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Community Response to Wind Farm Noise

The possible role of turbulence, shear, and wake effects

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Variable community responses to wind farm noise

Cummings: Guest seminar, NREL May 2, 2013 and Sandia National Lab May 16, 2013

Variable community responses to wind farm noise

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Are concerns about turbine noise hurting wind's brand?

Noise concerns have become a primary consideration during planning, permitting, and operation of new wind farms in an increasingly wide range of communities

Wisconsin Minnesota Michigan Massachusetts California Connecticut Maine Vermont New York Oregon Ontario Ohio Illinois Arizona Nebraska *(even Wyoming!)*

No matter how common or how unusual noise problems may be, building closer to more homes creates a need to reduce the sound output of turbines

"It's on the top of the minds for all manufacturers. We're all doing things to reduce the amount of noise that's generated."

Paul Thompson, Mitsubishi
North American Windpower, July 2011

Cummings: Guest seminar, NREL May 2, 2013 and Sandia National Lab May 16, 2013

Turbulence research:
noise reduction as secondary benefit of innovation

inflow turbulence / turbine wakes / directional wind shear

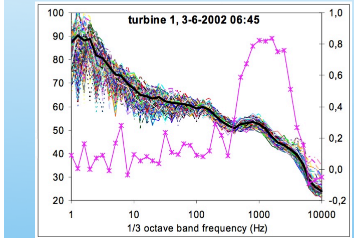
Primary drivers for turbulence research:
Reducing blade loads (system wear/fatigue; facilitating longer blades)
Minimizing power losses

Many of the most troublesome aspects of turbine noise for neighbors may be associated with likely turbulence effects
"Knocking" "Banging" "Sneakers in drier"
Deep rumbling low frequency noise

These more intrusive sounds and harder-to-ignore sound qualities are key drivers of negative attitudes toward turbines
difficult to accept – perhaps making it harder to live with typical gentler turbine sounds

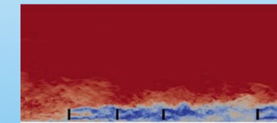
The relative lack of turbulence in open, flat ranch country may contribute to the lower incidence of noise issues
more consistent sound, less intrusive sound qualities

So: What have we learned about what may be behind the noise issues?



Variability

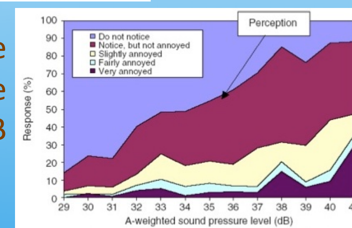
LF Content



Turbulence/Wakes?

Graphic: M. Churchfield, 2012 Eddy simulation, Lillgrund wind farm

Annoyance rates rise at >40dB



Turbine Sound Variability:
averages & peaks

Projects can operate in compliance……
generally based on average sound levels
….yet generate widespread community complaints
triggered by peak sound levels

Most projects *do* meet regulatory average noise levels

Violations, when they occur, are usually just 1-3dB

Noise models, using conservative assumptions about propagation, are generally working fairly well, at least for average sound levels

Peaks are another story….and one that turbulence likely plays a role in

Turbine Sound Variability:
averages & peaks

David Hessler: Best Practices Guidelines, 2011
National Association of Regulatory Utility Commissioners

"Extensive field experience measuring operational projects indicates that **sound levels commonly fluctuate by roughly +/- 5 dBA** about the mean trend line and that short-lived (10 to 20 minute) spikes on the order of **15 to 20 dBA above the mean** are occasionally observed"

David Hessler (2011). Best Practices Guidelines for Assessing Sound Emissions From Proposed Wind Farms and Measuring the Performance of Completed Projects. Prepared for the Minnesota Public Utilities Commission, under the auspices of the National Association of Regulatory Utility Commissioners (NARUC). October 13, 2011.

Turbine Sound Variability: averages & peaks

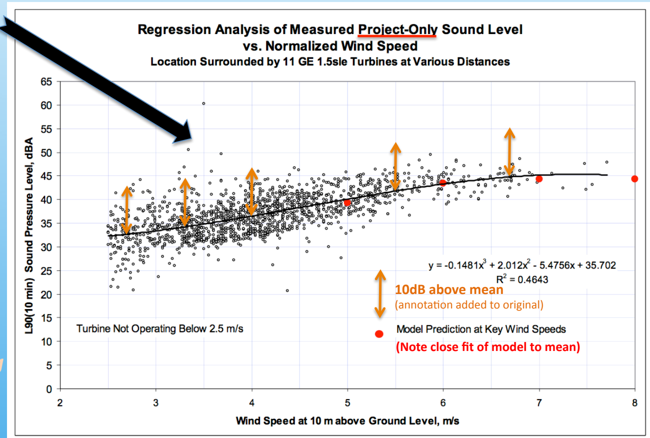
The most variability,

largest peak/mean differences

and some peak sound levels

occur at low to moderate wind speeds

Note lots of 5-10dB over mean at low wind speeds, and nothing approaching 10dB over mean at high wind speeds



Turbine Sound Variability: averages & peaks

Other researchers note similar high peaks and variability around averages

Bob Thorne

Australian acoustician with focus on human response to moderate noise

Peaks:

"Predicted values are given as a range, ±3 dB(A) at 1,000 meters for the most common prediction method with the predicted value being the "middle" of the range. **The uncertainty increases with distance** and the effect of two or more turbines operating in phase with a light/strong breeze blowing toward a residence…Sound levels could vary significantly (6-7dB) in comparison with the predicted sound level. This is without the additional effect of any adverse wind effects or weather effects such as inversions."

*As also noted by Hessler, when considering all such effects, **peaks of up to 20dB over the predicted (average) levels can be expected at times**.*

Variability:

In 60 seconds the sound varies regularly by 10-20db (around the average)

Bob Thorne. The Problems with "Noise Numbers" for Wind Farm Noise Assessment. Bulletin of Science Technology and Society 2011 31: 262.

Turbine Sound Variability: averages & peaks

Thorne: Heightened Noise Zones:

Phase interactions between blades of multiple turbines: constructive/destructive interference of sound wave trains

Propagation variations, including wind speed/direction, temperature pockets, and varying wake effects

HNZ can be small in extent, even for low frequencies, and shift as rotation rates and propagation change

"leading to turbine sounds 'appearing' and 'disappearing' in areas spaced only a few metres apart"

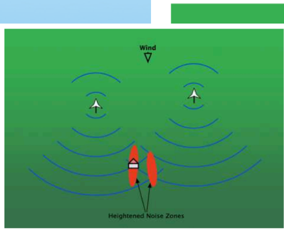


Figure 18: Noise from 2 turbines creating Heightened Noise Zones

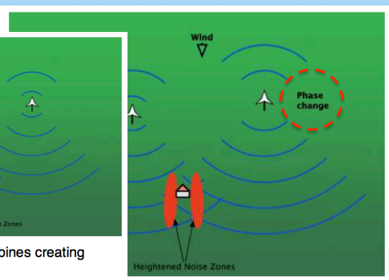


Figure 19: Noise from 2 turbines under slightly different conditions moving Heightened Noise Zones

Bob Thorne. Wind Farm Noise and Human Perception: A Review. Noise Measurement Services. April 2013.

Turbine Sound Variability: turbine source levels

Møller and Pedersen

Danish acousticians with looking at recent Danish LF criteria

Variability in turbine source levels:

Field measurements of dozens of turbines, per IEC 61400-11, 8m/s wind

- Standard deviations for turbines of same size and make: 1.6-3.5dB
- 90% confidence interval (per IEC 61400-14) requires 1.645x this: 2.6-5.75dB above average SPL
- **3dB increase in measured apparent SPL results in 41% greater distance requirement** (or, more likely in practice, higher received levels than models predict at any given distance)

No investigation here of the causes of the variation in similar models:
Could be wear, or differences in load noise or near-field propagation conditions that day

For our purposes, most interested in instances in which the elevated source level, even a few dB, may be caused by increased load noise

Møller and CS Pedersen (2011). Low-frequency noise from large wind turbines. J. Acoust. Soc. Am. 129 (6), June 2011, 3727-3744.

Turbine Sound Variability:
turbine source levels

Variability in turbine source levels:
And indeed, modeling from **measured apparent SPLs of 2.3-3.6MW turbines**, the distance required from either single or multiple turbines, to meet Danish and Swedish noise criteria varied dramatically:

Modeling a 4-turbine array, to meet Danish 44dB requirement:

Required setback ranged from 375m to 1241m

(6 of 23 were over 1km)

Also: large variability in low-frequency components

(measured using Danish dBALF, which is dBA weighting, but limited to 10-160Hz bands)

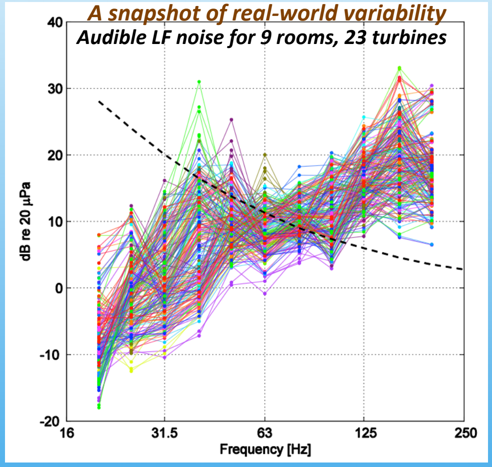
dBALF ranged from **34.5-41.8** when dBA was 44dB

This extreme variability is based ***solely*** on differences in source levels of similar machines….nothing here about variations in propagation conditions.

Our reliance on idealized Sound Power Levels in sound models likely obscures important real-world variability in source levels

CS Pedersen, Henrik Moller, Steffan Pedersen. Low-frequency noise from large wind turbines – additional data and assessment of new Danish regulations. 15th International Meeting on Low Frequency Noise and Vibration and its Control. Stratford upon Avon, UK. May 22-24, 2012

Turbine Sound Variability:
turbine source levels



Indoor LF sound:

23 turbines
(apparent sound power measured in field and modeled to receptor location)

9 rooms
(sound insulation measured on site)

When outdoor received level is 44dB:
(likely to occur fairly frequently even when regulatory limit is 40dB, averaged over time)

Some audible LF in all rooms for every turbine source level

In over half the combinations (122/207), hearing threshold exceeded by 15dB in at least one one-third-octave band:
"risk that a considerable part of the neighbors will be annoyed by the noise"

Turbine Sound Variability:
averages & peaks

OK: it's clear that there's a lot of variability, both between turbines and around any given turbine or wind farm over time

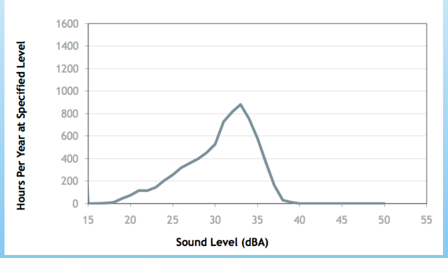
Periods of peak sound or peak audibility will be the most troublesome for neighbors

✧Peaks above the regulatory average
✧Times of easy audibility of moderate noise in low ambient conditions

Again, hold in mind the question for today's group:
How much might inflow turbulence and shear contribute to these times of peak, above-average sound?

A key question:
How often do received sound levels approach the peak?

Turbine Sound Variability:
how common are peaks?



Kenneth Kalisky. Wind Turbine Noise Regulation: Perspectives in New England. NEWEEP Webinar #2, July 2010.

Kalisky used manufacturer sound power levels per wind speed

"Atmospheric stability" factors (vertical wind shear and temperature profile, atmospheric turbulence) used only to model propagation—no effect presumed on source levels

Ken Kalisky
Calculating annualized sound levels for a wind farm
(ASA/NOISE-CON 2010)
(NEWEEP 2010)

Meteorological records used to calculate received sound levels for a year, on an hourly basis

Sound levels are within 5dB of their peak just **12% of the hours** that the turbines are operating

Sounds pretty reassuring…

Turbine Sound Variability:
how common are peaks?

Yet: if we ***very conservatively* equate percent time operating with capacity factor** (say, 33%), we would find peak noise levels occurring for just **4%** of the hours of the year

Doing the math, 4% of hours in the year is:
58 days with peak sound for 6 hours
or 116 days (a third of the days in the year) with peak sound for 3 hours

Louder times are **more likely to cluster seasonally**, when high winds or shear conditions or turbulence are more common, making peak conditions **more frequent** in some seasons.

For neighbors, 4% of the time may plausibly feel like a chronic experience of peak sound conditions

And bear in mind:

- This is an extremely conservative, likely under-estimation of total hours operating
- Many of the extra hours will be at less than full power, where some of the most variable sound levels occur.

Turbine Sound Variability:
sound quality: varying, at times intrusive

Steady/Repetitive Sounds
Whoosh
Roar (distant jet)
Pulsing/Thumping

Irritating Sounds
Grinding
Whining

Irregular/Intrusive Sounds
Knocking
Banging
Like sneakers in a drier
Pressure waves felt in chest

"The first time they started them up, I didn't know what it was. I was like man, that's a weird noise."
2000 ft

"When it's really bad it takes on a repetitive, pulsating, thumping noise that can go on for hours or even days."
2500 ft

"**I think the worst is the foggy, raining nights when you get the banging, the thumping.** It brings you straight out of bed…We were told, 'you'll never know they're back there..'"
1500 ft

Community noise tolerance

Wind farm hearing in Merritt Township, Michigan, February 2012

Community noise tolerance

Again, we are dealing with variability:
between different types of communities, and within any given community

And with peaks and averages:
community-wide acceptance of wind is often not shared by those living close enough to hear turbines routinely

Community noise tolerance variability: **place identity**

Wide range of recent local wind farm ordinances

From the **familiar and generally accommodating** (1000-1700 ft)

Mostly in working farm and ranch county

To the **effectively exclusionary** (2 miles)

Mostly in rural towns where peace and quiet is the priority

With many **attempts at a "happy medium"** (2500-4000 ft)

Willing to hear turbines sometimes, but avoid more intrusive conditions

Why such a variability?

Place Identity

Working landscape	**Tranquil refuge**
Rural areas are places for economic activity and technological development/ experimentation; *we like big machines!*	Rural areas are places for peace and restoration; *we choose to live far from background road or other constant noise!*
Turbine sound is relatively insignificant compared to what we're used to, and is easy to live with	**Turbine sound is an intrusion, often the loudest thing we hear and so randomly variable it just gets under our skin**

Pedersen, E., Hallberg, R-M. and Waye, K.P. (2007) Living in the Vicinity of Wind Turbines – A Grounded Theory Study. Qualitative Research in Psychology, 4:1, 49-63

Community noise tolerance variability: **place identity**

Many wind farms *don't* spur widespread complaints

Why are complaints much more rare in working farm and ranch country?

Texas, Iowa, Wyoming, Nebraska

Residents less noise sensitive?

Turbine sound level and sound quality more consistent?
(wind steady and less turbulent?)

Is the variability more of a trigger than the absolute noise level?

Is there a hidden level of "quiet annoyance" among close neighbors?

Not expressed because of widespread landowner benefits of wind?
Sparse population means this affected percent is just a few people?

Community noise tolerance

In towns *with* issues, how many people are *actually* upset?

Broad community acceptance is not the whole story

Commonly find 70-85% wind approval in town or county as a whole

How do those *<u>who routinely hear</u>* the new source of community noise react?

Within a half mile or so, 20-40% of residents can be upset *<u>about the noise</u>*

This is the seedbed for the backlash we're now dealing with

Even the Gold Standard of community annoyance surveys shows this dichotomy:

<u>Pedersen et al: 3 studies, 1700 people</u>

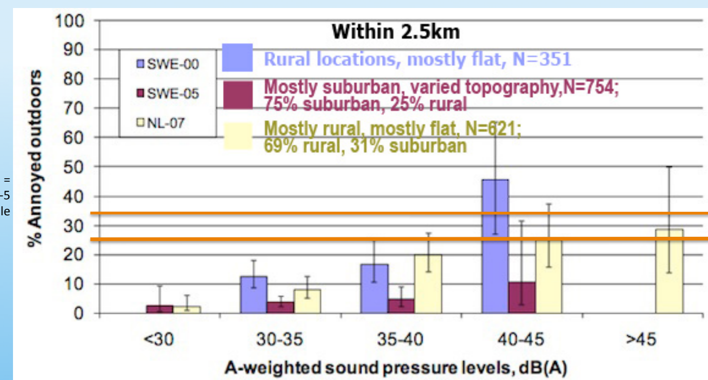
(Scandinavia 2000-2007; **annoyance = 4 or 5**, on 5 point scale)

8-9% noise annoyance among all those surveyed (out to 1 or 1.5mi.)

But: 22% of those who can hear turbines

In rural areas: 25-45% of those who hear 40dB or more

"Annoyed" = 4 or 5 on a 1-5 scale



33%
25%

One clear pattern: annoyance is notably higher in rural settings than in more built up areas

Rural areas: Purple bars **Mostly rural: yellow bars**

Above 40dB: "very" or "rather" annoyed tops a quarter of the rural population

At 35-40dB (far more people hear this level): annoyance of 15-20%

(These bars do not include "slightly" annoyed, which at 30-40dB generally doubles the charted percentages)

SWE-00 and SWE-05 1095 people, virtually 50/50 rural/suburban

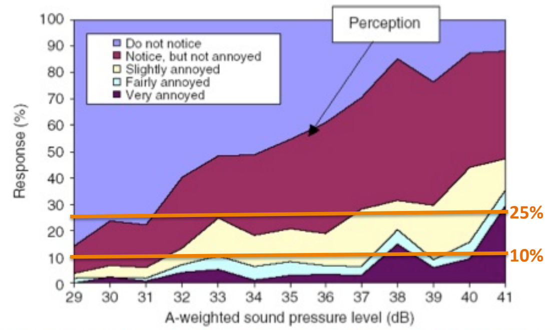


Figure 1 Response to wind turbine noise in relation to A-weighted sound pressure levels outside the dwellings of respondents (n= 1095). E. Pedersen, K. P Waye (2008).

"Very annoyed" spikes to over 25% as sound passes 40dB **(purple)**

"Slightly annoyed" is significant proportion above 33dB **(yellow)**

Also note large section of audible but not annoyed (red)

Community noise tolerance

Those Scandinavian surveys are by far the most rigorous and least "contaminated" by pre-existing noise complaints in the area

Several other surveys in towns where noise issues had become a hot topic came up with generally similar results

When adjusted to account for possible self-selection bias among those who returned surveys, all suggest moderate to high noise annoyance in 20-45% of those living within regular earshot of turbines

(See AEI's Wind Farm Noise 2012 report for further survey analysis)

Still need more surveys in areas where noise has not cropped up as a major local issue!

Do annoyance rates vary with Place Identity?

Community noise tolerance: **audibility in ambient**

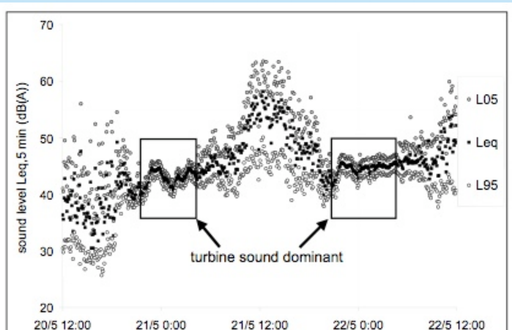


Figure IV.4: 48 hour registration of immission level (L_5, L_{eq} and L_{95}) per 5 minutes at location A; turbines are considered the dominant sound source if L_5-$L_{95} \leq 4$ dB

G.P. van den Berg. The sound of high winds: the effect of atmospheric stability on wind turbine sound and microphone noise. Thesis, Rijksuniversiteit Groningen, 2006.

Audibility/Dominance of turbine sounds

About a week of measurements

<u>400m from closest turbine</u>

Turbine sound dominant:

25% of all hours

72% of night time hours

(Leq ranging from 40-45dBA)

4% of daytime hours

<u>1500m from closest turbine</u>

Turbine sound dominant:

13% of all hours

38% of night time hours

(Leq typically from 30-35dBA, at times dropping to inaudibility, as low as 23dBA and even to the noise floor of 20dBA)

Community noise tolerance: **audibility in ambient**

How the sound fits into, or stands out from, the existing ambient sounds of a place

EPA research of 55 case studies of community responses to noise (urban/suburban):

5dB above background ambient: **sporadic** complaints

10dB above background ambient: **widespread** complaints

15dB above background ambient: **strong appeals** to stop noise

20dB above background ambient: **vigorous community action**, legal challenges

Turbines operating in compliance with 40-45dB noise limits can be 5-20dB above quiet rural *night-time ambient levels of 20-35dB*

When average turbine sound is at one of these levels, transient load-noise peaks of 5-10dB more may spur next higher reaction

especially the more intrusive sound qualities

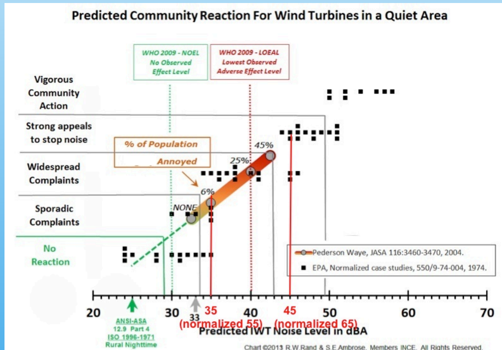
especially at night

Community noise tolerance: **audibility in ambient**

EPA "normalization" recommendations to keep community response at "sporadic" level (i.e., penalty added to measured noise OR reductions in noise limits)

10dB for quiet rural areas   5dB for new or unfamiliar noise source

5dB for impulsive noise source (extreme AM?)



Should we be normalizing turbine limits from typical urban/suburban noise limits of 55db (sometimes 45dB night)?

10dB minimum

15dB plausibly

20dB arguably

20dB normalization matches the EPA case studies with observed turbine community responses

(at least in more noise sensitive communities; need studies elsewhere)

Chart: R.W. Rand, S.E. Ambrose, 2013. Adapted/annotated by Cummings. From Ambrose, Wind Turbine Noise Complaint Predictions Made Easy, 2013.

Community noise tolerance: **adapting to population density**

Some annoyance appears as turbines become audible (30-35dB)

and becomes more widespread as noise levels approach 45dB

Annoyance rates can reach 20-40% when sound levels are 40-45dB

When there are relatively few homes in this range, noise issues are minimal

When 100 – or 200 – homes are in this range, dozens of complaints can ensue

(Hardscrabble, Falmouth)

Hessler thus **recommends an ideal design goal of 40dB** (24-hr mean) **or less at residences in more populated areas, and feels 45dB offers a good balance** "as long as the number of homes within the 40-45 dBA range is relatively small."

(i.e., aiming to assure that relatively few people live in the higher annoyance zone)

David Hessler (2011). Best Practices Guidelines for Assessing Sound Emissions From Proposed Wind Farms and Measuring the Performance of Completed Projects. Prepared for the Minnesota Public Utilities Commission, under the auspices of the National Association of Regulatory Utility Commissioners (NARUC). October 13, 2011.

Community noise tolerance: **The health effects question**

Has come to dominate much of the local public discussion, often along with concern about infrasound levels

Most researchers are looking primarily at **sleep disruption and stress-induced symptoms**, rather than infrasound

Many sources of stress related to presence of turbines, including sound

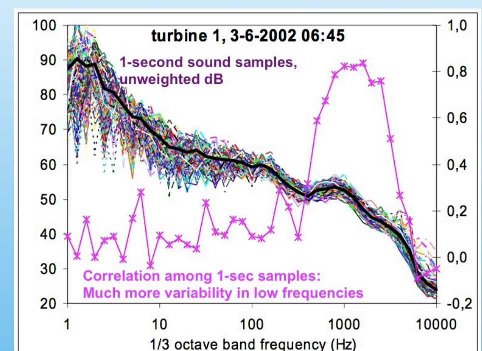
Most suggest that health effects may develop in 5-10% of those who hear turbines regularly

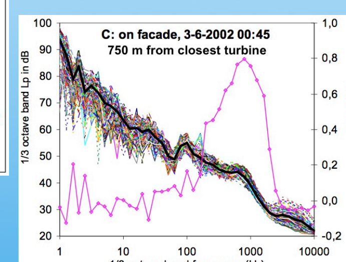
Worst cases lead to home abandonment

Health effects, while important to understand, impact a far smaller proportion of nearby neighbors than the 20-45% who are trying to adapt to the presence of the new audible noise in their rural soundscape

For more detailed analysis of the health questions, see AEI's Wind Farm Noise 2012 report, especially Appendix C; also see http://aeinews.org/?s=wind+health

Audible low frequency noise





G.P. van den Berg. The sound of high winds: the effect of atmospheric stability on wind turbine sound and microphone noise. Thesis, Rijksuniversiteit Groningen, 2006.

Audible low frequency noise

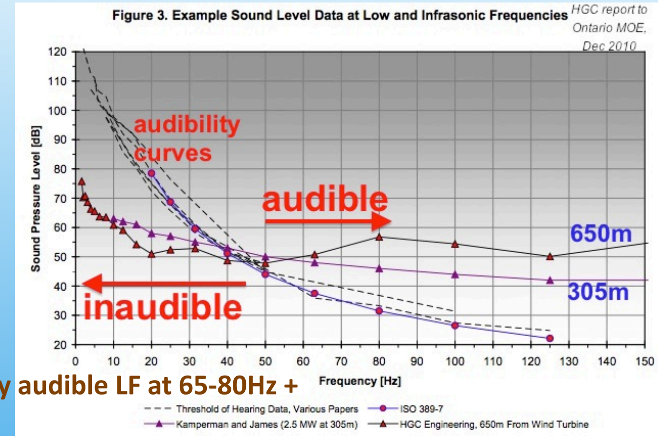
This factor may underlie much of the community response

Propagation of LF over distance may extend audibility zone
Cylindrical rather than spherical spreading?

Sleep disruption and stress responses
LF annoyance often occurs near audibility thresholds

Questions emerging about effect of larger rotor diameters
Larger area subject to turbulence: more load noise?
More vertical shear enhances Amplitude Modulation?
Sound spectrum shifts to more LF
Blade-pass rate slows: nauseogenicity?

Audible low frequency noise



Clearly audible LF at 65-80Hz +

Source level or LF propagation variability?

Typical models would expect 650m to be about 6dB LOWER than 305m

HGC Engineering, Low frequency noise and infrasound associated with wind turbine generator systems: A literature review. Ontario Ministry of the Environment RFP No. OSS-078696. 2010.

Audible low frequency noise

Two recent papers stress that the known infrasonic attenuation of **3dB per doubling distance** (cylindrical spreading) rather than the 6db per doubling distance (spherical spreading) assumed by most sound models **can at times apply in practice to audible low frequencies, primarily when sound is channeled** between the ground and density boundaries in the air

HGC's 2010 literature review on LF sound and infrasound for the Ontario Ministry of Environment
Also stressed the need to assess low frequency noise inside homes

Møller and Pederson, JASA 2011
"Cylindrical propagation may thus explain case stories, where rumbling of wind turbines is claimed to be audible kilometers away."

Overall dBA audibility of turbines may at times be higher than presumed in models using spherical spreading assumptions
Could affect peak received levels at moderate to large distances

Møller and CS Pedersen. Low-frequency noise from large wind turbines. J. Acoust. Soc. Am. 129 (6), June 2011, 3727-3744.
HGC Engineering (2010). Low frequency noise and infrasound associated with wind turbine generator systems: A literature review. Ontario Ministry of the Environment RFP No. OSS-078696.

Audible low frequency noise

Møller and Pedersen's individual turbine real-world sound power level study:

They also modeled sound from each individual turbine, out to the point where it drops below 35dB
(point at which annoyance starts to rise above 10%; Swedish night limit for quiet areas)

Distances varied to similar range as their model of a linear 4-turbine wind farm:
2063ft to 4024ft

Even more striking: Modeled propagation with a sound channeling layer, with cylindrical spreading at greater distances, and 35dB was reached **at more than twice as far from the turbine:**
4600ft to 11,421ft (2.16 mi)

Of course, at these distances, the sound spectrum will be strongly weighted to lower frequencies

Møller and CS Pedersen. Low-frequency noise from large wind turbines. J. Acoust. Soc. Am. 129 (6), June 2011, 3727-3744.

Audible low frequency noise

Related issues

Even in normal propagation conditions, the strong low-frequency content of turbine sounds affects perceptibility in ways that are sometimes not considered

Masking — or not

Some siting plans assume turbine sound will be masked by similar dBA levels of ambient noise

But: masking is frequency-dependent: As sound spectrum shifts lower with distance, *turbine sound audible even at similar (or even lower) dB as ambient*

This can also be a factor even at closer range, since turbine sound spectrum can be quite distinct from wind-in-trees sound spectrum

Enhanced low-level LF sound perception/annoyance

Low frequencies are more perceptible and annoying when there's less mid- and high-frequency content in the sound spectrum or local soundscape

As distance increases, this becomes an increasingly important factor for barely-audible LF components

Inside homes, it can be a major factor

Con Doolan. A Review of wind turbine noise perception, annoyance and low frequency emission. School of Mechanical Engineering, University of Adelaide, South Australia. December 11, 2012.

Audible low frequency noise

More noticeable inside homes?

Several acousticians have investigated reports of low-frequency "thumps" experienced inside homes.

The sound is often more perceptible inside than outside

Less higher-frequency content makes LF more perceptible?
More aware of LF when trying to sleep?
Room or wall resonance?

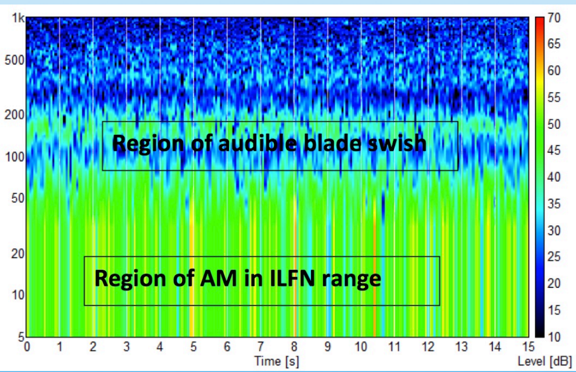
"It is not clear what an acceptable level of impact is. **Annoyance by low-frequency noise occurs usually at low levels, often in the range of a person's hearing threshold** and can vary significantly between individuals"

Con Doolan, University of Adelaide

Bob Thorne. The Problems with "Noise Numbers" for Wind Farm Noise Assessment. Bulletin of Science Technology and Society 2011 31: 262.
Benjamin Nobbs, Con Doolan, Danielle Moreau. Characterization of noise in homes affected by wind turbine noise. Proceedings of Acoustics 2012, Fremantle. November 21-23, 2012, Fremantle, Australia.
Ambrose, Rand, Krogh. Falmouth, Massachusetts turbine infrasound and low frequency noise measurements. Internoise 2012, August 19-22, 2012.

Audible low frequency noise

Rapid pulsing: enhancing perceptibility?



Audible LF and Infrasonic Amplitude Modulation

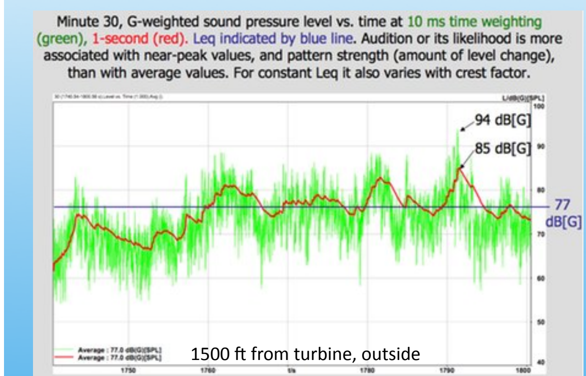
20-40dB of AM, up to 50Hz

Often several pulses per second: *not* blade-passes

Wade Bray and Rick James. Dynamic measurement of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception. NOISE-CON 2011, July 25-27. 2011.

Infrasonic & lowest freq. audible noise

Rapid pulsing: enhancing perceptibility?



dBG weighting accentuates 10-30Hz, includes 2Hz-70Hz

Provocative possibility:
Pulses at time frames relevant to human hearing response show peaks much higher than typical averaging/sampling times

Human threshold 95-100dbG (but 10dB individual variability, and threshold based on pure tones; pulses likely to be more perceptible)

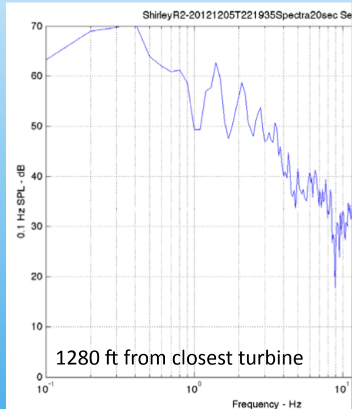
Needs replication and testing at more locations
(this is one of several louder sections of longer data set)

Wade Bray and Rick James. Dynamic measurement of wind turbine acoustic signals, employing sound quality engineering methods considering the time and frequency sensitivities of human perception. NOISE-CON 2011, July 25-27. 2011.

Infrasonic noise
Late 2012 collaborative study, Shirley WI

George and David Hessler   Paul Schomer   Bruce Walker   Rob Rand

3 days of measurements at three homes abandoned near wind farm



Clear signature of six harmonics of 0.7Hz blade-pass frequency
(found both inside and outside house; below standard perception thresholds)

Navy study: nauseogenic trigger when pulses move below 1Hz, increasingly nauseogenic down to a peak effect at 0.2Hz **(not far from blade-pass rate of future turbines)**

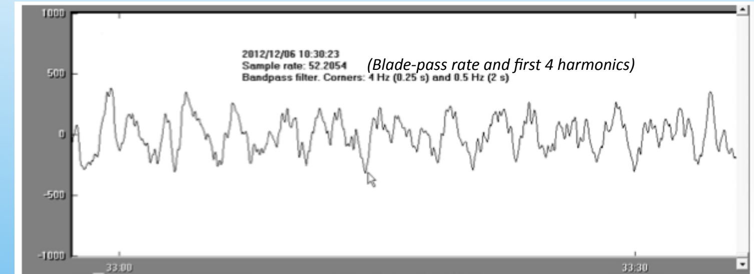
2MW turbines: 0.7Hz

"It is very possible that this nauseogenic condition has not appeared frequently heretofore because older wind farms were built with smaller turbines."

Paul Schomer

Hessler, et. al. A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin. 12/24/2012.

Infrasonic noise
Late 2012 collaborative study, Shirley WI



To directly measure pressure Rob Rand employed a seismometer

(avoiding some concerns re: mic noise and post-measurement filtering/sampling/weighting)

In the same house, peak levels ranged to 0.2 to 0.3 Pa

(80-83dB peak equivalent)

Rand also raised the question of whether blade-flexing at the rotation rate (1/3 the blade-pass rate) could be a contributor to some infrasonic and/or pressure signals

Hessler, et. al. A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin. 12/24/2012.

Infrasonic noise
Late 2012 collaborative study, Shirley WI

Questions and ambiguities remain

Blade-pass signature clearest at closest house

Other abandoned homes less distinct or not present inside

Some indications that turbines were not operating at full power all days; clearly, study of decay of these signals over distance is needed.

Nauseogenicity

Navy study was looking at body moving in air; this is air moving around body

Is inner-ear response to turbines similar to that of test pilots?

Human perception thresholds / rates

One investigator felt nausea in two homes and could perceive turbines in all homes

One investigator could *faintly* detect turbines in one home

Three investigators could *not* detect turbines in any homes

Severely negative responses in some residents in the three homes led to their abandonment;

some family members were unaffected

Threshold of Perception testing of larger population is recommended

Hessler, et. al. A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin. 12/24/2012.

Infrasonic noise
Late 2012 collaborative study, Shirley WI

Questions and ambiguities remain

While this study found clear blade-pass signatures,

David Hessler remains skeptical that most recorded high levels of lowest audible frequencies and infrasound are turbine-related

Suspects microphone pseudo-noise

Study in Mojave in low-wind conditions is underway

Still, the four investigators agreed that:

"The four investigating firms are of the opinion that enough evidence and hypotheses have been given herein to classify LFN and infrasound as a serious issue, possibly affecting the future of the industry"

Hesslers frame it slightly differently in their appendix:

"It can be mutually agreed that infrasound from wind turbines is an important issue that needs to be resolved in a more conclusive manner by appropriate study"

Hessler, et. al. A Cooperative Measurement Survey and Analysis of Low Frequency and Infrasound at the Shirley Wind Farm in Brown County, Wisconsin. 12/24/2012.

Audible low frequency noise

Evolution of noise standards: a historic perspective

In 2010, acoustician Richard Horonjeff pointed out similarities between increasing complaints from modern wind turbines and step-by-step regulatory responses to previous technology changes

Propeller planes to jet planes:
Similar noise levels on ground—more complaints due to the nature of the noise

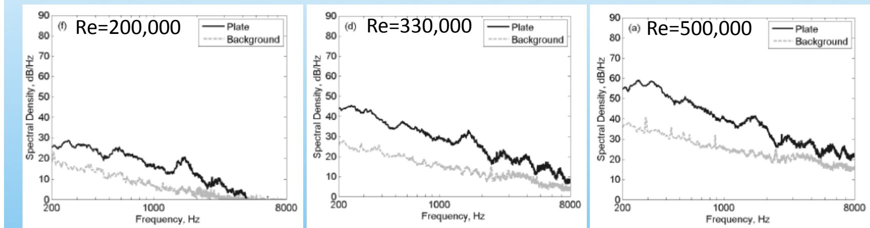
Highways, aircraft, railroads, industry, other sources often see a 5-10 year process:
- ✧ First, public welfare effects crop up, not accounted for by existing regulations
- ✧ Literature reviews of possibly relevant previous studies
- ✧ New research conducted; consensus reached regarding nature of new noise and cause/effect relative to community responses
- ✧ Promulgation of agreed-upon standards for the new noise source

Are larger turbines in the midst of a similar adaptation to changes in sound quality?
More audible LF content, more vertical shear (AM)
Perhaps more load noise with larger rotor diameters
Perhaps new blade-pass or blade-flex infrasonic or LF components

Horonjeff, Siting of wind turbines with respect to noise emissions and their health and welfare effects on humans. Submission re: Wisconsin PRC noise measurement guidelines. July 6, 2010.

Wakes, shear, turbulence

Suggestions, indications, hints



In turbulent conditions, broadband trailing edge noise increases a bit more in its lower frequencies
(peaks are not necessarily at *lowest* frequencies, though)

Moreau, D., Brooks, L. & Doolan, C. (2011), 'Broadband trailing edge noise from a sharp-edged strut', The Journal of the Acoustical Society of America 129(5), 2820)

Con Doolan, Danielle Moreau, Elisa Arcondoulis, Christobal Albarracin. 2012. Trailing Edge Noise Production, Prediction and Control. New Zealand Acoustics, Vol 24, #3, p 22-29

Wakes, shear, turbulence

Suggestions, indications, hints

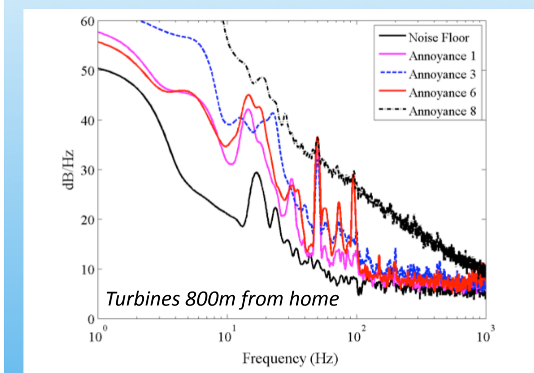


Figure 4. Power spectral density (unweighted) of the acoustic data for various resident-rated annoyance levels.

Nobbs, B., Doolan, C.J., Moreau, D.J. (2012) Characterization of noise in homes affected by wind turbine noise. Proceedings of Acoustics 2012, Freemantle. 21-23 November 2012.

More annoyance at sounds described as:
Pounding
Roaring
Thumping/rumbling

Less annoyance:
Hum
Murmur

Thumping or pounding may be associated with the broad peak between 10-30 Hz

Rumbling and roaring may be associated with the broadband energy to 1000 Hz as well as the spectral balance.

Acoustic energy below 10 Hz may be responsible for *thumping* noise

Wakes, shear, turbulence

Suggestions, indications, hints

Pinnacle Wind Farm
Keyser WV
(55dB limit)
Neighbors measure 60-70dB

Neighbors:
"A hammering sound, like thunder….It's so loud, you can't drown it out with the television or anything"

Site manager:
Same turbine model, no noise issues in OK, TX; but those aren't on mountain ridges
"I don't like it (the noise) any more than you do"

Wakes, shear, turbulence

Suggestions, indications, hints

An air traffic controller living in the neighborhood reports **possible wake effect:**
49 pressure headaches (ear/sinus)
Never occurred before turbines

"On numerous occasions, I've left my property (walking a few hundred feet laterally from the turbines) and gained relief. I've also noted that upon returning to my property, all wind direction and velocities being constant, the same symptomatic pressure headache returned The only change – my spatial relationship to the wind turbine."

Falmouth, MA:
2 town-owned turbines

Mark Cool, Letter to Falmouth Health Board, October 2012.

Wakes, shear, turbulence

Suggestions, indications, hints

Knocking
Banging
Tumbling
Sneakers in Dryer

? →

Directional shear
Unstable or changing wind direction
Wake effects
Other atmospheric turbulence

Enhanced Amplitude Modulation
(10dB or more, rather than 3-5db)
↓ ?
More extreme vertical shear

Pressure in ears, chest
Palpable sense of pressure waves
? ↓
Turbine wakes

Wakes, shear, turbulence

Suggestions, indications, hints

Hot topics for further study

Heightened Noise Zones
Phase interactions, wake effects on propagation, etc.
Implications for unexpected audibility or intrusiveness, as compared to sound models

Real-world turbine source levels
How much variation from idealized manufacturer ratings?
Implications for sound modeling, average and peak received levels

How sound spectrum changes with distance in different propagation conditions
LF audibility as broadband "bed" fades

Rapid pulses in low frequencies?
How common, how intense, peak levels?
Perceptibility implications

Wakes, shear, turbulence

Suggestions, indications, hints

Among the things I'm interested in learning from you:

Your observations, re: changes in sound quality or transient peak sound levels in wakes or turbulence, or while yawing to meet new wind direction

Any sound changes heard in conjunction with innovations aimed at reducing/dissipating turbulence (AALC, etc.)
Are there secondary benefits here, in reducing average or peak sound levels?

Wake studies: quantifying changes in noise levels/sound spectrum?
Can greater turbine spacing help companies meet stricter noise standards?
Or reduce the intensity of transient peak sound levels?

Any other observations about noise considerations
And keep me apprised of any ongoing studies involving noise measurements!

Jim Cummings

cummings@acousticecology.org

Three comprehensive annual reports on wind farm noise science and policy, along with my NEWEEP presentation on community responses are available at the link below

AEI Wind Farm Noise Resources

AcousticEcology.org/wind

The slides that follow were included in my presentation at Renewable Energy World North America, December 2012, and may be of interest for readers of this presentation as well

See acousticecology.org/wind/
for this and other AEI papers and presentations

Community noise tolerance

Creating realistic expectations

"You won't hear it"

Residents 1/2 - 3/4 mile away
(Turbines routinely clearly audible, sometimes intrusive)

Wind in trees equal to or louder than turbines

(yet: masking requires similar frequency spectrum; often less wind noise on ground)

Experience tells us people live even closer with ease

(yet: steadier winds in ranch country, more turbulence and low clouds here; more noise sensitive than ranchers)

Community noise tolerance

Creating realistic expectations

"I don't think you'll hear it most of the time"

Residents 1 to 1 ½ miles away
(Turbines faintly audible on still mornings and winter days, never intrusive)

Takes into account variability/uncertainties

Ridge to valley wind/ambient noise factors
Variability of source levels and propagation

Working with communities:
adapting to local differences

Developers willing to work with a variety of setback and noise limits will have far more opportunities

Focus on less contentious regions

Most new wind farms are still built far from non-participating homeowners and with hosts who don't mind some noise

Ranchers and working farmers remain willing and eager hosts

Seek sites with few homes close enough to hear

Work with towns to forge a win-win approach for noise sensitive areas

Oregon wind farms built with 36dBA
Record Hill Wind, Roxbury ME

Continue current practices and be prepared to spend time/money addressing noise concerns

Proactive pre-proposal community engagement
Gratiot County Wind (MI), Blue Creek Wind Farm (OH)
Possible heated resistance: appeals/litigation
Cape Vincent (NY), Mars Hill (ME), Kent Breeze (ONT)
Possibility of post-construction mitigation of complaints at margins of noise criteria
Pinnacle (louvers), Hardscrabble (experimental NRO), Fox Islands (serrated blades, NRO)

Operational adjustments
Aerodynamic blade noise

Serrated edges

Sandia research suggests 3-8dBA reductions
(Barrone, 2011)

Fox Islands Wind retrofit to reduce sound levels for neighbors

Neighbors report less lower-frequency thumping, perhaps a slight increase in higher-frequency whoosh
This would be consistent with Sandia study, which found serrations reduce lower frequencies and slightly increase >2kHz

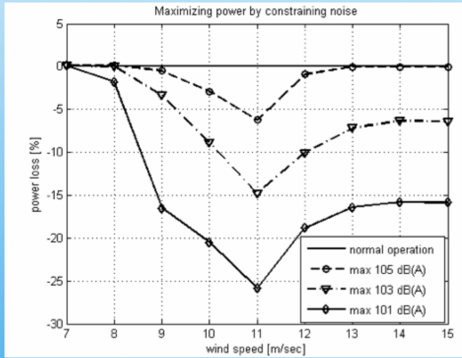
Operational adjustments
Aerodynamic blade noise

NRO: Noise Reduced Operation

Computer controlled adjustment of blade pitch and RPM
Options allow choice of noise reduction, typically from 1-5dBA

Power loss is minimal (<5%) in moderate winds at 1-2dB reduction; power loss increases (up to 25%) with higher winds and more dB reduction

Routine (close siting)
Night (lower noise limits)
Conditional (wind speed/directions that increase noise at receptors)



G. Leloudas, et al 2007; NRO applied on a 2.3MW turbine

Turbulence research:
noise reduction as secondary benefit of innovation

Adaptive blade design to reduce transient loads in turbulence
Sandia National Lab / NREL / turbine manufacturers

Passive Load Mitigation

Modern materials
Carbon fiber integrated as targeted component in blade core designs

Innovative blade geometries
"Bend-twist coupling"

Good first step forward from reducing stress primarily by adjusting pitch angle

Active Aerodynamic Load Control (AALC)
Electronic sensors instantly trigger discrete blade flaps

Sandia SMART blades

Other flap and flexible blade tip designs

Blades respond to local load variations along blade length, relieving transient pressures

Turbulence research:
noise reduction as secondary benefit of innovation

Turbine wake research

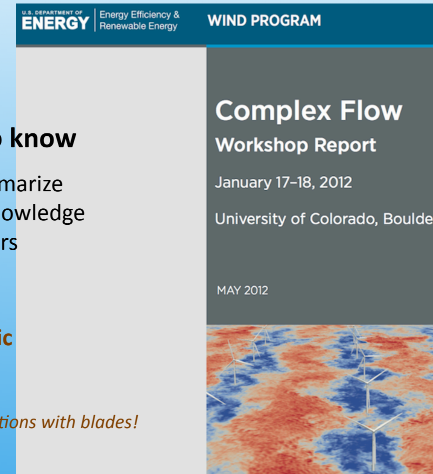
Sandia SWiFT facility
Lubbock, TX
Being built to study turbine wake interactions; will include acoustic data

NREL wake research
60-70% decrease in power output behind first row of turbines (Churchfield, 2012)

NREL directional shear studies looking beyond "the narrow definition of shear (change in wind speed with height)... Directional shear can be 20-40 degrees or more...and can impart considerable stress on the turbine infrastructure"

Jeffrey Freedman & Kathleen Moore (2012). Wind Shear and Why it Matters. North American Windpower, Volume 9, Number 5, June 2012, p.48-51.

Turbulence research:
noise reduction as secondary benefit of innovation



<u>2012 DOE report</u>
What we know
What we need to know

Working groups summarize
- current state of knowledge
- complicating factors
- desired next steps

at several scales:
Regional atmospheric
Wind-farm scale
Single-turbine scale
down to mm-scale interactions with blades!