

Recommended noise level design goals and limits at residential receptors for wind turbine developments in the United States

David M. Hessler^{a)} and George F. Hessler Jr.^{b)}

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Potential impacts from operational noise produced by wind turbines is a major issue during the project planning and permitting process, particularly for projects east of the Mississippi River in fairly populous areas. While still an issue farther west, more buffer space and lower population densities sometimes make noise less of a factor. In general, however, noise may be the principal obstacle, from an environmental impact standpoint, to the more rapid growth of this renewable energy source in the United States. Proposed projects are frequently opposed on noise concerns, if not outright fear, usually aroused by the highly biased misinformation found on numerous anti-wind websites. While significant noise problems have certainly been experienced at some newly operational projects, they are usually attributable to poor design (siting units too close to houses without any real awareness of the likely impact) or to unexpected mechanical noises, such as chattering yaw brakes or noisy ventilation fans. A common theme at sites with legitimate complaints is that no one—not the developer, their consultants or the regulatory authority—really understood the import and meaning of the sound levels predicted at adjacent homes in project environmental impact statement (EIS) noise modeling. This paper seeks to address this lack of knowledge with suggested design goals and regulatory limits for new wind projects based on experience with the design of nearly 60 large wind projects and field testing at a number of completed installations where the apparent reaction of the community can be compared to model predictions and measurements at complainant’s homes. © 2011 Institute of Noise Control Engineering.

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1 INTRODUCTION

Typical wind turbine generators (WTG) used today are generally in the 1.5 to 3 MW range of electrical generation capacity and all of them produce a moderate amount of generally mid-frequency aerodynamic noise. All are three-bladed with the rotor forward, or upwind, of the supporting tower so that the blades do not pass through the tower wake avoiding the low frequency noise issues observed in the eighties¹ by downwind blades. This experience appears to have initiated the persistent but incorrect idea that wind turbines are substantial sources of low frequency noise, which, extensive field testing clearly

shows, is not at all the case with modern units.

Subjectively, fairly close to a typical wind turbine, one can observe a “whoosh” or “swish” sound with periodicity of about 1 second generated by the down-coming blade. While the “frequency” of this sound is low at about 1 Hz this sound is not low frequency or infrasonic noise, but rather a repeating, mid-frequency sound (with its peak generally around 500 Hz).

This periodic sound becomes less distinct with distance and, usually together with neighboring units, blends into a more continuous low magnitude “churning” sound that is often likened to a plane flying over at fairly high altitude; particularly since the sound tends to fluctuate or fade in and out randomly in the same way that aircraft noise is usually perturbed by the intervening atmosphere. Wind turbine sound emissions sometimes contain minor tones associated with mechanical components (usually ventilation fans) but almost never produce prominent “pure tones” per the commonly used EPA definition².

^{a)} Hessler Associates, Inc., 3862 Clifton Manor Place, Suite B, Haymarket, VA, 20169, USA, email: David@HesslerAssociates.com.

^{b)} Hessler Associates, Inc., 3862 Clifton Manor Place, Suite B, Haymarket, VA, 20169, USA, email: George@HesslerAssociates.com.

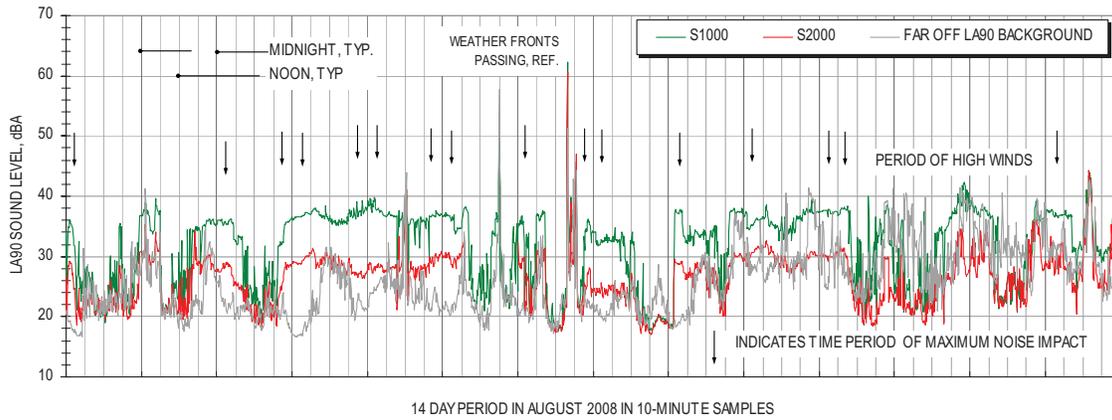


Fig. 1—Operational measurements over a 14-day period at two distances (1000 and 2000 feet south, 300 and 600 meters) from a single wind turbine compared to the prevailing macro area ambient sound level at the same locations for determining noise impact.

2 POTENTIAL FOR ADVERSE NOISE ANNOYANCE

Adverse impact in the form of annoyance and complaints can occur if facility noise emissions significantly exceed the prevailing environmental background sound level, as with any power project. Because wind turbine sites are typically in rural areas the existing background sound level is often very low, even when its dependence on wind speed and wind-induced sounds is taken into consideration.

As an example, Fig. 1 shows over 2000 ten minute residual measurements (LA₉₀ Level exceeded 90% of the time) over a 14 day survey at distances of 300 and 600 meters from an operating single wind turbine compared to the average concurrent background level measured at several off-site locations. Hypothetical noise impacts exist wherever the turbine sound level significantly exceeds the background level. In Fig. 1, the maximum differential between the measured sound level and the background level often occurs at night on nights when the winds are fairly light. When it's windy the differential and the perceptibility of the project is usually less irrespective of time of day as wind generated sources of environmental sound become more dominant.

This time-of-day dependency can be explained by examining the typical wind speed gradient with elevation as a function of time of day. Figure 2 shows the shear exponent, a term that corresponds to the curvature of the gradient, measured empirically over a two year period at a planned wind project site in the Midwest. The shear exponent is low during the day time hours due to atmospheric mixing resulting in a more vertical gradient, as shown in Fig. 3, while the exponent is significantly higher at night due to thermal layering; a phenomenon that is more pronounced during lower wind conditions. As described and reported by van den Berg³, at night the upper elevation

wind speed can be high enough to operate the turbine while at ground level it is quite low, which can lead to relatively low sound levels, such as those observed most nights in Fig. 1.

It can be concluded from these data that the potential for annoyance is most likely during the evening and nighttime and less likely during the day implying that any design goal or regulatory limit should focus on the nighttime sound level.

As a final note on background levels, Fig. 4 shows a typical set of natural background sound levels (without any turbine noise) measured in a quiet rural environment plotted as a function of wind speed at a typical hub height elevation of 80 m. Modern wind turbines begin to produce power at a cut-in speed of roughly 3 m/s. The red lines on this graphic show an analytical model by Donovan⁴ where the background sound has two components: the residual level (shown here at 38 dBA) and the wind generated level plotted as the 6th power of wind speed, which would be expected from a flow-induced acoustic source. The logarithmic summation

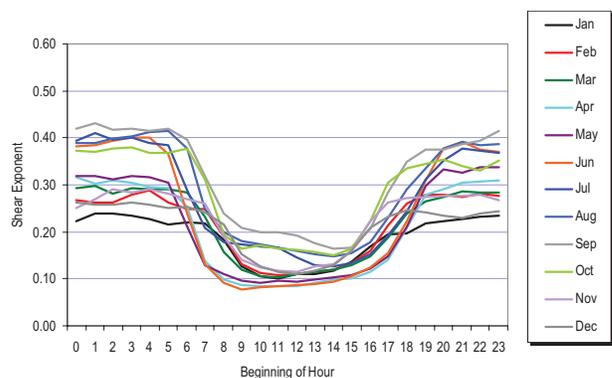


Fig. 2—Wind Shear Exponent, α , as defined by $V1/V2 = (H1/H2)^\alpha$ where V and H stand for velocity and height above grade.

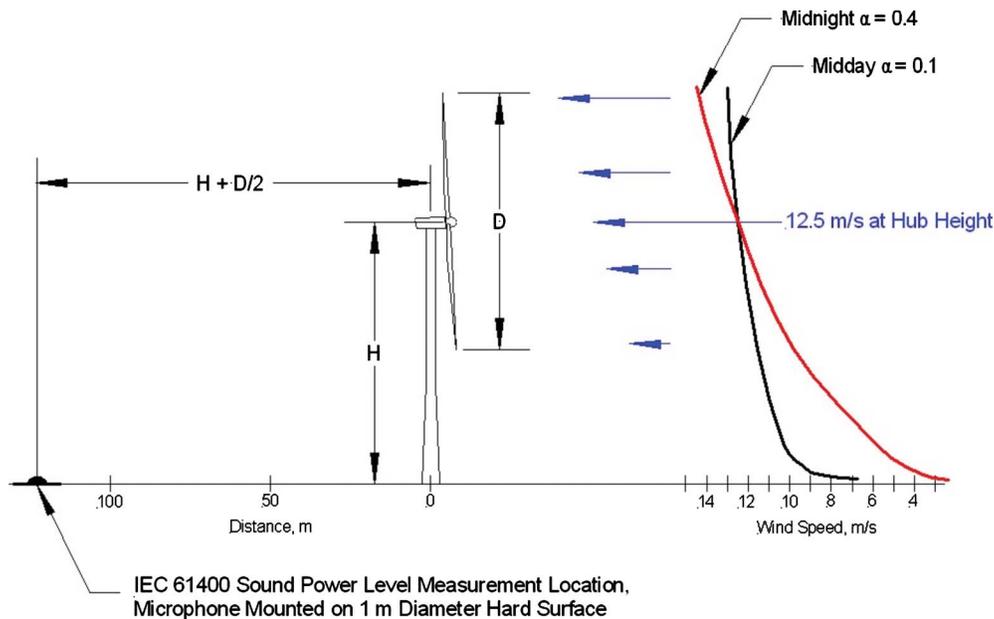


Fig. 3—Typical wind profiles for day and night periods. The figure also shows the measurement location for IEC 61400.

of these two components would closely track the mean linear trend of the measured data (black line).

3 NOISE LIMITS FROM THE LITERATURE

3.1 World Standards and Guidelines

The World Health Organization (WHO) published the following 1999 guidelines⁵ for community noise in residential environments:

55 dBA Leq Daytime Levels: “Serious Annoyance, daytime and evening”

50 dBA Leq Daytime Levels: “Moderate Annoyance, daytime and evening”

45 dBA Exterior/30 dBA Interior Leq Nighttime Levels: To avoid sleep disturbance issues.

The nighttime sleep disturbance threshold has recently been reexamined by the WHO (2009)⁶ and has been lowered from 45 dBA to 40 dBA outside of residences. No inside value is specified. The level is expressed as a design target to protect the public. Considering this guideline, nighttime sound levels from wind developments outside of residences should be generally targeted at 40 dBA as an ideal design goal to avoid sleep disturbance issues.

3.2 World Wind Turbine Noise Limits

Wind turbine development in European countries and in other parts of the world has been proceeding for

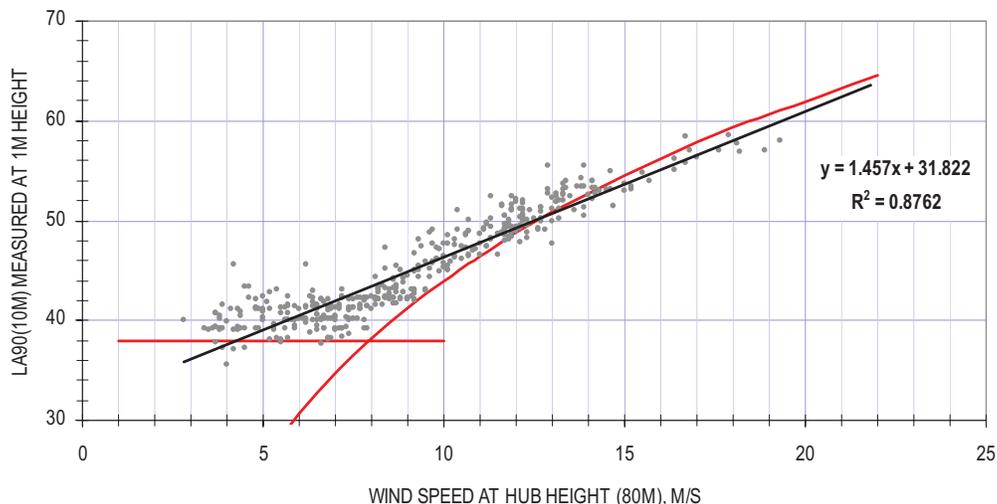


Fig. 4—Typical LA90 measurements as a function of wind speed at hub height.

Table 1—Typical worldwide wind turbine noise limits.

LOCATION	CRITERIA VALUE(S)	METRIC	FEATURES
ALBERTA, CANADA	50D/40N	dBA	
QUEBEC, CANADA	45D/40N	dBA	
ONTARIO, CANADA	45D/40N	dBA	
MANITOBA, CANADA	60D/50N	MAX dBA	MAX ACCEPTABLE
MANITOBA, CANADA	55D/45N	MAX dBA	MAX DESIRABLE
DENMARK	40	L _{eq} dBA	DAY AND NIGHT
GERMANY	60D/45N	dBA	MIXED RESIDENTIAL/COMMERCIAL
	55D/40N	dBA	GENRAL LIVING AREAS
	50D/35N	dBA	PURE LIVING AREAS (1)
NETHERLANDS	40D/30N	L _{eq} dBA	
NEW ZEALAND	40	L90 dBA	PRIMARY, WHICHEVER
NEW ZEALAND	AMBIENT+5	L90 dBA	IS GREATER
UK	43N	dBA	
UK	35–40 (37.5 FOR AVERAGING)	dBA	FOR LOW NOISE ENVIRONMENTS
UK	AMBIENT+5	dBA	DAY AND NIGHT
UK	35	dBA	AVOIDS AMBIENT STUDY
ARITHMETIC AVERAGE	45D/40N		(1)-USE FOR AVERAGING

some time now while widespread development has only really started in the United States within the last 5 years or so. Thus, the question of allowable limits specifically for wind turbines has already been addressed by a number of other countries. Storm⁷ presents a summary of world standards in Tables 3 and 4 of his paper, the core of which is reproduced here in Table 1.

3.3 U.S. Federal Standards

The U.S. federal government issues no standards for industrial noise but does promulgate noise regulations for major transportation systems. These regulations by the Federal Aviation Authority (FAA) and the Federal Highway Administration (FHWA) are fundamentally predicated on the idea that some noise annoyance is justified or offset by the public good provided by the systems. Generally, acceptable regulatory levels in the 60 to 65 DNL (day night sound level) range have been shown to “highly annoy” approximately 10 to 20% of affected residential receptors. However, these published standards are not particularly useful for wind turbine noise emissions, since the public good of a new power plant or industrial facility is not obvious to its immediate neighbors, and conscientious owners would ideally want no annoyed neighbors.

The U.S. EPA Office of Noise Abatement was unfunded in the late seventies but did issue a landmark report suggesting guidelines for environmental noise in residential communities from all environmental sources. The report⁸ is often referred to as the “Levels” document for short and has become a de facto standard

for such organizations as the World Bank and others. Unfortunately, this report is often misused and the cited recommended level of DNL=55 dBA for residential land use is commonly interpreted as an acceptable criterion level for new noise sources in any type of residential environment—whereas the intent was to provide a guideline, or national goal for total environmental noise (ambient noise including all industrial and transportation sources). The report acknowledges that no cost-benefit analysis was performed.

In addition, the report clearly indicates that the level of DNL=55 dBA is applicable to an urban residential background and must be normalized to the specific environments under consideration to obtain an acceptable level of correlation between DNL and community response. Without background normalization, correlation is very poor based on the analysis presented in the levels document and elsewhere. This is no surprise since a level of DNL=55 dBA cannot be expected to be satisfactory at the same time in both a very quiet rural and noisy urban residential setting. Schomer⁹ suggests that an adjustment of 10 dBA should be subtracted for quiet rural environments and perhaps another 5 dBA if the project is newly introduced into such a long-standing quiet setting.

For a steady source, which a wind turbine could be broadly considered, a level of 39 dBA would be equivalent to DNL=55 dBA if reduced by 10 dBA; or 34 dBA if reduced by 15 dBA to compensate for a very quiet rural setting.

The EPA did conclude in the levels document that an outside sound level of 45 dBA at night (10 p.m. to 7

Table 2—Tabulation of state nighttime noise regulations and siting standards.

STATE	NOISE LIMIT AT RESIDENTIAL RECEPTORS “A” WTD. EMISSION LEVEL	COMMENTS
MARYLAND	55	EMISSION LIMIT, ANY AMBIENT
DISTRICT OF COLUMBIA	55	EMISSION LIMIT, ANY AMBIENT
DELAWARE	55	EMISSION LIMIT, ANY AMBIENT
ILLINOIS	51	EMISSION LIMIT, ANY AMBIENT-EQUIVALENT A-WTD LEVEL FROM SPECIFIED OCTAVE BANDS
CONNECTICUT	51	EMISSION LIMIT, ANY AMBIENT
MINNESOTA	51	EMISSION LIMIT, ANY AMBIENT
NEW JERSEY	50	EMISSION LIMIT, ANY AMBIENT
OREGON	50	L50 IN ANY ONE HOUR IN “QUIET” ENVIRONMENTS
COLORADO	50	EMISSION LIMIT, ANY AMBIENT
MAINE	45	50 dBA WHEN AMBIENT LEQ > 35 dBA, 45 dBA BELOW (USE $L_{eq} = 33$ dBA)
MASSACHUSETTS	40	MAXIMUM OF 5 TO 10 dBA ABOVE LOWEST L90 AMBIENT (USE MIN L90 = 33 + 7 dBA)
WASHINGTON	39	EMISSION LIMIT DEPENDING ON RURAL (39) OR RESIDENTIAL (42) ZONING
CALIFORNIA	38	MAXIMUM OF 5 dBA ABOVE L90 AMBIENT (FOUR QUIETEST CONSECUTIVE HOURS, USE MIN L90 = 33 dBA)
NEW YORK	38	MAXIMUM OF 5 dBA ABOVE UNDEFINED AMBIENT (USE MIN L90 OR $L_{eq} = 33$ dBA)
MEAN STATE NIGHTTIME LIMIT:	50	
AVERAGE STATE NIGHTTIME LIMIT	47.7	

a.m.) is adequate to preclude sleep-interference issues. This was based on a typical noise reduction of 10 dBA with open windows that would result in an interior bedroom level of 35 dBA. The much later work by the WHO mentioned above now recommends an exterior background level of 40 dBA to avoid sleep issues.

Considering the EPA guidelines as published in the seventies and later analysis, DNL levels from wind developments outside of residences should ideally be targeted at DNL=45 dB, or preferably 5 dBA less. A DNL level of 45 dBA is equivalent to 45 dBA day/35 dBA night or a steady 24 hour level of 39 dBA. A 45 dBA CNEL (Composite Noise Equivalent Level with a 5 dBA evening weighting) would be even more ideal at 45, 40 and 35 dBA for day, evening and nighttime levels, respectively.

3.4 State Standards

Just over a dozen states have codified regulations, zoning guidance or siting standards, presented in Table 2, that fundamentally have the same result as regulations for industrial noise. Most allow a higher limit for

daytime hours. The *nighttime* limits for industrial noise sources are tabulated in Table 2 for fourteen states. For the three states using an ambient based limit (CA, MA and NY), we use a representative background level of 33 dBA as an approximate, if somewhat conservative, design datum.

Clearly, there is a large variance, ranging from 38 dBA to 55 dBA, in what is considered “acceptable” for nighttime noise emissions at sensitive receptors. Not all can possibly be appropriate.

It should also be mentioned that the units and time periods of measurements for “emission limits” are not always well defined and one must refer to the actual standard for guidance.

Eight states use absolute ‘maximum emission limits’ for daytime and nighttime hours that are applicable at residential receptors regardless of the acoustic environment in those areas. While simple to codify and enforce, it is illogical that the same level could be satisfactory for any residential environment ranging from noisy urban to quiet rural residential locations. The state of Maryland¹⁰ acknowledges this and has found

Table 3—Summary of existing guidelines and standards relevant to typical wind projects.

Source	Effective Limits	Comments
WHO	40 dBA Night	Sleep Disturbance Threshold
Consensus of Int'l Limits Specifically on Wind Turbine Noise	45 dBA Day/40 dBA Night	Arithmetic Average of all Standards
U.S. EPA	45 dBA Day/35 dBA Night	DNL=45 dBA
State Standards	38 to 40 dBA Night	Based on the 3 States using an Ambient-Based Approach

that fully 50% of excessive noise complaints occur in situations where the noise source is in compliance with the State's regulations. Maine and Washington acknowledge differing ambient environments by including a clause that reduces the allowable emission limit for "quiet" areas in Maine and "rural" areas in Washington.

The states of New York, Massachusetts and California use ambient-based emission levels, i.e., the allowable emission level is calculated based on a prescribed increase to the existing ambient, or background sound level. An ambient-based method is based on the *perception* of the new sound in the *specific* residential community. A perception-based method is clearly a better approach than a single absolute limit, and, in fact, many years of experience have shown that this approach is working well in these three states. Based on an assumed generic background level of 33 dBA for rural areas where wind projects are usually sited, the effective design level for a new project would range from 38 to 40 dBA in these three states.

3.5 Local Standards

Finally, it should be mentioned that countless counties and local municipalities have enacted noise laws and ordinances specifically with respect to wind turbine projects—usually in response to a proposed project. Most commonly an absolute limit of 50 dBA is prescribed. Field experience, which is discussed in further detail in Sec. 4, indicates that such a limit is insufficient to avoid annoyance from wind turbine noise if the actual project sound level closely approaches this limit.

3.6 Summary of Existing Guidelines and Standards

Table 3 summarizes the general noise limits and guidelines from all known existing entities domestic and foreign that would be relevant to typical wind turbine projects in rural areas.

4 DIRECT EXPERIENCE AND PREVIOUS ANNOYANCE STUDIES

It is only through field experience testing newly operational wind projects that the actual community reaction can be directly compared to the sound levels produced by a project. Over the last few years we have had the opportunity to conduct sound surveys at 8 new operational wind turbine sites, of which 7 may be considered representative of the typical U.S. domestic project in the sense that a fairly large number of turbines (50 to 100) are sited over a large area within which there is a fairly uniform distribution of farms and homes; i.e., the turbines and residences are thoroughly intermixed. Out of these 7 typical project sites long-term sound monitoring surveys were carried out at 5, usually over a 2 to 3 week period. The principal objective of these surveys was to determine whether the projects were compliant with the applicable regulatory noise limit (usually 50 dBA) but they also afforded important opportunities to quantify the sound levels produced exclusively by the project at a number of the closest homes and to compare these measurements with model predictions. In addition, the community reaction to each project could be generally discerned because monitors were deliberately placed at the homes of all those who were known to have complained or otherwise expressed concern about noise, whether participating in the project or not. Monitoring stations were also set up at other homes where no complaints had been received but where maximum project sound levels were expected based on modeling. Informal discussions about the resident's subjective reaction to project noise occurred at most monitoring positions.

In general, these studies involved continuous monitoring in 10 minute increments over at least a 14 day period at numerous on-site positions supplemented by a number of off-site monitors generally 2 miles beyond the project perimeter recording the likely concurrent background sound level without any project noise. In this way it was possible to reasonably correct the

Regression Analysis of Measured Project-Only Sound Level vs. Normalized Wind Speed
Position 9

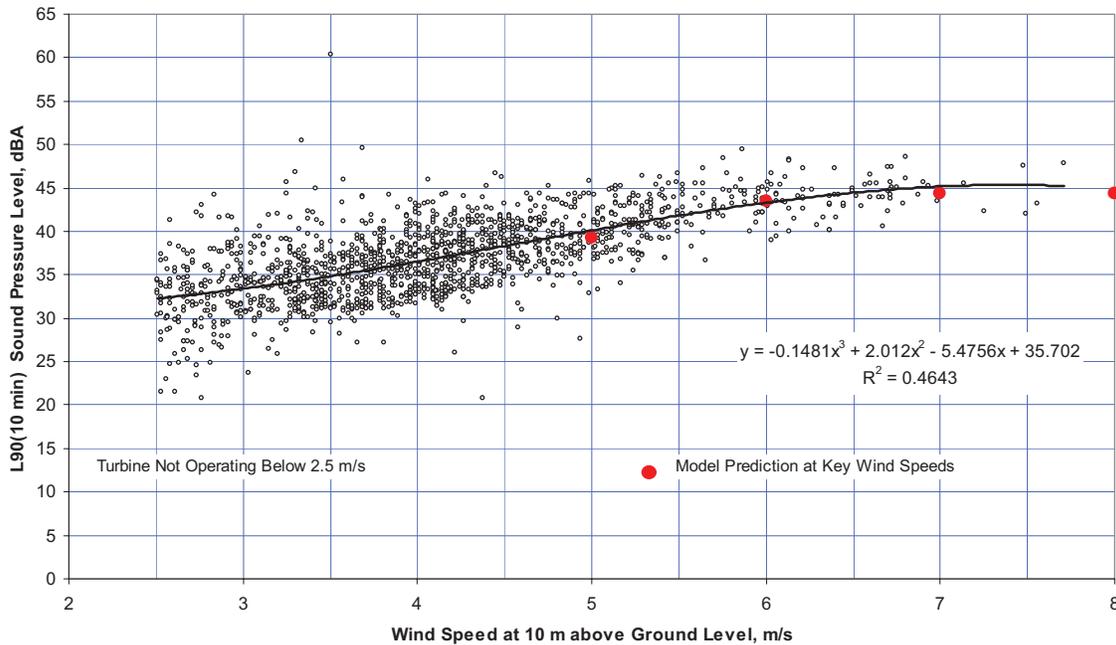


Fig. 5—Measured vs. modeled sound levels at a typical on-site receptor.

on-site sound levels for background noise contamination (which is often very significant during windy conditions) thereby deriving the project-only sound level at each position—the quantity predicted by analytical models. As an example, Fig. 5 is a typical plot that shows the corrected project-only sound level as a function of wind speed rather than time. The scatter in the data, which is typical and expected, is due to fluctuations in the project sound level at the observation point due to variations in atmospheric conditions (path effects) and fluctuations in the aerodynamic noise produced by the rotor due to inevitable inconsistencies in wind speed, gradient or direction (source effects). More importantly, Fig. 5 shows the essentially universal result from all positions in all the surveys that the model predictions at integer wind speeds agree extremely well with the mean trend through the measured performance, thus demonstrating that ISO 9613-2¹¹ (assuming a moderate 0.5 ground absorption coefficient) is a perfectly valid methodology for predicting wind turbine sound levels, recognizing that path and source effects will lead to levels that vary by about ± 5 dBA about the predicted mean.

In terms of noise impact, the results of these studies indicate that the actual degree of adverse impact, defined as the number of serious complaints relative to the total number of households in the project area (within 2000 ft. of the project perimeter), was fairly small at about 4%. The specific numbers associated with each project are tabulated in Table 4.

Just because the total number of complaints is fairly small in each case one should not be dismissive of

these people, because there were usually one or two at each site that were profoundly disturbed by project noise. However, it must also be said that the vast majority of people apparently had no objections to noise, even people who consistently experienced turbine sound levels in the 45 to 50 dBA range. Based on discussions with non-participating and participating residents at more or less randomly selected monitoring positions in close proximity to turbines, the most common reaction was generally that operational noise was certainly audible, particularly during certain wind conditions or times of day, but that it was to be expected and they didn't pay any real attention to it. Of course, this general assessment is not the result of a rigorous scientific study on wind turbine annoyance; that was never the objective of the surveys, but a milder than anticipated reaction was observed at each site.

The low apparent rate of adverse reaction to projects where numerous residences were exposed to relatively high sound levels (up to 55 dBA in some cases) was surprising because it stood in stark contrast to the results of previous annoyance studies; in particular, the extensive work carried out from 2000 to 2007 in Sweden and the Netherlands by Pedersen and Persson Waye¹² and Persson Waye¹³. These studies generally predict an annoyance rate ranging from 10 to 45%, or more, for wind project sound levels in the 40 to 45 dBA range. For example, the earliest study¹², based on questionnaire responses collected in 2000 from residents living in proximity to five small wind projects in Sweden, found the annoyance rate as a function of sound level plotted in Fig. 6.

Table 4—Number of observed complaints relative to the total number of households in close proximity to turbines.

Project	Total Households in the Site Area (Approx.)	Number of Complaints as a Function of Project Sound Level (dBA) (1)			Total Number of Complaints	Percentage Relative to Total Households
		<40	40–44	45 or Higher		
Site A	107	0	2	1	3	3%
Site B	147	0	3	3	6	4%
Site C	151	0	3	0	3	2%
Site D	268	0	2	4	6 (2)	2%
Site E	91	1	1	4	6	7%
Overall Average:						4%

(1) Sound levels expressed as long-term, mean values
(2) There were only 3 reported complaints at this site but others may have existed that we were not made aware of; hence a total number of 6 were assumed

This steeply rising curve apparently indicates that a sound level of 40 dBA, for instance, leads to a 26% annoyance rate, implying that out of the study population of 513, 133 were highly annoyed. However, this is not at all the case. On further analysis it turns out that the response curve percentage is not related to the overall study population—i.e., the total number of households within the project area with a predicted sound level of 30 dBA or more, whether they responded to the survey or not—but rather to the percentage of people exposed to a particular sound level that reported annoyance due to that sound level (see Table 5 of the paper). Now it must be pointed out that only 351 of the 513 individuals forming the study population returned the questionnaire, so the views of the missing 32% are not known, but in the

37.5 to 40 dBA category, for example, 20% of the 40 respondents exposed to that sound level range reported being highly annoyed—which is just 8 people. Viewed in terms of the overall population of 513 that is equivalent to a highly annoyed response of just over 1% for that particular sound level range (37.5 to 40 dBA). In general, across all sound level ranges the total number of people responding that they were highly annoyed was 31, or 6% of the total number of households. In contrast to the alarmingly steep response rate curve in Fig. 6, this 6% figure agrees much more closely with the 4% complaint rate (based on the total number of households) observed during our own field studies of projects in the United States. A further and much larger questionnaire study modeled on the 2000 study was performed in the Nether-

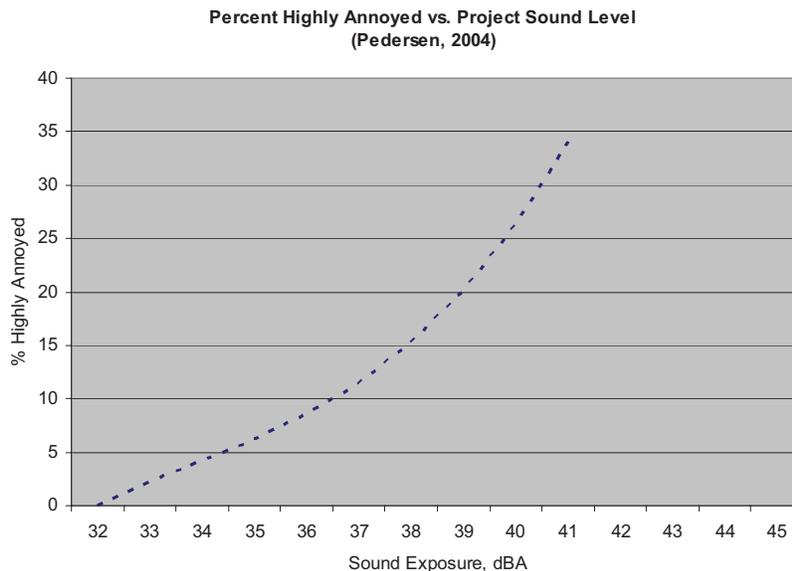


Fig. 6—Response analysis from Pedersen¹⁴.

lands in 2007 and reported in 2009 (Pedersen et al.¹⁴). This study is the most representative of current projects with large turbines and essentially flat topography. In this study out of 1948 queries sent out 708 were received. Across all sound level categories a total of 29 respondents (back-calculated from the results expressed as percentages in Table 2) reported being very annoyed. If only the 708 respondents are assumed to make up the pool of potentially affected residences in the project area (rather than 1948), this equates to a 4% rate of high annoyance.

On the other side of the coin, the number of individuals concerned about or annoyed by noise at each of the sites we studied may not have been definitive, since the number represents those who were troubled enough to call in and complain, as reported by project management, and any others we may have learned of indirectly in discussions with neighbors. The possibility that others were annoyed certainly cannot be ruled out and, in fact, seems likely but it appears that the actual rate of serious annoyance to noise from wind projects may not be nearly as high as previously supposed.

5 LOW FREQUENCY NOISE AND ADVERSE HEALTH EFFECTS

Harmful, or at least disturbing levels of low frequency or infrasonic noise and potential adverse health effects are almost always feared, based largely on internet misinformation, and cited as major reasons why proposed projects should not go forward. However, the fact of the matter is that wind turbines do not produce significant or even remotely problematic levels of low frequency noise and that a link between health complaints and turbine noise has only been asserted based on what is essentially anecdotal evidence without any valid epidemiological studies or scientific proof of any kind. The latter assertions are all the more suspect in that they are often predicated on or directly associated with the assumed existence of high levels of low frequency noise.

It is well outside the scope of this paper to go over the basis for these conclusions but readers are referred to a recent review by a panel of independent doctors on wind turbine health effects¹⁵ and some extensive testimony by the leading experts in the field (now public record) regarding potential low frequency noise impacts recently filed in conjunction with a proposed wind project in Wisconsin¹⁶.

Because low frequency noise from wind turbines, essentially irrespective of distance, is well below the point where it might begin to be audible or initiate perceptible vibrations (windows or dishes rattling, for example) there is no actual need for a design goal or regulatory limit. However, if one desires just to be on

the safe side, so to speak, a limit of 65 dBC might be used. In over 30 years of investigating countless genuine low frequency noise complaints, usually associated with simple cycle combustion turbines, there was only one outlier below 65 dBC. A maximum regulatory limit of 70 dBC is recommended if one must have a low frequency limit.

Having said that, it must be strongly cautioned that C-weighted sound levels do not mix well with wind turbine applications because it is extremely difficult to accurately measure C-weighted sound levels in the presence of any kind of wind¹⁷. Self-generated, false signal noise, which occurs in the low frequencies, from wind blowing through even sophisticated windscreens and over the microphone tip will drastically elevate the apparent C-weighted sound level and, by extension, the *apparent* low frequency sound level. Consequently, it would be a significant technical challenge to accurately field verify the C-weighted performance of a wind turbine project. Any casual measurement in a windy field will ostensibly yield a relatively high C-weighted sound level, possibly in excess of the 65 to 70 dBC levels suggested above, whether a wind turbine is present—or not.

Finally, Fig. 3 also shows the measurement location prescribed in IEC 61400-11 for determining the sound power level from wind turbines. Sound pressure is measured on a reflective ground plane with the microphone on the surface where wind speed is theoretically zero, but a $\frac{1}{2}$ sphere wind screen will blow away unless attached securely. Still another common example is dry leaves blowing along the ground in fall. Even with this test set up, measurement of LFN is problematical.

6 RECOMMENDED DESIGN GOALS AND NOISE LIMITS

Based on the existing guidelines and limits outlined in Sec. 3, combined with our direct experience summarized in Sec. 4, the following design goals and regulatory limits given in Table 5 are recommended.

The nighttime level of 40 dBA is suggested as an ideal design goal rather than a firm regulatory limit because a legal limit must reasonably protect the public from legitimate annoyance and, at the same time, not stand completely in the way of economic development, which 40 dBA would tend to do in some instances. Because the actual number of complaints observed at sites where the project sound level exceeded, or even substantially exceeded, 40 dBA is small at 4%, a sound level of 45 dBA at residences, as an ordinance or legal limit, appears to balance the desire on everyone's part to avoid complaints and annoyance on the one hand with practical constructability on the other. Sound levels of less than

Table 5—Recommended regulatory noise limits and design goals for wind turbine projects.

	Sound Level, dBA (1)	Applicable	Time of Day
Regulatory Limit:	45	Outside Residences	Day and Night
Design Goal:	40	Outside Residences	7 p.m. to 7 a.m.

(1) Long-term, mean project sound level (normally measured in terms of the L90(10 min) statistical sound level)

45 dBA would theoretically lead to a very low complaint rate of 2% based on the data in Table 4.

It is important to note that both of the levels above are mean, long-term values and not instantaneous maxima. Wind turbine sound levels naturally vary above and below their mean or average value due to wind and atmospheric conditions and can significantly exceed the mean value for brief periods. As illustrated in Fig. 5, project sound levels commonly fluctuate by roughly ± 5 dBA about the mean trend line but short-lived (10 to 20 minute) spikes on the order of 15 to 20 dBA above the mean are occasionally observed (less than 1% of the time) that are ostensibly attributable to turbine noise—although the possibility exists that some or all are extraneous noise events. Because it would be completely impractical to design any project so that all such spikes would remain below the 40 and 45 dBA, these values are expressed as long-term mean levels, or the central trend line through the data scatter as shown in Fig. 5.

Some degree of dissatisfaction due to audibility is largely inevitable. The very definition of noise is unwanted (audible) sound. For example, in isolated incidences we are familiar with complaints have been engendered by wind project sound levels as low as 23 and 34 dBA. Therefore an objective of completely eliminating the possibility of any negative response is largely impractical and the imposition of extremely low regulatory noise limits or of vast minimum setbacks—as championed by James and Kamperman¹⁸, for instance—would not necessarily eliminate all adverse impact but would, in fact, make most projects impossible to build, even in sparsely populated areas of the country.

During the design phase of a wind project, particularly for projects where the turbines are interspersed amidst a number of homes, there are several options, outlined below, that are available for mitigating potential project noise and bringing the project, hopefully, into conformance with one or both the recommended noise levels.

6.1 Site Layout Optimization

The most useful and effective method by far is the optimization of the site plan through iterative noise

modeling. This technique, which has been successfully applied to a number of projects, involves developing a baseline model of the project as initially conceived in terms of a sound contour map and then hypothetically relocating or removing certain units in order to *ideally* place all of the potentially sensitive receptors within the site area outside of the 40 dBA contour line.

The baseline layout is usually driven by where participating land parcels are in general and where the wind resource is best on those parcels in particular, rather than by noise concerns. Consequently, some degree of improvement, i.e., a reduction in the predicted sound levels at residences, can almost always be realized—so long as it is early enough in the design process that significant changes can be made. In fact, the best time to start evaluating potential noise impacts is when a project has just begun to coalesce and is considered generally viable, even if only a hypothetical or estimated turbine layout is all that is available for modeling. All too often noise is only considered at the eleventh hour just prior to submittal of the permit application, or even construction, when the flexibility to move turbines has been utterly lost.

Because of the numerous other constraints that always exist on exactly where turbines can be built, it is often necessary to go through several iterations of noise modeling to find the optimal arrangement that minimizes noise and still satisfies all other concerns.

6.2 Low Noise Operating Modes

If physical changes to the turbine site plan cannot be made or are still insufficient to realize the desired performance, further targeted reductions can sometimes be made by operating specific units in low noise operating mode—something that can also be evaluated prior to construction through iterative modeling. While still not universally available as an option on all turbine makes and models, there now appears to be a trend towards incorporating this capability into most new units or retrofitting it on existing models. Noise reductions of up to 5 dB relative to normal performance (it is claimed by some manufacturers) can nominally be achieved primarily through electronic manipulation of the blade pitch. Although this operating mode could theoreti-

cally be employed at all times, it adversely affects power production at higher wind speeds so it not desirable, or in some cases even economically unfeasible, to permanently de-rate the turbines; consequently, this option is more appropriate for use as a temporary measure under certain weather conditions or times of day, most likely during the critical nighttime hours when noise is typically more of an issue.

6.3 Operational Curtailment

Curtailment of operation, or temporarily shutting down specific turbines, is obviously onerous to the economics of a project that clearly involves a large capital investment, but it may be less devastating than first thought. The temporary shutdown of just one unit (overnight, for instance) can sometimes make a dramatic difference in the sound level at a particular point of interest. Depending on the geometry of the situation, model simulations taken from actual projects indicate that noise reductions from 2 to 8 dBA can be achieved by shutting down only the *single nearest* turbine to a particular house.

7 CONCLUSIONS

Measurements of operational wind turbine projects indicate that turbine noise is usually most perceptible relative to the background level at night suggesting that design goals and regulatory limits should either be focused on nighttime conditions or have differing goals for night and day

Existing guidelines and regulatory limits, interpreted within the context of the quiet rural environments in which wind projects are normally sited, generally point to a design goal sound level of 40 dBA at night and 45 dBA during the day.

Experience in measuring the sound levels produced by newly operational wind projects and comparing those levels to actual community reaction indicates that the number of complaints relative to the total number of potentially affected households within a given project area is fairly low at roughly 4% in cases where project sound levels exceed or even substantially exceed 40 dBA at residences. This finding was also found to generally agree with previous European research but only when the number of questionnaire responses reporting high annoyance is similarly viewed relative to the overall number of potentially affected households rather than by exposure levels.

Field surveys of operational projects also generally indicate that complaints engendered by wind turbine sound levels below 40 dBA are very rare therefore

suggesting that new wind projects should use a nighttime sound level of 40 dBA as an ideal design goal at all residences to minimize the probability of annoyance and complaints with a higher level of 45 dBA applicable during the day. However, the low (2%) rate of complaints observed in the studies when the project sound level was below 45 dBA points to this value (45 dBA) as an appropriate regulatory limit, irrespective of time of day, since it appears to strike a balance between the reasonable prevention of annoyance and what is generally achievable in terms of project sound levels at typical project sites.

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