



# Alberta Wind Power Variability Study



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## Executive Summary

The purpose of this study was to simulate and assess wind power variability over 1- and 10-minute intervals for various future potential development scenarios in Alberta. The result of this study was the projection of expected wind power variability resulting from various stages of growth of the Alberta wind energy industry. The Alberta Electric System Operator (AESO) was provided with simulated wind power generation time series for the year 2004. These will be used by the AESO to evaluate the impact of wind power variability on the reliability of the Alberta Interconnected Electric System (AIES).

This study consisted of two major parts. The first was to develop a model that is used to simulate short-term wind power generation and fluctuation. A modified multi-turbine power curve approach was proposed in order to take into account the effect of spatial diversity on the aggregate behaviour of a number of wind turbines. The proposed model was then validated by comparing measured and simulated wind power data. Future scenarios were simulated using measured local wind meteorological data collected specifically for existing and proposed wind power facilities. It was found that the effect of geographic diversity of wind power facilities (WPFs) could be realistically represented by using measured local wind data.

The second part of the analysis was to extract summary information from simulated wind power data (Jan. 1, 2004 – Dec. 31, 2004) to get insight into the wind power variability in Alberta. For three different potential development scenarios, the proposed capacities were 895, 1445 and 1994 MW, respectively. It was estimated that 97.5% of the 10-minute fluctuations for these scenarios were lower than 40, 56 and 70 MW, respectively. The maximum 10-minute fluctuations were estimated to be 202, 208 and 259 MW, respectively, for the period of analysis. It was estimated that 97.5% of the 1-minute fluctuations for these scenarios were lower than 9, 12 and 14 MW, respectively. The maximum 1-minute fluctuations were estimated to be 116, 149 and 222 MW, respectively, for the period of analysis.

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# Alberta Wind Power Variability Study

## 1 Introduction

Growth in the potential development of WPFs in Alberta has resulted in a need for understanding their impact on the reliability of the AIES. The AESO is interested in an assessment of wind power generation changes over periods of 10-minutes and less from geographically separated WPFs.

The objectives of this study were to simulate the wind power generation time series of geographically separated WPFs and to determine the wind power variability at different future development stages. To model and assess wind power fluctuations, the analysis procedures were organized as follows:

A preliminary analysis of wind power variation was performed for existing WPFs in the South Western region of Alberta. The results of this analysis are provided in Section 2.

As shown in Section 3, a model was developed to simulate 10-minute and 1-minute wind power generation time series. The model was validated by comparing simulated and measured wind power data for existing individual and grouped WPFs. Sensitivity of the model to various input parameters was also analyzed.

Simulated wind power time series for future scenarios were generated and analyzed. These results are provided in Section 4.

In Section 6, study implications and conclusions are provided.

## 2 Short-Term Wind Power Fluctuations in Alberta

The characteristics of short-term (10-minute and 1-minute) wind power fluctuations were examined in the context of Alberta. This analysis was performed to provide reference information in the development of models of WPF operation. These models were then used to simulate wind power generation and fluctuation for potential WPF development.

### 2.1 Wind Power Data

The AESO provided wind power generation data for five existing WPFs located in the South Western region of Alberta. The total installed capacity of the WPFs was 254 MW. The individual nameplate capacities were as low as 31 MW and as high as 75 MW. The raw data consisted of power and status flags indicating the quality of the data in 10-second or 1-minute step sizes. A summary of the wind power data is displayed in Table 1.

*Table 1: Summary of Wind Power Data*

	Time Interval	Start	End	Valid Percentage (%)
WPF1	1 minute	30-Nov-03	8-Dec-04	85
WPF2	10 second	21-Sep-04	30-Nov-04	100
WPF3	1 minute	30-Nov-03	9-Dec-04	97
WPF4	10 second	1-Dec-03	30-Nov-04	99
WPF5	1 minute	1-Aug-04	20-Dec-04	99

## 2.2 Wind Power Fluctuations

The first step in the analysis was to determine how power output varies at the WPF level. A set of summary statistics of fluctuations (the difference in power levels between consecutive time steps) was calculated in terms of the wind power output (relative to the installed capacities). For example, in Table 2, the average increase was 6% of the installed capacity when a WPF was generating less than 10% of its capacity. The values of summary statistics were normalized with respect to WPFs' capacities.

Table 2 shows that the maximum 1-minute fluctuations occurred at the cut-in and cut-out wind speeds of WPF1's power curve. The maximum power increase between 1-minute averages was seen when the WPF was running at 50-60% of its capacity; the maximum decrease occurred at 70-80% of the rated capacity. The maximum standard deviation of increase was seen when the WPF was running at 30-40% of the rated capacity; the maximum standard deviation of decrease occurred at 80-90% of rated capacity.

Table 3 shows that the 10-minute maximum increase occurred at the 30-40% of WPF1's capacity and the maximum decrease occurred at 80-90% of its capacity. The maximum increase between 10-minute averages was seen when the WPF was running at 50-60% of its capacity; the maximum decrease occurred at 50-60% of its capacity. The maximum standard deviation of increase was seen when the WPF was running at 30-40% of its capacity; the maximum standard deviation of decrease was at 70-80% of rated capacity.

The 1-minute and 10-minute wind power fluctuations for the four other WPFs are summarized in Table 9 through Table 16.

The combined short-term fluctuations for the group of 5 existing WPFs (with a total capacity of 254 MW) are summarized in Table 4 and Table 5.

Readers are cautioned that the maximum fluctuations in the tables might be caused not only by wind speed variation but also by forced or controlled outages and startups of the WPF that are unidentified in the measured wind power data.

*Table 2: 1-Minute Normalized Fluctuations of WPF1 as a Percentage of Capacity<sup>1</sup>*

Power	Sd. <sup>2</sup>	Max	Min	Avg. <sup>3</sup> Inc. <sup>4</sup>	Sd. Inc.	Max. Inc.	Avg. <sup>3</sup> Dec. <sup>5</sup>	Sd. Dec	Max. Dec.
3.14	2.44	10.00	0.00	0.06	0.70	89.95	-0.10	0.36	-7.00
14.60	2.90	20.00	10.00	0.25	0.90	76.71	-0.17	0.38	-13.04
24.77	2.89	30.00	20.00	0.32	0.72	17.73	-0.22	0.51	-15.20
34.85	2.92	40.00	30.00	0.44	1.09	50.39	-0.26	0.61	-18.80
44.88	2.68	50.00	40.00	0.47	1.05	43.50	-0.34	0.79	-43.65
54.79	3.11	60.00	50.00	0.54	1.05	16.89	-0.44	0.86	-18.80
64.91	2.94	70.00	60.00	0.45	0.91	14.74	-0.44	0.89	-18.80
75.23	3.03	80.00	70.00	0.50	0.90	16.94	-0.46	1.18	-77.29
85.44	2.87	90.00	80.00	0.35	0.70	11.29	-0.35	1.39	-85.69
94.34	2.48	99.58	90.00	0.15	0.31	4.99	-0.13	0.69	-94.02

<sup>1</sup> Units in the table are % of capacity

<sup>2</sup> Sd. : abbreviation of standard deviation

<sup>3</sup> Avg. : abbreviation of average

<sup>4</sup> Inc. : abbreviation of increase

<sup>5</sup> Dec. : abbreviation of decrease

*Table 3: 10-Minute Normalized Fluctuations of WPF1 as a Percentage of Capacity*

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
3.16	2.43	9.99	0.00	0.44	1.75	46.32	-0.52	0.99	-8.31
14.65	2.90	20.00	10.00	2.09	4.08	38.60	-1.23	1.89	-17.93
24.79	2.89	30.00	20.01	2.52	4.61	51.02	-1.46	2.57	-27.35
34.84	2.91	40.00	30.00	3.42	6.22	64.02	-1.81	3.38	-29.28
44.84	2.67	49.99	40.00	2.95	5.03	34.37	-2.10	3.84	-33.65
54.76	3.12	60.00	50.00	3.43	5.60	37.03	-2.75	4.58	-33.13
64.93	2.94	70.00	60.00	2.49	4.26	36.74	-2.49	4.26	-29.13
75.20	3.04	79.99	70.00	2.75	4.00	22.81	-2.70	4.84	-46.12
85.42	2.88	90.00	80.00	1.66	2.48	13.96	-2.33	4.37	-58.52
94.31	2.47	99.03	90.00	0.65	0.96	5.68	-1.09	2.44	-45.71

*Table 4: 1-Minute Normalized Fluctuations of 5 Existing WPFs as a Percentage of Total Capacity*

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
3.03	2.97	10.00	-0.14	0.09	0.17	2.75	-0.10	0.16	-1.79
14.59	2.97	20.00	10.00	0.31	0.32	3.64	-0.28	0.29	-5.16
24.82	2.95	29.99	20.00	0.48	0.46	4.55	-0.45	0.40	-3.53
35.12	2.92	40.00	30.00	0.50	0.47	4.44	-0.47	0.42	-3.55
45.19	2.88	50.00	40.00	0.53	0.53	7.95	-0.52	0.49	-8.27
54.86	2.92	60.00	50.00	0.55	0.51	7.70	-0.55	0.61	-22.24
64.54	2.92	70.00	60.00	0.52	0.55	9.13	-0.51	0.63	-23.47
75.49	2.79	80.00	70.00	0.47	0.49	7.94	-0.47	0.54	-12.84
84.78	2.98	90.00	80.00	0.41	0.39	5.93	-0.43	0.43	-6.55
91.47	0.99	94.57	90.00	0.24	0.23	1.84	-0.30	0.50	-11.99

*Table 5: 10-Minute Normalized Fluctuations of 5 Existing WPFs as a Percentage of Total Capacity*

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
3.06	2.98	9.98	-0.13	0.41	0.79	11.42	-0.33	0.51	-3.70
14.50	2.98	20.00	10.02	1.51	1.71	16.90	-1.20	1.14	-6.54
24.78	2.94	30.00	20.00	2.42	2.48	14.65	-2.22	1.70	-8.16
35.06	2.92	39.97	30.02	2.44	2.43	14.84	-2.19	1.99	-14.48
45.23	2.84	49.98	40.01	2.33	2.51	16.94	-2.21	2.10	-16.31
54.77	2.87	59.98	50.00	2.35	2.63	26.51	-2.18	2.19	-13.01
64.49	2.96	69.99	60.01	2.35	2.27	13.79	-2.37	2.84	-32.92
75.53	2.76	79.98	70.00	1.81	1.69	9.77	-2.00	2.09	-16.28
84.75	2.93	90.00	80.00	1.34	1.36	9.74	-1.85	2.06	-16.29
91.38	0.96	93.99	90.01	0.52	0.48	2.06	-0.90	1.39	-11.18

### 3 Modelling Methodologies and Analysis Steps

With the reference information produced in the preceding section, the next step in the study was to develop one- and ten-minute models.

### 3.1 10-Minute Model

A multi-turbine power curve approach (see [1]) was adopted and modified to simulate the effects of the aggregated wind power output from a number of wind turbines within a WPF. The major model inputs were one wind speed time series and a wind turbine power curve. Other model parameters were the size of WPFs, turbulence intensity<sup>6</sup>, wake/array loss and electrical loss.

#### 3.1.1 Methodologies

- *Weighted moving average wind speed time series*

The change in wind speed would propagate in the average wind direction with a speed similar to the average wind speed. For example, with an average wind speed of 7 m/s, a wind speed change would propagate approximately 5 km within 12 minutes. A wind speed measured near the area can be represented within the area in a time period corresponding to the traveling time of the air to pass the area. To represent the wind fluctuations over the area, the weighted moving average wind speed time series was generated from the original wind speed time series by specifying a time window. The length of the time window depended on the average wind speed of the original wind speed time series and the spatial distance of the area. The weighted moving average wind speed was defined as

$$v_j = \frac{1}{N + 1} \sum_{i=\frac{j-N}{2}}^{\frac{j+N}{2}} w_i v_i ,$$

where  $v_j$  was the  $j^{\text{th}}$  element in the weighted moving average time series,  $v_i$  was the  $i^{\text{th}}$  element in the original time series, and  $w_i$  was the weight for the wind speed in the time window.  $N$  was the number of points to be included in each average process and defined as the nearest even integer greater than or equal to  $T/\Delta t$ , where  $T$  was the propagation time and  $\Delta t$  was the time step in the time series. The relationship between the propagation time and the distance at various average wind speeds is illustrated in Figure 1.

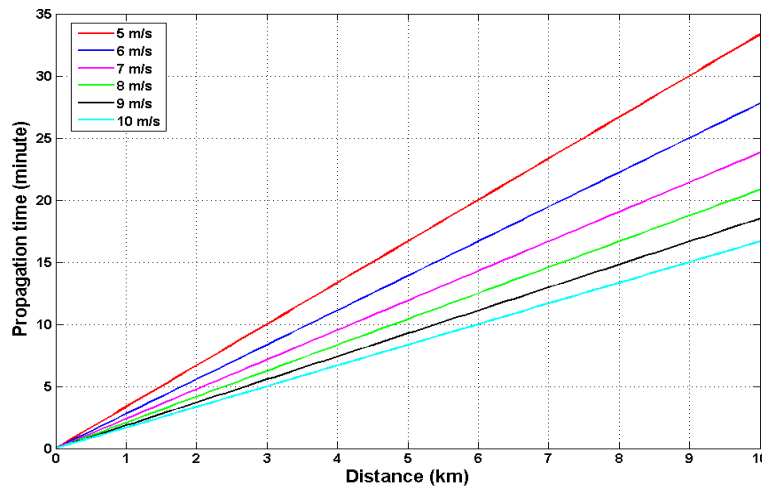


Figure 1: Relationship between the Spatial Dimension and the Propagation Time for Various Wind Speeds

- *Spatial wind speed distribution*

<sup>6</sup> Turbulence intensity: Quotient of instantaneous wind speed divided by the mean wind speed for a given period.

The modelled wind speeds at the individual wind turbines were assumed to be normally distributed at any specific time. For example, Figure 2 illustrates the frequency distribution of wind speeds measured at individual wind turbines in a WPF. The normalized standard deviation (relative to the average wind speed) of the distribution depended on the spatial dimension and turbulence intensity of the site. For example, it was proven by empirical studies (see [1]) that the normalized standard deviation was an approximate linear function of the distance when the distance was less than 50 km.

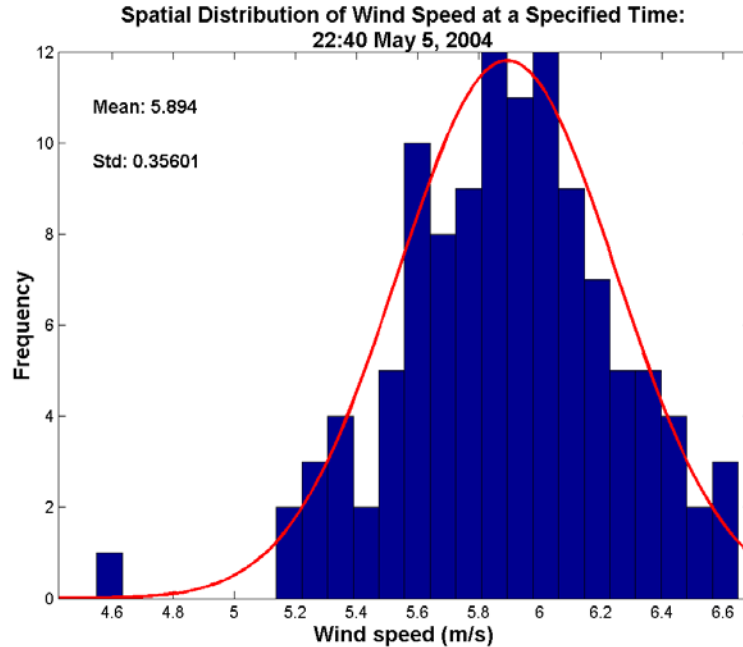


Figure 2: The Frequency Distribution of the Wind Speeds Measured at Individual Wind Turbines in a WPF

- *Multi-turbine power curves*

A multi-turbine (park) power curve was generated by applying the above normal distribution of wind speeds resulting from the spatial distribution of wind turbines to a representative power curve for the WPF. The  $j^{\text{th}}$  element of the (discrete) multi-turbine power curve,  $P_j^m$ , was found by

$$P_j^m = \sum_i P_{j+i}^s \times p_i^s,$$

where  $P_j^s$  was the  $j^{\text{th}}$  element of the (discrete) single-turbine power curve and  $p_i^s$  was the probability of the spatial distribution. The normalized single-turbine power and multi-turbine power curves for a WPF are displayed in Figure 3. It can be seen that the multi-turbine power curve has a lower cut-in wind speed and a higher cut-out wind speed than the single turbine power curve. This is due to the fact that in large WPFs some wind turbines cut in sooner than others and similarly some cut out later. As a result, the multi-turbine power curve has lower rates of change and has a smoothed appearance.

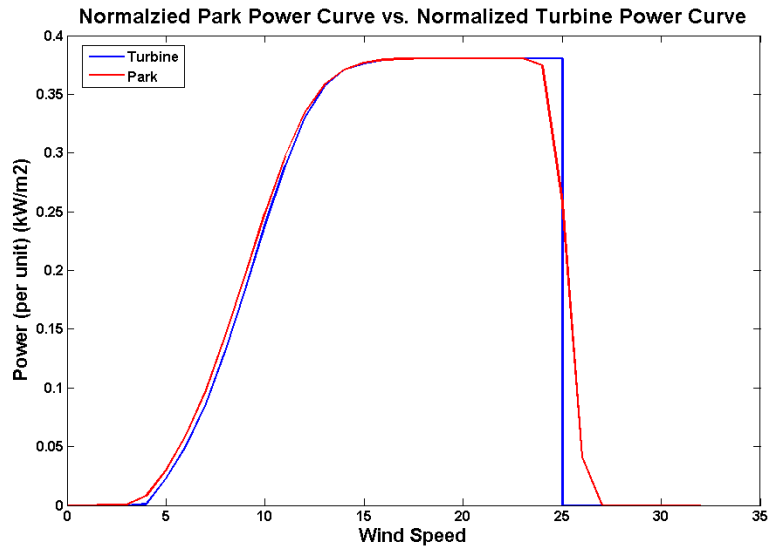


Figure 3: Normalized Single-Turbine and Multi-Turbine Power Curves for a WPF

- Adjusting energy production

The estimated annual energy productions for a given wind speed time series based on the two power curves in Figure 3 should equal. This was done by a minor offset adjustment of the spatial distribution.

- *Simulated wind power time series*

The multi-turbine power curve in combination with the weighted moving average wind speed time series was used to simulate a wind power output time series.

### 3.1.2 Model Assumptions

- All wind turbines within a WPF were assumed to be similar, i.e., equal in size and control principle.
- The distribution of the individual wind speeds at a given time was assumed to be normally distributed around the weighted moving average wind speed. The standard deviation of the distribution was assumed to depend on wind turbulence intensity and the spatial distance of a WPF.
- Wind speed time series were assumed to be representative of meteorological towers in or near the middle of a WPF.

### 3.1.3 Analysis Steps

A step-by-step analysis for the methodology was illustrated below.

1. A representative dimension was specified for the area of the WPF. For future WPFs, the dimension was estimated by comparing with existing WPFs. For example, in Figure 4, the *nameplate capacity density*<sup>7</sup> was approximately 3 MW/km<sup>2</sup> for the WPFs with a nameplate capacity of 75 MW. Therefore, the area of the WPFs was about 25 km<sup>2</sup> and the representative spatial distance was defined as the square root of the area, i.e. 5 km.

<sup>7</sup> Nameplate capacity density is defined as the ratio of a WPF's nameplate capacity to the area of the WPF and is in the unit of MW/km<sup>2</sup>.

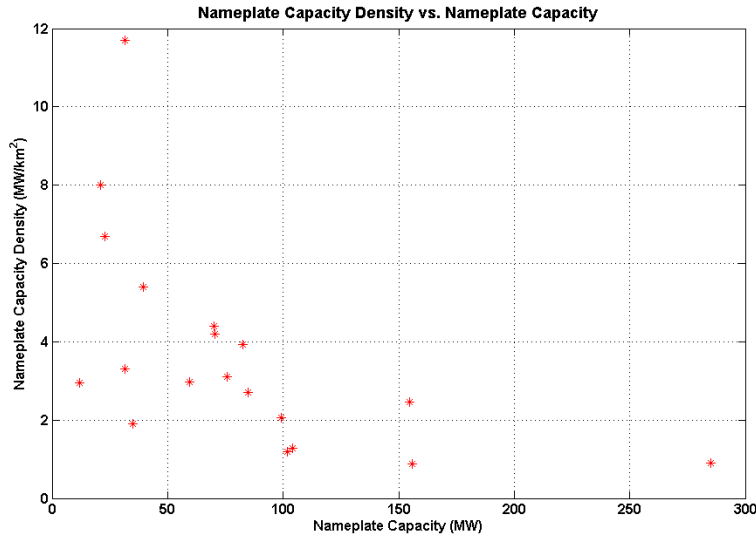


Figure 4: Scatter Plot of the Nameplate Capacity Density vs. Nameplate Capacity for Sampled Existing WPFs

2. The wind distribution was characterized in terms of the average wind speed, the Weibull fit and the turbulence intensity.
3. The wind speed time series was adjusted to the relevant hub height and a weighted moving average wind speed time series was generated.
4. The spatial wind distribution was characterized in terms of the normalized standard deviation and the actual standard deviation.
5. A single-turbine power curve was specified and adjusted to account for wake/array losses (5% of nameplate capacity) and electrical losses (2.5% of nameplate capacity).
6. A multi-turbine power curve was generated by using normally distributed variation in wind speed to adjust the single-turbine power curve.
7. The offset of the spatial wind speed distribution was adjusted so that the annual energy production from the normalized single-turbine and multi-turbine power curves were the same.
8. The wind power time series was generated by applying the multi-turbine power curve to the weighted moving average wind speed time series.

### 3.2 1-Minute Model

#### 3.2.1 Methodologies

Given a simulated 10-minute wind power time series, the 1-minute wind power was generated by linearly interpolating between two successive 10-minute wind power outputs with introduced randomness. For example, given the simulated wind power output at 9:30 and 9:40 from the 10-minute model, the wind power at 9:35 was generated from a normal distribution. The mean of the normal distribution was linearly interpolated from the wind power outputs at 9:30 and 9:40; the standard deviation of the normal distribution was assumed to be equal to one sixth of the difference between the wind power outputs at the two successive 10-minute time points. In so doing, the magnitude of variation generated in the 10-minute model can be used to restrict the magnitude of variation for the 1-minute model.

### 3.2.2 Model Assumptions

- The step changes were assumed to be very small for short periods (e.g. 1-minute). This was validated by actual production data: the average of all 1-minute step changes were nearly zero for all five existing WPFs; the standard deviations of 1-minute step changes for WPF1, WPF2, WPF3, WPF4, and WPF5 were 0.8%, 1.4%, 1.8%, 1.0%, and 1.9% of the individual nameplate capacities, respectively. These relatively small standard deviation values suggest that the step change distribution is tightly centred about zero.
- It was assumed that the magnitude of the step change decreases as a function of the length of the time window. For example, the 1-minute step changes were on average smaller than the 10-minute step changes. This characteristic is shown clearly in tables in Section 2.2.

### 3.3 Model Validation

To validate the models, the simulated and measured fluctuations for existing WPFs were compared. The performance of the models was measured from the perspectives of the magnitude and frequency of the fluctuations. The magnitudes of the fluctuations were measured by the average change at different levels of a WPF's nameplate capacity; the frequency of fluctuations was measured by the percentiles of the distribution of fluctuations. Further, to make fluctuations comparable at different capacities, the values of the above two statistics were normalized with respect to the individual WPFs' installed capacities or the total capacity for the region.

#### 3.3.1 Validation Within a WPF

WPF4 was used to illustrate the validation. In Figure 5, the x-axis represents the wind power level relative to the WPF's installed capacity; the y-axis shows the magnitude of the fluctuations normalized with respect to the WPF's installed capacity. Figure 5 shows that the shapes of the average fluctuations were captured even though the simulated fluctuations were lower than those measured. In Figure 6, the x-axis represents percentiles of the distributions of fluctuations; the y-axis shows the percentage of the fluctuations normalized with respect to the WPF's installed capacity. The 97.5 percentile of measured and simulated increase were 17.0% and 12.9% of the installed capacity, respectively; the 97.5 percentile of measured and simulated decrease were 15.5% and 12.4% the installed capacity, respectively. A short section of time series of measured and simulated 10-minute wind power generation is displayed in Figure 7. Results of the 1-minute fluctuations for WPF4 are displayed in Figure 8 and Figure 9.

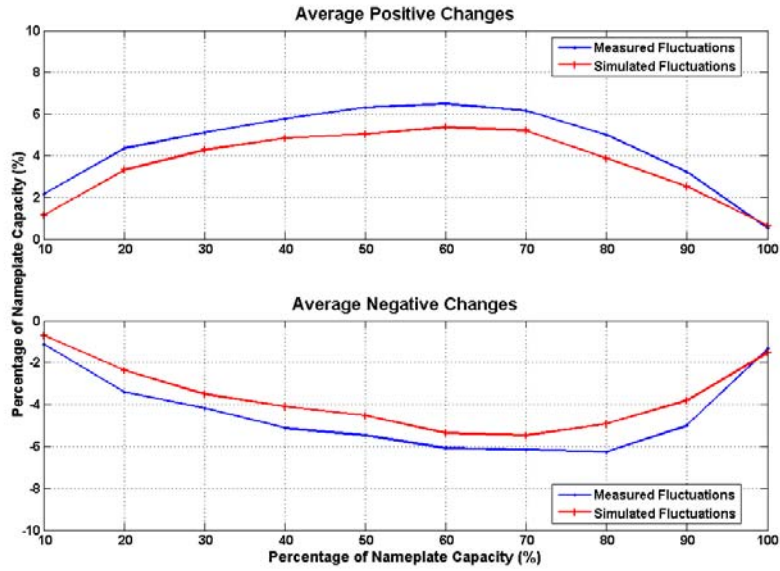


Figure 5: Comparison of Normalized Magnitudes of Measured and Simulated Power Fluctuations for WPF4 (10-Minute)

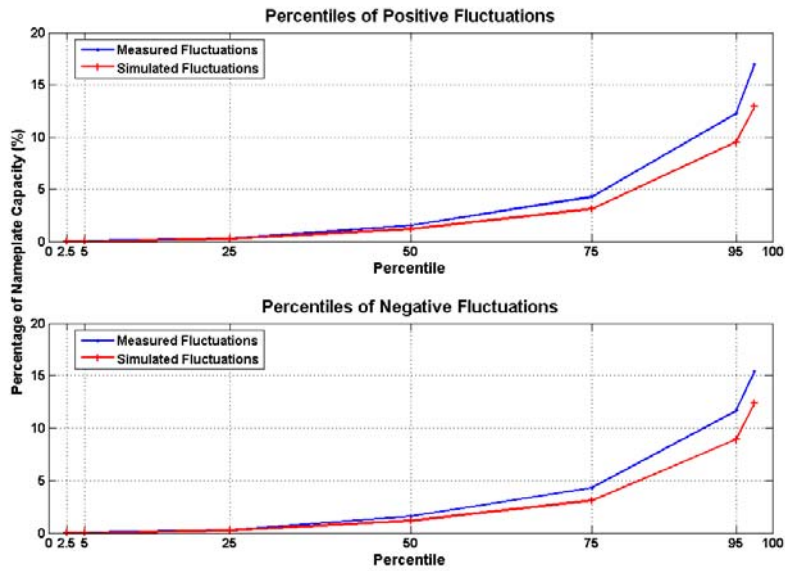


Figure 6: Comparison of Normalized Percentiles of Measured and Simulated Power Fluctuations for WPF4 (10-Minute)

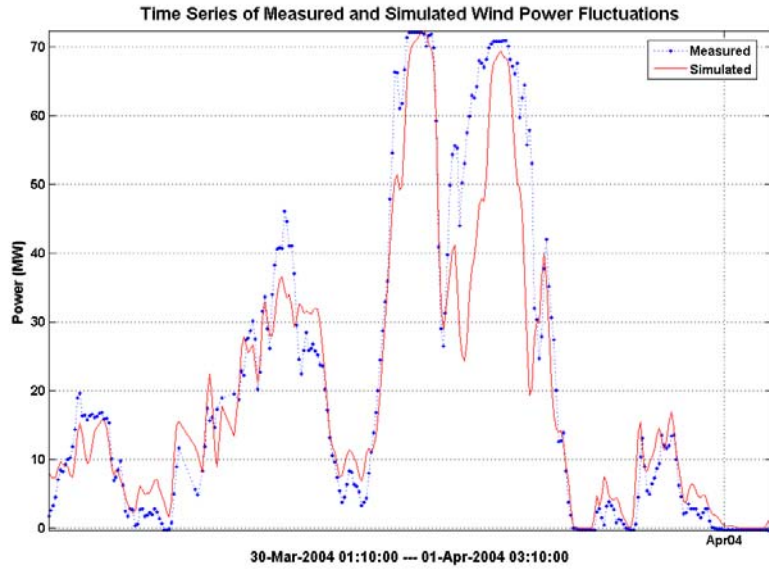


Figure 7: Comparison of Measured and Simulated Time Series for WPF4 (10-Minute)

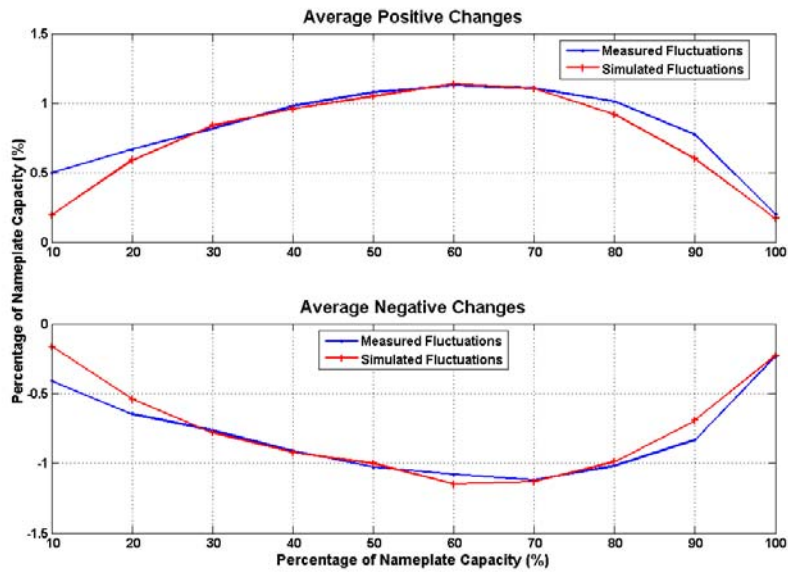


Figure 8: Comparison of Normalized Magnitudes of Measured and Simulated Power Fluctuations for WPF4 (1-Minute)

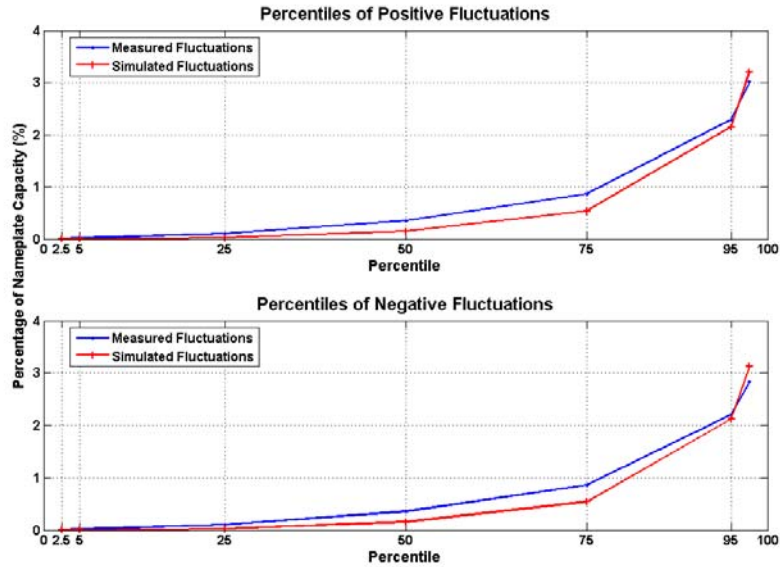


Figure 9: Comparison of Normalized Percentiles of Measured and Simulated Power Fluctuations for WPF4 (1-Minute)

### 3.3.2 Validation Within a Region

Validation was performed for the benchmark scenario consisting of four existing WPFs with a combined total capacity of 223 MW. The normalized magnitude of combined fluctuations shown in Figure 10 is significantly lower than that of the fluctuations for a single WPF, as shown in Figure 5. This indicates that geographical diversity of WPFs has the effect of decreasing wind power fluctuations as a percentage of capacity. The same pattern appeared for the normalized percentiles of fluctuations and is shown in Figure 11. A short section of time series of measured and simulated 10-minute wind power generation is displayed in Figure 12. The results of 1-minute fluctuations are displayed in Figure 13 and Figure 14.

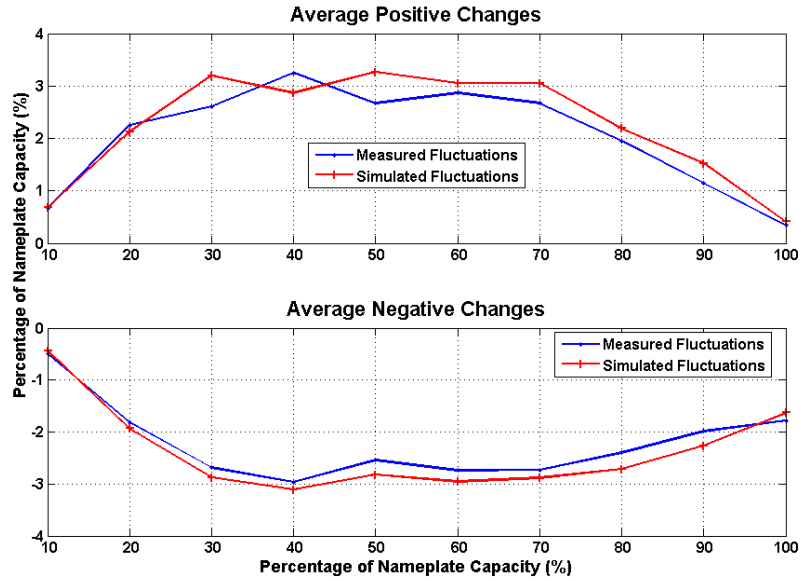


Figure 10: Comparison of Normalized Magnitudes of Measured and Simulated Power Fluctuations for the Benchmark Scenario (10-Minute)

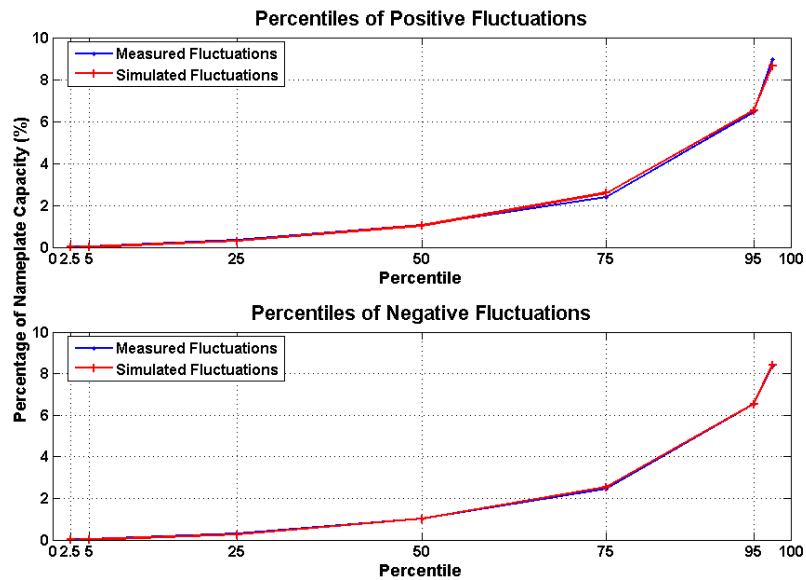


Figure 11: Comparison of Normalized Percentiles of Measured and Simulated Power Fluctuations for the Benchmark Scenario (10-Minute)

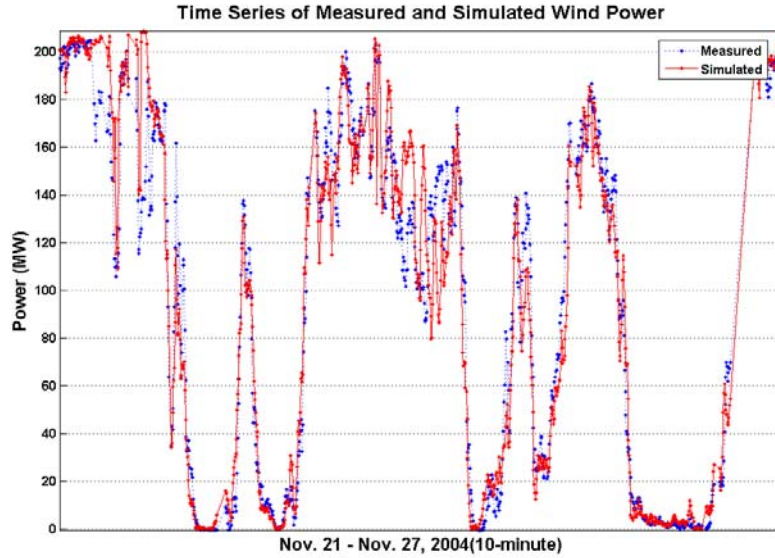


Figure 12: Comparison of Measured and Simulated Time Series for the Benchmark Scenario (10-Minute)

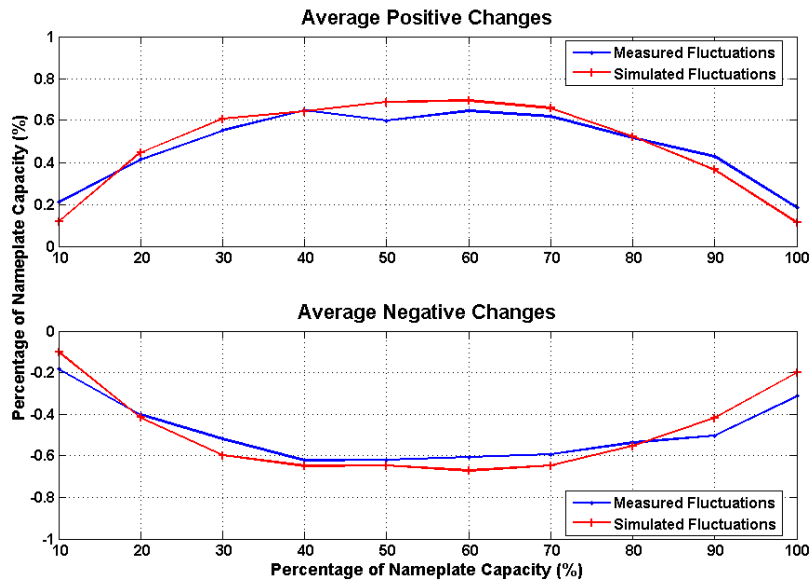


Figure 13: Comparison of Normalized Magnitudes of Measured and Simulated Power Fluctuations for the Benchmark Scenario (1-Minute)

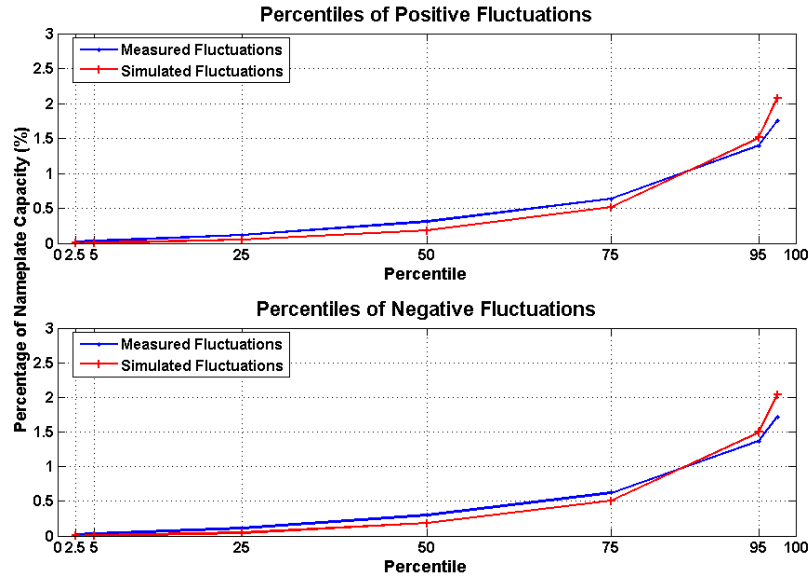


Figure 14: Comparison of Normalized Percentiles of Measured and Simulated Power Fluctuations for the Benchmark Scenario (1-Minute)

### 3.4 Sensitivity Analysis

The effects of varying model parameters were assessed: WPF dimensions, *turbulence intensity*, air density, wake/array losses, and electrical losses. To examine the effects of a particular model parameter, the values of other parameters must be fixed. This limits the effect of interaction between parameters and isolates the effects of the variable parameter.

#### 3.4.1 The Effect of Wind Turbine Power Curves

It was found that the proposed model is sensitive to the choice of the single-turbine power curve. The higher the rated power of the power curve, the lower the wind power variability for a fixed nameplate capacity. These results are illustrated in Figure 15. The reduction in wind power variability may be related to either the rated power of the wind turbine power curve or the effect of spatial separation of wind turbines since the two parameters are interrelated.

- Fixed model inputs: Area dimension = 10 kilometer; turbulence intensity = 10%; nameplate capacity = 100 MW; air density = 1.14 kg/m<sup>3</sup>.
- Varied model input: Vestas 90 (V90), Vestas 80 (V80), GE77, and Enercon70.

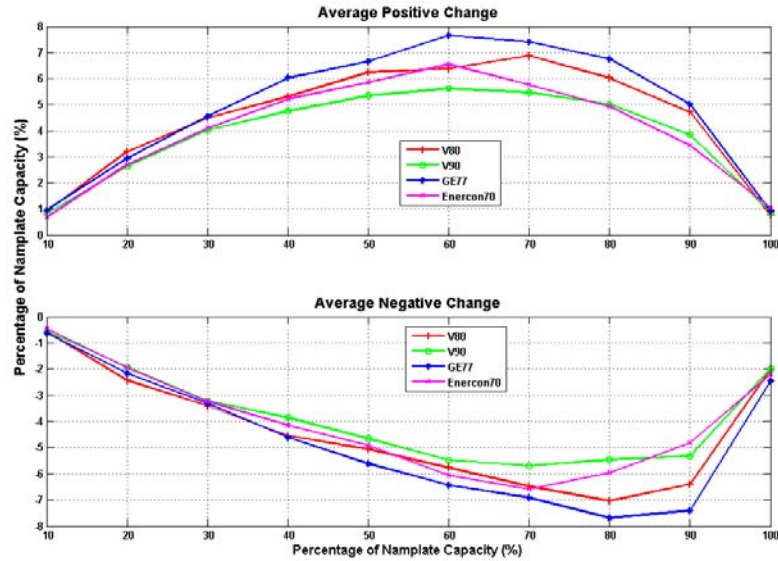


Figure 15: Sensitivity Analysis on the Effect of Wind Turbine Power Curves

### 3.4.2 The Effect of WPF Size

The model was found to be sensitive to the effect of spatial separation of wind turbines. The wind power variability decreases when the WPF dimension increases. To assess the effect of the size of WPFs in realistic scenarios, nameplate capacity density was used. Rather than specifying the dimensions of the WPF directly, the representative values of nameplate capacity density were first specified and then the corresponding WPF's dimensions were calculated as inputs to the model. Existing or planned WPFs' nameplate capacity densities are plotted against their nameplate capacities in Figure 4. Further, to control the effect of interaction between nameplate capacity and area dimension, the effect of area dimension was assessed at different levels of nameplate capacity: 200 MW, 100 MW, 70 MW, and 30 MW. The analysis output is illustrated in Figure 16 through Figure 18.

*Nameplate capacity = 200 MW*

- Fixed model inputs: turbulence intensity = 10%; turbine model = V90; air density = 1.14 kg/m<sup>3</sup>;

- Varied model input: size = 5.8, 7.1, 8.2, 10 and 14.9 kilometers, which correspond to approximate nameplate capacity densities of 6, 4, 3, 2, and 0.9 MW/km<sup>2</sup>, respectively.

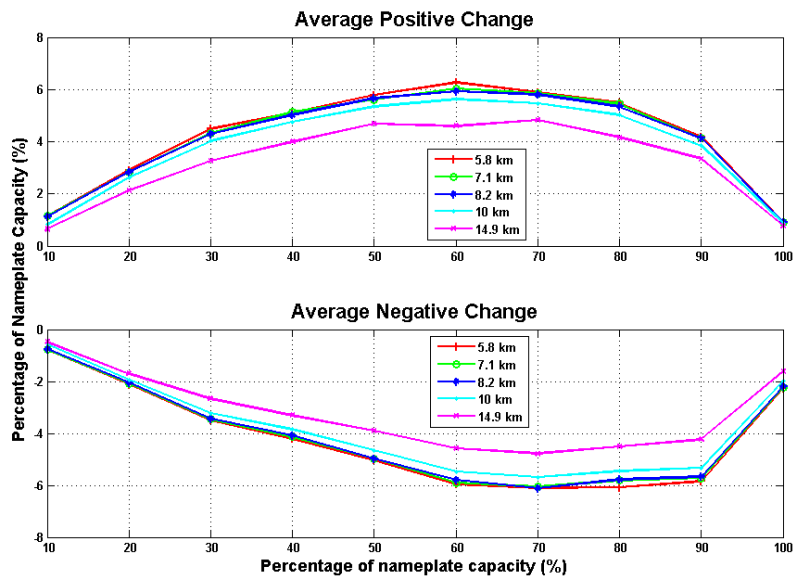


Figure 16: Sensitivity Analysis on the Effect of Area Dimension with a 200 MW Nameplate Capacity

Nameplate capacity = 100 MW

- Fixed model inputs: turbulence intensity = 10%; turbine model = V90; air density = 1.14 kg/m<sup>3</sup>;
- Varied model input: size = 4.1, 5, 5.8, 7.1 and 10.5 kilometers, which correspond to approximate nameplate capacity densities of 6, 4, 3, 2, and 0.9 MW/km<sup>2</sup>, respectively.

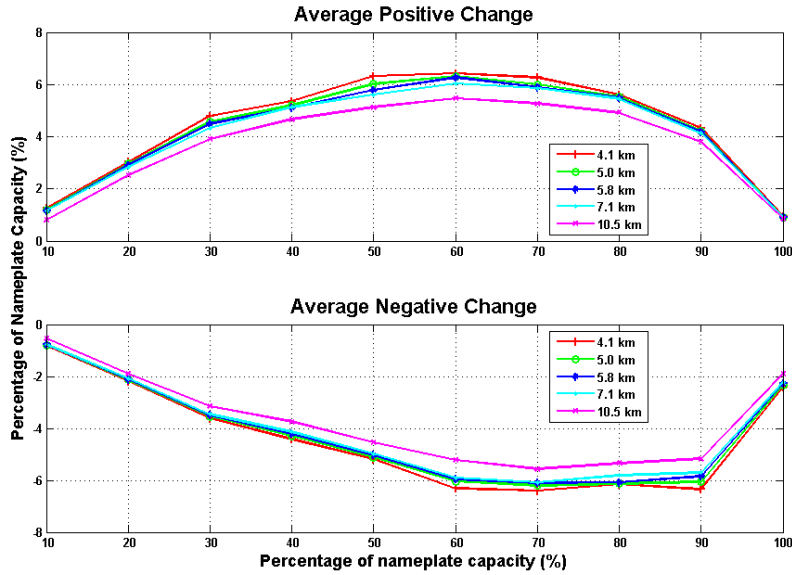


Figure 17: Sensitivity Analysis on the Effect of Area Dimension with a 100 MW Nameplate Capacity

Nameplate capacity = 70 MW

- Fixed model inputs: turbulence intensity = 10%; turbine model = V90; air density = 1.14 kg/m<sup>3</sup>;
- Varied model input: size = 3.4, 4.2, 4.8, 5.9 and 8.8 kilometers, which correspond to approximate nameplate capacity densities of 6, 4, 3, 2, and 0.9 MW/km<sup>2</sup>, respectively.

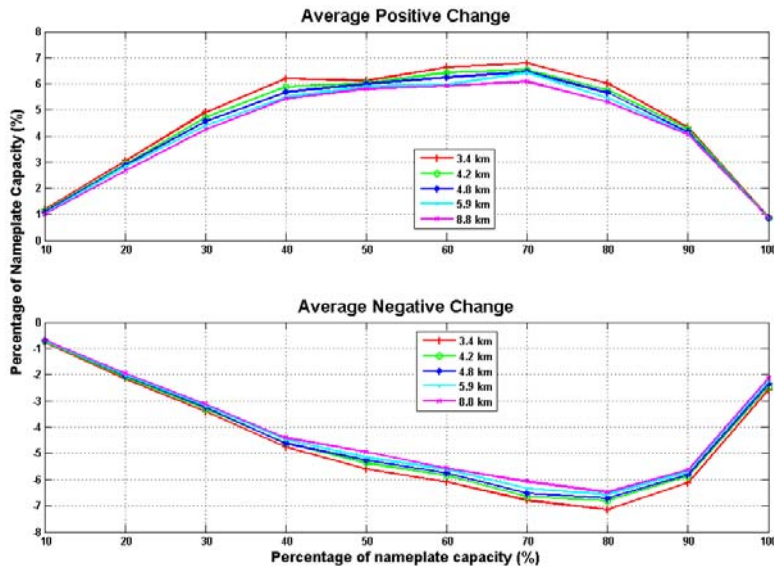


Figure 18: Sensitivity Analysis on the Effect of Area Dimension with a 70 MW Nameplate Capacity

Nameplate capacity = 30 MW

- Fixed model inputs: turbulence intensity = 10%; turbine model = V90; air density = 1.14 kg/m<sup>3</sup>;
- Varied model input: size = 2.2, 2.7, 3.2, 3.9 and 5.8 kilometers, which correspond to approximate nameplate capacity densities of 6, 4, 2, 3 and 0.9 MW/km<sup>2</sup>, respectively.

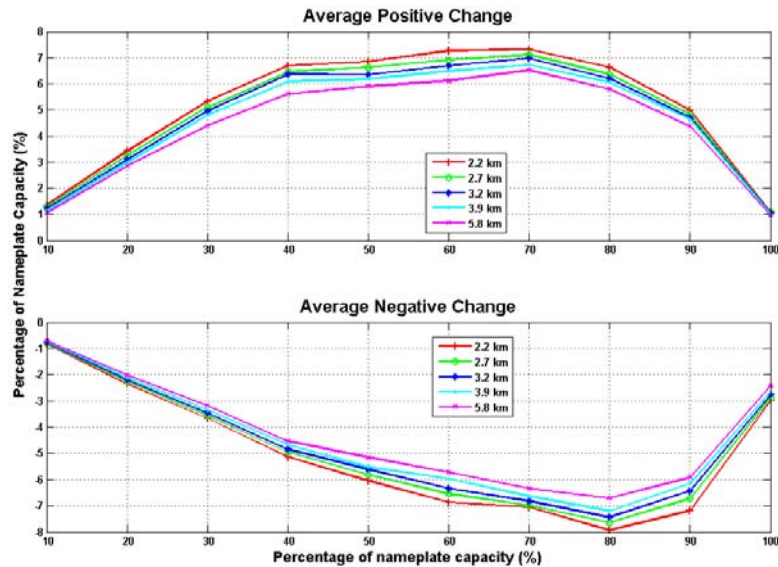


Figure 19: Sensitivity Analysis on the Effect of Area Dimension with a 30 MW Nameplate Capacity

### 3.4.3 The Effect of Turbulence Intensity

The model is not sensitive to turbulence intensity since the same wind speed time series was used for modelling each wind turbine in a given WPF. As a result, the real local turbulence intensity was not represented. The analysis output is illustrated in Figure 20.

- Fixed model inputs: Area dimension = 10 kilometers; turbine model = V90; air density = 1.14 kg/m<sup>3</sup>; nameplate capacity = 100 MW
- Varied model input: turbulence intensity = 5%, 10%, 15%, and 20%.

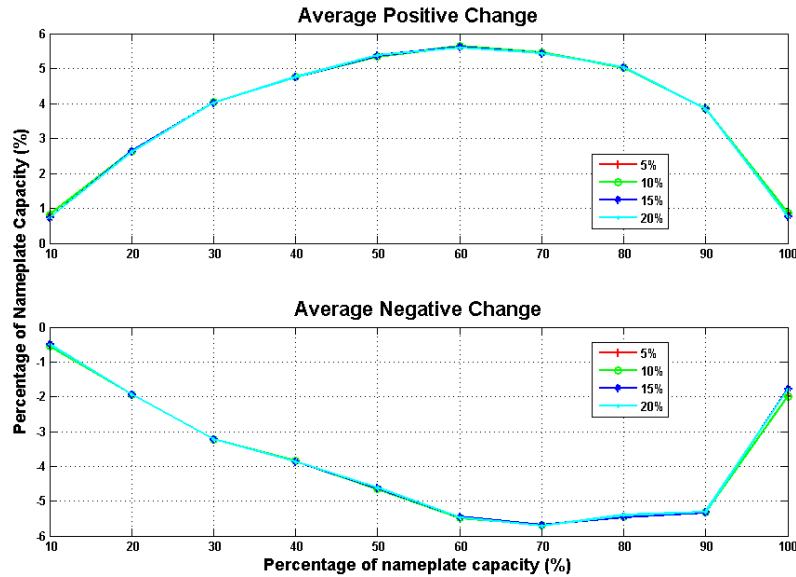


Figure 20: Sensitivity Analysis on the Effect of Turbulence Intensity

### 3.4.4 The Effect of Air Density

It was found that the higher the air density, the greater the wind power variability. This analysis was performed by specifying the wind turbine power curves at different air densities. The analysis output is illustrated in Figure 21.

- Fixed model inputs: Area dimension = 10 kilometers; turbulence intensity = 10%; turbine model = V90; nameplate capacity = 100 MW
- Varied model input: air density = 0.97, 1.06, 1.12, 1.18 and 1.27 kg/m<sup>3</sup>

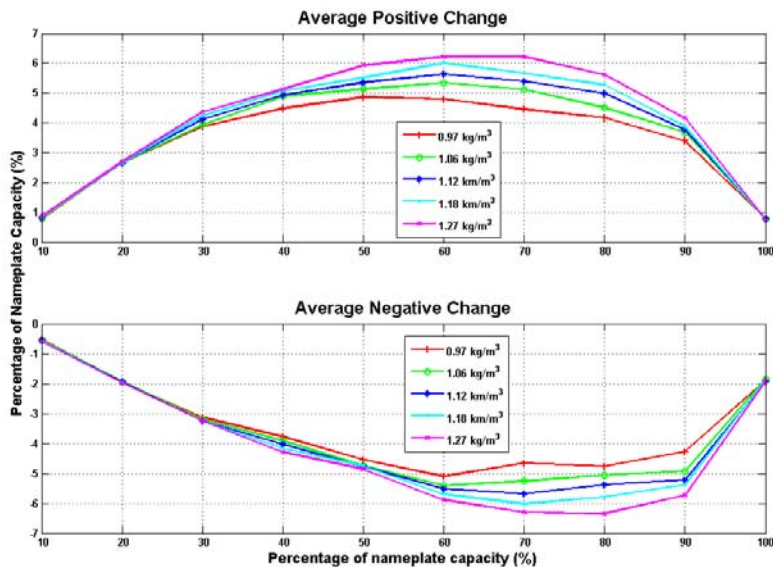


Figure 21: Sensitivity Analysis on the Effect of Air Density

### 3.4.5 The Effect of Wake/Array Loss

It was found that wake/array loss is not a significant parameter of the model. Comparison of a WPF's power curve with and without the effect of wake/array loss is illustrated in Figure 22. The analysis output is displayed in Figure 23.

- Fixed model inputs: Area dimension = 3.4 kilometers; turbulence intensity = 10%; turbine model = V90; air density = 1.14 kg/m<sup>3</sup>; nameplate capacity = 51 MW
- Varied model input: V90 power curve with and without wake/array loss

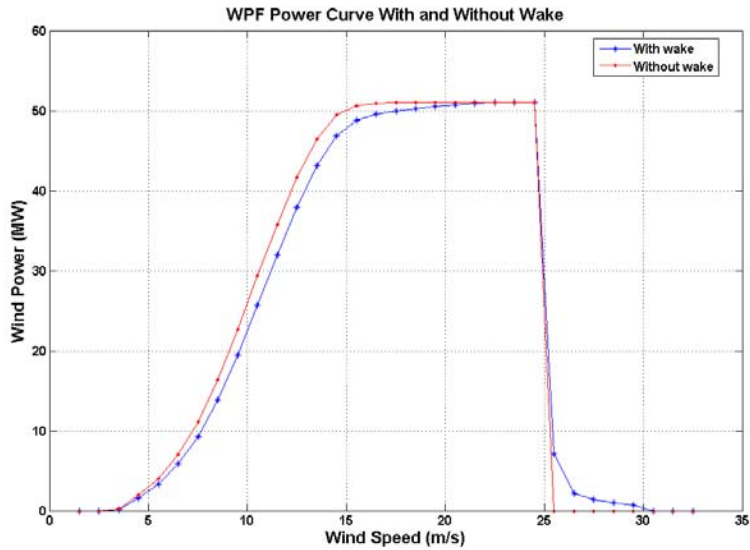


Figure 22: Power Curves With and Without Wake/Array Loss

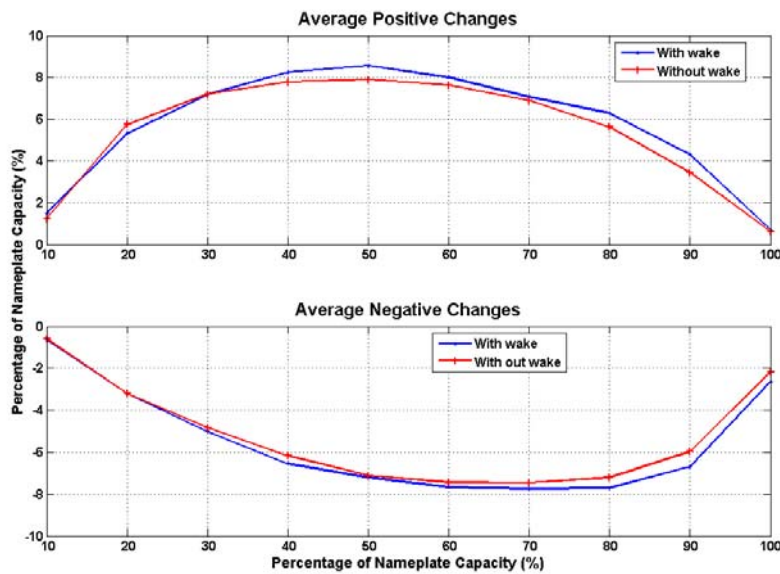


Figure 23: Sensitivity Analysis on the Effect of Wake/Array Loss

### 3.4.6 The Effect of Electrical Loss

The effect of electrical loss becomes more apparent as the output of a WPF approaches its nameplate capacity. Comparison of a WPF's power curve with and without the effect of electrical loss is illustrated in Figure 24. The analysis output is displayed in Figure 25.

- Fixed model inputs: Area dimension = 10 kilometers; turbulence intensity = 10%; turbine model = V90; air density = 1.14 kg/m<sup>3</sup>; nameplate capacity = 100 MW
- Varied model input: V90 power curve with and without 5% electrical loss

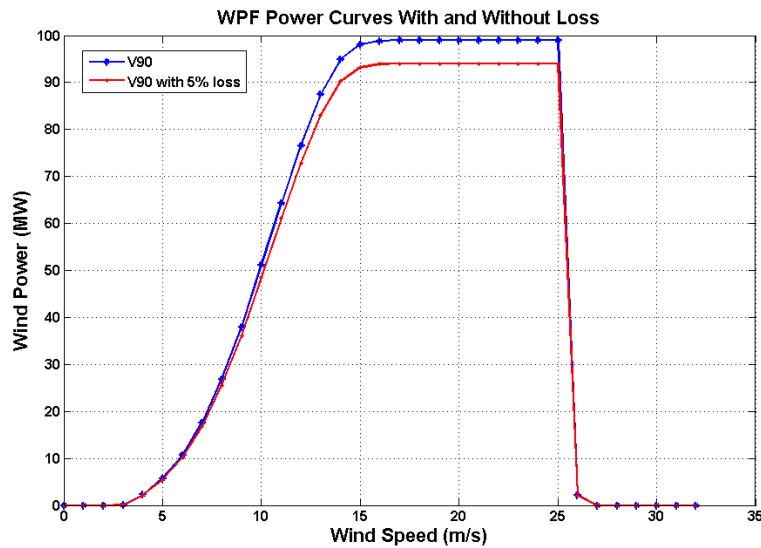


Figure 24: WPF Power Curve With and Without 5% Electrical Loss

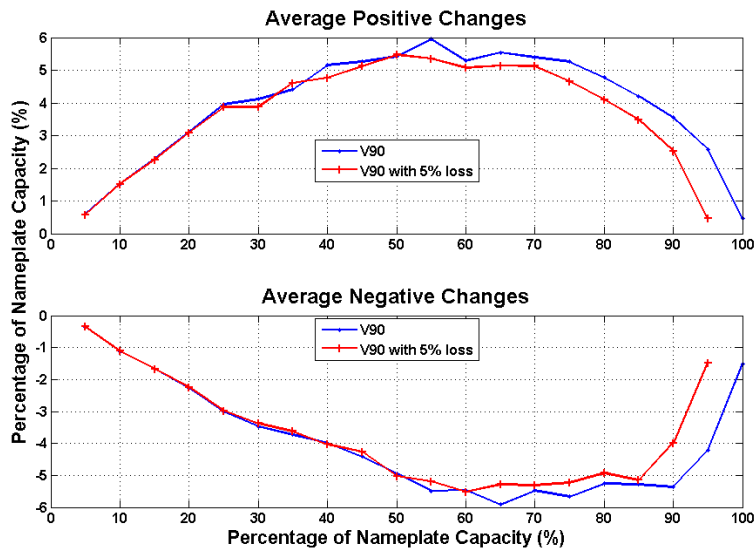


Figure 25: Sensitivity Analysis on the Effect of Electrical Loss

## 4 Simulation of Existing and Future Scenarios

Using the validated models described in the preceding section, wind power generation time series were simulated for existing and potential future WPFs. The simulated wind power generation time series were then combined for the potential WPF development scenarios.

#### 4.1 Scenario Description

Figure 26 illustrates the distribution of potential WPF development areas. The Southern part of Alberta was divided into six areas. These areas are Pincher Creek, Waterton, Fort Macleod/Magrath, Taber, Medicine Hat, and North; however, potential WPF development in the North area is not included in the analysis since local wind meteorological data is unavailable until late in August 2004.

One existing scenario (Scenario A) and three future scenarios (Scenarios B, C and D) were studied. Future development scenarios were grouped according to approximate commissioning dates envisioned by the wind developers. Three future scenarios were presented based on proposed total provincial WPF capacities of 895, 1445, and 1994 MW. The design of the future scenarios was addressed in the Scope Document [2].

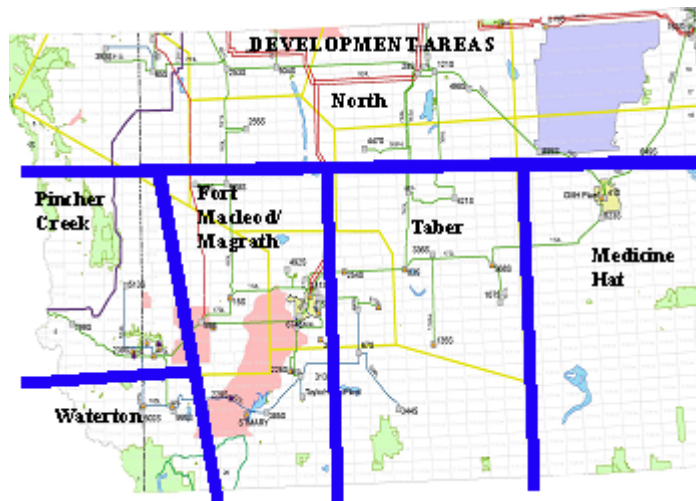


Figure 26: Distribution of Potential WPF Development Areas

Scenario A includes 5 existing WPFs and has a total nameplate capacity of 254 MW. The WPFs in Scenario A are located in the areas of Pincher Creek and Fort Macleod/Magrath. Wind meteorological data has been collected from 5 monitoring towers that are designed for wind resource assessment of these WPFs.

Scenario B has 5 existing and 9 proposed WPFs and a total nameplate capacity of 895 MW. The WPFs in Scenario B are located in the areas of Pincher Creek, Fort Macleod/Magrath and Taber. Wind meteorological data has been collected from 14 local monitoring towers. The quality of wind data (Jan. 1, 2004 – Dec. 31, 2004) is summarized in Table 17 and Table 18 of the Appendix.

Scenario C has 5 existing and 17 proposed WPFs and a total nameplate capacity of 1445 MW. The WPFs in Scenario B are located in the areas of Pincher Creek, Fort Macleod/Magrath, Taber and Medicine Hat. Wind meteorological data has been collected from 22 local monitoring towers. The quality of wind data (Jan. 1, 2004 – Dec. 31, 2004) is summarized in Table 19 and Table 20 of the Appendix.

Scenario D has 5 existing and 22 proposed WPFs and a total nameplate capacity 1994 MW. The WPFs in Scenario B are located in the areas of Pincher Creek, Fort Macleod/Magrath, Taber, Medicine Hat and Waterton. Wind meteorological data has been collected from 27 local monitoring towers. The quality of wind data (Jan. 1, 2004 – Dec. 31, 2004) is summarized in Table 21 and Table 22 of the Appendix.

#### 4.2 Simulated Wind Power Fluctuations

The top percentiles of simulated 10-minute and 1-minute fluctuations for the above scenarios are summarized in Table 6 and Table 7. These values are independent of the direction (positive and negative) of fluctuation. In Table 6, the maximum of the simulated 10-minute fluctuations are 32.3%, 22.6%, 14.4%, and 13.0% of the total capacities for Scenarios A, B, C and D, respectively. In Table 7, the maximum of the simulated 1-minute fluctuations are 25.8%, 12.9%, 10.3%, and 11.1% of the total capacities for Scenarios A, B, C and D,

respectively. It can be seen that extreme fluctuations are rare. For example, Table 6 shows that only 0.5% of the simulated 10-minute fluctuations are greater than 30, 63, 85, and 106 MW for Scenarios A, B, C and D, respectively. Similarly, Table 7 shows that only 0.5% of the simulated 1-minute fluctuations are greater than 8, 15, 19, and 23 MW for Scenarios A, B, C and D, respectively.

*Table 6: Percentiles of Simulated 10-Minute Fluctuations for Scenarios A, B, C, and D (MW)*

	95.0%	97.5%	99.5%	Maximum
Scenario A (254 MW)	14.70	18.76	29.69	82.01
Scenario B (895 MW)	31.68	40.08	62.99	202.07
Scenario C (1445 MW)	44.84	56.33	84.85	208.48
Scenario D (1994 MW)	55.34	69.60	105.58	259.12

*Table 7: Percentiles of Simulated 1-Minute Fluctuations for Scenarios A, B, C, and D (MW)*

	95.0%	97.5%	99.5%	Maximum
Scenario A (254 MW)	3.48	4.69	8.24	65.63
Scenario B (895 MW)	6.81	8.82	14.63	115.86
Scenario C (1445 MW)	9.14	11.67	18.64	148.61
Scenario D (1994 MW)	11.09	14.17	22.87	221.87

Comparisons of the magnitudes and percentiles of simulated 10-minute fluctuations for the various scenarios are displayed in Figure 27 and Figure 28. Comparisons of the normalized magnitudes and percentiles of simulated 10-minute fluctuations are displayed in Figure 31 and Figure 32 of the Appendix.

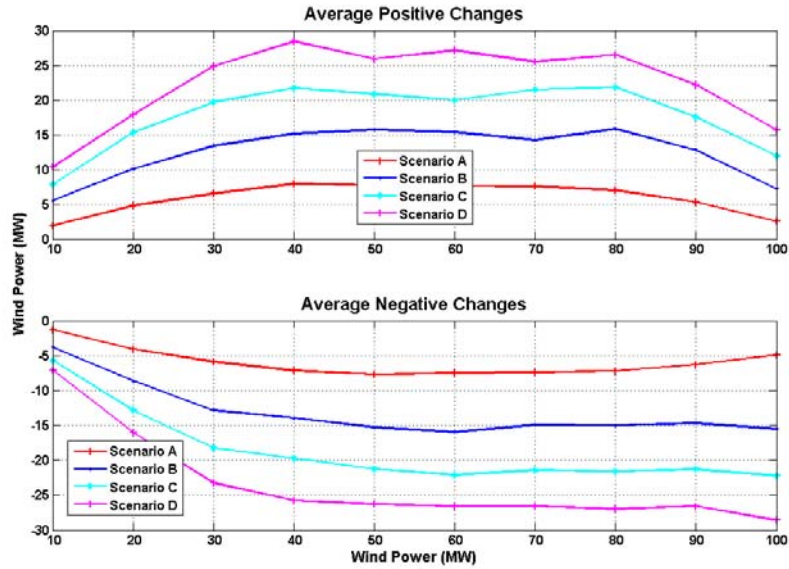


Figure 27: Comparison of the Magnitudes of Simulated Fluctuations for Scenarios A, B, C, and D (10-Minute)

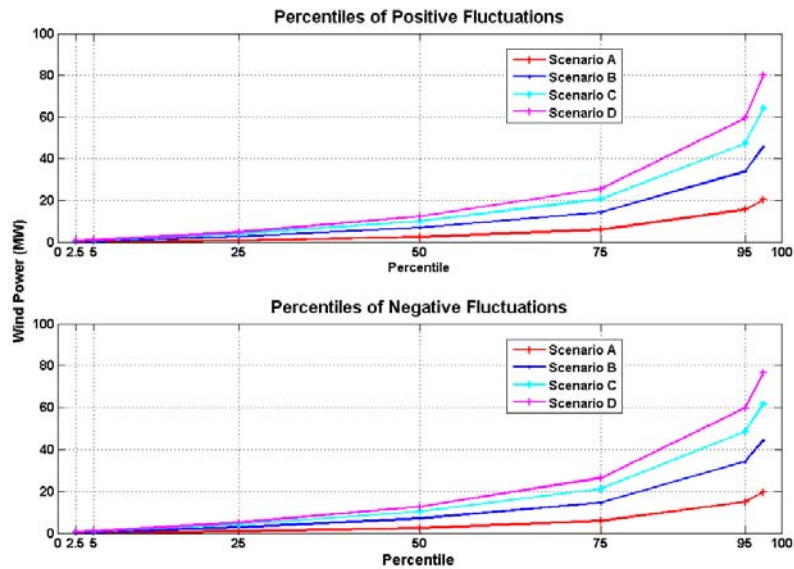


Figure 28: Comparison of the Percentiles of Simulated Fluctuations for Scenarios A, B, C, and D (10-Minute)

Comparisons of the magnitudes and percentiles of simulated 1-minute fluctuations for the various scenarios are displayed in Figure 29 and Figure 30. Comparisons of the normalized magnitudes and percentiles of simulated 1-minute fluctuations for the various scenarios are displayed in Figure 33 and Figure 34 of the Appendix.

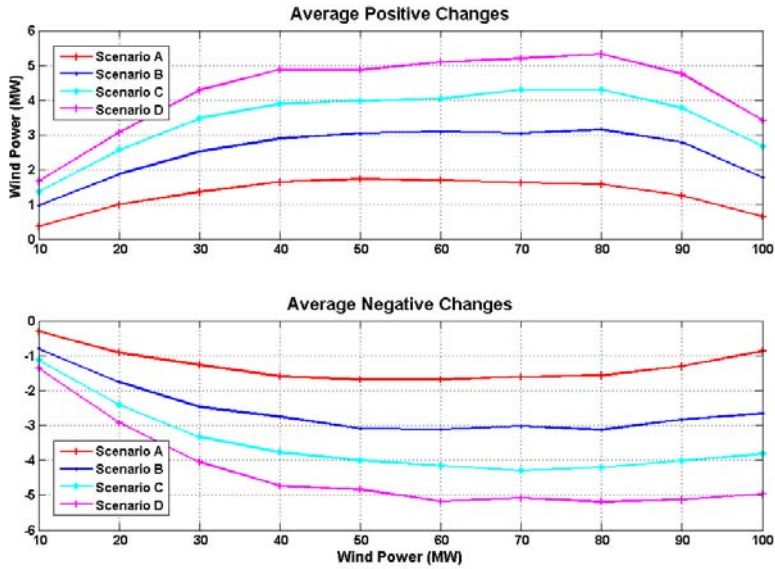


Figure 29: Comparison of the Magnitudes of Simulated Fluctuations for Scenarios A, B, C, and D (1-Minute)

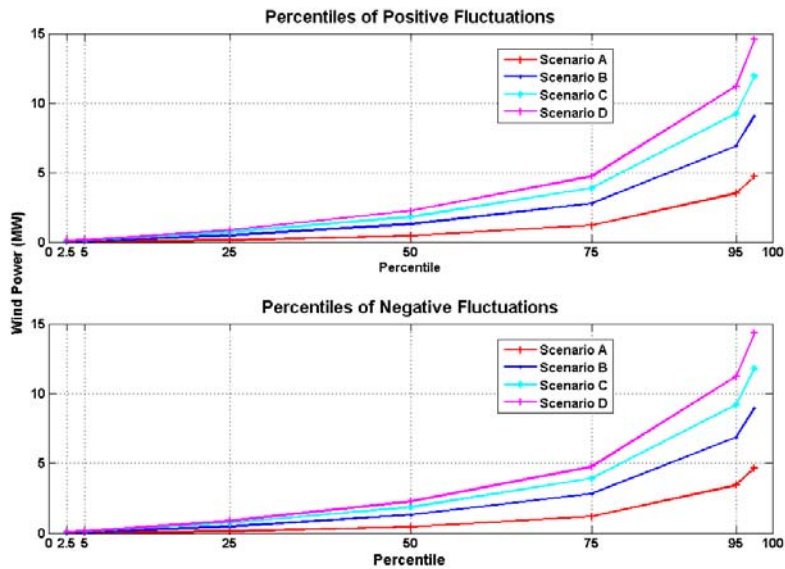


Figure 30: Comparisons of the Percentiles of Simulated Fluctuations for Scenarios A, B, C, and D (1-Minute)

The time series of simulated wind power at high, moderate and low capacity factors for future scenarios are displayed in Figure 35 through Figure 43 of the Appendix. These illustrate the real-time simulated wind power generation.

The distributions of WPFs that are simultaneously in high wind speed cut-out mode are shown in Table 23, Table 24 and Table 25. These figures show the frequency of high wind speed cut-out for 10-minute, 1-hour and 2-hour time intervals. It was found that large numbers of WPFs are rarely in high wind speed cut-out mode simultaneously.

## 5 Conclusions

One of objectives of this study was to simulate wind power generation in future scenarios in which the wind power capacity ranges from 254 MW to 1994 MW. Based on the investigation of fluctuation characteristics of the existing WPFs in Southern Alberta, a modified multi-turbine power curve approach was proposed. The approach was validated by comparing the measured and simulated fluctuations within a WPF and a region. The approach was able to capture the magnitude and frequency of short-term fluctuations (10-minute and 1-minute) with reasonable accuracy. The performance of the simulation is summarized in Table 8. Sensitivity analyses for the variation of a number of model parameters were also performed.

*Table 8: Normalized 97.5 Percentiles of the Measured and Simulated Fluctuations*

	10-minute		1-minute	
	Measured	Simulated	Measured	Simulated
WPF1	14.6	12.5	2.6	3.1
WPF2	18.3	21.1	3.8	4.9
WPF3	17.2	17.1	5.4	4.2
WPF4	16.1	19.9	5.1	4.7
Aggregate Scenario	8.4	8.5	1.7	2.1

Another objective of the study was to assess the magnitude and frequency of wind power fluctuations at different wind energy penetration levels. The major statistical findings can be summarized as follows:

- The magnitude of power fluctuations caused by wind speed variations was seldom extreme even though wind power fluctuations were stochastic in nature. For example, the maximum normalized 97.5 percentile of 10-minute measured fluctuation among 4 existing WPFs was 18.3% of the corresponding installed capacity while it was 5.4% for 1-minute fluctuations.
- The effect of geographically separated WPFs was shown clearly by the measured and simulated wind power data. For example, the normalized 97.5 percentile of 10-minute and 1-minute measured fluctuations for aggregate scenarios (8.4% and 1.7%, respectively) were lower than those for any single WPF. The normalized 97.5 percentiles of 10-minute simulated fluctuations for Scenarios A, B, C, and D were 7.4%, 4.5%, 3.9%, and 3.5% of the corresponding total capacity while they were 1.8%, 1.0%, 0.8%, and 0.7% for 1-minute simulated fluctuations.
- The absolute magnitude of fluctuations increased when the system nameplate capacity increased. For example, The 97.5 percentiles of 10-minute simulated fluctuations for Scenarios A, B, C, and D were 18.8, 40.1, 56.3 and 69.6 MW, respectively, while they were 4.7, 8.8, 11.7, and 14.2 MW for 1-minute simulated fluctuations.

## 6 References

- [1] Per Nørgard and Hannele Holttinen, A Multi-Turbine Power Curve Approach. Proceedings of Nordic Wind Power. Conference NWPC'04, 1.-2.2004.
- [2] Baker, D.R., Alberta Wind Power Variability Study: Draft Scope Document, Phoenix Engineering Inc. Under Contract to the Alberta Electric System Operator, Calgary, Alberta. November 2004.
- [3] Yih-huei Wan and Demy Bucaneg, Jr., 2002. Short-Term Power Fluctuations of Large Wind Power Plants. National Renewable Energy Laboratory.
- [4] Per Nørgard, Hannele Holttinen and Astrid Petterteig. Fluctuations and Predictability of Wind and Hydropower. RisØ National Laboratory, Denmark, 2004.

## 7 Appendix

*Table 9: 1-Minute Normalized Fluctuations of WPF2 as a Percentage of its Capacity*

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
0.82	2.41	9.99	-36.60	1.36	1.68	93.42	-1.23	1.14	-8.33
14.69	2.89	19.98	10.01	1.23	1.30	33.85	-1.12	1.02	-10.96
24.85	2.93	30.00	20.00	1.43	1.54	31.41	-1.30	1.22	-23.27
34.87	2.79	39.99	30.02	1.62	1.72	23.85	-1.50	1.46	-37.21
45.21	2.92	50.00	40.01	1.73	1.79	21.98	-1.65	1.63	-28.07
54.96	2.88	59.99	50.00	1.72	1.80	32.16	-1.69	1.80	-51.78
65.48	2.77	69.98	60.01	1.48	1.57	19.01	-1.53	2.00	-64.94
75.28	2.96	80.00	70.00	1.58	1.46	12.72	-1.65	1.89	-71.64
85.77	2.76	89.99	80.02	1.03	0.95	9.06	-1.14	1.32	-43.42
93.57	2.04	97.22	90.01	0.55	0.50	5.12	-0.64	0.73	-27.78

*Table 10: 10-Minute Normalized Fluctuations of WPF2 as a Percentage of its Capacity*

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
0.85	2.38	9.99	-3.51	3.58	5.77	78.00	-2.11	1.84	-9.99
14.76	2.90	19.99	10.00	5.16	6.90	62.82	-3.43	2.88	-16.78
24.83	2.89	29.99	20.00	6.45	7.89	52.03	-4.74	3.98	-26.62
34.75	2.81	39.99	30.00	6.80	7.50	57.16	-5.60	5.26	-31.30
45.20	2.93	49.99	40.00	7.33	7.20	46.94	-6.80	6.77	-43.23
55.04	2.85	60.00	50.00	7.07	6.81	41.62	-6.55	6.64	-50.01
65.52	2.79	69.99	60.01	5.06	5.90	29.86	-5.93	7.66	-65.07
75.27	2.93	80.00	70.00	5.06	4.40	21.58	-7.37	8.17	-60.99
85.78	2.79	89.99	80.00	2.49	2.42	13.01	-4.18	5.95	-63.13
93.54	2.01	96.64	90.00	0.57	0.82	6.05	-1.50	3.35	-45.94

*Table 11: 1-Minute Normalized Fluctuations of WPF3 as a Percentage of its Capacity*

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
1.02	2.65	10.00	-2.86	0.55	0.77	34.29	-0.45	0.46	-9.92
14.82	2.91	20.00	10.00	1.28	1.55	28.00	-1.08	1.05	-15.35
24.99	2.88	30.00	20.00	1.73	1.94	25.34	-1.51	1.46	-29.05
34.97	2.88	40.00	30.00	2.02	2.27	43.15	-1.82	1.77	-30.33
44.95	2.88	50.00	40.00	2.13	2.19	30.32	-2.01	1.97	-22.50
55.05	2.90	60.00	50.00	2.23	2.20	33.06	-2.19	2.29	-53.36
65.04	2.88	70.00	60.00	2.02	1.87	20.58	-2.14	2.12	-42.62
75.13	2.88	80.00	70.00	1.77	1.58	15.16	-1.87	1.78	-20.50
85.33	2.86	90.00	80.00	1.24	1.14	13.31	-1.41	1.45	-43.35
93.16	1.94	99.98	90.00	0.70	0.63	7.04	-0.89	1.04	-36.32

Table 12: 10-Minute Normalized Fluctuations of WPF3 as a Percentage of its Capacity

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
1.02	2.64	10.00	-2.38	1.42	3.18	63.16	-0.78	1.05	-9.59
14.79	2.95	19.99	10.00	5.23	6.26	60.93	-3.60	2.86	-18.44
25.02	2.94	29.99	20.00	6.21	6.32	45.50	-4.89	4.18	-29.17
35.01	2.84	40.00	30.00	7.01	7.35	48.51	-5.64	5.11	-38.94
44.98	2.84	49.99	40.01	6.75	6.70	52.16	-6.30	6.08	-43.81
54.96	2.89	60.00	50.01	6.28	5.74	35.98	-6.64	6.27	-50.87
65.00	2.87	70.00	60.01	5.43	4.67	29.00	-6.69	6.68	-57.83
75.12	2.86	80.00	70.00	4.48	3.86	22.18	-5.90	6.07	-51.53
85.35	2.87	90.00	80.01	2.53	2.20	14.43	-4.45	5.48	-59.63
93.49	2.12	99.94	90.01	1.00	1.00	6.76	-2.27	3.77	-56.01

Table 13: 1-Minute Normalized Fluctuations of WPF4 as a Percentage of its Capacity

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
0.73	2.39	10.00	-22.92	0.49	0.97	59.87	-0.41	0.60	-6.32
14.75	2.85	20.00	10.00	0.66	0.85	21.62	-0.64	0.72	-16.12
24.90	2.88	30.00	20.00	0.81	1.27	69.24	-0.77	0.90	-27.49
34.83	2.88	40.00	30.00	0.97	1.23	41.10	-0.91	1.08	-49.66
44.97	2.89	50.00	40.00	1.07	1.29	43.25	-1.02	1.01	-14.15
55.02	2.89	60.00	50.00	1.13	1.46	37.43	-1.08	1.18	-31.30
64.94	2.91	70.00	60.00	1.11	1.17	27.31	-1.12	1.44	-65.59
75.15	2.87	80.00	70.00	1.02	0.99	16.33	-1.02	1.05	-20.49
85.42	2.88	90.00	80.00	0.78	0.74	9.25	-0.84	1.18	-81.69
94.29	1.54	96.48	90.00	0.20	0.28	4.24	-0.24	0.71	-80.06

Table 14: 10-Minute Normalized Fluctuations of WPF4 as a Percentage of its Capacity

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
0.76	2.41	9.99	-21.49	2.12	4.50	65.09	-1.13	1.49	-9.13
14.71	2.84	19.99	10.00	4.27	5.83	63.78	-3.38	2.98	-34.28
24.90	2.91	29.99	20.00	5.13	6.37	63.63	-4.16	3.87	-27.17
34.79	2.88	40.00	30.01	5.73	6.45	53.90	-5.11	4.74	-34.62
44.90	2.89	49.99	40.00	6.26	6.32	40.09	-5.46	5.36	-48.74
55.07	2.87	59.99	50.00	6.53	6.27	35.85	-6.08	6.04	-56.32
64.97	2.91	69.99	60.01	6.19	5.65	31.62	-6.17	6.62	-62.47
75.22	2.84	79.99	70.00	5.04	4.27	22.14	-6.20	6.45	-57.65
85.47	2.89	90.00	80.00	3.25	2.62	14.68	-5.11	6.22	-71.02
94.27	1.52	96.31	90.00	0.53	0.78	5.11	-1.35	3.35	-65.63

*Table 15: 1-Minute Normalized Fluctuations of WPF5 as a Percentage of its Capacity*

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
1.57	2.74	9.99	0.00	0.87	1.11	39.71	-0.70	0.48	-9.99
14.71	2.87	19.99	10.03	1.33	1.30	19.14	-1.13	0.87	-10.42
24.80	2.89	29.98	20.02	1.76	1.76	29.16	-1.55	1.43	-28.90
34.77	2.87	39.97	30.01	2.19	2.16	24.66	-1.89	1.66	-30.01
45.08	2.96	49.97	40.01	2.50	2.53	29.20	-2.28	2.23	-48.33
54.95	2.85	59.99	50.00	2.52	2.41	29.88	-2.43	2.21	-28.80
65.03	2.91	69.99	60.03	2.68	2.48	23.78	-2.61	2.28	-18.39
75.17	2.91	79.98	70.02	2.63	2.34	22.01	-2.60	2.61	-79.23
85.95	2.97	89.97	80.01	2.21	1.82	14.86	-2.39	2.20	-36.77
95.62	2.75	99.97	90.01	1.37	1.13	7.61	-1.89	1.87	-33.51

*Table 16: 10-Minute Normalized Fluctuations of WPF5 as a Percentage of its Capacity*

Power	Sd.	Max	Min	Avg. Inc.	Sd. Inc.	Max. Inc.	Avg. Dec.	Sd. Dec	Max. Dec.
1.57	2.73	10.00	0.00	1.98	3.66	55.10	-1.07	1.11	-7.86
14.73	2.88	20.00	10.01	3.95	5.82	60.41	-2.59	2.33	-18.86
24.85	2.89	30.00	20.00	5.29	6.45	60.59	-3.98	3.61	-24.50
34.79	2.84	39.99	30.00	6.81	8.44	60.35	-5.17	5.06	-33.92
45.14	2.90	50.00	40.00	7.29	7.79	53.15	-6.43	5.83	-35.13
54.90	2.88	60.00	50.00	6.86	7.01	45.35	-6.48	6.35	-56.95
64.98	2.91	70.00	60.00	7.80	6.89	34.14	-7.56	7.26	-59.13
75.03	2.87	79.98	70.04	6.17	5.21	27.61	-7.55	7.30	-72.47
85.81	3.06	90.00	80.00	4.13	3.69	19.38	-6.27	8.17	-64.24
95.74	2.82	99.97	90.00	1.55	1.64	9.36	-3.16	4.52	-41.70

*Table 17: Distribution of Qualified Wind Data in Terms of the Number of Meteorological Towers (Scenario B)*

Number Of Met Towers Providing Valid Measurement	Number Of Valid Records in 2004	Percentage of Time in 2004 (%)
<= 3	0	0
4	3	0.01
5	99	0.19
6	112	0.21
7	111	0.21
8	186	0.35
9	347	0.66
10	717	1.36
11	1557	2.95
12	1110	2.11
13	5091	9.66
14	43371	82.29

*Table 18: Distribution of Qualified Wind Data in Terms of the Nameplate Capacity (Scenario B)*

Capacity (MW)	Number of Records in 2004	Percentage of Time in 2004 (%)
[0 - 100)	0	0.00
[100 - 200)	3	0.01
[200 - 300)	110	0.21
[300 - 400)	189	0.36
[400 - 500)	167	0.32
[500 - 600)	646	1.23
[600 - 700)	1944	3.69
[700 - 800)	1490	2.83
[800 - 900)	48155	91.37

*Table 19: Distribution of Qualified Wind Data in Terms of the Number of Meteorological Towers (Scenario C)*

Number Of Met Towers Providing Valid Measurement	Number Of Valid Records in 2004	Percentage of Time in 2004 (%)
<= 6	0	0.00
7	4	0.01
8	7	0.01
9	23	0.04
10	114	0.22
11	67	0.13
12	141	0.27
13	151	0.29
14	154	0.29
15	401	0.76
16	804	1.53
17	861	1.63
18	540	1.02
19	627	1.19
20	936	1.78
21	6812	12.93
22	41062	77.91

*Table 20: Distribution of Qualified Wind Data in Terms of the Nameplate Capacity (Scenario C)*

Capacity (MW)	Number of Records in 2004	Percentage of Time in 2004 (%)
[0 - 300)	0	0.00
[300 - 400)	4	0.01
[400 - 500)	30	0.06
[500 - 600)	89	0.17
[600 - 700)	153	0.29
[700 - 800)	198	0.38
[800 - 900)	293	0.56
[900 - 1000)	965	1.83
[1000 - 1100)	888	1.68
[1100 - 1200)	895	1.70
[1200 - 1300)	982	1.86
[1300 - 1400)	6636	12.59
[1400 - 1500)	41571	78.88

*Table 21: Distribution of Qualified Wind Data in Terms of the Number of Meteorological Towers (Scenario D)*

Number Of Met Towers Providing Valid Measurement	Number Of Valid Records in 2004	Percentage of Time in 2004 (%)
<= 7	0	0.00
8	4	0.01
9	0	0.00
10	8	0.02
11	7	0.01
12	81	0.15
13	49	0.09
14	78	0.15
15	80	0.15
16	95	0.18
17	175	0.33
18	288	0.55
19	288	0.55
20	399	0.76
21	812	1.54
22	565	1.07
23	462	0.88
24	726	1.38
25	991	1.88
26	6803	12.91
27	40793	77.40

*Table 22: Distribution of Qualified Wind Data in Terms of the Nameplate Capacity (Scenario D)*

Capacity (MW)	Number of Records in 2004	Percentage of Time in 2004 (%)
[0 - 400)	0	0.00
[400 - 500)	4	0.01
[500 - 600)	7	0.01
[600 - 700)	17	0.03
[700 - 800)	98	0.19
[800 - 900)	41	0.08
[900 - 1000)	116	0.22
[1000 - 1100)	100	0.19
[1100 - 1200)	368	0.70
[1200 - 1300)	265	0.50
[1300 - 1400)	312	0.59
[1400 - 1500)	445	0.84
[1500 - 1600)	931	1.77
[1600 - 1700)	941	1.79
[1700 - 1800)	914	1.73
[1800 - 1900)	5597	10.62
[1900 - 2000)	42548	80.73

*Table 23: Distribution of High Wind Speed Cut-out (10-Minute)*

Number of WPFs Simultaneously in High Wind Speed Cut-out Mode	Percentage of Time in 2004 (%)
0	97.657
1	2.135
2	0.089
3	0.083
4	0.027
5	0.008
6	0.002
>= 7	0.000

*Table 24: Distribution of High Wind Speed Cut-out (1-hour)*

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Number of WPFs Simultaneously in High Wind Speed Cut-out Mode	Percentage of Time in 2004 (%)
0	97.586
1	2.232
2	0.057
3	0.091
4	0.034
>= 5	0.000

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*Table 25: Distribution of High Wind Speed Cut-out (2-hour)*

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Number of WPFs Simultaneously in High Wind Speed Cut-out Mode	Percentage of Time in 2004 (%)
0	97.540
1	2.255
2	0.068
3	0.114
4	0.023
>= 5	0.000

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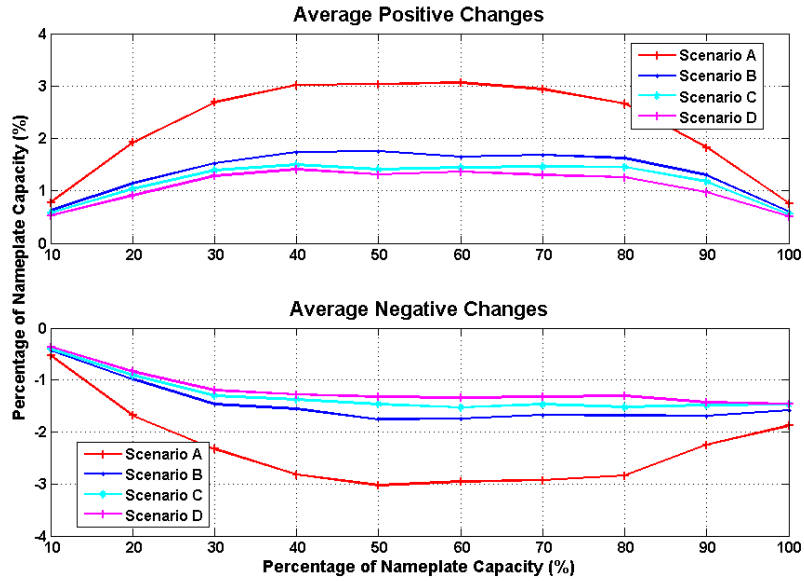


Figure 31: Comparison of the Normalized Magnitudes of Simulated Fluctuations for Scenarios A, B, C, and D (10-Minute)

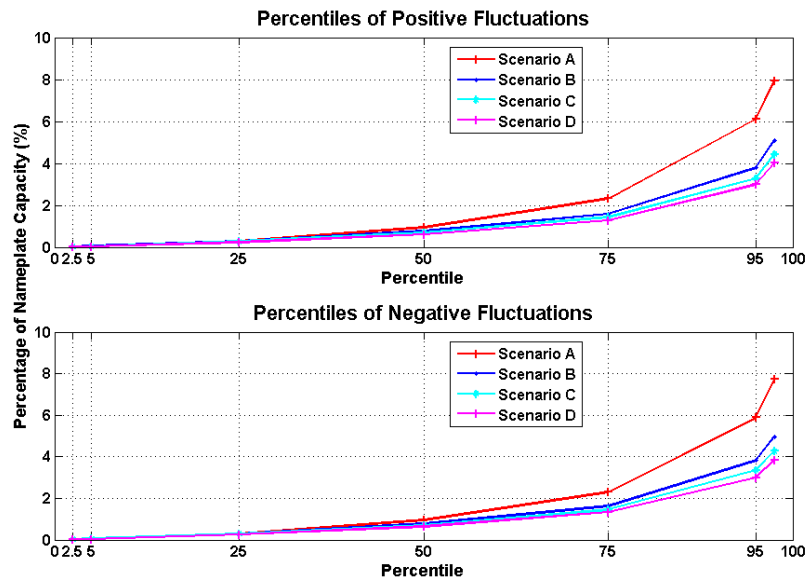


Figure 32: Comparison of the Normalized Percentiles of Simulated Fluctuations for Scenarios A, B, C, and D (10-Minute)

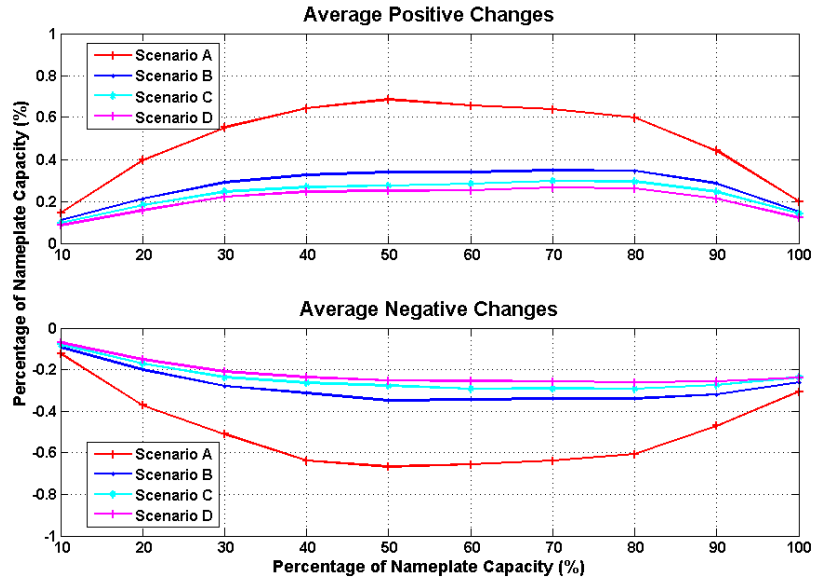


Figure 33: Comparison of the Normalized Magnitudes of Simulated Fluctuations for Scenarios A, B, C, and D (1-Minute)

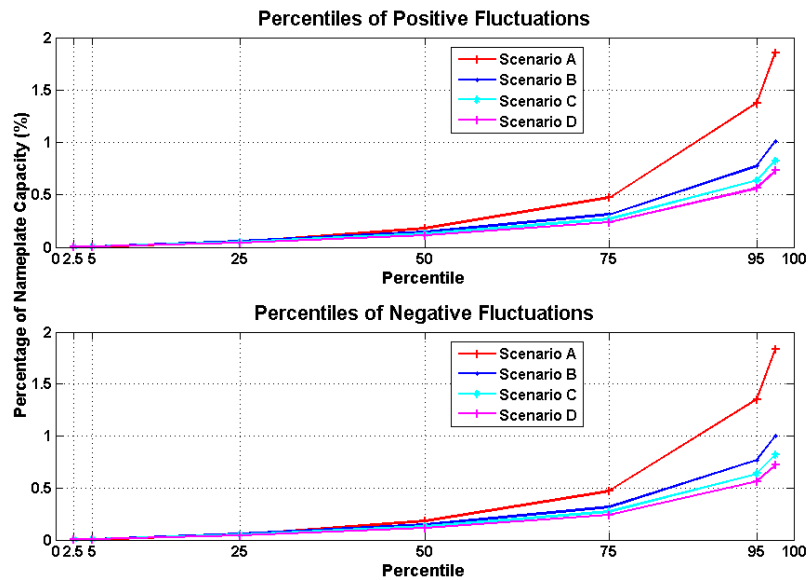


Figure 34: Comparison of the Normalized Percentiles of Simulated Fluctuations for Scenarios A, B, C, and D (1-Minute)

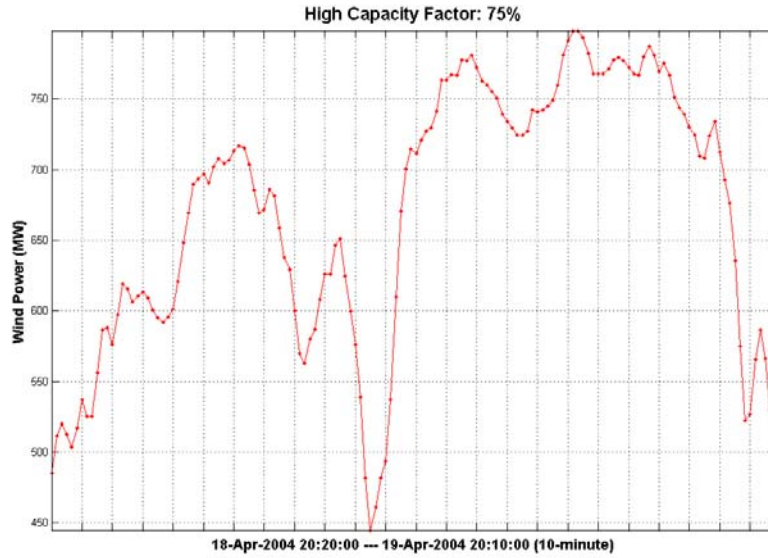


Figure 35: Time Series of Simulated 10-Minute Wind Power Generation at High Capacity Factor in Scenario B (895 MW)

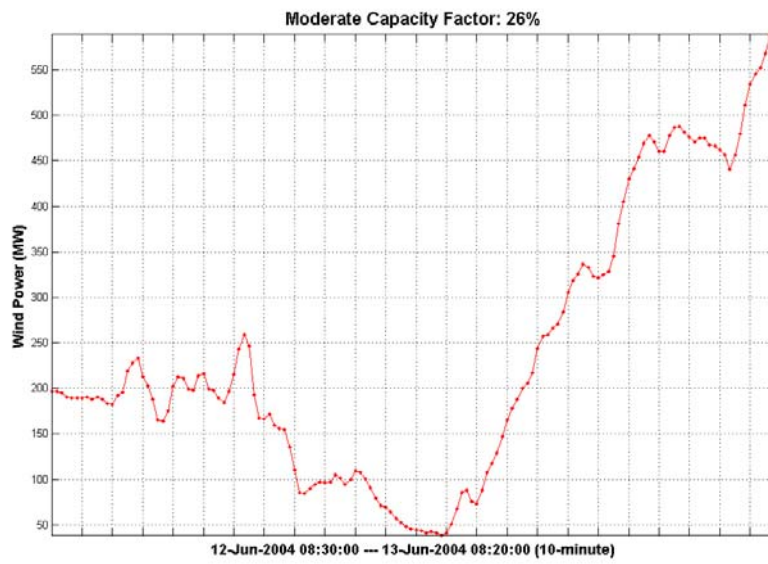


Figure 36: Time Series of Simulated 10-Minute Wind Power Generation at Moderate Capacity Factor in Scenario B (895 MW)

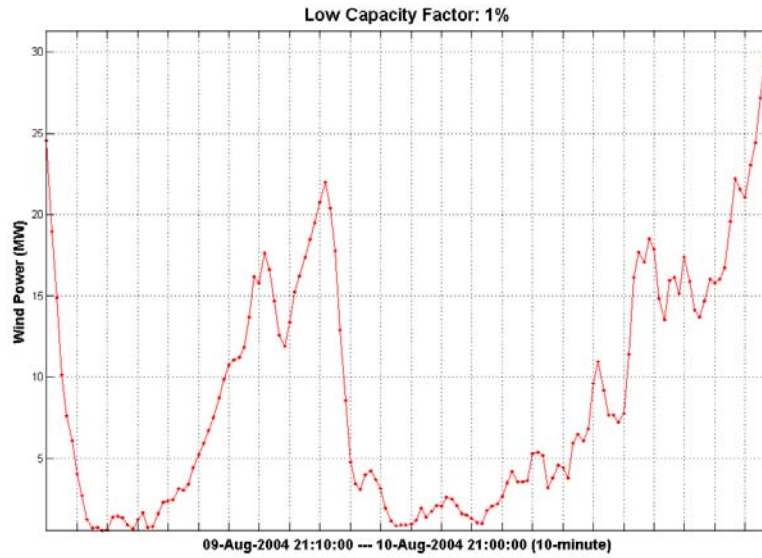


Figure 37: Time Series of Simulated 10-Minute Wind Power Generation at Low Capacity Factor in Scenario B (895 MW)

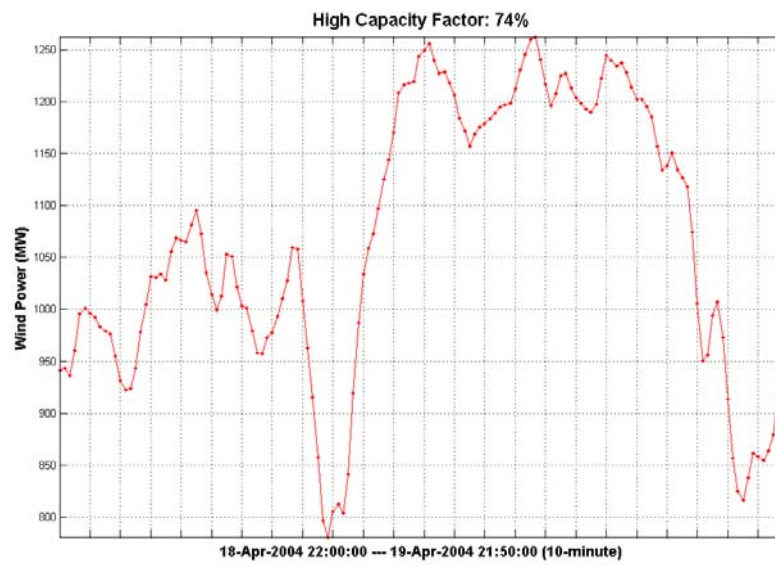


Figure 38: Time Series of Simulated 10-Minute Wind Power Generation at High Capacity Factor in Scenario C (1445 MW)

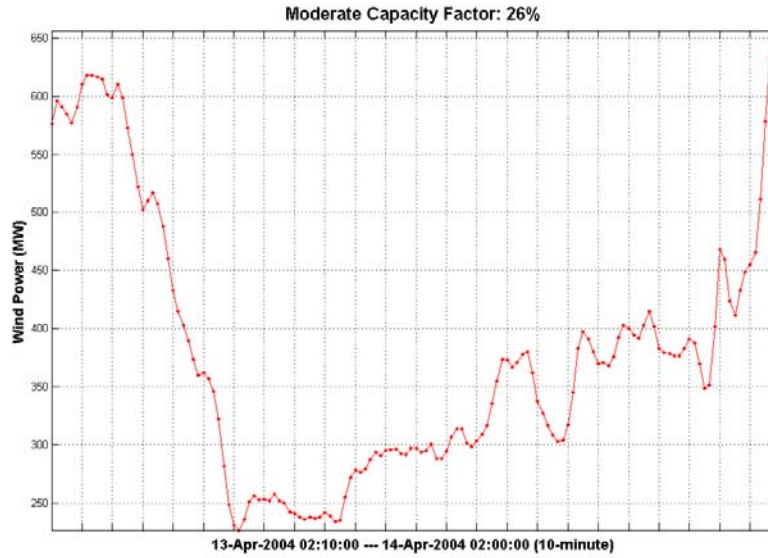


Figure 39: Time Series of Simulated 10-Minute Wind Power Generation at Moderate Capacity Factor in Scenario C (1445 MW)

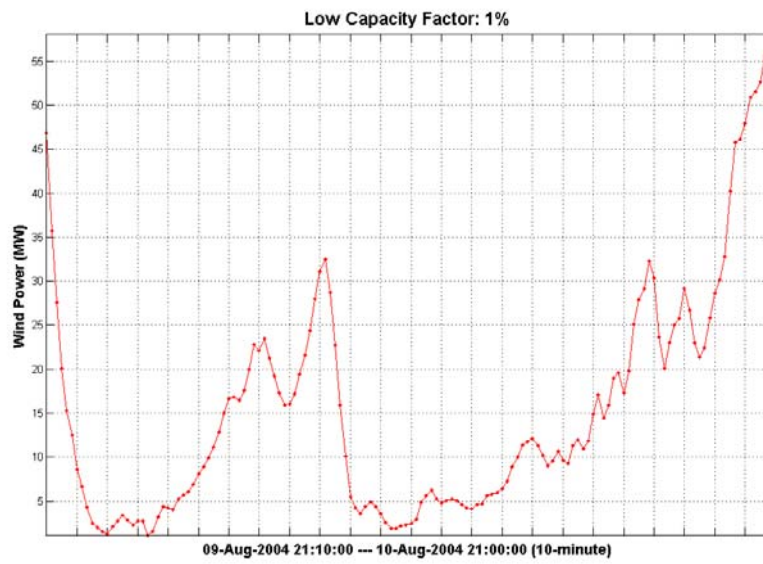


Figure 40: Time Series of Simulated 10-Minute Wind Power Generation at Low Capacity Factor in Scenario C (1445 MW)

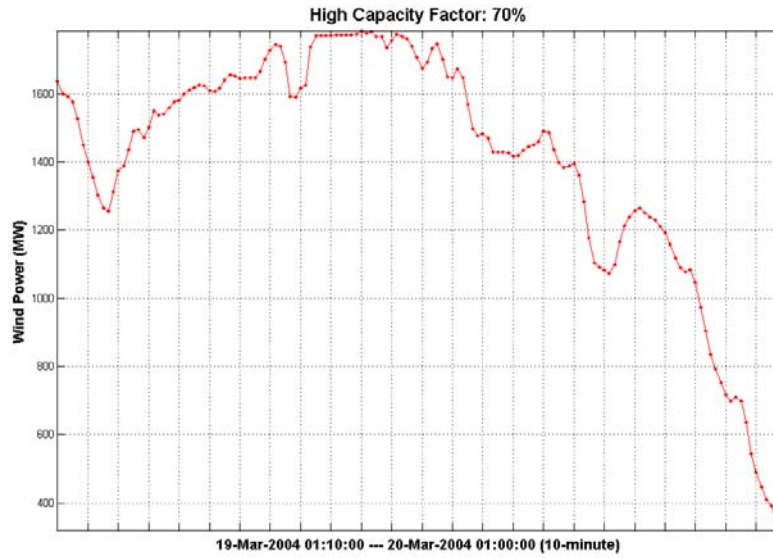


Figure 41: Time Series of Simulated 10-Minute Wind Power Generation at High Capacity Factor in Scenario D (1994 MW)

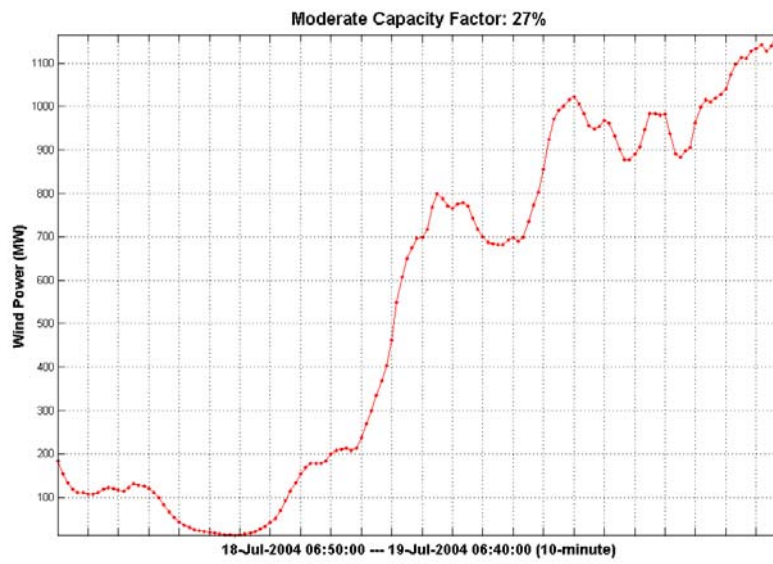
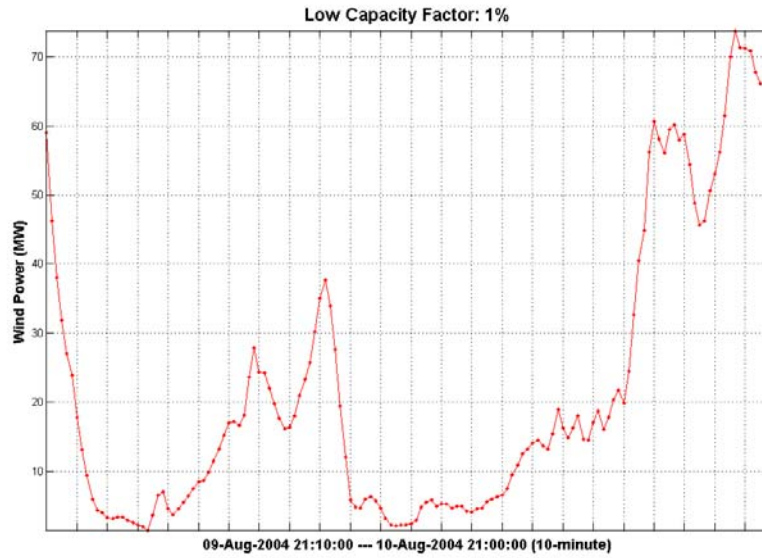


Figure 42: Time Series of Simulated 10-Minute Wind Power Generation at Moderate Capacity Factor in Scenario D (1994 MW)



*Figure 43: Time Series of Simulated 10-Minute Wind Power Generation at Low Capacity Factor in Scenario D (1994 MW)*