Analysis of Wind Power Ramping Behavior in ERCOT

Yih-huei Wan

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1. Introduction

Texas leads the nation in terms of total wind generating capacity. Texas had more than 9,400 MW of wind power installed at the end of 2009.[1] The majority of Texas's wind power is located within the Electricity Reliability Council of Texas (ERCOT) system. The increased wind power in the electric system requires ERCOT system operators to pay more attention to the variable nature of the wind energy. From time to time, rapid changes or ramping of wind power can pose a challenge to operators to maintain grid reliability. Two such large wind ramping events—one on February 24, 2007[2] and one on February 26, 2008[3] received some media attention. This report analyzes the wind power ramping behavior using 10-minute and hourly average wind power data from ERCOT and presents statistical properties of the large ramp events. Finally, it compares these two wind ramping events with other large wind ramp events in terms of ramp duration, rate of change, and overall magnitude.

2. Data

The data used to in this report are 1-minute wind power time series of all operating wind power plants in the ERCOT system. The National Renewable Energy Laboratory (NREL) received these data on a six months delayed basis starting in 2004. ERCOT collects power output from all wind plants through a supervisory control and data acquisition (SCADA) system and uses a Plant Information (PI) system to archive the data. Data from 2004 to 2009 are analyzed. During this six-year period, ERCOT experienced a tremendous growth of wind power within its grid. The installed nameplate capacity grew from 1,200 MW in January 2004 to more than 8,900 MW at the end of 2009.[4] Figure 1 below plots ERCOT monthly peak wind generation during this period. The trend line (blue dashed line) shows the nearly constant increase in peak wind generation every month after 2004.

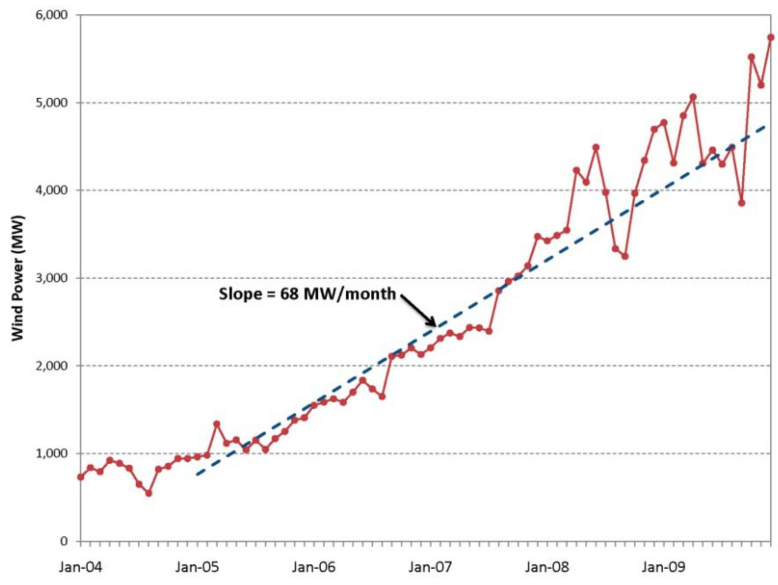

Figure 1 - Growth of Wind Generation in ERCOT.

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[1] AWEA Annual Wind Industry Report—Year Ending 2009 (2010).

[2] ERCOT Compliance Report. EECP Step 1 Event. February 24, 2007.

[3] Dallas Business Journal, *Wind Power Drop Forces ERCOT Emergency Declaration*, February 29, 2008.

[4] The capacity figures are based on the plant record in the ERCOT PI system. The actual commissioned plants before the end of 2009 may differ from the entries in the PI system. Also, the PI system does not contain data for small wind installations.

Short-term fluctuations of individual wind plant outputs are independent. In longer time frames from hourly to daily, the outputs of wind plants are correlated and the correlation is a function of the distance separating wind plants.[5] However, variability of individual wind plants is less a concern for a system operator than the variability of the aggregate wind power of all wind plants combined for the same reason a system operator is focusing on the changes of the total system load, not the changes of individual load. Actually, in most parts of the country, it is the variability of combined load and wind power that the system operator must manage because wind power plants are usually regarded as must-run units, or in a market operation, as a price taker. The system will take all the available wind power whenever the wind plants are producing. Wind power is more or less treated as a negative load in this sense. The resulting net load (load minus wind power) was one of the major analysis subjects in many recent wind integration studies including, the net load statistical properties, its impact on system operations, and ways to mitigate the impact.

Except for 2008 and 2009, ERCOT load data were not available as 10-minute time series data. This study first analyzed the ERCOT wind power data with an emphasis on its ramping behavior. Our interest is to find out how very large aggregate amounts of wind power over a wide area will behave in terms of typical or average magnitude and duration of ramping events and the extreme values. It is not expected that the six years of data could provide a complete picture of ramping characteristics. Three issues may skew the statistics: curtailments of wind power plants due to transmission constraints, forced outages on the grid, and the ever-increasing installed wind capacity during these years. Without wind resource data and information about transmission system status, it is not possible to separate the events of curtailments or forced transmission outages from natural ramping events. Capacity increases can be identified and removed from later years, but doing so will leave a much smaller installed capacity base for the analysis. It was decided to use the actual recorded wind power dataset in its entirety and normalize the results by yearly capacity to minimize the bias caused by size differences. For 2008 and 2009, when load data are available, fluctuations of net load are analyzed.

3. Ramping

Wind power changes constantly. Even for the aggregate wind power of a large system such as ERCOT, the power level still moves up and down in a stochastic fashion. Figure 2 is an example of the ERCOT daily wind power profile plotted with 1-minute average power.

[5] Wan, Y. (2004), Wind Power Plant Behaviors: Analyses of Long-Term Wind Power Data, NREL Report No. TP-500-36551.

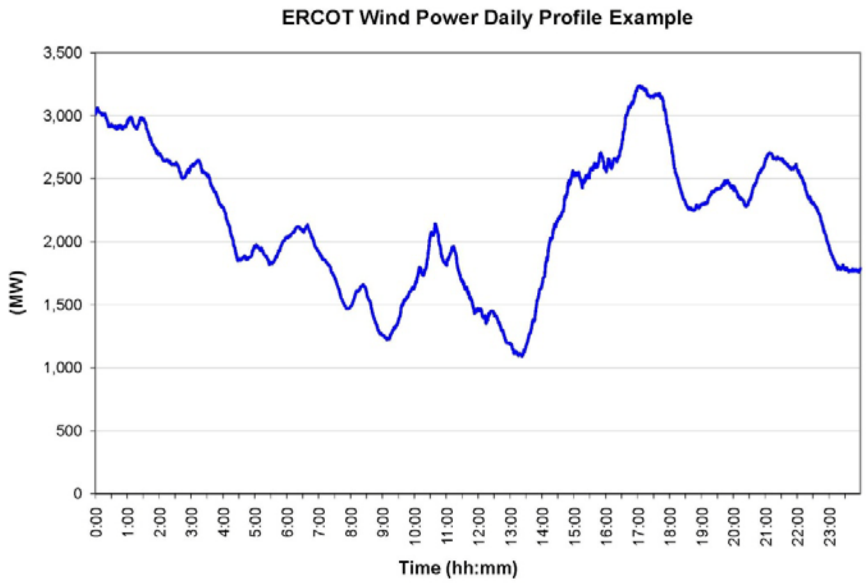


Figure 2 − Daily wind power profile example.

In this example, the difference between daily maximum power and daily minimum power is over 2,100 MW. Starting at about 3,000 MW at midnight, it took about 13 hours for the wind power to decrease to around 1,100 MW. The wind power increased to about 3,300 MW four hours later. However, the long decline to daily minimum and the relatively short climb to daily maximum were not monotonic. There are smaller up and down movements with durations ranging from minutes to hours interspersed in between that create local peaks and valleys. This example points to the difficulty of objectively identifying wind power ramping events. Depending on the defining criteria of a ramp event, the starting and ending point and duration of a ramp can change substantially.

For the electric system to operate reliably, generation must match load all the time. With wind power in the system, generation is usually managed to match the net load. In actual operations, the system must always maintain a generating capacity that is larger than the expected load to guard against the sudden loss of any generating unit. Different methods are used to balance the generation and load for different time frames. For longer time frames of days to weeks, operators will plan and commit different generating units to match the forecasted daily load profiles of weekdays and weekend. Daily load profiles can vary significantly between peak and minimum, and load profiles of weekdays and weekends can also differ substantially. Longer time is therefore needed to plan and manage the generating plants needed for load because certain generating plants need longer time from start-up to synchronizing with the load. During the day, operators routinely adjust schedules of generating units to follow the load based on system economics and updated information (e.g., weather conditions). Time frames for these operations range from hours to minutes. For still shorter time frames, the random fluctuations of load, which affect system frequency and interchange schedules, but are beyond the operators' ability to manage, are met by automatic generation control (AGC) of the generating plants and each generating units' governor response. Working together, AGC and governor response rapidly changes the output of generating units to match load in real time.

It is clear that the variability of wind power affects the system operations. This analysis will concentrate on the large wind-power ramping events that could affect system operations in the sub-hourly and hourly time frames. The original 1-minute wind power time-series data are processed into 10-minute average power time-series data and hourly average power time-series data. The 10-minute and hourly time-series data are used to investigate wind power ramping events.

3.1 Hourly Step Changes

Ramping of wind power (rate of change) is the result of wind power differences from one instance to the next. The power ramps in short time frames such as seconds and minutes are of less concern to grid operators because they are usually small in magnitude.[6] Large ramps in longer time frames from one hour to several hours impact system operations. The simplest measure of wind power ramps is the differences of average power between two consecutive hours. Because the wind power level is not expected to be constant, the standard statistical properties (average and standard deviation values) of hourly step change provide the first order indication of wind power ramping behavior. Step changes can be positive and negative, and over a year the average value of such step changes tends to be zero (or a small value) because the total wind capacity is not unlimited and the changes in positive direction are balanced out by changes in negative direction. The statistics of the absolute step-change values (magnitude) provide a better indication of wind power variability from one hour to the next. Table 1 lists the average and standard deviation values or sigma (σ) of the magnitude of hourly ERCOT wind power changes for 2004 through 2009. It also lists the values of three times standard deviation (3σ) and 3σ in terms of total capacity, and the largest changes in both positive and negative direction in an hour. The percent of capacity values are calculated with total installed wind capacity at the end of respective year.

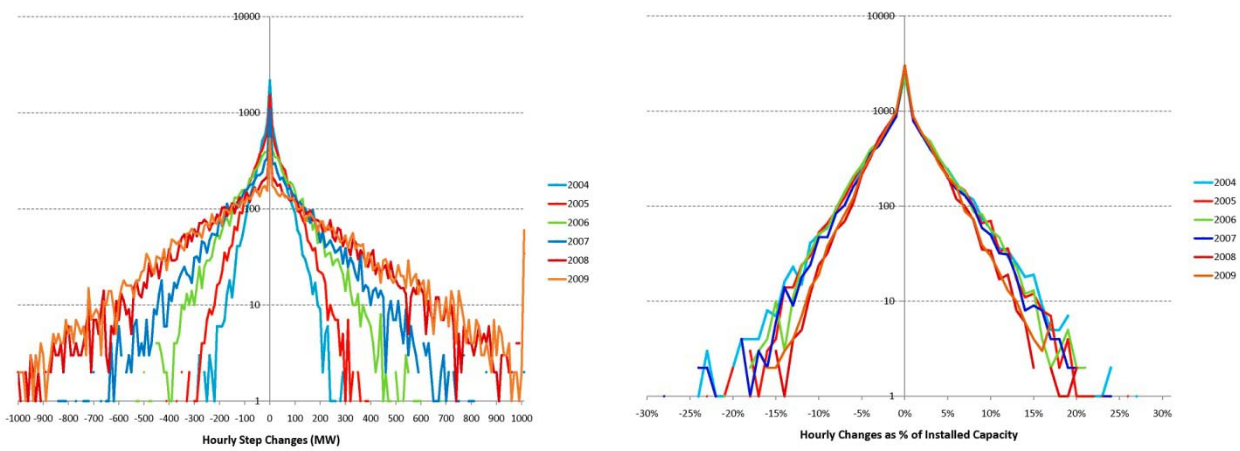
Table 1 − Wind power hourly step-change statistics.

	Average		**Standard Dev.**			**Maximum (MW)**			
	(MW)	% of Capacity	σ (MW)	3σ (MW)	% of Capacity	Up	% of Capacity	Down	% of Capacity
2004	38	3.2%	39	117	9.7%	327	27.0%	-295	24.3%
2005	55	3.1%	54	162	9.2%	470	26.6%	-413	23.4%
2006	89	3.2%	85	255	9.0%	682	24.2%	-613	21.7%
2007	119	2.7%	129	387	9.2%	1,030	24.4%	-1,212	28.7%
2008	199	2.5%	198	594	7.3%	1,869	23.0%	-1,946	24.0%
2009	226	2.5%	224	672	7.5%	2,314	25.8%	-1,782	19.9%

The magnitudes of average hourly step changes increased significantly from 2004 to 2009. However, relative to the total wind generating capacity, they actually decreased slightly, as shown in Table 1 in the column under the heading of percent of capacity. To put these numbers in perspective, 3σ in 2008 was 594 MW, which appears big but is only 7.3% of the installed wind capacity in ERCOT for 2008. And it is less than 1% of ERCOT 2008 peak demand of 62 GW.

Figure 3(a) shows the distribution of hourly step changes. When total wind capacity increases, the numbers of step changes with bigger magnitude also increase as expected. However, when plotting the step distribution in terms of total installed wind capacity, different information appeared. Figure 3(b) shows the step distribution as a percentage of yearly installed wind capacity. It can be seen that as capacity increases, the distribution actually becomes tighter with more small (relatively to the capacity) step changes than larger ones. And for all years, more than 95% of the hourly ramps had a magnitude less than 3σ of the step changes for the respective year. To focus on large ramp events that have the potential to impact system operation, this analysis only examined ramps which had a magnitude of at least 3σ in an hour.

[6] Wan, Y. (2005), Primer on Wind Power for Utility Applications, NREL Report No. TP-500-36230.



(a) (b)

Figure 3 − Distribution of hourly ramps.

3.2 Monotonic Ramp Events

After identifying the beginning of a large ramp from the results of hourly step changes, the next step was to check if the ramp will continue in the same direction in the following hours. This process continues until the wind power reverses its direction. The hour when the wind power is no longer increasing or decreasing is the end of a ramp. The duration of the ramp is the time between the beginning and ending hours, and the magnitude of the ramp is the differences between the beginning power level and ending power level. This process identifies all monotonic up and down ramp events in the hourly time series. Table 2 lists the numbers of up and down ramps with a magnitude of at least 3σ, the largest up and down ramp events of the year, the average duration, and the longest durations.

Table 2 − Summary of monotonic ramp events.

	Up Ramp Events					Down Ramp Events				
			Largest Ramp					Largest Ramp		
	No. of Events	Average Duration (hours)	(MW)	% of Cap.	Duration (hours)	No. of Events	Average Duration (hours)	(MW)	% of Cap.	Duration (hours)
2004	456	5.4	907	75%	10	476	5.6	-725	60%	7
2005	448	5.8	1,261	71%	9	493	5.9	-1,086	61%	12
2006	472	5.8	2,088	74%	12	497	5.9	-1,974	70%	20
2007	441	5.8	2,949	70%	12	419	6.3	-3,135	74%	11
2008	496	5.1	3,980	49%	10	482	5.6	-4,211	52%	9
2009	473	5.1	4,613	51%	11	507	5.2	-4,788	53%	13

Several noteworthy features can be gleaned from the table. The numbers of large ramp events as defined by a change of power level greater than 3σ in an hour are fairly constant every year. On average, such events last slightly less than 6 hours in duration. The largest of such ramp events can cause wind power to change more than 4,200 MW in 9 hours. The magnitudes of the largest ramp events increase along with the growth of wind power in the grid. However, when expressed in terms of the total installed wind capacity, the percentage values actually decrease because of the wind power plant spatial diversity. A single large up or down ramp can last more than half a day and has a magnitude of 75% of the total installed wind capacity. However, those are not necessarily the most severe ramp events. Average ramp rates for the largest ramps range from -468 MW/h to 419 MW/h, or -78 MW/10 min. to 70 MW/10 min.

In terms of installed wind capacity, those are equivalent to 8.5% per hour (1.4% per 10 minutes) in 2004 and to 4.7% per hour (0.8% per 10 minutes) in 2009. Ramp rates will be discussed more in subsequent sections.

As shown in Table 1, a magnitude of 3σ is only about 8-10% of the total wind capacity. Ramp events selected based on a magnitude of at least 3σ that are shown in Table 2 still contain many insignificant events. Table 3 shows the magnitude in MW of 25%, 40%, and 50% of the total installed wind capacity for a specific year. Also included in Table 3 are 25%, 40%, and 50% of the yearly peak wind generation in MW. Table 4 lists the numbers of ramp events with magnitudes of 25%, 40%, and 50% of the total installed wind power capacity. It can be seen from Table 4 that ramp events with a magnitude of at least 25% of the total wind capacity are fairly common. Changes with a magnitude of 25% of the installed wind capacity are equivalent to ramp rate of about 6% per 10-minute duration. However, as installed wind capacity becomes larger, the number of large ramp events tends to decrease. The numbers in Table 4 suggest that such events occurred about once every other day in 2004 and gradually decrease to about once in four days in 2009.

Table 3 – Yearly wind power capacity and peak wind power outputs.

	Total Installed Wind Capacity			Yearly Peak Wind Generation		
	25%	40%	50%	25%	40%	50%
2004	303	485	606	236	378	472
2005	442	707	883	352	563	704
2006	706	1,130	1,412	551	881	1,102
2007	1,056	1,688	2,111	869	1,390	1,737
2008	2,028	3,244	4,055	1,174	1,879	2,348
2009	2,240	3,585	4,481	1,437	2,298	2,873

Table 4 − Number of occurrences of large ramp events (based on total wind power capacity).

	Up Ramps			Down Ramps		
	Total >25%	>40%	> 50%	Total >25%	>40%	>50%
2004	170	55	25	165	44	20
2005	183	61	30	168	48	12
2006	188	65	24	185	47	14
2007	160	45	16	150	48	19
2008	91	11	0	88	14	2
2009	96	14	1	86	11	2

There can be noticeable differences between the monthly highest peak wind-power output in ERCOT and the total installed wind capacity (tallied at the year-end). It is common that wind energy developers try to commission the turbines before the end of a calendar year for tax purposes. There were sizeable wind power capacity additions at the end of a year, but these additions did not actually generate energy during the year. A more useful figure to gauge the wind capacity for a year in ERCOT may be the highest coincidental peak wind generation of the year.[7] The numbers of large ramp events were often more if the magnitudes of ramps were expressed in term of highest wind production for the year. Table 5 lists the numbers of large ramp events with magnitudes of 25%, 40%, and 50% of the yearly highest wind generation. The frequency of large ramp events expressed this way increases substantially.

[7] It should be noted that this is not exactly accurate either due to curtailment of wind power in ERCOT.

Table 5 − Number of occurrences of large ramp events (based on yearly peak wind generation).

	Yearly Peak Wind Generation	Up Ramps			Down Ramps		
	(MW)	Total > 25%	>40%	>50%	Total > 25%	>40%	>50%
2004	944	239	113	61	233	98	45
2005	1,408	235	117	61	240	95	49
2006	2,204	248	124	76	251	117	51
2007	3,475	206	93	37	200	77	41
2008	4.697	256	108	60	252	106	53
2009	5,746	226	91	55	201	76	31

For the really large ramp events (a magnitude of at least 50% of total wind capacity), the data show that these occurrences were not evenly distributed over a year. Table 6 lists the distribution of such ramp events over the year. About a quarter to more than a half of the very large ramp events occurred in just two months; November and December, and they seldom occurred in July and August.

Table 6 − Monthly distribution of large ramp events.

	Up Ramp Events						Down Ramp Events					
	2004	2005	2006	2007	2008	2009	2004	2005	2006	2007	2008	2009
Jan	5%	7%	3%	3%	5%	15%	9%	8%	0%	2%	4%	19%
Feb	10%	0%	7%	0%	5%	7%	4%	0%	6%	0%	9%	13%
Mar	10%	10%	7%	3%	5%	5%	2%	6%	2%	10%	6%	3%
Apr	16%	8%	5%	8%	13%	9%	13%	12%	4%	7%	9%	6%
May	13%	11%	9%	3%	15%	7%	11%	14%	10%	7%	11%	3%
Jun	8%	8%	11%	5%	8%	5%	11%	4%	8%	5%	9%	0%
July	0%	2%	12%	3%	5%	5%	2%	10%	10%	0%	6%	3%
Aug	0%	2%	4%	3%	2%	2%	0%	2%	4%	0%	4%	3%
Sep	8%	15%	13%	3%	0%	0%	4%	12%	12%	10%	0%	0%
Oct	5%	8%	7%	16%	12%	9%	9%	6%	14%	7%	13%	3%
Nov	15%	13%	14%	24%	10%	15%	20%	8%	20%	24%	9%	19%
Dev	10%	16%	9%	30%	20%	20%	13%	16%	12%	27%	19%	26%

Figure 3 shows the daily wind power profiles for when the largest positive ramp events occurred in each year. Figure 4 shows the daily wind power profiles for when the largest negative ramp events occurred. Some prominent features of the largest ramp events can be observed from these two figures. Figures 3 and 4 show that large positive ramp events tend to start in the afternoon hours or early evening hours and the large negative ramp events tend to start in the early morning hours. Also, very large up or down ramps are usually followed or preceded by another large ramps in the opposite direction. As a result, the daily wind power profiles of the days with large ramp events generally form a V-shaped curve with the low point situated in the middle of the day. As mentioned previously, the very large ramp events tend to occur in winter. In fact, 10 out of the 12 largest ramp events shown in Figures 3 and 4 occurred in November and December.

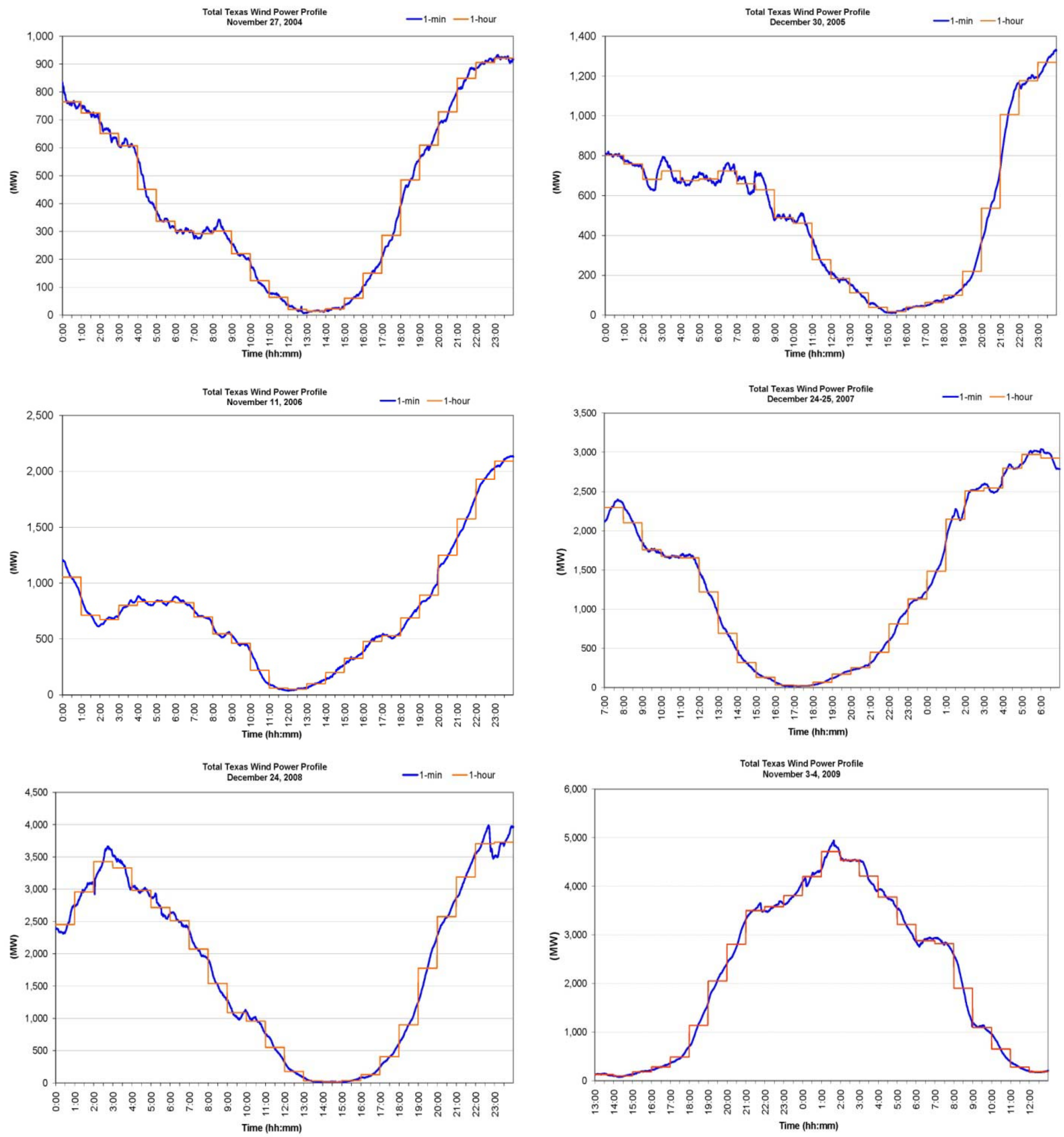


Figure 3 − Daily wind power profiles of the largest positive ramp events.

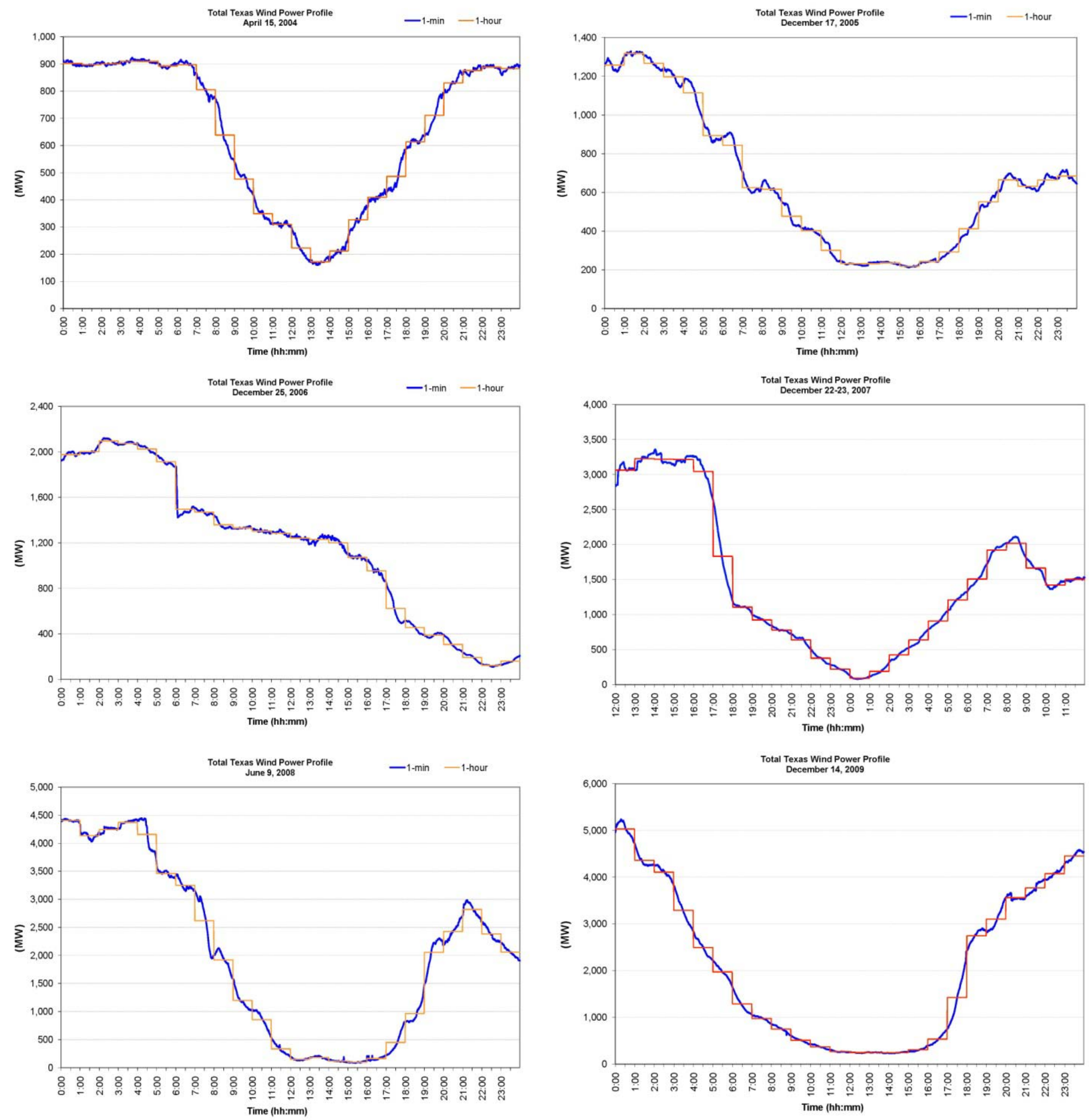


Figure 4 − Daily wind power profiles of the largest negative ramp events.

Further analysis confirmed that what is shown in Figures 3 and 4 are not coincident. From 52% to 77% of the large positive ramp events (with a magnitude greater than 50% of yearly peak production) started in the afternoon hours (between 12:00 and 18:00). On average, about 80% of all large positive ramp events started in the afternoon and evening hours, and such events started very infrequently during the morning hours (between 0:00 and 6:00). The distribution of down ramp events' starting time is not as concentrated as the up ramp events. Still, a very large portion of the large negative ramp events (almost 47%) started in the morning hours (between 0:00 and 6:00). Large down ramp events usually did not start during the afternoon hours. Table 7 provides detailed breakdowns of the beginning of large ramp events. Figure 5 shows the same information more graphically.

Table 7 − Distribution of starting hours of the large ramp events.

	0:00 – 5:59	6:00 – 11:59	12:00 – 17:59	18:00 – 23:59
Up Ramp Events				
2004	3%	11%	72%	13%
2005	2%	15%	77%	7%
2006	1%	26%	67%	5%
2007	5%	16%	68%	11%
2008	5%	20%	52%	23%
2009	7%	13%	62%	18%
Down Ramp Events				
2004	49%	20%	7%	24%
2005	53%	12%	6%	29%
2006	49%	10%	6%	35%
2007	39%	17%	12%	32%
2008	43%	28%	13%	15%
2009	48%	23%	3%	26%

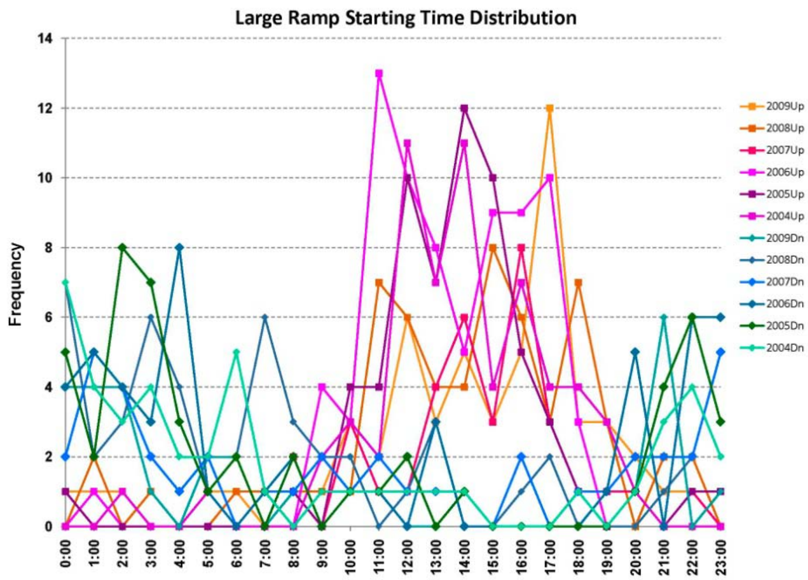


Figure 5 – Distinctive pattern of large ramp start times.

4. Ramping Rate

Analysis of the ramp events shows that the largest of such events can result in wind power level changes in thousands of MW (more than 50% of the total wind power capacity) in 9 or 10 hours. Such events, although massive in terms of net power level changes, usually do not result in very high rates of change because they took more hours to complete. The equivalent ramping rates (in both MW per hour and percentage of total wind capacity per hour) of the largest ramp events for each year (listed in Table 2) are shown in Table 8. The largest down ramp event occurred on June 9, 2008, when wind power dropped 4,211 MW in 9 hours. This event resulted in an average rate of -468 MW per hour, or about 5.8% of the total wind capacity per hour. Moving down on the time steps, it is equivalent to less than 1% per 10 minutes, which is not a severe event. However, the actual sub-hourly ramping rate can be much higher. For example, Table 1 shows the maximum hourly step change is 2,382 MW, or 26.6% of the total wind capacity in an hour. It is equivalent to 397 MW or 4.5% per 10-minute period. To investigate the sub-hourly ramping rate, 10-minute wind power time-series data are used because the hourly averaging process smoothed out the fast, sub-hourly fluctuations.

Table 8 − Average ramping rates of the largest ramp events.

	Up Ramp Events		Down Ramp Events	
	(MW/h)	(%/h)	(MW/h)	(%/h)
2004	90.7	8.5%	-103.6	8.5%
2005	140.1	7.9%	-90.5	5.1%
2006	174.0	6.2%	-98.7	3.5%
2007	245.8	5.8%	-285.0	6.8%
2008	398.0	4.9%	-467.9	5.8%
2009	419.4	4.7%	-368.3	4.1%

4.1 Ten-Minute Step Changes

Table 9 shows the statistics of 10-minute wind power step-changes (magnitude only). The values in Table 9 are smaller than the corresponding values in Table 1. However, if these values are normalized to hourly values by multiplying by 6 (1 hour = 6 x 10 minutes), it becomes clear that short-term wind power ramping rates can be very high. Taking the 2004 maximum 10-minute step change as an example, the wind power can ramp up at a rate of 936 MW per hour (or 77% of total wind capacity per hour) and ramp down at an even higher rate of 1,056 MW per hour (or 87% of total wind capacity per hour). However, it should be noted that these are not sustained ramping rates, i.e., neither the 10-minute period prior to it nor the 10-minute period after it shows the same high ramping rate.

Table 9 − Wind power 10-minute step change statistics.

	Average		Standard Dev.	Maximum (MW)	
	(MW)	(% of Capacity)	(MW)	Up	Down
2004	11	0.9%	12	156	-176
2005	14	0.8%	15	213	-185
2006	21	0.7%	22	272	-279
2007	28	0.6%	34	509	-392
2008	49	0.6%	58	839	-935
2009	58	0.6%	64	918	-1,256

4.2 Ramping Events from 10-minute Time Series Data

The criterion adopted to identify monotonic ramp events in the hourly wind power time-series data needs to be modified before applying it to the 10-minute time series data. On average, wind power in the hourly time-series data will reverse its direction in 3.2 steps (3.2 hours) and in 10-minute time series data in 3.8 steps (38 minutes). Identifying only monotonic increases or decreases in the 10-minute time series data will result in many relatively small events and missing some otherwise truly significant ramp events that have underlying increasing or decreasing trends, but are temporarily punctuated by brief reverses. A typical example can be seen in Figure 6.

Figure 6 plots the wind power profile during a 24-hour period plotted with 10-minute and hourly average power time-series data. From midnight to about 8 o'clock in the morning, there were some fluctuations of the wind power on top of a persistent downward trend. After a period of lull during the middle of the day, the wind power increased sharply (an increase of 636 MW in an hour and a half), but the up ramp was not monotonic. Searching for only monotonic ramps would have missed these large events and identified several smaller ramp events instead.

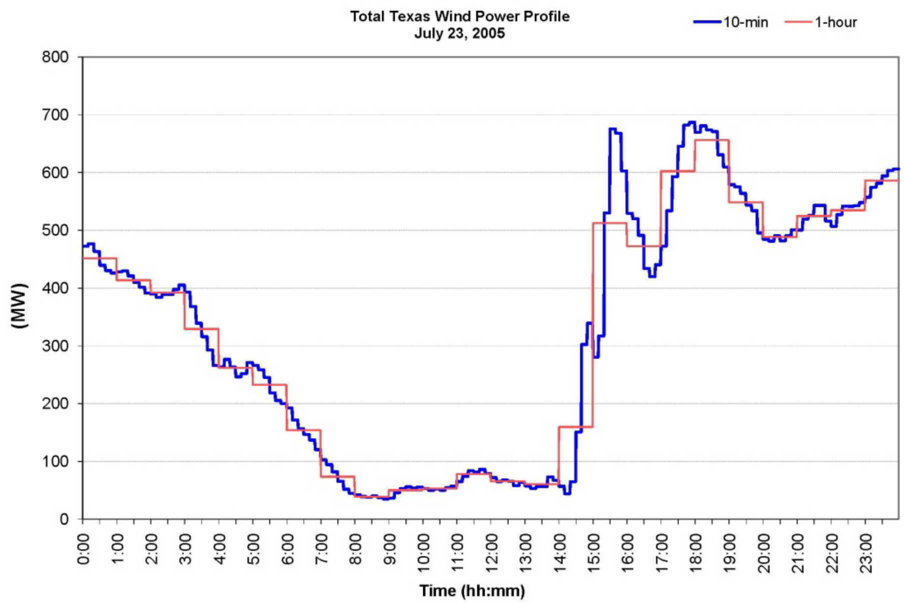


Figure 6 − Example of daily wind power profile plotted with 10-minute and hourly average values.

To capture the significant ramps in 10-minute time series data, the ramping selection criterion was modified to use values of both 10-minute and hourly time-series data in determining a ramp event. The start of a ramp event in the 10-minute time series is determined when both the 10-minute and hourly wind power move in the same direction. During the ramp, the hourly average values determine if the ramp is continuing on the 10-minute time series, i.e., the hourly trend overrides the 10-minute fluctuations. The end of a ramp is when both 10-minute and hourly time-series values change direction. To distinguish the ramping events from the simple 10-minute step changes, a ramping event must be at least 20 minutes (two 10-minute steps) long for it to be identified. With this selection criterion, the downward trend in the morning in Figure 5 is counted as one down ramp event, and the upward trend in early afternoon is counted as one up ramp event. To further eliminate smaller ramp events from being counted, the same 3σ rule (the overall magnitude of any ramp event is greater than three times the standard deviation values of the 10-minute step changes) is applied.

The numbers of large ramp events identified in the 10-minute wind power time-series data by using the modified selection criterion are very similar to that of monotonic large ramp events from the hourly time series. The distribution of large ramp events from 10-minute wind power time-series data is also very similar to the distribution of large ramp events from hourly wind power time-series data. These are expected results because the modified ramp selecting criterion still uses the trend in the hourly wind power time-series data to determine a ramp event in the 10-minute time series. However, the large ramp events from 10-minute time series and the hourly time series do differ slightly in terms of event durations and ramp rates. Because of higher temporal resolution of the 10-minute time series data, ramp events identified with 10-minute wind power time-series data have a more accurate starting and ending time. The hourly averaging process which acts like a low pass filter will smooth out some of the fluctuations on the 10-minute time series. As a result, the large ramp events from the 10-minute time series tend to have a higher rate of change. Figure 6 above clearly illustrates these two points. Based on the hourly average power trace (in orange) in Figure 6, the early afternoon up-ramp event lasted two hours (from 13:00 to 15:00) with a magnitude of 452 MW. Using the 10-minute average power (in blue) time-series data, the duration of this ramp was one hour and twenty minutes with a magnitude 631 MW. In terms of ramp rate, the difference is more dramatic; 226 MW/h in the hourly time series compared to 473 MW/h in the 10-minute time-series data.[8]

Table 10 lists maximum ramping rates of large up and down ramp events identified from the 10-minute wind power time-series data. The ramp events were first grouped according to the durations of the ramp events, and the maximum ramp rates within each duration group were selected. The maximum ramping rates shown in the table are in MW/10-min. period. Blanks in the table mean no ramp events with a particular duration in that year. The hours in the Ramp Durations column should be interpreted as up to that amount. For example, the row of 5 hours includes all ramp events with a time longer than 4 hours and up to 5 hours.

Table 10 − Maximum ramping rates grouped by duration of ramp events.

Ramp Durations (h)	2004		2005		2006		2007		2008		2009	
	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up	Down
1	86	-79	84	-71	182	-202	251	-206	342	-452	429	-619
2	48	-59	79	-57	118	-90	179	-134	249	-308	265	-305
3	36	-35	43	-46	84	-83	124	-137	178	-156	272	-160
4	29	-28	36	-33	61	-60	88	-85	145	-136	174	-128
5	23	-25	30	-30	51	-44	70	-65	134	-109	153	-111
6	22	-20	20	-27	44	-45	66	-73	104	-95	116	-94
7	18	-15	26	-19	40	-41	62	-60	89	-94	100	-79
8	16	-15	26	-18	41	-36	46	-58	75	-74	88	-71
9	14	-12	25	-18	31	-26	43	-61	72	-69	70	-73
10	17	-11	19	-15	31	-28	44	-34	63	-55	59	-54
11			15	-14	22	-19	40	-41	27	-53	46	
12		-10	13		20	-23		-30	43	-43	40	-53
13			13		21					-36		-67
14					14						37	
15						-20						

The numbers in Table 10 show that more installed wind power capacity will result in a higher wind power ramping-rate, and wind power can change at a very fast rate in a short time frame. In 2009, the highest down ramp rate was 619 MW per 10 minutes. It was equivalent to more than 3,700 MW per hour. However these high ramping rates are not sustainable. For example, this particular down ramp, which occurred in March 2009 only lasted 30 minutes before its direction was reversed. It is also noted that these highest ramping rates when expressed in terms of percentage of total installed wind capacity per 10 minutes are in the range of 6%-8% per 10-minute period. They are much less than 10% per minute that some utilities and system operators have established.[9]

From Table 9, it can be seen that the maximum magnitude of a single 10-minute step change can be greater than 10% of the installed wind capacity, but Table 10 shows that based on the selection criteria adopted for this report, none of the ramping events has a rate greater than 10% of the installed wind capacity per 10 minutes. This suggests that a ramping rate of more than 10%/10-minute period is very rare with large amounts of wind power capacity. Table 11 below shows the number of 10-minute periods in each of six years when the wind power change is greater than 10% of the installed capacity.

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[8] 631 MW change in 1 hour and 20 minutes is the equivalent to a rate of 631MW ÷ 1.33 h = 473 MW/h.
[9] For example, Alberta Electric System Operator, Level I ISO Rules, Part 500, Facilities Division 502 – Technical Requirements, Section 502.1 – Wind Aggregated Generating Facilities Technical Requirements.

Table 11 – Number of 10-minute periods with a change greater than 10% of installed wind capacity.

	Up	Down	Total	No. of consecutive 10-minute periods
2004	6	6	12	0
2005	5	1	6	0
2006	0	0	0	0
2007	4	0	4	2
2008	1	1	2	0
2009	1	2	3	0

All but two in 2007 of the 32 10-minute periods in Table 11 are nonconsecutive. The two consecutive 10-minute periods in 2007 were part of a large ramp event that occurred on November 28, 2007. However, the average ramp rate of that particular event was only 138 MW/10-min. period, or 3%/10-min. period.

ERCOT approved a nodal protocol limiting wind power ramp rates to 10% per minute of on-line installed wind capability.[10] When taking the outputs of all on-line wind plants as a whole, wind power ramping rates are not likely to exceed the 10%-per-minute limit. The data did show incidents where the ramping rate of the combined output was greater than 10% of the installed capacity. Closer examination of the data suggests that those incidents were not the results of natural wind plant behavior, e.g., one minute at full power and zero at the next minute or vice verse. Those sudden changes in wind power level are likely the results of a line outage or curtailment. It should be noted that ramping from individual wind plant can exceed the 10%-per-minute limit.[11,12]

5. Apparent Effect of Wind Power on System Net Load

Wind power in ERCOT has not been actively controlled by system operators to follow the load or track a fixed schedule. One way to gauge the effect of large amounts of wind power on system operations is to analyze the fluctuations of the net load, i.e., load minus wind power, and compare it to how the load would fluctuate if there is no wind power.

Changes of wind power level from one period to the next are independent of changes of load level from one period to the next. If the changes are in the same direction, i.e., both increase or decrease at the same period, the effect is less change on other generators that are used to follow the load. If the load and wind power changes are in opposite directions, it will require more change for other generators. Figure 7 is a scatter plot of load and wind step changes using 2008 hourly data.

[10] PRR771 Ramp Rate Limitation of 10% per minute of On-Line Installed Capability for Wind-powered Generation Resources. This limit applies to a wind plant that is rapidly increasing power after a curtailment or outage. It doesn't apply to a wind plant whose power is decreasing due to falling wind speed. http://www.ercot.com/mktrules/issues/nprr/226-250/239/index.

[11] Wan, Y. H. (2004). Wind Power Plant Behaviors: Analyses of Long-Term Wind Power Data. 66 pp.; NREL Report No. TP-500-36551.

[12] Wan, Y. (2005). Fluctuation and Ramping Characteristics of Large Wind Power Plants. WindPower 2005 (WindPower 05) Conference and Exhibition (CD-ROM), 15-18 May 2005, Denver, Colorado. Washington, DC: American Wind Energy Association; Content Management Corp. 13 pp.; NREL Report No. CP-500-38057.

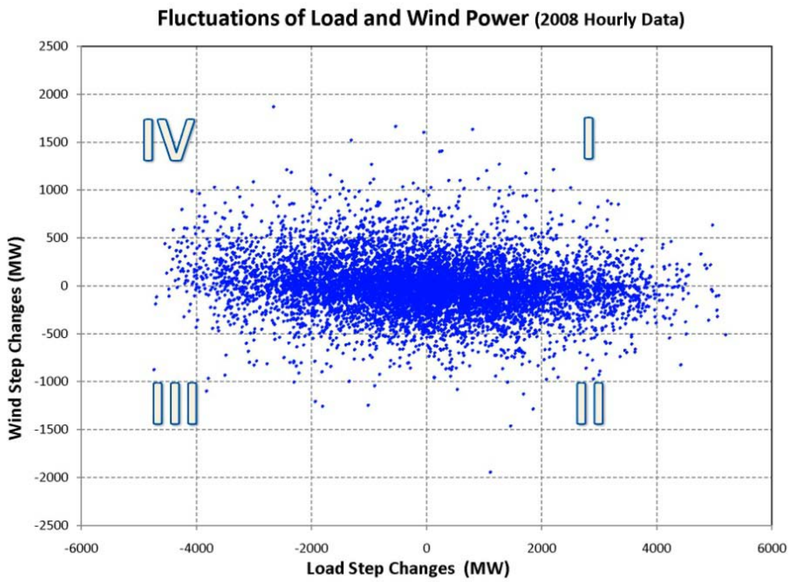

Figure 7 – Scatter plot of load and wind power step changes.

Data points in the first and third quadrants represent the hours both load and wind power are changing in the same directions. Data points in the second and fourth quadrants are the hours when load and wind power changes in the opposite direction. Although the hourly data points (dots) in the plot appear to be evenly distributed among all four quadrants, there are actually more data points in the second and fourth quadrants than that in the first and third quadrants. The breakdown is 56% and 44%, which means more than half of the time the fluctuations of wind power are in the opposite direction of the load changes and impose additional requirements on other generators used for following the load. The plot using 2009 data has an almost identical pattern with more data points in the second and fourth quadrants (55%) than that in the first and third quadrants (45%).

Standard deviation values (σ) of load, wind, and net load step changes are shown in Table 12. Also included in the table are maximum step-change values. The σ of net load experienced a 4% increase in 2008 and 5% increase in 2009. It confirms the observation from Figure 7—that wind power in EROCT will increase the regulation requirements on the system. When the maximum wind and load step changes will occur appears to be random. Evidently, the probability of both happening at the exact same time is very small. The magnitude of maximum net load step changes is smaller than the sum of wind and load step changes, and the maximum step changes of net load can be larger or smaller than the maximum step changes of load alone.

Table 12 – Statistics of Load and Net Load Step Changes.

	Hourly Data								
	Standard Deviation (MW)			Max Up (MW)			Max Down (MW)		
	Load	Wind	Net Load	Load	Wind	Net Load	Load	Wind	Net Load
2008	1,032	198	1,068	5,199	1,869	5,712	-4,736	-1,946	-5,064
2009	1,060	224	1,105	5,234	2,314	5,451	-6,461	-1,782	-6,591
	10-minute Data								
	Standard Deviation (MW)			Max Up (MW)			Max Down (MW)		
	Load	Wind	Net Load	Load	Wind	Net Load	Load	Wind	Net Load
2008	194	58	202	3,520	839	3,528	-4,642	-935	-4,585
2009	196	64	206	1,787	918	1,778	-1,906	-1,256	-1,904

It should be noted that this analysis applies to shorter term fluctuations of wind power and system load. There is no reason to think the change of wind power from one 10-minute period to the next with cause the system load to change in the same (or opposite) direction during the same 10-minute periods, and the available data support it. The correlation coefficient of the 10-minute wind power change and load change for 2009 was -0.05. Figure 7 showed that there were slightly more incidences of wind power and load moving in opposite directions than in the same direction.

Longer term wind power profiles such as daily and seasonal patterns are not random, and its effects on system net load are easier to predict. Figure 8 shows average daily wind power profiles for 2009 by month. It can be seen that for the most part the installed wind power capacity will produce a daily profile that is opposite to the typical daily profile of the system load, especially during summer months of May through September. Although traces in Figure 8 are based on hourly average valued over an entire month, its shapes still suggest that large down ramps tend to start in the early morning hours and large up ramps tend to start in the afternoon hours as discussed in section 3.2 of this report.

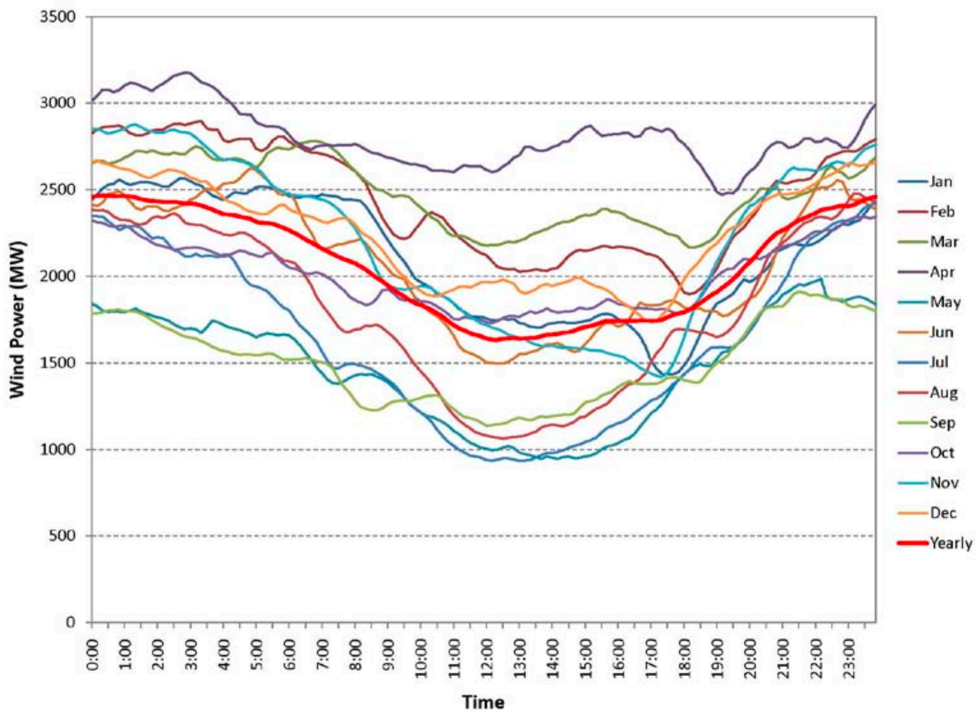

Figure 8 – Average daily profiles of combined wind power in ERCOT

However, Figure 8 is from the outputs of all large wind plants in ERCOT. It is important to know that winds from different regions will have different profiles because of the differences in the weather mechanisms that produce winds. A case in point is the wind plants in the coastal region of ERCOT. Figure 9 plots the same 2009 average daily wind power profiles of the wind plants in the coastal region.[13] It can be seen that not only do the wind profiles from the coastal region bear close resemblance to the system daily load profiles (peaking in the afternoon hours) they also have a close match to seasonal load patterns (peaking in summer months). Future study will analyze the ramping characteristics of these coastal wind power plants when more data are available.

[13] Four wind power plants on the Texas Gulf Coast in Kenedy County, Texas.

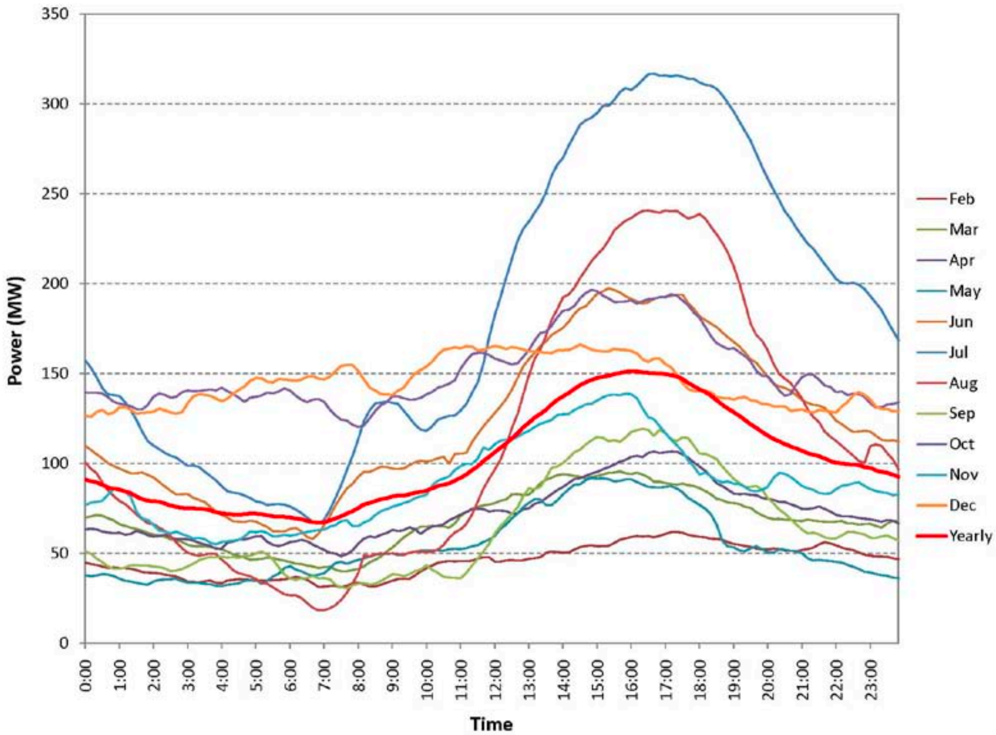

Figure 9 – Average daily profiles of wind power from coastal region of ERCOT

6. Event on February 24, 2007

On February 24, 2007, starting at approximately 9:00 in the morning, wind power in the ERCOT area began to drop at a rate of 624 MW/h. The precipitous drop continued for about two hours and thirty minutes for a loss of 1,560 MW of wind power. This amount represents 36% of total installed wind capacity for 2007 and 45% of the highest coincidental-peak wind generation during 2007. Figure 10 below shows the wind power profile of that day. This drop of wind power coincided with the ERCOT morning load pick up of that day (a Saturday). ERCOT needed to initiate Step 1 of the Emergency Electrical Curtailment Plan (EECP) for 32 minutes because of the low Adjusted Responsive Reserve (ARR) and violation of Control Performance Standard 1 (CPS1).

This down ramp of wind power was the most severe case in 2007, although neither its magnitude (-1,560 MW) nor its down ramp rate (624 MW/h) by itself was the worst for 2007. There were much larger changes in magnitude of -3,116 MW (but it took 9 hours), and higher down ramp rates of -1,235 MW/h (in an hour) and -631 MW/h (in 2 hours). This event's high ramp rate with a somewhat longer duration (2.5 hours) made it the most severe case in 2007. The drop of wind power was the result of very high wind in west Texas that caused the wind turbines to shut down. The load picked up at about 1,000 MW/h that morning, which was actually much greater than the highest up wind-ramp rates in the entire 2007. The ERCOT report did include other factors such as load changes in steel mills and slow response by other generating units at low load levels that contributed to ERCOT's action of entering Step 1 of EECP. It should be noted that this event resulted in no loss of load, which is the ultimate goal of system reliability.

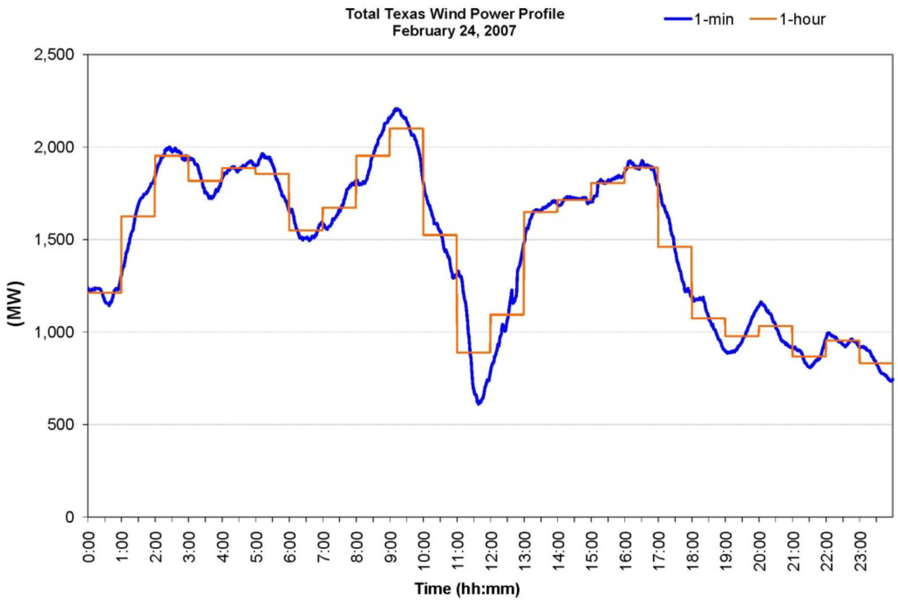

Figure 10 – Wind power profile of February 24, 2007.

7. Event on February 26, 2008

On February 26, 2008, starting at approximately 10:20 in the morning, wind power in the ERCOT system reached its peak of that day of 2,650 MW and started to drop. The down ramp started a slow pace of 189 MW/h and quickened to 395 MW/h after 14:00 in the afternoon. The down ramp continued until 22:00 in the night when there were only about 64 MW of wind power. The long wind power down-ramp coincided with ERCOT's evening load pick up (after 15:10 at a rate of 2,500 MW/h) of the day. Coupled with a trip of one conventional generating unit, ERCOT entered Step 1 and Step 2 of EECP due to low ARR. Total wind power drop in 10.8 hours was 2,586 MW, which was 55% of the highest coincident-peak wind generation in 2008. In terms of total installed wind capacity for 2008, it was only 34%. The average rate of this down ramp event was -239 MW/h with a peak rate of -395 MW/h. Figure 11 shows the 1-minute and hourly wind profiles of the day.

Unlike the event of February 24, 2007, this ramp event was not the worst case in 2008. On November 11, 2008, wind power in the ERCOT system dropped 3,430 MW in 10.8 hours. This down ramp rate was not the most severe either. For all down ramp events in the 11-hour duration group, the highest down ramp rate was -431 MW/h (see Table 9). In terms of ramp magnitude, this event ranked 7th for all down ramps in the 11-hour duration group and 53rd of all down ramp events in 2008. Its average down ramp rate of -239 MW/h ranked 8th among all down ramps in the 11-hour duration group. Even the highest down rate of this event is less than the maximum down ramp rate of -431 MW/h (itself an average rate) in the 11-hour duration group. There were two other factors that contributed to ERCOT's action of entering Steps 1 and 2 of EECP; the unexpected loss of a conventional generator and a quicker than forecasted evening load pick-up.[14] Again, no loss of firm load resulted from this event.

[14] Ela, E. and Kirby, B. (2008), ERCOT Event on February 26, 2008: Lessons Learned, NREL Report No. TP-500-43373.

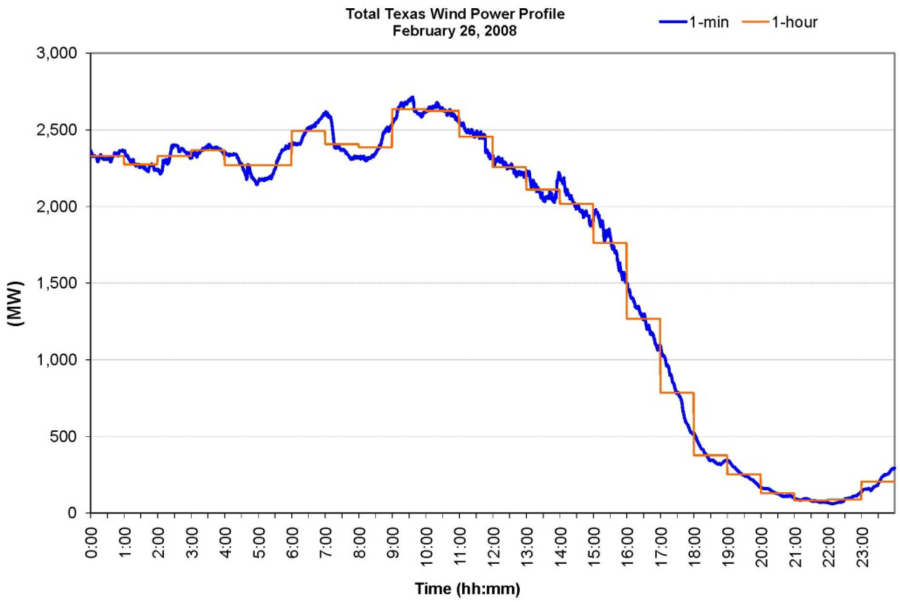

Figure 11 − Wind power profile of February 26, 2008.

8. Conclusions

The data has shown that large wind power ramping events occurred often. A relatively large ramp with a magnitude of at least 25% of total wind power capacity will occur about once every other day. As the installed wind generation continues to increase, very large ramp events with a magnitude of 50% of total wind capacity actually decrease. In terms of actual peak wind generation, the numbers of very large ramp events (those with a magnitude greater that 50% of the peak wind generation) stay at a fairly constant frequency of about once every week. The majority of up ramp events started in the afternoon hours and the majority of down ramp events started in the morning hours. In addition, very large ramp events tend to occur in the winter months as well-defined weather fronts in these months affect large numbers of wind turbines in the same time period.

None of the large ramping events identified from the available data had a ramping rate greater than 10% of the wind generating capacity per minute. Individual wind plants can ramp faster than 10% of its capacity per minute under certain wind conditions, but when aggregating this much wind generating capacity over a wind area as is the case in ERCOT, the combined output does not have a high ramping rate that exceeds 10% of the capacity per minute.

Because the system load is still much larger than the actual production of wind power in ERCOT system, load fluctuations still dominate the overall net load fluctuations. Wind power only increases the net load σ 4-5% over the σ of load alone. The two widely reported wind ramp-events in ERCOT were not the most severe ramp events in terms of overall magnitude and ramping rates. There were much more severe down ramp events in ERCOT that did not result in reportable events for ERCOT grid operators. This suggests that for a system as large as ERCOT, the current level of wind power penetration is not likely to cause reportable events, even for very large wind ramp-events. Only when other unforeseeable incidents such as large errors in forecasting load and forced outages of conventional generators that aggravate the situation will a large wind ramp become a problem for grid operators. This is not to say that large wind ramps are of no concerns to grid operators. However, as operators gain more experience with large wind ramps and with better wind ramp forecasting, their ability to cope with such events will improve.

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This report analyzes the wind power ramping behavior using 10-minute and hourly average wind power data from ERCOT and presents statistical properties of the large ramp events.

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