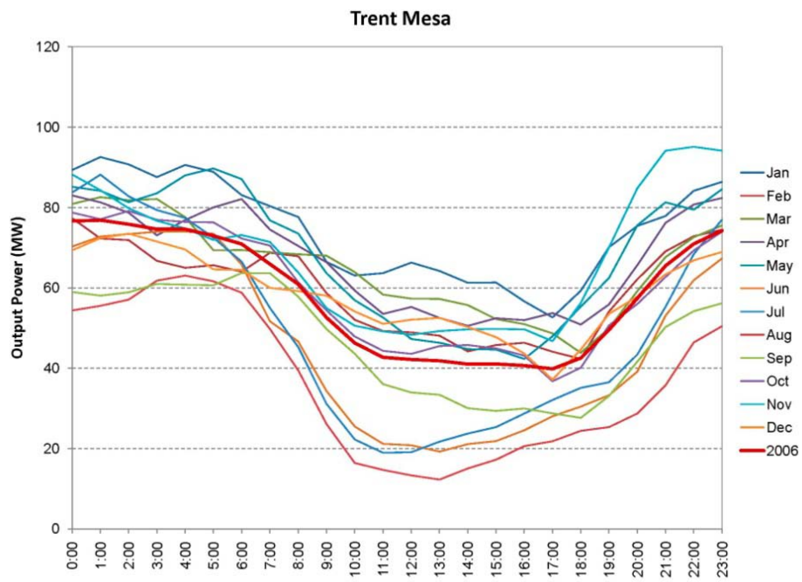

Figure D-3. 2006 average hourly wind power profiles by month from Trent Mesa

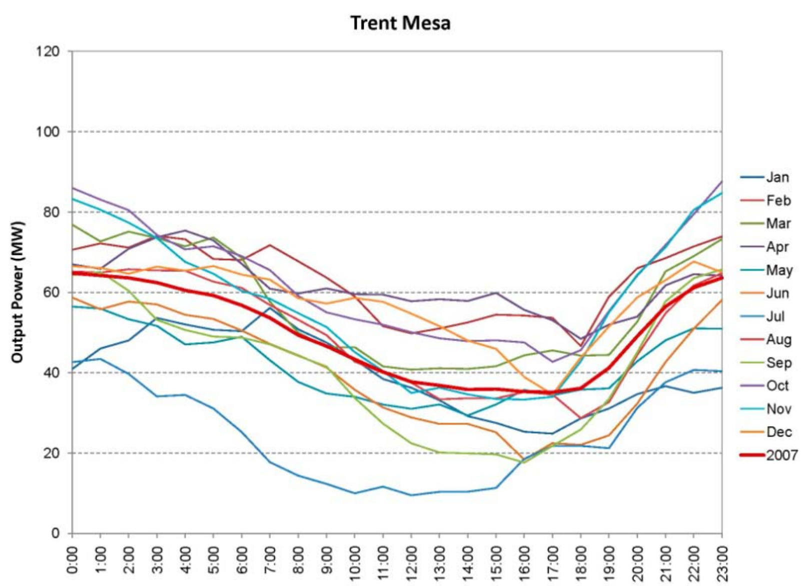

Figure D-4. 2007 average hourly wind power profiles by month from Trent Mesa

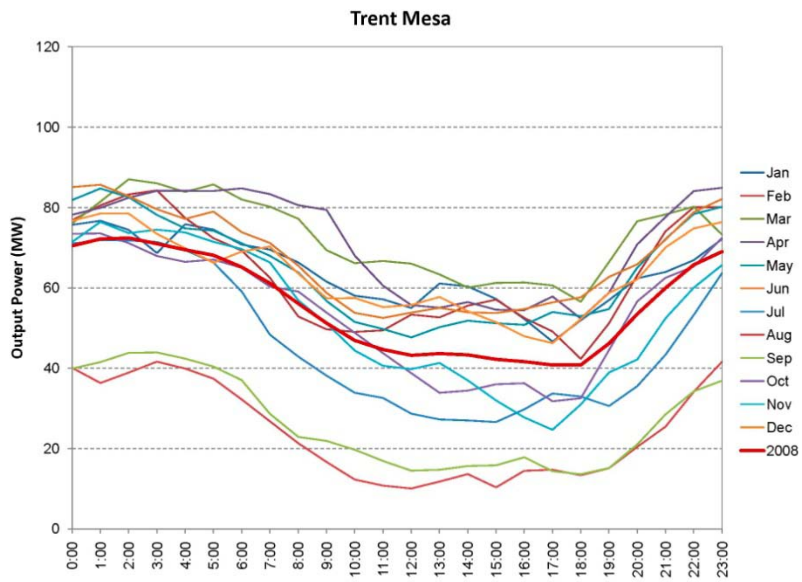

Figure D-5. 2008 average hourly wind power profiles by month from Trent Mesa

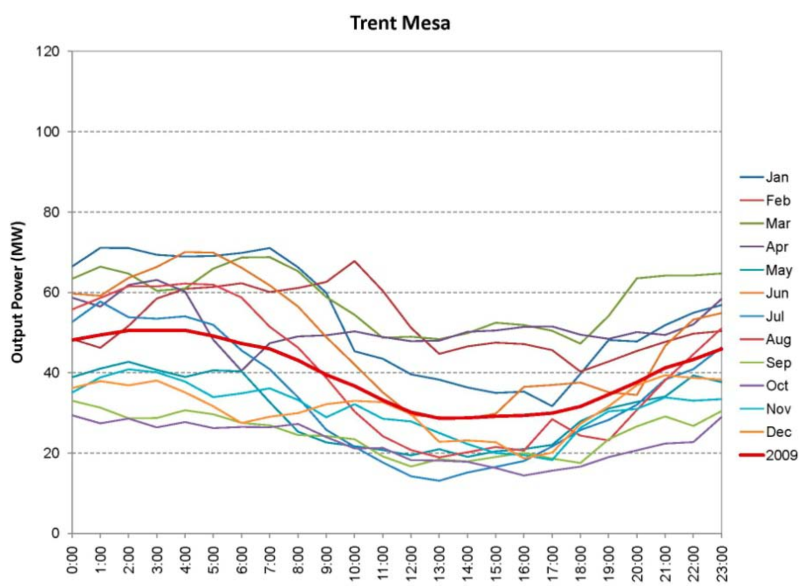

Figure D-6. 2009 average hourly wind power profiles by month from Trent Mesa

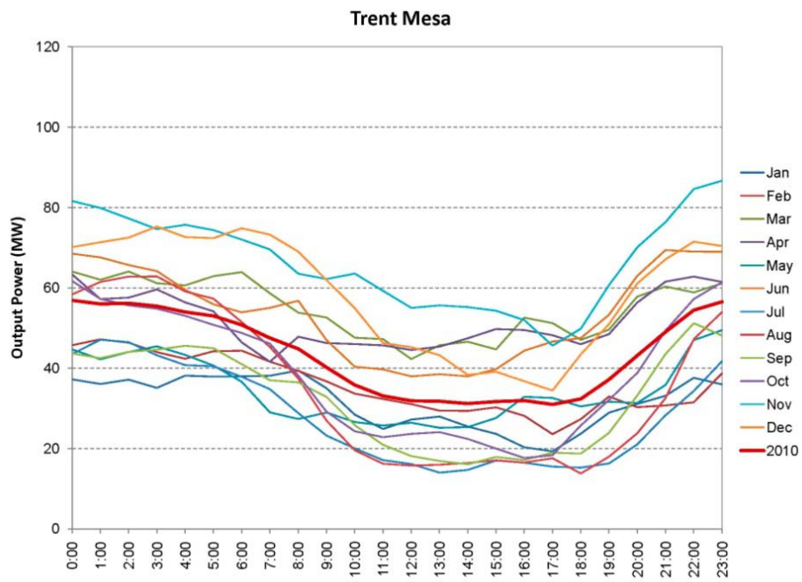

Figure D-7. 2010 average hourly wind power profiles by month from Trent Mesa

Appendix E: Monthly COV of hourly wind power level changes

Table E-1. Hourly Wind Power Variability by Month at Storm Lake

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Jan	0.8	0.8	0.9	0.9	1.1	0.8	0.7	0.7	0.8	1.2
Feb	0.8	0.6	0.8	0.8	0.9	0.8	1.0	1.0	0.9	1.1
Mar	0.9	0.9	0.8	0.8	0.9	0.8	0.7	0.9	0.8	1.0
Apr	0.8	0.7	0.8	0.8	0.7	0.8	0.8	0.7	0.8	
May		0.8	1.1	0.8	0.6	0.7	0.7	0.8	0.9	
Jun	1.0	0.7	1.1	1.2	0.9	1.1	0.9	1.2	1.1	
Jul	1.	1.0	1.1	1.3	1.0	1.0	1.0	1.2	1.3	1.3
Aug	1.0	1.0	1.3	1.1	1.1	1.0	1.1	1.3	1.1	1.1
Sep	1.1	0.8	0.8	0.7	0.8	1.0	0.8	0.9	1.4	0.9
Oct	0.8	1.0	0.8	0.9	0.9	0.8	0.9	0.8	1.0	0.9
Nov	0.8	0.9	0.7	0.8	0.7	0.9	0.7	0.8	0.8	0.8
Dec	0.9	0.8	0.7	0.8	1.0	0.8	1.2	0.7	0.9	0.9

Table E-2. Hourly Wind Power Variability by Month at Blue Canyon

	2004	2005	2006	2007	2008	2009	2010
Jan	0.8	1.0	0.7	1.1	0.7	0.8	1.1
Feb	0.9	0.9	0.8	0.8	0.8	0.6	1.5
Mar	0.8	0.8	0.7	0.8	0.6	0.6	0.6
Apr	0.8	0.6	0.6	0.8	0.6	0.6	0.6
May	0.5	0.9	0.7	1.1	0.6	1.0	0.9
Jun	0.9	0.7	0.9	1.2	0.8	0.8	0.7
Jul	0.8	1.0	0.8	1.2	0.8	1.0	0.8
Aug	1.0	1.0	1.0	0.9	1.1	0.8	0.9
Sep	0.9	0.9	1.0	0.9	1.1	0.9	0.8
Oct	0.9	0.8	0.8	0.8	1.0	0.9	0.8
Nov	0.9	0.7	0.7	0.9	0.8	0.8	0.6
Dec	0.7	0.8	0.7	1.0	0.7	0.8	1.0

Table E-3. Hourly Wind Power Variability by Month at Trent Mesa

	2003	2004	2005	2006	2007	2008	2009	2010
Jan	0.9	0.8	0.9	0.7	1.2	0.8	0.8	1.1
Feb	0.8	0.9	1.0	0.9	0.8	0.8	0.9	1.1
Mar	0.8	0.8	0.7	0.7	0.9	0.7	0.7	0.8
Apr	0.6	0.8	0.7	0.6	0.8	0.7	0.7	0.8
May	0.9	0.5	0.9	0.7	1.1	0.7	1.0	1.1
Jun	1.0	0.8	0.6	1.0	1.0	0.7	0.8	0.7
Jul	0.9	0.8	0.9	0.8	1.2	0.8	1.0	1.0
Aug	1.1	1.0	1.0	1.0	0.9	1.3	0.9	0.9
Sep	0.9	0.9	0.9	1.0	1.0	1.1	1.0	1.1
Oct	0.9	0.9	0.9	0.7	0.8	0.9	1.1	1.0
Nov	0.7	1.0	0.8	0.7	0.9	0.9	1.0	0.7
Dec	0.7	0.7	0.8	0.8	0.9	0.8	1.1	0.8