Wind Ramp Events at Turbine Height–Spatial Consistency and Causes at two Iowa Wind Farms

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1. Introduction

The U.S. Department of Energy's scenario to generate 20% of electrical energy from wind by 2030 (Department of Energy 2008) drives meteorologists to have a better understanding of the wind profile from the surface to turbine height. Wind energy can be an unreliable resource because wind is inconsistent. With added issues from lack of storage capabilities, ramp events are another downfall to wind energy because they bring sudden changes in power output and are difficult to predict. If these events were better understood, they might be forecast better. However, little work has been done to study the behavior of these events, and forecasts generally continue to lack skill.

In a recent study of a northwestern Iowa wind farm, Showers Walton et al. (2012) discovered that there were many causes for ramp events in Pomeroy, IA from 29 May 2008—12 November 2009, but thunderstorms and the presence of a strong pressure gradient, suggesting strong winds and mixing, were the most prevalent causes, agreeing at least partially with other studies that found convection, fronts, and low level jets (LLJ) to be the biggest causes of ramp events (e.g., Freedman et al. 2008). In the same study, Showers Walton also compared the causes of 154 ramp events in Pomeroy, IA to the causes of 1485 events among six turbines at a central Iowa wind farm, roughly 160 km away, over the same period.

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They found that 40% of the ramps in central Iowa occurred within 6 hours of a ramp in Pomeroy, suggesting some spatial consistency. The present study expands on these results through the analysis of the meteorological causes of these ramp events.
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2. Data and Methods

The current study utilizes wind speed data from Pomeroy, IA and wind speed and direction data from six nacelles in a central Iowa wind farm that underwent extensive quality control in Showers Walton et al. (2012). All data were taken every 10 minutes from 26 June 2010–8 September 2010 and from 28 June 2011–16 August 2011, and periods when the wind speed suddenly dropped to zero were considered erroneous and therefore excluded. Ramp-ups and ramp-downs were classified by a change in wind speed of 3 ms^{-1} or more between 6 and 12 ms^{-1} in 4 hours or less as in Deppe et al. (2012). Meteorological causes were sought out for the Pomeroy, IA ramps in 2008 and 2009 using Iowa State University's meteorological archive data server, the Iowa Environmental Mesonet (2012) archives, Unisys (2012) archive, and the Hydrometeorological Prediction Center (2012) surface analysis archive. These resources provided mean sea level pressure maps, radar, wind profiler, and surface station archives to determine possible meteorological causes for ramp events.

Ramp causes were assigned by assessing large scale features such as the presence of a front or a LLJ. If neither of these phenomena were present, radar archives were used to look for thunderstorms and associated outflow. Finally, if none of the above factors was present, the pressure gradient and PBL growth/collapse were analyzed assuming that with a strong pressure gradient there would be stronger winds above the friction layer which, assuming mixing, could lead to larger sudden changes in wind speeds and thus more ramp events. PBL growth could result in turbulent mixing due to diabatic heating which could lead to ramp events as well.

This same method was applied to find causes for ramp events in 2010 and 2011 using meteorological tower data at 80 m, as well as ASOS 10 m wind data within 20 miles of the central Iowa turbines. According to the power law, winds near the surface are not the same as at 80 m. Therefore, the ramp definition was scaled down for the ASOS 10 m winds according to the equation:

$$(1)\ \frac{u_{10}}{u_{80}} = \left(\frac{z_{10}}{z_{80}}\right)^{\alpha}$$

Where u_{10} and z_{10} are the wind and height at 10 m, and u_{80} and z_{80} are the wind and height at 80 m. In a neutral atmosphere, α can be assumed to be 1/7; however, this is a poor assumption at night because of the nocturnal LLJ. Therefore, from sunset to sunrise α was set to 1/4. This resulted in 10 m ramps being a 3 ms^{-1} change from 4.5–8.9 ms^{-1} during the day and from 3.6–7.1 ms^{-1} at night.

Ramps occurring in central Iowa within 6 hours of a ramp of the same type in Pomeroy, IA were considered to be the same ramp. This study looked into the causes of these spatially consistent ramps. Finally, when a ramp only occurred at some of the six central Iowa turbines, this study considered the meteorological cause and wind speeds at turbines that did not experience a ramp to determine whether they were close to ramping or if the ramps at the other turbines were due to very small-scale phenomena.

3. Results

The present study expanded on the results of Showers Walton et al. (2012) which discovered a variance in the peak in frequency of ramp-ups by location and year, but there was a general consensus that ramp-ups peak in the late night/early morning, 2200–0200 LST, and again from 0600–1000 LST (Fig. 1, 2). While there is a smaller peak in frequency from 1800–2100 LST +/- 2 hours as in Deppe et al. (2012), the main peaks in the present data set did not match up well with those found in Deppe et al. This difference could be due to the much shorter data set used in the present study, 2 ½ months compared to 2 years, or the difference in seasons. The present data set only observed summer ramp events which would imply more convection and turbulent mixing with different timing than the winter. Ramp-downs didn't seem to follow as distinct of a pattern as ramp-ups, as seen in Fig. 3 and Fig. 4.

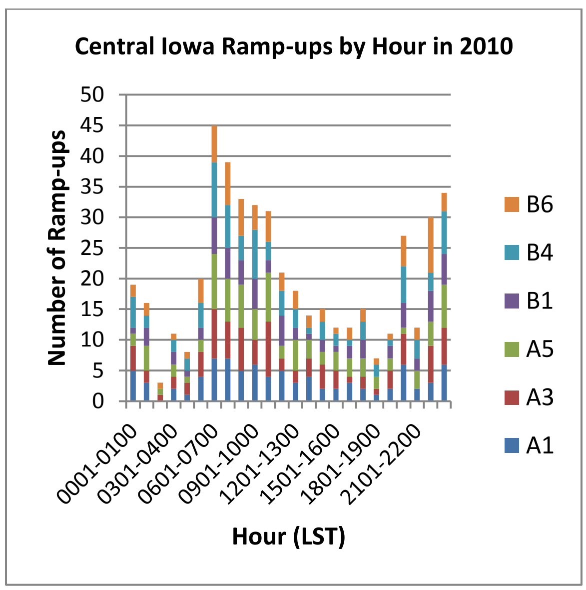

Figure 1: Number of ramp-ups by hour at each turbine in central Iowa (A1-B6)

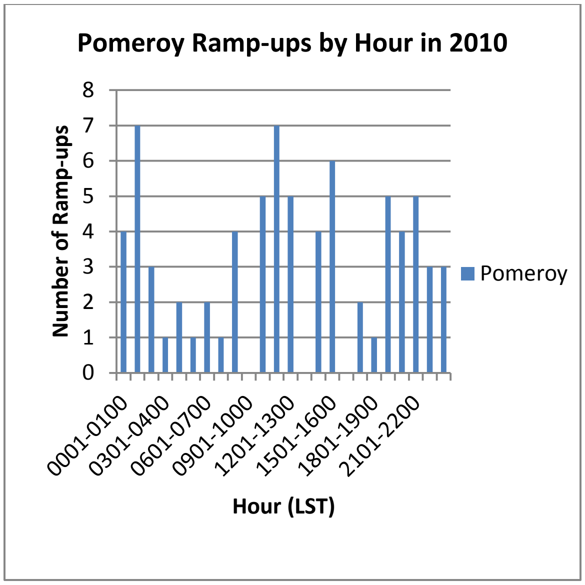

Figure 2: Number of ramp-ups by hour at the Pomeroy meteorological tower

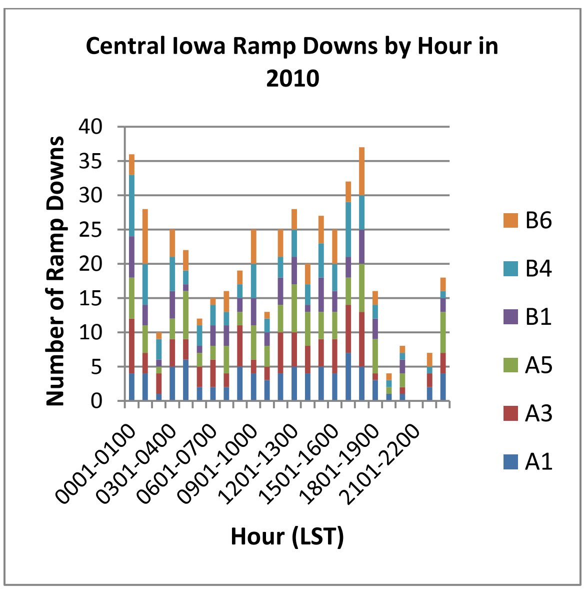

Figure 3: Number of ramp-downs by hour at each turbine in central Iowa. Notice multiple peaks in frequency

As noted by Fig. 3 and Fig. 4, the timing of ramp-downs is very different in central Iowa than in Pomeroy suggesting little spatial consistency for ramp downs.

Meteorological causes were assigned to the 256 spatially correlated ramps between Pomeroy and central Iowa, a total of 133

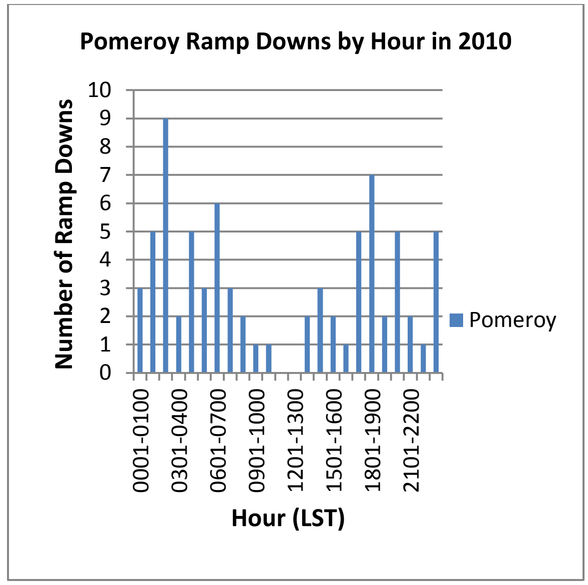

Figure 4: Number of ramp-downs by hour at the meteorological tower in Pomeroy, IA. Two significant peaks in frequency around 0300 and 1800 LST.

ramp-ups and 123 ramp-downs. Forty percent of all ramps in central Iowa occurred within six hours of a ramp of the same type in Pomeroy, IA. Thirty six percent of all ramps in central Iowa occurred within two hours of a ramp in Pomeroy (Fig. 5). The presence of a strong pressure gradient was the biggest contributor to spatially consistent events, those that occurred 2 hours apart or less. For twenty-six percent of the ramps no

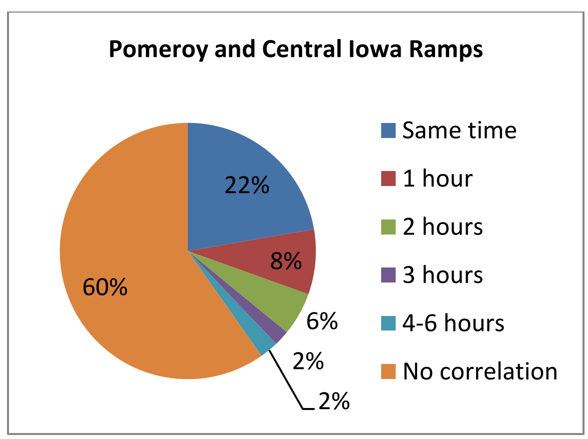

Figure 5: Spatial consistency of ramps from Pomeroy to central Iowa

cause could be identified (Fig. 6). The inability to attribute a cause for these events may be due to missing profiler data, or insufficiently fine resolution observations to identify small-scale features such as turbulence that were responsible for the ramps.

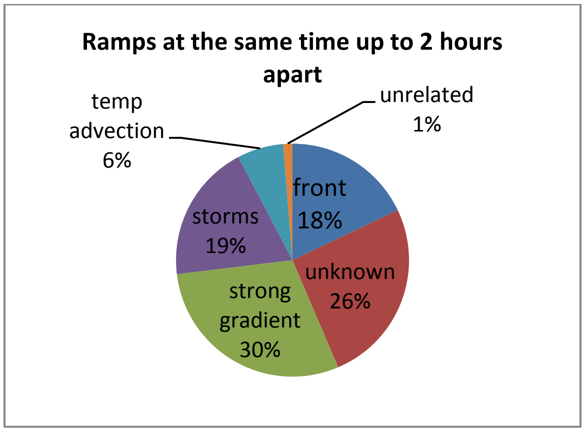

Figure 6: Causes of ramps in central Iowa occurring at the same time as ramps in Pomeroy up to 2 hours prior.

Fronts in the spatially-consistent cases were oriented in a way that they affected both locations around the same time. Thunderstorms were oriented in a similar manner or were rapidly moving.

When timing differences grew to be 3-6 hours, only three causes were identified, possibly due to the fact only 11 ramps fell into this category (Fig. 7). For these cases, 46% of ramps were due to fronts. For several cases, a cause could not be assigned.

The meteorological cause for 154 ramp events in Pomeroy, IA in 2010 and 1485 ramp events among the six turbines in central Iowa in 2010 and 2011 found by Showers Walton et al. (2012) was also examined. Most of the Pomeroy ramp events could not be assigned a cause, with the presence of a strong gradient or front being the most common cause for those events for which a cause could be assigned (Fig. 8).

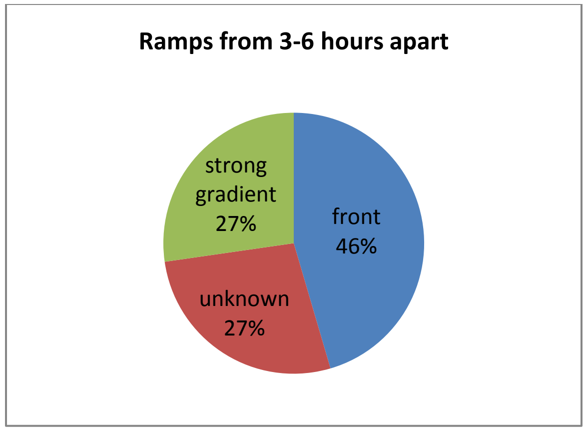

Figure 7: Causes of ramps in central Iowa occurring 3-6 hours prior to a ramp of the same type in Pomeroy, IA

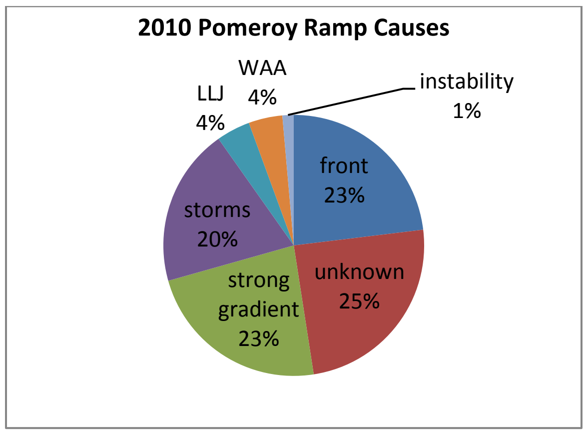

Figure 8: Causes of 2010 Pomeroy ramps determined from meteorological data archives.

It should be noted, however, that there were several cases where wind profiler data was unavailable, and the sample size in general was rather small because only 2.5 months of data were available in 2010. Therefore, future work should use a larger dataset to create a comprehensive climatology of 80 m ramp behavior. Most of the 2010 central Iowa ramps, evaluated during the same time period as the Pomeroy ramps, were also associated with a strong pressure gradient or thunderstorms (Fig. 9).

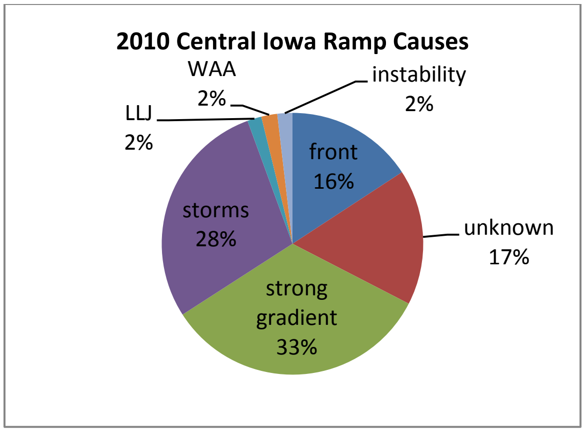

Figure 9: Cause of 2010 central Iowa ramps determined from meteorological data archives.

The percentage break down of causes at the two sites is within 10% of each other indicating generally similar trends at the two sites. Finally, for the 2011 central Iowa ramps, the largest fraction could not have a cause assigned to them (Fig. 10).

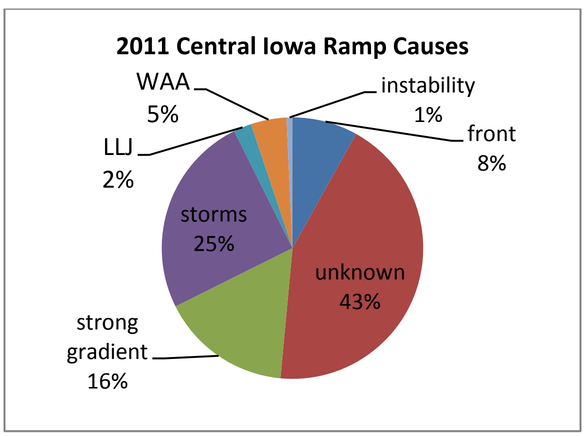

Figure 10: Cause of 2011 central Iowa ramps determined from meteorological data archives.

Again, wind profiler data were often unavailable so ramps due to LLJs would not be determinable. This period was also shorter, only 1 ½ months long.

ASOS wind speed data at 10 m was used during the same time period as the central Iowa data in order to examine any relationship present between 10 m and 80 m ramps. As shown by Eq. 1, the definition of a ramp was scaled for 10 m according to the power law. Using the new definition, this study found 115 scaled ramp events at 10 m in 2010 in central Iowa and 63 scaled ramp events in 2011 in central Iowa. In using the original ramp definition, 59 unscaled ramps were found in 2010 and 27 unscaled ramps were found in 2011. This study was not able to collect 10 m data for Pomeroy due to the ASOS station near the wind farm being down during the data period.

When there was a scaled ramp at 10 m, 72% of the time there was a ramp at 80 m in 2010 and 59% of the time in 2011. This implies that when a ramp occurs at the surface, it usually occurs at 80 m as well. However, the 28% of ramps that occurred in 2010 and the 41% that occurred in 2011 where a surface ramp was not associated with a ramp at 80 m, were mostly due to unknown meteorological causes, or the 80 m wind speeds did not meet the criteria used to be considered a ramp in this study.. Ten meter wind speed data is readily available in the Midwest, unlike 80 m data. Therefore, this relationship between ramps at the surface and ramps at 80 m could result in a broader sample of ramp events and more potential for research to improve forecasting.

Since wind data were available from several wind turbines at the central Iowa wind farm, the behavior of ramp events within a wind farm was also explored. Several cases were found where one or more turbines did not experience a ramp while the others within the same line of turbines did. When one or more turbines did not experience a ramp, the speed by which the turbine was off from 3 ms^{-1} was calculated. This value was converted to a percentage in order to see how close the turbines that missed a ramp were to a 3 ms^{-1} change (Fig. 11).

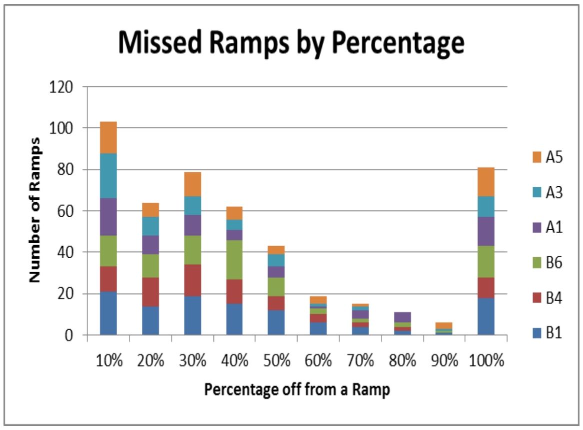

Figure 11: The number of non-ramps by turbine organized by percentage away from a ramp

In cases where one or more turbines did not experience a ramp, the turbines that did not ramp generally had magnitudes only 10% or less too small to be counted as a ramp, with some others only short by 20%-40%. This indicates that the ramp events are weakened as they pass through the wind farm, as would be expected. Turbines assigned a value of 100% experienced a ramp of the opposite type (a ramp-up when there were ramp-downs at the other turbines) or were outside the limits of this study's definition of a ramp. This occurred in 80 cases. Once ramps enter the first line of turbines in a wind farm there is evidence suggesting small-scale turbulence is created causing the ramp to die out or even turn into a ramp of the opposite type by the time it reaches the next line of turbines.

4. Conclusions

Ramp-ups and ramp-downs are hard to predict due to many possible meteorological causes for the ramps, the need to accurately predict on very small spatial and temporal time scales, and the fact relatively few studies have been done on these events. The present study has discovered ramps to be somewhat spatially consistent within 160 km at 80 m. Forty percent of all ramps in central Iowa found in this study occurred within six hours of a ramp of the same type in Pomeroy, IA. To ensure that the ramps reaching central Iowa were the same ramps that took place in Pomeroy, meteorological data archives were used to determine the cause of each ramp. Most of the ramps in central Iowa that occurred within 2 hours of a ramp in Pomeroy were associated with a strong pressure gradient, implying strong winds with a likely strong vertical wind shear that via mixing might lead to ramps. Ramps in central Iowa occurring within 3-6 hours of a ramp in Pomeroy were mostly due to frontal passage.

Ten meter ramp events in central Iowa found using a scaled definition through the power law revealed a correlation between these surface ramps and ramps at 80 m with 47-56% of 80 m ramps found to occur at roughly the same time at 10 m. Since 10 m wind observations are more abundant in the Midwest than 80 m observations, 10 m wind speeds could be used to estimate behavior at wind turbine height enhancing the sample size of ramp events, and possibly assisting with the forecasting of ramps.

Finally, this study looked into the behavior of ramp events within a wind farm. In cases where one or more turbines did not experience a ramp the percentage by which that turbine failed to be defined as a ramp was studied. It was found that most of these were roughly 10% too weak to be counted as a ramp, exhibited an opposite ramp, or were outside the 6-12 ms^{-1} range of wind speeds used to define a ramp. This result indicates micro-scale features are occurring which alter ramps throughout wind farms. Much more work is needed to explore small-scale variations in wind speed and possible causes for ramp events, hopefully improving the forecasting of ramps.

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