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Assessing the Impacts of Reduced Noise Operations of Wind Turbines on Neighbor Annoyance:

A Preliminary Analysis in Vinalhaven, Maine

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Environmental Energy Technologies Division

June 2010

The work described in this report was funded by the Office of Energy Efficiency and Renewable Energy (Wind & Hydropower Technologies Program) of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.

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Assessing the Impacts of Reduced Noise Operations of Wind Turbines on Neighbor Annoyance: A Preliminary Analysis in Vinalhaven, Maine

Prepared for the

Office of Energy Efficiency and Renewable Energy
Wind & Hydropower Technologies Program
U.S. Department of Energy
Washington, D.C.

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Executive Summary

Neighbors living near the 3 turbine, 4.5 MW Vinalhaven, Maine wind power facility, which began operations in late 2009, have complained that the noise from the turbines is unwelcome and annoying. Fox Islands Wind, the owner of the facility, hypothesized that implementing a Noise Reduced Operation (NRO) for the turbines, which effectively limits the turbines' maximum rpm and power output, would reduce the sound levels produced by the turbines, and therefore might also reduce the degree to which the neighbors report being annoyed by those sounds. To test this hypothesis in a preliminary fashion, a pilot study was conducted in early 2010, the results of which are the subject of this brief report.

The study included asking near-by residents - those within roughly 3000 feet - to rate the sounds and the degree to which they were annoyed by them using logs which they filled out at multiple times during the day on as many days as were possible in the 35 day study period in February and March, 2010. Meanwhile, FIW adjusted the NRO settings of the turbines in a random fashion in the evenings during the same period, but in a pattern that the respondents were not made aware of. Ultimately, nine individuals turned in roughly 200 log entries (i.e., responses), each of which was time coded to allow testing if the response was correlated with the wind facility operating conditions at that time.

The analysis of these data found small, non-statistically-significant differences in self-reported turbine loudness and annoyance ratings between the periods when the NRO was enacted and when it was not, after controlling for many of the relationships that could independently influence perceived loudness and annoyance (e.g., wind direction, time of day). Possible explanations for these small differences in self-reported turbine loudness and annoyance ratings include: the relative difference in sound output from the turbines when NRO was engaged and when it was not was small; and/or that differences in turbine sound outputs that did exist might have been masked by higher (non-turbine) wind sound levels that were coincident with NRO periods. Because this preliminary test only included a small portion of the population surrounding the turbines, the sample of self-reported ratings was itself very small. In addition, the conditions varied greatly over the study period, as described in the report that follows. Consequently, the results presented here should be considered preliminary, and further data collection and analysis are warranted.

The main findings of this preliminary study are:

- As planned, periods in which the NRO was engaged were found to have noticeably lower turbine rotational speeds (rpm), based on turbine operational data.
- 11% of responses overall indicated that the turbines were perceived as either “very” or "extremely" loud at the time they were logged, and roughly two thirds of those (7% overall) indicated the sounds to be “very” or "extremely" annoying.
- Self-reported turbine loudness and annoyance ratings were higher during the night and when the wind was from the North (participants in the study were located to the east and south of the turbines).
- Self-reported turbine loudness and annoyance ratings were generally found to be lower during the NRO periods, but these observed differences are relatively small in magnitude, and are not statistically significant.
- There is some limited evidence that high-speed surface winds mask self-reported turbine loudness and annoyance ratings. Therefore, because NRO settings are only engaged during periods of high winds, the true effects of the NRO adjustments might be diluted to some degree.
- The results of this preliminary assessment should not be applied to the full population of homeowners near the turbines in Vinalhaven, Maine because the potentially most-sensitive individuals (those most vocal of their dislike of the turbine sounds) opted not to participate in the study, and because the study did not include the relatively large number of individuals who primarily visit the island during the summer months.

1. Introduction

Fox Islands Wind (FIW) is the owner of a 3 turbine, 4.5 MW wind power facility on Vinalhaven Island off the coast of Maine. The facility was erected and began operation in late 2009. Some near-by residents have since voiced concerns that the turbines are creating a surprisingly large amount of unwanted sound that they consider annoying and disturbing to their use and enjoyment of their properties. In response to these concerns, FIW conducted an experiment in which it adjusted the turbines to operate at night in a Noise Reduced Operation (NRO) mode, which effectively limits the maximum rotational speed of the turbines, resulting in lower power output and reduced sound output.[1]

To determine if the NRO settings were effective in reducing perceived turbine loudness and annoyance, FIW conducted a pilot study asking near-by residents to rate the loudness and annoyance using daily logs, while FIW adjusted the NRO settings of the turbines during random times of the study period.[2] FIW hoped that if a noticeable reduction in the perceived loudness and related annoyance ratings were found to be strongly associated with the NRO settings, then FIW could potentially use the NRO settings as one of their options to mitigate local annoyance concerns.

In addition, only two turbines were operating during a portion of the experiment. Because it is theorized that two turbines would necessarily make less sound then three, a test was created to determine if turbine loudness ratings were lower during the periods in which only two of the turbines were operational. Although FIW does not consider turning one of the three turbines off entirely as a reasonable option to mitigate annoyance, the possibility of studying the effects of two turbines as compared to three presented an opportunity for research.

Finally, it is theorized that wind sounds may mask turbine sounds. Because NRO is only engaged when turbine power output is near to or at its maximum, which coincides with periods of high winds, it is possible that the louder wind sounds during these periods will mask the true NRO effects, as perceived by near-by residents. Therefore a test was conducted to test whether wind sounds mask turbine sounds during NRO periods.

[1] One of four NRO settings were used each of which further reduced the noise of the turbines and related rpm and power, with each being used as much as the others. For the purposes of this analysis no distinction was made between the settings when testing for effects.
[2] Since the facility began operation FIW had been operating one of the three turbines under NRO settings. The adjustment was for 1 decibel. For this study, they used adjustments of all three turbines by as much as four decibels.

This brief report outlines the outcomes of this study and is broken into five parts: data overview, data summary, study design, results, and conclusions and recommendations.

2. Data Overview

During the period of February 1, 2010 to March 7, 2010 FIW adjusted the operating turbines using one of four NRO settings. For roughly the first 18 days of the experiment only two out of three turbines were operating.[3] All households within roughly two thirds of a mile of the turbines were each delivered logs to fill out during the study period, in which they could describe the sounds from the turbines and their annoyance while noting the corresponding date, time, and location.[4] The initial log that was distributed to the community (Log #1 - Attachment 1) was replaced with a more comprehensive log (Log #2 - Attachment 2) roughly 14 days into the study period. The initial log encouraged respondents to rate perceived turbine loudness levels once a day, while the latter log encouraged respondents to not only rate turbine loudness levels but also the degree to which they were annoyed by those turbine sounds, and wind loudness levels, and to do so at multiple times during each day. Wind loudness levels were to be used to test if they masked turbine sounds.[5] Additionally, data were obtained from the wind facility operator (General Electric) on rotational speed (rpm) and power output from each of the three turbines as well as wind speed and direction at the turbine hub, which is roughly 80 meters above the ground. Surface wind speed and direction was obtained from a National Oceanic and Atmospheric Administration (NOAA) buoy in Penobscot Bay roughly ten miles from the facility and four meters above sea level, which was used as a proxy - in place of wind sound levels - for ground level speeds at the homes, a potentially masking correlate.[6] Collection of all these data allowed for a test of the correlation of self reported sound/annoyance levels and NRO adjustments while accounting for other potential correlates, such as: wind direction and wind speed at hub height and at ground level, whether the response was from inside or outside the home, the distance the respondent's home was from the turbines, and whether it was day or night. They also allowed for an investigation of the other two hypotheses: 1) if turbine loudness and annoyance ratings were significantly different when two or three turbines were operating, and 2) if wind related sounds mask turbine sounds at higher wind speeds, when the NRO would tend to be implemented.

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[3] NRO settings were applied during these periods in a similar fashion as during the periods when all three turbines were operating.

[4] Although desired, ground level sound and wind speed measurements near the homes were not obtained for this analysis, therefore only self-reported wind and turbine sound levels were used.

[5] Wind loudness includes not only the sound of wind itself but also sounds of other objects reacting to the wind (e.g., the leaves on the trees).

[6] NOAA buoy number F01: West Penobscot Bay

3. Data Summary

Nine households, representing about fifty percent of all households within roughly two thirds of a mile of the turbines, provided data during the study period in the form of 197 log entries (i.e., responses).[7] A summary of the data collected for the analysis is presented in Table 1 and Table 2: 78% of the responses were recorded outdoors; 54% were recorded during the day (between the hours of 6:00 AM and 6:00 PM); and the closest respondent's home was roughly 1,700 feet from the center point of the three turbines, whereas the furthest was roughly 3,600 feet. From the turbine operational data, it was determined that the NRO adjustment was in effect for 42% of the time during the study period, but because high winds at hub height (over at least 6.5 meters per second) were required to have NRO effects engage, only 18% of the time during the study period had NRO engaged.[8] Because these latter periods coincided with periods of higher response rates, however, 22% of the total number of responses occurred during NRO engagement periods. Finally, the hub-height wind direction during the study period was from the north (due north plus or minus 45 degrees) 47% of the time, from the west 30% of the time, and from the east 23% of the time. All respondents reside either to the south or the southeast of the wind power facility.

26% of the responses included self reported turbine loudness rated as "not audible", 47% as "slightly audible", 18% as "moderately loud", 7% as "very loud", and 3% as "extremely loud".[9] This corresponds somewhat to the self reported degree of annoyance 65% that were rated as "not annoying", 21% as "slightly annoying", 6% as "moderately annoying", 4% as "very annoying", and 3% as "extremely annoying". In summary, about one tenth of responses (11%) included ratings of the sounds of the turbines as "very loud" or "extremely loud", while two thirds of those (7% overall) included annoyance ratings of "very annoying" or "extremely annoying." Finally, 39% of responses included ratings of the wind loudness levels as "not audible" , 32% as "slightly audible", 16% as "moderately loud", 8% as "very loud", and 4% as "extremely loud".

[7] Roughly 20 households, within one mile, live on the island during the winter, while roughly 50 do so during the summer. Many of the "non-responding" households living on the island during the winter are known to be highly annoyed by the turbines (n~8) but chose not to turn in their logs. All of the roughly 200 responses were useable for analysis of turbine sound ratings, but because only the second log allowed respondents to rate annoyance directly, approximately 140 responses were usable for analyzing annoyance.

[8] At lower wind speeds the NRO adjustments do not "engage" because the turbines do not reach their maximum rotational speed or power output.

[9] The responses on the initial logs (n=56) for "perceived turbine sound levels" were converted into the "turbine sound levels" used for the latter logs so that they could be analyzed as one "combined" dataset.

Table 1: Turbine, Buoy, and Respondent Descriptive Statistics and Expected Signs

Turbine Information	Freq.†	Mean	Stand. Dev.	Min.	Max.	Expected Sign
Revolutions Per Minute (RPM)	197	13.0	4.0	0.1	18.4	n/a
Hub Wind Speed (m/s)	197	7.9	3.1	1.6	18.3	+
3 Turbines (in operation at the time)	81			0	1	+
Noise Reduced Operation (NRO) Engaged	43			0	1	-
Buoy Information						
Buoy Wind Speed (m/s)	197	8.0	3.2	1.8	17.6	-
Respondent Information						
Distance (in feet from the center of the 3 turbines)	197	2,769	690	1,704	3,631	-
Inside (rating made inside the home)	44			0	1	-
Daytime (rating made between 6 AM and 6 PM)	107			0	1	-
Compass East*	45			0	1	-
Compass North*	92			0	1	+
Compass West*	60			0	1	+
Compass South*	0			0	1	n/a
Wind Loudness Rating	140	2.1	1.1	1	5	-
Turbine Loudness Rating - Combined**	196	2.1	1.0	1	5	n/a
Turbine Sound Annoyance Rating	141	1.6	1.0	1	5	n/a

† Frequency applies to the number of cases, out of 197 in total, the variable's value is not zero
** Compass categories signify the direction of the wind as determined at the hub (i.e., from the north) +/- 44.99 degrees*
*** Combined turbine loudness level ratings include those from both Log #1 and Log #2*

Table 2: Summary of Log Responses

	None†	Slightly	Moderately	Very	Extremely	Total Responses
Wind Loudness Rating	55	45	23	11	6	**140**
Turbine Loudness Rating - Log #1*	10	31	12	2	1	**56**
Turbine Loudness Rating - Log #2	41	61	23	11	4	**140**
Turbine Loudness Rating - Combined**	51	92	35	13	5	**196**
Turbine Sound Annoyance Rating	92	30	9	6	4	**141**

"audible_quiet"="slightly", "sound masked by wind"="none", "moderate"="moderate", "very loud"="very", "extremely loud"="extremely"
*** Combined turbine loudness rating includes those from both Log #1 and Log #2*
† "None" corresponds to "not audible" for the loudness ratings, and "not annoying" for the annoyance ratings.

4. Study Design

This study was specifically designed to test:

1. If self-reported turbine loudness and annoyance ratings are lower during NRO periods.
2. If self-reported turbine loudness and annoyance ratings are lower during periods when only 2 turbines are operating (vs. three).
3. If self-reported turbine loudness and annoyance ratings are masked by wind sounds.

To test the three hypotheses a total of four regression models were created: two for self-reported turbine loudness ratings (combining responses from logs #1 and #2) and two for self-reported turbine sound annoyance ratings, with each pair consisting of a pooled dataset of all possible cases and a smaller dataset of responses only when all three turbines were operating.[10] Therefore, two models use turbine loudness ratings as the dependent variable and two use turbine sound annoyance ratings.

All models use the following independent variables: distance (from the home to the center point of the turbines), wind direction at the hub (e.g., "Compass East"), wind speed at the hub (to capture absolute sound levels at the hub), whether it is daytime or not, whether the respondent was inside or outside, if three turbines are in operation or not, and if NRO is engaged or not. To capture the potentially masking effects of ground level winds, the turbine loudness rating models use the wind speed at the buoy while the turbine sound annoyance rating models use self-reported wind loudness ratings.[11] The expected signs of each of the parameters are noted in Table 1.

5. Results

Prior to running the regressions, a number of confirmatory relationships were investigated, which help to validate the logic of the study design and measurements. For example, buoy wind speed is found to be strongly correlated to hub height wind speed ($r=0.74$, $p < 0.01$). Hub height wind speed is strongly correlated with turbine rpm ($r = 0.53$, $p < 0.01$) and power ($r = 0.66$, $p < 0.01$). Similarly, respondents' ratings of wind loudness levels are well correlated with wind speeds at the hub ($r = 0.49$, $p < 0.01$) and at the buoy ($r = 0.44$, $p < 0.01$). Further, the average turbine rpm during the NRO engagement periods is

[10] Turbine sound level models use the combined ratings from both log #1 and log #2, while turbine sound annoyance models use responses only from log #2.

[11] It was assumed that self-reported wind sound level was a better predictor of ambient background ground-level sounds than its proxy of wind speeds at the buoy, but self-reported wind sound level ratings were only included in the second log (Attachment 2) and therefore could not be used for the turbine sound level models that included responses from both the first and second logs.

lower by an average of 1.3 (13.5 rpm vs. 12.2 rpm) as compared to the periods when NRO was not engaged ($t = 2.28$, $p < 0.05$).

The results from the four regressions are shown in Table 3. In each case, the analysis again finds evidence of a number of relationships that were expected to exist and that therefore help validate the model. For example, turbine sound and annoyance ratings are consistently lower during the day (versus during the night) and are higher when the wind is coming from the North (when homeowners were downwind of the turbine sounds), with the daytime distinction being statistically significant in two of the four models. Other variables have less consistent relationships to rated sound and annoyance levels. For example, distance (from the turbines) is found to have a statistically significant and positive relationship to turbine loudness ratings in just one of the four models, indicating (opposite of what one would expect) higher ratings as distance increases, but the coefficient is very small (for each 100 feet from the turbines the rating increases by 0.02) and the magnitude and sign of the coefficient is not consistent across all four models. Further, being inside or to the east is not observed to consistently affect either sound or annoyance ratings.

Concentrating on the NRO effects, while holding the other relationships constant (e.g., distance, direction, wind speed, etc.), we find that during NRO engagement periods, observed turbine loudness ratings are lower in the pooled model (-0.21, *p*-value 0.34) and essentially non-existent in the three turbine model (0.03, *p*-value 0.91). Further, observed annoyance ratings are lower in both models (pooled model -0.17, *p*-value 0.46; three turbine model -0.12, *p*-value 0.62). None of these relationships, however, for either loudness or annoyance ratings, are statistically significant (at the 10% level). Moreover, the predicted difference in loudness and annoyance ratings between any period of NRO intervention and those without is no more than roughly one fifth of one rating point (e.g., -0.21). In other words, if given five responses, on average, only one would change during a NRO period and would do so by only one level (e.g., “moderately” to “slightly).[12]

The second hypothesis - if three turbines were noticeably louder than two - was investigated using a fixed-effect variable for the three turbine condition ("3 Turbines") in the two pooled models for turbine sound level and turbine sound annoyance (models one and three). In both models, a significant negative relationship is discovered indicating that, during the period when all three turbines were operating, turbine loudness ratings ($\hat{\chi} = -0.47$, *p*-value 0.04) and annoyance ratings ($\hat{\chi} = -0.51$, *p*-value 0.02) were

[12] Conceivably, if more responses were obtained, a continuous relationship between NRO and annoyance could be investigated. For this analysis, however, average (e.g., fixed effects) for any/all NRO interventions were tested.

significantly lower, a counter-intuitive result. If true, this would indicate that the turbines are considered less loud and annoying when all three are operating.

A further investigation finds purely coincidental yet significantly <u>higher</u> hub wind speeds ($\hat{x}$ = 2.7 m/s, *p*-value 0.00), buoy wind speeds ($\hat{x}$ = 2.3 m/s, *p*-value 0.00), rpm ($\hat{x}$ =4.8 rpm, *p*-value 0.00), and self-reported wind loudness ratings ($\hat{x}$ = 0.6, *p*-value 0.00) during the periods when three turbines were operating versus when only two were operating.[13] These operating conditions likely strongly influenced the results, because many other parameters in the model are driven by wind speed, and therefore make it difficult to disentangle the effects and derive credible conclusions to the second hypothesis using the regressions. Potentially interesting, however, is that that despite the higher wind speeds, which would be expected to be correlated with higher turbine loudness and annoyance ratings during the period in which all three turbines were operating, lower ratings of sound and annoyance were discovered. One possible explanation for this counter-intuitive result is that the considerably higher wind speeds during the three turbine period masked the higher levels of sounds from the turbines.

To that end, we turn now to the third hypothesis, and investigate whether other parameters in the models further support this masking hypothesis. The coefficients for wind loudness ratings would be negative if those coefficients accurately captured ground level wind sounds and those sounds masked annoyance related to turbine sounds. We find the opposite to be the case for the pooled annoyance model (#3) (0.3, *p*-value 0.00) and (though not statistically significant) for the three turbine annoyance model (#4) (0.1, *p*-value 0.19). This is an indication that, in the sample, wind loudness ratings are strongly correlated with turbine annoyance ratings and that as the former increases so does the latter, indicating, potentially, that wind sounds might contribute to annoyance. Alternatively, wind loudness ratings might not accurately capture wind sounds on the ground and therefore might be capturing sounds closer to the hub, which are likely strongly correlated with hub height wind speeds, and therefore turbine sounds. Without ground level sound measurements (and/or wind speed measurements at the respondent locations) it is difficult to determine what effect wind loudness ratings are measuring. Turning to the turbine loudness rating models (#1 and #2), where buoy wind speed is used - a potentially more accurate proxy for ground level wind sounds - the coefficients are appropriately signed, but are not statistically significant. This indicates a potential masking effect, but one that cannot be confirmed without more responses. Therefore based on the set of tests - evidence from the two turbine period and the two sets of regressions - we find some support for the hypothesis that wind sounds mask turbine sounds, and therefore posit that wind sounds

[13] The choice to have either three turbine operating or two was governed by the repair schedule. Once the repair was made, on or about February 20th, all three turbines began operating.

might mask the true effects of the NRO adjustments, a relationship that cannot be confirmed without further study.

Table 3: Results from Regression Models

	Model 1	Model 2	Model 3	Model 4
Dependent Variable	**Turbine Loudness Rating**	**Turbine Loudness Rating**	**Turbine Sound Annoyance Rating**	**Turbine Sound Annoyance Rating**
Independent Variables				
Intercept	2.43 (5.54) ***	2.68 (3.86) ***	2.07 (3.95) ***	0.58 (0.67)
Distance (100s feet)	0.02 (2.03) **	-0.01 (-0.99)	0.02 (1.50)	0.02 (1.54)
Inside	0.14 (0.74)	-0.24 (-1.17)	0.03 (0.11)	-0.06 (-0.26)
Compass East	-0.28 (-1.28)	-0.08 (-0.15)	-0.19 (-0.78)	0.40 (0.56)
Compass North	0.18 (1.04)	0.15 (0.27)	0.10 (0.48)	0.59 (0.81)
Daytime	-0.19 (-1.18)	-0.37 (-1.95) *	-0.20 (-1.16)	-0.39 (-2.03) **
Wind Loudness Rating	--	--	0.32 (4.35) ***	0.10 (1.32)
Buoy Wind Speed (m/s)	-0.03 (-1.09)	-0.03 (-1.01)	--	--
Hub Wind Speed (m/s)	0.07 (1.95) *	0.01 (0.39)	-0.03 (-1.11)	-0.03 (-1.04)
3 Turbines	-0.47 (-2.44) **	--	-0.51 (-2.34) **	--
NRO	-0.21 (0.95)	0.03 (0.11)	-0.17 (-0.75)	-0.12 (-0.50)
Model Statistics				
Sample	Pooled	3 Turbines	Pooled	3 Turbines
n	195	80	139	76
R-Squared	0.11	0.14	0.22	0.15
F-Value	2.66 ***	1.42	4.18 ***	1.55

*Significant at or above the: *** 1% level, ** 5% level, * 10% level. t-values shown in parenthesis.*

6. Conclusions and Recommendations

Taken together, we find that there is some limited evidence that self reported turbine loudness and annoyance ratings are lower during NRO engagement but that the differences are relatively small and are not statistically significant. We cannot draw conclusions as to the effects of two turbines versus three given this sample, and we find some limited evidence that masking of turbine sounds may exist at higher level wind speeds. Therefore, it follows that because the NRO settings engage during periods of higher winds, and these same winds might mask the differences in turbine loudness levels attributable to the NRO settings, the true effect of the NRO adjustments might be diluted and therefore might not present an effective mitigation strategy for FIW. A follow up study, with more data, should occur to investigate this further though.

Additional research is recommended for other reasons as well. For example, because the potentially most sensitive homeowners chose not to participate in this study, the true effects of the NRO adjustments on the full “population” cannot be determined. Further, other homeowners who do not live on the island during the winter, but instead visit during the summer, could be surveyed. Additionally, wind speed and sound measurements at the respondent locations were not obtained for this study but would be very helpful in identifying differences in sound output at the turbines, to qualify responses from the logs, and to independently measure for ground level wind masking effects. With those data in hand, a more clear determination of annoyance influences and the true effects of the NRO adjustments might be determined for the population living near the turbines. Finally, it might be worth studying the effectiveness of engaging NRO during periods of high wind shear, when low ground level wind speeds are coupled with high hub height wind speeds, a time when it is theorized that turbines are the loudest.