Wind Farm Noise Dose Response

Dani Fiumicelli. **A Literature Review**

INTRODUCTION

A literature search reveals most wind farm noise dose response studies have been carried out in Scandinavia, the Netherlands and Germany. Transposing these studies to other countries may not be reliable as methodological and analytical issues, and differences in topography, population density and distribution, as well as variation in societal, language, cultural, environmental and political factors between these countries and elsewhere, militate against the direct transfer of these dose responses. However, these studies make a useful contribution to trying to understand wind farm noise dose response overall.

Review of dose response research

A substantial review of wind farm noise dose response was produced in 2003 by Eja Pedersen[1] on behalf of the Swedish Environmental Protection agency. As a starting point this study looked at work done by Wolsink et al (1993) in the early 1990's, which is summarised below.

1. In all, 13.5% of the study respondents were exposed to turbine noise in the range <25 to 30 dB(A) , 70% of the study respondents were exposed to turbine noise in the range 30 to 40 dB(A), and 16.4% were exposed to turbine noise above 40dB(A);
2. The proportion of persons indicating any noise annoyance is low at only 6.5% of the survey sample;
3. The degree of annoyance is only slightly related to noise level;
4. *'The fact that someone was complaining was mainly determined by the personality of the individual';*
5. *'The conclusions must not be misunderstood. The fact that sound level is not predicting annoyance does not mean that people are not really annoyed when they are reporting it.'*

Importantly, the Wolsink et al (1993) study sounds a note of caution regarding interpretation of its results as 'There are a number of methodological problems involved in the project'.

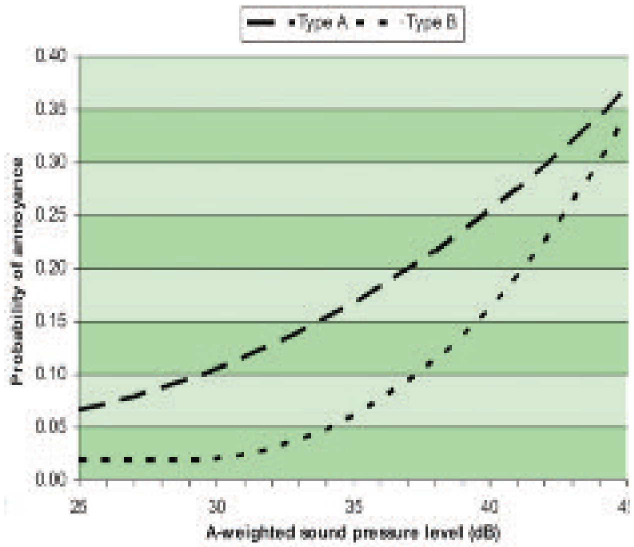
The Swedish study

Another more recent (2007) field study has been carried out in Sweden[2] (referred to hereafter as 'the Swedish study'). This study consisted of multiple phases, including cross-sectional social surveys to derive a dose-response relationship. Subjective responses were obtained from 1,288 respondents across the different phases of the study. The first phase was carried out in an area of flat terrain in a mainly quiet rural area, whereas the later phase was carried out in areas with different types of terrain (flat or complex) and different degrees of urbanisation and higher ambient noise levels.

Overall the Swedish study found a greater probability of the perception of wind turbine noise in quieter rural areas compared with noisier suburban locations; and a greater annoyance response rate in quieter compared to noisier locations.

The Swedish study also considered the impact of visual factors by comparing responses from respondents who could see wind turbines with those who could not see wind turbines. The study found that 'being negative towards the visual impact of wind turbines on the landscape scenery, rather than towards wind turbines as such, was strongly associated with annoyance.'

Dose-response relationships were found in the Swedish study both for perception of noise and for noise annoyance in relation to turbine A-weighted sound levels derived in accordance with the Swedish Environmental Protection Agency (2001) Guidelines†. Two dose-



Type A Rural location, with low background noise levels

Type B Suburban location with higher background noise levels

Figure 1

Probability of annoyance with wind turbine noise outdoors: E Pedersen and K Persson Waye (2007) Wind turbine noise, annoyance and self-reported health and well-being in different living environments. Occup. Environ. Med. 64, 480–486.

response relationships were presented: one for rural areas (Type A) and the other for suburban areas (Type B) and these are reproduced here in Figure 1.

However, caution is advised when considering the masking effect of other noises, as the distinctive temporal and frequency characteristics of wind turbine noise may mean that it is not completely masked until other noises eg road traffic noise, are at A-weighted levels least 20dB greater than the turbine noise[3]. However, as the Pedersen and Persson Waye (2007) work referred to above shows, when making decisions on wind turbine noise policy or in regard to specific developments, complete masking so that the turbine noise is not audible is not required in order to manage the impact of turbine noise. As with most other noise sources, there is generally a substantial gap between the proportion of persons who can perceive wind turbine noise at a particular noise level, and the much smaller proportion of persons reporting annoyance, as will be shown shortly in this review. In line with most other noises, this suggests that whilst the overall community response of the relevant proportion of a population reacting adversely to turbine noise at specific levels may ultimately be capable of prediction, the wide variability of human response to noise and the influence of non-acoustical factors typically makes precise prediction of the reaction of individuals to wind turbine noise impracticable.

The graphs in Figure 2 are from the Swedish study and show the proportion of respondents who noticed and/or were annoyed by wind turbine noise in Phases I and III. Care should be taken when comparing the two studies as Phase III was not intended to replicate Phase I:the studies were in different landscapes with different geographical characteristics, and Phase III included questions about evaluation of the environment and feelings invoked by wind turbines and coping strategies

* The paper is unclear as to what noise index applies, but it is assumed that the $L_{Aeq,t}$ is relevant as it is applied to wind turbine noise in all the countries in the study.

† The text this report suggests that the dose responses use the $L_{Aeq,T}$ noise index. Whilst in the UK ETSU-R-97 advises use of the statistical method (L_{A90}) for the measurement of noise from wind farms, most other countries in Europe use the equivalent continuous noise index ($L_{Aeq,T}$). Most other EU countries have fixed limits, the lowest being Sweden and Ireland (40dB(A) $L_{Aeq,T}$ and the highest being Spain (65dB(A) $_{LAeq,T}$ – although care should be taken when comparing advice from different countries as noise index, time period and definition of night and day periods can vary substantially.

that were not asked in Phase I. The two phases show clear differences in the degree of response, which suggests that amongst other variables the response rate is influenced by location specific factors.

Both phases of the Swedish study reinforce that mere perception of wind turbine noise is not sufficient to provoke annoyance in most of the respondents, as there is a significant difference in the percentage perceiving the wind farm noise and those who are annoyed, with a smaller differential at lower noise levels compared to higher values.

Both Phases I and III of the Swedish study have in common the general trends that:

- annoyance increases with increasing noise level;
- sleep disturbance was associated with annoyance (although only Phase I showed an association between noise level and sleep disturbance);
- Descriptors of the turbine noise characteristics including 'swishing', 'whistling', pulsating/throbbing' and 'resounding' were highly correlated with noise annoyance in both Phase I and Phase III.

Recent developments

More recently (2009), work[4] has been published that considers two surveys in Sweden and one in the Netherlands on wind farm noise dose response compared with industrial noise. This concluded that:

- *'At outdoor exposure levels higher than 40dB(A), the expected percentage of annoyed persons indoors due to wind turbine noise is higher than due to industrial noise from stationary sources at the same exposure level;*
- *Besides noise exposure, various individual and situational characteristics were found to influence the level of annoyance;*
- *Having economic benefit from the use of wind turbines, or being able to see one or more wind turbines from within the home are two particularly influential situational factors [with positive and negative effects respectively];*
- *The economic benefit factor is reminiscent of earlier findings that being employed at the noise source (eg airport or industry) attenuates the annoyance reported;*
- *Also, visibility from the home (eg living room, bedroom) has been reported earlier to affect annoyance from stationary sources;*
- *In addition, noise sensitivity and age had similar effects on [increasing] annoyance to those found in research on annoyance by other noise sources.'*

The chart in Figure 3 (taken from the Netherlands study) illustrates that wind turbine noise measured using Lden in dB(A) appears to have a higher annoyance rate than industrial noise.

Also in 2009 further work[5] concluded that:

- *'A dose-response relationship between calculated A-weighted sound pressure levels and reported perception and annoyance was found;*
- *Wind turbine noise was more annoying than transportation noise or industrial noise at comparable levels (see Figure 4), possibly due to specific sound properties such as a 'swishing' quality, temporal variability, and lack of night time abatement. High turbine visibility enhances negative response, and having wind turbines visible from the dwelling significantly increased the risk of annoyance;*
- *Annoyance was strongly correlated with a negative attitude toward the visual impact of wind turbines on the landscape;*
- *People who benefit economically from wind turbines have a significantly decreased risk of annoyance, despite exposure to similar sound levels.'*

The Janssen, Eisses and Pedersen (2009) study compared the Dutch

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study results with results from the Swedish study‡ and concluded the following;

- *'The study confirms that wind turbine sound is easily perceived and;*
- *Compared with sound from other community sources, relatively annoying, and;*
- *Annoyance with wind turbine noise is related to a negative attitude toward the source and to noise sensitivity, and;*
- *In that respect it is similar to reactions to noise from other sources, and;*
- *This may be enhanced by the high visibility of the noise source, the swishing quality of the sound, its unpredictable occurrence, and the continuation of the sound at night.'*

The importance of acoustic features

G P van den Berg[6] (2005) has investigated the possibility that uneven wind speed across the rotor plane may cause fluctuations in noise emission and has suggested that in stable atmospheric conditions the difference in wind speed between the top and bottom of the rotor of a large turbine is relatively high. This may contribute to a cyclical variation in the noise level, which may be characterised as a 'beating' – an effect referred to as amplitude modulation of aerodynamic noise (AM). This type of noise is of interest, as it is likely that a modulated noise will be more annoying than a non-modulated noise at the same sound pressure level. In regard to this point, it has recently (2009) reported that:

> *'Acoustically this may be due to the diurnal course of the noise and the rapid fluctuation in level related to the rotation, which are not usual features of most transportation and industrial noise sources. It can also be a result of non-acoustic factors such as visual intrusion and the perceived distribution of benefits and adverse effects.'*[7]

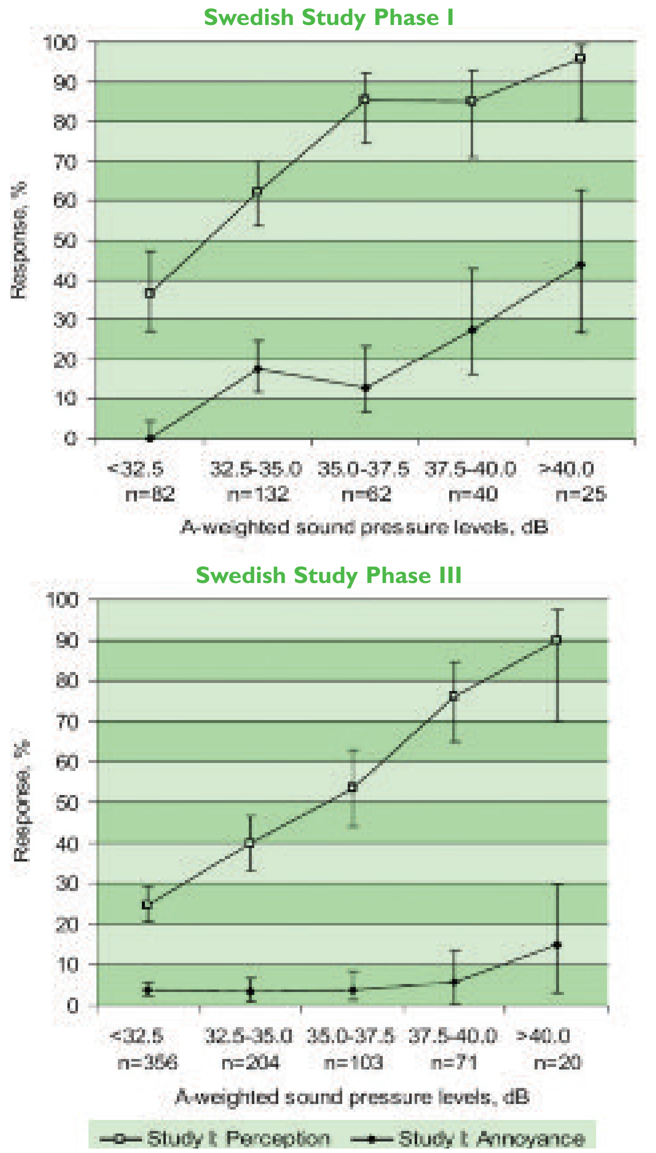

Figure 2

Response to wind turbine noise: E Pedersen and K Persson Waye (2007) Wind turbine noise, annoyance and self-reported health and well-being in different living environments. Occup. Environ. Med. 64, 480–486.

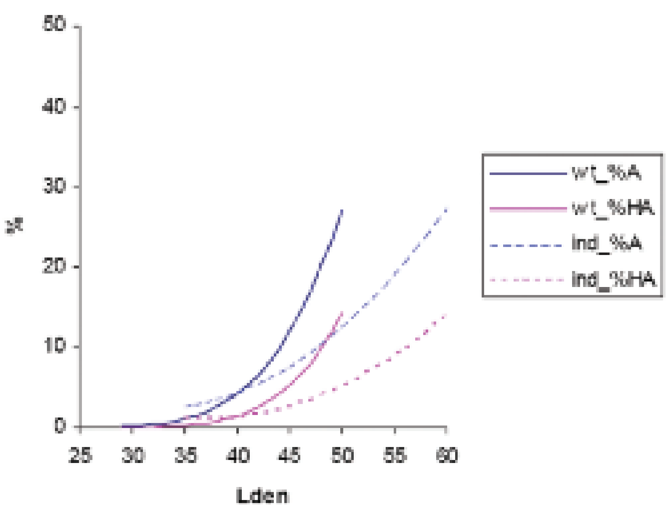

Figure 3

Comparison of the percentage annoyed and highly annoyed persons indoors (%A indoors and %HA indoors) due to wind turbine noise (wt) and industrial noise (ind). Janssen, Eisses and Pedersen, Exposure-response relationships for annoyance by wind turbine noise: a comparison with other stationary sources, EURONOISE 2009, Edinburgh.

As wind farm noise typically includes a degree of modulation it will normally be appropriate to include assessment of this factor when assessing dose response. However, aerodynamic modulation of the aerodynamic noise emitted by wind turbines is not well understood and there are presently no peer reviewed and validated models available through which the occurrence of aerodynamic modulation can be reliably predicted. Additionally, there is currently little understanding of the factors that influence how modulation of the turbine noise may affect its impact, or any established thresholds of modulation beyond which the impact is clearly unacceptable.

In 2002 in a laboratory study[8] 25 subjects were exposed to five wind turbine noises of different character, but all at the same noise level of 40dB $L_{Aeq,t}$, in order to see if differences between the noises with regard to annoyance could be found. The most annoying noises were predominantly described as 'swishing', 'lapping' and 'whistling'. These descriptors could all be regarded as related to the aerodynamic noise and as descriptions of a time varying (modulated) noise with high frequency content.

In another laboratory study[9] (2007) 20 subjects were asked to rate recordings of wind turbine noise with different acoustic features, principally tonal components and aerodynamic noise from the rotating blades. The rated tonality of the stimuli did not correlate well with the metric developed for the prominence of tones - ΔLta. However a metric for calculating 'swishing sound' was developed ie fluctuation strength, which is a measure of amplitude and frequency modulation. This was measured in the 350 – 700 Hz band, and correlated well with the ratings on 'swishing sound' in the sound played to the test subjects. The frequency band between 350 and 700 Hz was chosen because it

‡ Again the study is unclear as to the noise index or the measurement time period, but the propagation model used (ISO 9613) suggests $L_{Aeq,T}$.

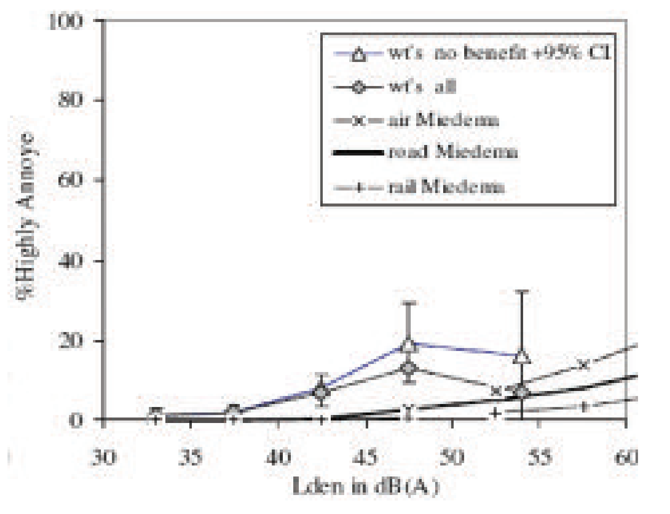

Figure 4

F van den Berg, E Pedersen, R Bakker, J Bouma: Project WINDFARM perception – Visual and acoustic impact of wind turbine farms on residents, University of Groningen, UMCG and Universiteit Göteborg (2008)

seemed to be the optimum range for 'swishing sound' from large modern wind turbines.

Caution should be exercised in transposing results from laboratory studies to the field, as many other studies have identified that laboratory tests often overestimate the impact of noise compared with field studies.

The 2007 Salford University field study[10] attempted to establish the prevalence of amplitude modulation of aerodynamic noise (AM) of wind turbine noise in the UK. Information was gathered from local authorities, and the personal knowledge of council staff was used to determine whether AM was likely to be a factor in complaints about wind turbine noise. Local authorities were asked if the noise contained a number of different features, certain of which could be indicative of AM eg 'like a train that never gets there', 'distant helicopter', 'thumping', 'thudding', 'pulsating', 'rhythmical beat', and 'beating'. The study suggested that aerodynamic modulation may have been a factor in four of the 27 sites associated with complaints included in the survey and a possible factor in complaints at a further eight sites.

However, the Salford University study's categorisation of AM and the subsequent findings differ from other studies which suggest that swishing and other similar descriptors could be associated with AM and that such features are more widely prevalent than the Salford study reported. However, this may simply be a question of semantics as the report by Salford University suggested that swishing type features could be associated with blade resonance not amplitude modulation of aerodynamic noise. Additionally, analysis of the complaint information used in the Salford University study suggests that a significant proportion of the cases may have contained acoustic features that could attract attention and may therefore enhance annoyance. For example, if the four cases in the Salford study where AM was a recognised factor are added to the eight where AM was a possible issue, this gives 12 of 27 cases where complaints were made, or approximately 44% where AM may have been a factor. Some commentators have distinguished the four cases where the Salford study recognises AM as a factor, as probably being 'excess AM' of greater modulation over and above the normal 'swish' AM typically expected for a wind turbine.

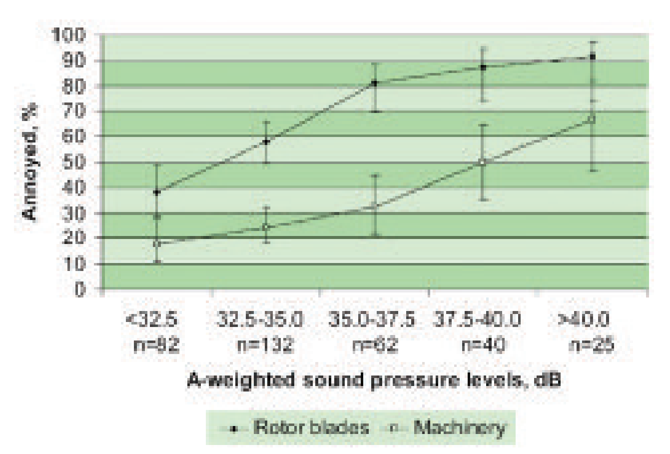

Figure 5

Annoyance of wind turbine noise and mechanical sources. Pedersen (2007) Proportion of respondents annoyed by sound from rotor blades and machinery, respectively, outside their dwelling in Study 1, in relation to sound pressure levels in 2.5dB intervals.

The Swedish field study referred to earlier found that the sound characteristics of wind turbine noise, generated by the rotation of the blades, were found to be especially annoying. Noise from rotor blades was noticed more than noise from machinery (see Figure 5). Whilst descriptors of sound characteristics relating to sound from the rotor blades were highly correlated with noise annoyance, sound characteristics describing the aerodynamic modulation were appraised as the most annoying eg 'swishing, whistling and pulsating/throbbing'.

A case study carried out in the Netherlands (G P Van den Berg, 2004) showed that aerodynamic modulation can be stronger under certain meteorological conditions and that periodic swishes are louder in a stable atmosphere associated with night-time than in daytime, and residents can use words like 'clapping, beating or thumping' to describe the character or the sound. In the case of the Rhede wind park, the beating could be heard clearly at distances up to 1km, and at night the beat of the noise could be used to determine the rotational speed of the turbine. When the atmosphere becomes more stable, which is

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usual during the night when there is a partial clear sky and a light to moderate wind (at ground level), there can be an important change in the wind profile affecting the performance of modern, tall wind turbines. The airflow around the blade then changes to less than optimal, resulting in added induced turbulence. It was suggested that this effect is strongest when the blades pass the tower, causing short lasting higher sound levels at the rate of the blade passing frequency. The synchronisation of these pulses from multiple turbines can give rises to additive effects at a distance and the repetitive pulses may be expected to cause added annoyance.

However, the effect of the tower is dismissed by the SIROCCO[11] study which shows that the effect of the passage of the blade past the tower is relatively small in comparison to that attributable to the downward sweep of the blade as it approaches the observer, according to the data on which the study was based[12], indicating that the latter can give rise to a modulation of some 12dB in certain third-octave bands.

A study undertaken for the Department of Trade and Industry[13] looked at low-frequency noise from three wind farms within the United Kingdom, and found that the turbines were not significant sources of low-frequency noise, and that it was the slow cycle of AM that was being mistaken for low frequency noise. The study indicates that the level of modulation from peak to trough was 2 to 5 dB when measured externally and 4 to 6dB when measured internally (in terms of overall A-weighted levels). The depth of the modulation within individual third-octave bands was found to be up to 10dB. The report concludes that

> *'some wind farms clearly result in modulation at night which is greater than that assumed within the ETSU-R-97 guidelines'*

ie excess AM. The report then goes on to suggest that in conditions of high aerodynamic modulation it may therefore be appropriate for a correction for the character of the noise to be applied.

The Salford University AM study (Moorhouse et al 2007) reports in regard to the four sites where AM was identified as a factor in complaints, modulation in noise levels as follows:

> *'Measurements of the internal noise levels during these periods of wind farm operation indicate that A-weighted noise levels are subject to amplitude modulation levels of between 3 and 5 dB. Analysis of these periods using third-octave band analysis indicates that between 200 and 800 Hz, noise levels in specific frequency bands may change between 8 and 10 dB. External measurements indicate that for external A-weighted changes in level of 3 to 4 dB, third-octave band levels may change by between 7 and 9 dB. Measurements reported for Wind Farm D (Table 1) have indicated that third-octave band levels when complaints were received (before the implementation of wind turbine control features) indicated level changes of 12 to 15 dB. (All the above figures are ranges from peak to trough).'*

The DTI report into low frequency noise and wind turbines (Hayes Mackenzie, 2006), states that

> *'the dominant audible noise associated with wind turbine operation is acoustic energy within the 250 to 800 Hz frequency region which originates from the aerodynamic modulation of the wind turbine noise'.*

Whilst the Salford AM study advises that

> *'The finding that this modulation is concentrated between the frequency bands of 200 and 800 Hz is significant in that this is generally generated by the trailing edge of a wind turbine blade. This has been identified as one of the main sources of aerodynamic noise associated with the operation of wind turbines (Oerlemans and Lopez, 2005)'.*

Individual and other situational factors

Human response, and hence complaints, can be strongly influenced by individual and situational factors. It is known from other studies of general environmental noise that visual impact and other variables are important, and may be found to be equally relevant or more relevant than noise level in influencing response. For example, work[14] on the influence of non-acoustic factors on the human response to noise has concluded that:

> *'It is well known that annoyance reactions of residents exposed to environmental noise are determined partly by acoustical features of the environment, partly by features of the residents. At best, about a third of the variance of annoyance reactions can be 'explained' by the variance of acoustical features, and another third by the variance of personal or social variables.'*

> *'Noise annoyance is considered to be the (long-term) negative evaluation of living conditions with respect to noise. This evaluation is not simply dependent on past disturbances, but on attitudes and expectations too. The personal factors influencing the evaluation are: sensitivity to noise, fear of harm connected with the source, personal evaluation of the source, and coping capacity with respect to noise. The social factors are: general (social) evaluation of the source, trust or misfeasance with source authorities, history of noise exposure, and expectations of residents.'*

Additionally, other researchers[15] have concluded that the following individual factors can influence the response to environmental noise:

- 'The awareness of non-noise problems may increase annoyance, and;
- Fear of the noise source can increase annoyance, and;
- The belief that the noise source is important can decrease annoyance, and;
- The belief that the noise could be prevented can increase annoyance.'

The above suggests where wind turbines are regarded as an unwelcome, dangerous or avoidable intrusion that the response of some people to the noise may be more than in circumstances where such factors do not apply. The outlook of study respondents towards the source is known from other community noise studies to influence annoyance, and was found to be associated with noise annoyance in the Swedish study referred to above. In the Phase I and Phase III surveys, 13% and 8% of the respondents respectively had negative or very negative attitudes towards wind turbines. Having such negative opinions towards wind turbines was not associated with the A-weighted noise level but was associated with annoyance due to wind turbine noise. The Swedish study states that

> *'Of the respondents in Phase I, 40% were negative or very negative about the impact of turbines on the landscape scenery' and '16% of the respondents in Phase III were negative or very negative to this impact.'*

There were no differences between residents living in flat areas and those in complex terrains, although in the Phase I study, residents in rural areas were slightly more negative than those in suburban areas. Wind turbines were judged to be environmentally friendly by most of the respondents, followed by positive evaluation of the utility ('necessary' and 'efficient') and a negative evaluation of aesthetic appearance ('ugly' and 'unnatural'). However, the correlation coefficients between the study subject's general point of view towards wind turbines and noise annoyance in these studies were lower than those found in other community noise studies. The general outlook towards wind turbines was of less importance than was visual opinion.

The Swedish study investigated the relationship between noise annoyance and the visibility of the turbines and people's attitudes about the visual appearance of the turbines. Visibility was investigated using a measure of the vertical visual angle, defined as the angle between the horizontal plane and an imaginary line from the dwelling of a respondent to the hub of the nearest wind turbine, expressed in degrees. Visual attitude was measured in terms of the respondents' attitude towards the impact of the wind turbines on the landscape scenery, using bipolar descriptions such as 'beautiful/ugly' and 'natural/unnatural'. Visual attitude had a large influence on noise annoyance among respondents living on flat terrain, but no statistically significant influence among respondents living on complex terrain. The main individual factor that influenced response to wind turbine noise was attitude towards the visual aspects of the turbines.

Pederson (2007) suggests that negatively appraising the impact of the wind turbines on the landscape scenery was highly associated with noise annoyance. The risk of noise annoyance increased when the wind turbines were visible ie residents who could see at least one turbine from their home were more negative about the impact of wind turbines on the landscape.

Adverse feelings aroused by the wind turbine noise were influenced by feelings of lacking control, being subjected to injustice, lacking influence, and not being believed. Appraising an exposure to noise as an unfair social situation has, in experimental studies, been shown to increase the risk of noise annoyance[16]. Surprisingly, noise sensitivity was only correlated to response to wind turbine noise to a low degree. The results of the work regarding social justice and other research, highlights the complexity and interdependency of the factors influencing the subjective response to wind turbines and wind farms. This strongly suggests that the manner in which sites for wind turbine and wind farm schemes are chosen, how schemes are permitted and developed, and the community and individual perception of these phases, strongly influence the subjective response and are possibly as important or more important than the physical effects of such schemes including noise.

Type of area and relevance of background noise

An increased risk of perception of wind turbine noise was found in the Swedish study in those areas that were rated as quiet compared with non-quiet areas. Also, the risk of annoyance was increased in quiet areas, indicating that the contrast between the wind turbine noise and the background noise could make the turbine noise more easily detectable and subsequently more annoying, although confounding factors such as expectation of peace and quiet, effects of visual impact, and attitude to wind turbines would have an influence on annoyance response, and may be more marked in quiet rural/natural areas compared with urbanised/non-quiet areas.

The higher risks of perception and annoyance in quiet areas were reflected in the differences found between rural and suburban areas in the Swedish study. The results showed higher risks of both perception and annoyance in rural landscapes compared with suburban areas. The rural areas were presumably subject to background sounds of lower levels than those found in a suburban area. Pederson argues that the character of the sound is also different and that background sound of a rural area mainly contains natural sounds leading to large contrasts between the wind turbine noise and the background sound. A persistent swishing noise could in the context of such a soundscape be experienced as intrusive, and may also be incongruent with sounds normally expected in such a surrounding.

However, there are limitations associated with the calculation method used to establish dose in the Swedish study, and that study was not sufficiently powerful by itself to conclude safely that response is significantly influenced by the contrast or the difference between the background noise and the specific wind turbine noise.

The influence of background noise was investigated in the laboratory study referenced earlier (S V Legarth, 2007). In a carefully constructed living room setting within a laboratory 20 subjects were asked to rate recordings of wind turbine noises with and without background noise. The results of the listening tests are shown in Figure 7, reproduced from the paper, which are presented alongside the results from other wind turbine field studies[17]. The laboratory study clearly found that by adding natural background noise, the wind turbine sound at low levels becomes less annoying as presumably it is better masked.

Legarth is careful to note that the difference in response between the laboratory and the field studies is substantial, with the laboratory study showing a greater response rate than found in the field studies, as is common for other noise sources. He goes on to suggest that the difference between the laboratory and field study results is primarily due to the different context in which the subjects listened to the noise in the laboratory study compared with the field survey eg it was not possible to make them feel at home, only to ask them to imagine themselves at home. Additional reasons given are that the questions and the scales used to record the subject's responses were different between the field and laboratory studies.

Work undertaken by G P van den Berg (2005) and by others[18] suggests that in situations with high wind shear, when the noise emitted from the turbine may be higher than expected from the wind speeds at 10 metres, the background noise at ground level may still be relatively low. Consequently, the degree of masking provided by the background noise in such circumstances may be reduced in comparison with low or zero wind shear conditions with lower turbine emissions.

Health effects

Eja Pederson carried out a review of health effects from wind turbine noise in 2003. She found that there was no scientific evidence that noise at levels emitted by wind turbines could cause health problems other than annoyance. However, she suggested that sleep disturbance should be further investigated. Because noise from wind turbines can have special characteristics (amplitude or aerodynamic modulation and 'swishing' sounds), as for any noise that has temporal and spectral characteristics different from the prevailing soundscape it may be detected when close to or even below existing background noise levels: this may increase the probability of annoyance and sleep disturbance[19] (although the Swedish study suggests a significant gap between wind turbine noise being audible and significant annoyance effects). Pedersen comments that the combination of different environmental impacts (intrusive sounds, visual disturbance and the inability to avoid the source in the living environment) could lead to a low-level stress-reaction which should be further studied.

These findings were seemingly confirmed in the Swedish study. In Phase I of the study, the A-weighted sound pressure level was correlated with sleep disturbance; however this result was not replicated in the Phase III survey. In the first survey 16% of the respondents exposed to noise levels above 35dB(A) stated in an open question that they were disturbed in their sleep by wind turbine noise. Only a few respondents reported impaired health and social well-being and no association between wind turbine noise and health was found. It is not known how many of the subjects may have had underlying sleep problems, or how many cases of sleep disturbance were due in part or wholly to other sources but were attributed by the respondent to turbine noise.

The absence of strong evidence on the existence of health effects from wind turbine noise should not be taken as proof that such effects do not occur. However, it would appear that the self-reported health effects associated with wind turbine noise are significantly weaker compared with other types of noise, for example the findings reported for domestic noise[20].

Pedersen has updated her earlier work with a recently published paper[21] (2009) and reports that:

- *'Based on data from two Swedish studies and one Dutch study in which self-reported health and well-being were related to calculated wind farm A-weighted sound pressure levels outside the dwelling of each respondent, the main adverse effect was annoyance due to the sound, and the prevalence of noise annoyance increased with increasing sound pressure levels;*
- *Disturbance of sleep was related to wind turbine noise; the proportion of residents reporting sleep disturbance in one of the Swedish studies due to noise increased significantly at sound*

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levels close to those recommended as the highest acceptable levels in Sweden (maximum recommended external level for houses, educational establishments, nursing homes/hospitals is 40dB LAeq,t - Swedish EPA report 78.5 – as amended) while the Dutch study showed this at a higher level of 45dB);

- *No other clear associations between sound levels and self-reported health symptoms have been found;*
- *However, a statistically significant association between annoyance and symptoms of stress was found;*
- *The study design does not allow causal conclusions, but the association indicates a possible hindrance of psycho-physiological restitution. Such a hindrance could in the long term lead to adverse health effects not detected here.'*

None of the above effects are unique to wind turbine noise[§], although it is unclear whether the dose-response for wind turbine noise is the same as for other noise sources, as several of the studies referenced above suggest that wind turbine noise is more disturbing than transportation and industrial noise sources.

Differences between large and small wind turbines in respect of noise annoyance

Turbines on modern wind farms are substantially taller than those erected ten to 20 years ago. It has been hypothesised that this could lead to greater noise annoyance, not simply because the turbines emit more noise, but because larger turbines could produce disproportionately more low-frequency noise and the overall noise emission could have different temporal and frequency characteristics from those of smaller turbines.

Recent work[22] has started to examine these questions and has so far reported that the spectral characteristics of large and smaller turbines are generally very similar, apart from a slight increase in the low-frequency content for large turbines. Listening tests simulating an indoor scenario and an outdoor scenario with and without masking garden noise concluded the following:

- Relative sensation levels were calculated from equal annoyance contours to determine whether low frequency tones are relatively more annoying than high frequency tones.
- The frequency dependence was not shown to be significant. The main influence on these levels is the tone level above masking level.
- Tones at higher levels are more annoying than tones at lower levels above masking.
- Both findings are common for the indoor and outdoor scenarios.
- The listening tests showed the spectral characteristics of the small turbine to be more annoying outdoors than those of the large turbine recording. This has been attributed to the different spectral characteristics of the two turbines.
- The indoor scenario did not find the turbines to be differently annoying.

However the report does caution that

'the finding that the small turbine is more annoying cannot be generalised to large and small wind turbines or to a wider range of wind and terrain conditions than were used in the test. The listener responses were, however, consistent and therefore demonstrate the potential of the comparison method.'

Discussion

Evidence of the effects of wind turbine noise is strongest for annoyance and sleep disturbance.

Studies carried out in Sweden, Germany and Holland have shown that a minority of persons report annoyance at relatively low levels of exposure to wind turbine noise, although other factors can strongly

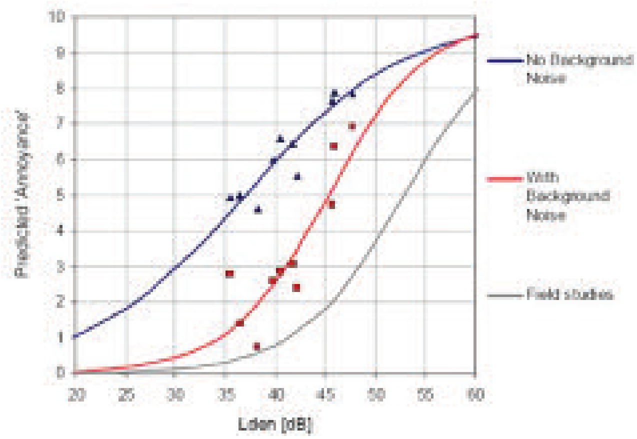

Figure 7

Annoyance of wind turbine sounds. Prediction model on annoyance for 90-second wind turbines sounds with and without natural background noise. S V Legarth, Auralisation and assessment of annoyance from wind turbines: 2nd international meeting on wind turbine noise, Lyon, France 2007.

influence the responses, such as the visual impact of the wind farms and real and perceived injustices regarding the development of such schemes. Additionally, several studies suggest that wind farm noise can be more disturbing than transportation and general industrial noise sources.

The dose responses established so far typically follow the pattern already established for many types of noise source. The data on response versus level are widely spread and therefore the correlation between level and response is not particularly strong. There does not appear to be a step change in response at any specific threshold noise level, or over a narrow range of noise levels.

Virtually all studies so far on the impact of wind farm noise have been cross-sectional studies of the effects of the noise under steady state conditions ie studies of the reaction of a sample of individuals exposed to different wind turbine noise levels, not the reaction of individuals to changing turbine noise levels or the introduction of turbine noise into an existing soundscape without such noise. A cross-sectional approach only considers the impact of the absolute level of the noise and either does not take into account the characteristics of the noise or takes much less account of them, nor does it consider the possibility that the change itself may aggravate the noise impact, which is a well established effect (for example for transportation noise[23]). It has been suggested[24] that when analysing possible statistical trends in noise annoyance reactions, even for steady-state noise, and especially for changing soundscape situations, the effects of the change should also be taken into account.

The type and level of background noise against which the wind turbine noise is heard may be important because it can help mask turbine noise and affect the connotation of the wind farm noise and therefore influence its intrusion and the subjective response. Although wind turbine noise can be perceived at levels below the existing ambient noise level, the onset of significant levels of community annoyance appears to at substantially higher levels: this means that there appears to be a reasonable degree of community tolerance of wind turbine noise, although this varies significantly at an individual level.

In common with other noise sources, the presence of acoustic features in wind turbine noise such as tonality and AM and the influence of non-acoustic factors are important in dictating the degree of impact.

However, whilst there are various methods which can potentially be used to assess the tonality of noise emissions, there is little guidance regarding the objective rating of effects attributable to other acoustic features such as AM. If methods of objectively rating the effects of these features can be developed, then it is likely

[§] For example, noise annoyance for the same level of transportation noise is greatest for aircraft, less so for road traffic and least for railway noise – H M E Miedema and H Vos: Exposure response functions for transportation noise. Journal of the Acoustical Society of America 104, 3432-3445 (1998);

that suitable corrections to take their impact into account can be developed.

Accounting for the effect of non-acoustic factors is likely to be impracticable as the prevalence and degree of effect on individual response varies substantially, is location and scheme specific, and is volatile over time. Instead, as is common for many other noise sources, these factors are taken into account to some degree by the 'averaging' inherent in the development of community dose responses and using them to derive control limits.

This review has highlighted work which shows general trends in the response to wind turbine noise, but also indicates that there is sufficient uncertainty about human response to wind turbine noise to prevent a robust dose response being formulated at this stage. This is not unique for wind farm noise as similar degrees of uncertainty exist for other noise sources eg industrial noise in general[25]. It may be that owing to the significant influence of individual non-acoustic factors, such a dose response may never be established. As a result, any guideline or noise limit criterion for wind turbines can only be informed by indicative trends in regard to response, weighed against the benefit of the turbines. This means that unless an unduly prohibitive stance is taken, whereby the guideline or limit criterion is that turbine noise must never be heard at any time, it is probable that some persons will inevitably exhibit negative responses to turbine noise whereever and whenever it is audible, no matter what the noise level.

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A persistent swishing noise could be inconsistent with sounds normally expected in such surroundings

The spectral characteristics of large are generally very similar to those of smaller models apart from a slight increase in the low-frequency content for large turbines