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Noise annoyance from wind turbines - a review

Eja Pedersen, Högskolan i Halmstad

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Noise annoyance from wind turbines
a review

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Preface

Wind power is a relatively new generator of electricity in Sweden. Legislation and regulation regarding noise from wind turbines in Sweden have been discussed. Eja Pedersen at Halmstad University has at the request of the Swedish Environmental Protection Agency prepared this report as a base for further discussions on regulation and guidelines on noise from wind turbines in Sweden. The report reviews the present knowledge on perception and annoyance of noise from wind turbines in residential areas as well as in recreational areas. It also summarizes regulations in some European countries. The author Eja Pedersen is responsible for the content of the report.

Stockholm, August 2003

Contents

Summary

This study summarises present knowledge on noise perception and annoyances from wind turbines in areas were people live or spend recreation time. There are two main types of noise from a wind turbine: mechanical noise and aerodynamic noise. The aerodynamic noise emits from the rotor blades passing the air. It has a swishing character with a modulation that makes it noticeable from the background noise. This part of the wind turbine noise was found to be the most annoying.

Field studies performed among people living in the vicinity of wind turbines showed that there was a correlation between sound pressure level and noise annoyance, but annoyance was also influenced by visual factors such as the attitude to wind turbines' impact on the landscape. Noise annoyance was found at lower sound pressure levels than in studies of annoyance from traffic noise. There is no scientific evidence that noise at levels created by wind turbines could cause health problems other than annoyance.

No studies on noise from wind turbines in wilderness areas have been found, but the reaction to other noise sources such as aircraft have been studied. In recreational areas, the expectation of quietness is high among visitors, but wind turbines are, in contrary to aircraft, stationary and could be avoided by recreationists. The visual impact of wind turbines might though be the dominant source of annoyance.

Regulations on noise from wind turbines are based on different principles. Some states, e.g. Denmark, have a special legislation concerning wind turbines, while others, like Sweden, have used recommendations originally developed for a different noise source. The noise level could either be absolute, as in Germany, or related to the background noise level as in France. This background noise level could be standardised, measured or related to wind speed.

Sammanfattning

Denna rapport har tagits fram av Eja Pedersen, Högskolan i Halmstad på uppdrag av Naturvårdsverket. Syftet är att ge underlag för fortsatta diskussioner om bedömning av ljud från vindkraftverk i Sverige

Rapporten sammanfattar kunskapsläget kring människors uppfattning och störning av buller från vindkraftverk vid bostäder och i friluftsområden. Vindkraftverk ger upphov till två typer av ljud: mekaniskt och aerodynamiskt. Det aerodynamiska ljudet uppstår när rotorbladen passerar luften. Det har en svischande karaktär med en modulation som gör det urskiljningsbart från bakgrundsljudet. Den här delen av vindkraftljudet har visat sig vara mest störande.

I fältstudier genomförda bland människor boende i närheten av vindkraftverk fann man ett samband mellan ljudnivå och bullerstörning, men störningen påverkades också av visuella faktorer som attityden till vindkraftverkens påverkan på landskapsbilden. Andelen störda av buller var högre än vad som tidigare funnits i studier av trafikbuller. Det finns inga vetenskapliga bevis för att buller med de nivåer som vindkraftverk ger upphov till skulle kunna orsaka hälsoproblem andra än störning.

Det gick inte att hitta några studier som behandlade buller från vindkraftverk i vildmark, men effekten av andra bullerkällor såsom flyg har studerats. I friluftsområden är förväntningen på tystnad hög hos besökarna, men vindkraftverk är till skillnad från flyg en stationär källa och kan undvikas av besökarna. Det visuella intrycket av vindkraftverken kan därför vara den dominerande källan till störning.

Regler för buller från vindkraftverk baseras på olika principer. I några länder, t.ex. i Danmark, finns en speciell lagstiftning för vindkraftverk, medan man i andra, som Sverige, använder rekommendationer ursprungligen framtagna för en annan bullerkälla. Gränsvärdet för buller kan antingen vara absolut, som i Tyskland, eller relateras till bakgrundsljudets nivå. Ljudnivån i bakgrundsljudet kan vara standardiserad, mätt eller relaterad till vindstyrka.

1. Introduction

The aim of this study is to summarise present knowledge on noise perception and annoyance from wind turbines in areas where people live or spend time for recreational purposes. This review will also present examples of legislation regarding noise from wind turbines. The study was financed by the Swedish Environmental Protection Agency to form a base for regulation regarding wind turbine noise. Kerstin Persson Waye has 1995 reviewed noise annoyance from wind turbines [Persson Waye 1995]. The present study will recall some of her results, but focus on articles published from 1995 and later.

Noise from wind turbines is a relatively new noise source in Sweden. It can be classified as an outdoor source of community noise. WHO defines community noise as noise emitted from all noise sources except at occupational settings [Berglund et al 1999]. This includes for example road, rail and air traffic, industries, construction and public work as well as neighbours.

This study does not examine the measurements and calculations of noise exposure used in various studies. As many assumptions, on for instance sound pressure levels causing annoyance or sleep disturbance, are based on dose-response relationships were the dose were either measured or calculated (or both) this is a crucial point. This is though a matter of acoustics and not within the subject of this review.

2. Method

Reviewed articles were searched for in relevant databases (Medline, SveMed, ISI, Science direct, Papers First) as well as in journals relevant for the topic. As these searches did not result in many articles, proceedings from well-known conferences have been searched in addition. One must bear in mind that this latter type of papers has often been accepted to conferences without closer examination. As a complement, Internet was searched. Direct contacts with researchers and developers have been made regarding health aspects and noise regulations.

3. Results

3.1 Noise sources from wind turbines, sound characteristics and masking possibilities

There are two main types of noises from a wind turbine: mechanical noise and aerodynamic noise. Mechanical noise is mainly generated by the gearbox, but also by other parts such as the generator [Lowson 1996]. Mechanical noise has a dominant energy within the frequencies below 1000 Hz and may contain discrete tone components. Tones are known to be more annoying than noise without tones, but both the mechanical noise and tones that may occur can be reduced efficiently [Wagner et al 1996]. In the turbines erected during the last ten years, the manufacturers have been able to reduce the mechanical noise to a level below the aerodynamic noise. This is also due to the fact that the size of the turbines has increased and mechanical noise does not increase with the dimensions of turbine as rapidly as aerodynamic noise.

The aerodynamic noise from wind turbines originates mainly from the flow of air around the blades and therefore the noise generally increases with tip speed. It is directly linked to the production of power and therefore inevitable [Lowson 1996]; even though it could be reduced to some extend by altering the design of the blades [Wagner et al 1996]. The aerodynamic noise has a broadband character and is typically the dominating part of wind turbine noise today.

When listening to a wind turbine, one may distinguish broadband noise and a beating noise. Broadband noise is characterised by a continuous distribution of sound pressure. The beating noise is amplitude modulated, i.e. the sound pressure level rises and falls with time. This noise is of interest for this review, as it seems to be more annoying than a non-modulated noise at the same sound pressure level. Only a few studies have however explicitly compared noises with and without modulations. In one experimental study, it was found that a 30 Hz tone, amplitude modulated with a modulation frequency of 2.5 Hz, generally caused higher annoyance, symptoms and change in mood, however the difference compared to a non-modulated tone at 30 Hz was only statistically significantly different for subjective reports of drowsiness [Persson et al 1993]. It has also been found that annoyance caused by diesel trains decreases when the modulation depth was reduced over time from 13 dB to 5 dB [Kantarelis and Walker 1988]. Modulated noise from wind turbines has the beat of the rotor blades' pace. The amplitude modulation has in experimental studies found to be most apparent in the 1 and 2 kHz octave band with amplitude of ± 2-3 dB [Dunbabin 1996]. Theories have been put forward regarding the source and extent of the amplitude modulation. One possible mechanism is the interaction of the blade with disturbed airflow around the tower, another the directionality of radiation from the blades as they rotate. Finally it is possible that variation in noise levels occur due to the atmospheric wind profile, which would result in a slight variation in angel of attack as the blade rotates [Dunbabin 1996]. In summery, the modulation in the noise from wind turbines is not yet fully explained and will probably not be reduced in the near future and is therefore a factor of importance when discussing noise annoyance from wind turbines.

The modulation frequency for a three-blade 600 kW turbine, a common size in Sweden today, with a steady speed of 26 rpm is 1.3 Hz. This is a frequency somewhat lower than the frequency of 4Hz known to be most easily detected by the human ear [Zwicker and Feldtkeller 1967]. The amplitude of the modulation does not have to be very high. The threshold for detection of a sound with a modulation frequency of 1 Hz was in one experimental study found to be 1-2 dB below a masking noise (white noise). The masking noise had its energy within the same frequency band as the modulated sound, thus providing optimal possibilities for masking. It was also found that the detection threshold was not depending on modulation depth or modulation frequencies (1Hz and 10 Hz) [Arlinger and Gustafsson 1988]. The new turbines erected today often have variable rotor speed. This means that the modulation frequency will be low at low wind speed, typically 0.5 Hz at 4 m/s and higher at high wind speed, typically 1.0 Hz at 20 m/s. This is still in the span were modulations could easily be detected. A lower modulation frequency is preferable, as it will then be less detectable and also most likely less annoying. It is however not known how much less annoying these types of turbines will be.

In experimental studies, where 25 subjects were exposed to five different wind turbine noises at the level of 40 dBA Leq, differences between the noises regarding annoyance were found [Persson Waye and Öhrström 2002]. The most annoying noises were predominantly described as “swishing”, “lapping” and “whistling”. These adjectives could all be seen as related to the aerodynamic noise and as descriptions of a time varying (modulated) noise with high frequency content.

In summery it can be concluded that the modulating characteristics of the sound makes it more likely to be noticed and less masked by background noise. Recent reports have indicated yet another complication. Common hub height of the operating wind turbines today in Sweden is 40-50 meters. The new larger turbines are often placed on towers of 80 – 90 meters. The wind speed at this height compared to the wind speed at the ground might (up to now) been underestimated. In a report published by Rijksuniversiteit Groningen it was found that the wind speed at 80 meter was 4.9 times higher then at 10 meter at night instead of 1.4 times as calculated [Kloosterman et al 2002]. The study was rather small, but indicates that the masking of the background noise is lower than calculated. Further studies need to be performed.

Topographical conditions at site have importance for the degrees to which the noises from wind turbines are masked by the wind. Dwellings that are positioned within deep valleys or are sheltered from the wind in other ways may be exposed to low levels of background noise, even though the wind is strong at the position of the wind turbine [Hayes 1996]. The noise from the turbine may on these conditions be perceived at lower sound pressure levels then expected. Current recommendation state that measures and sound propagation calculations should be based on a wind speed of 8 m/s at 10 meter above the ground, down wind conditions, creating a "worst case" scenario. This recommendation does not consider the case described above.

3.2. Perception and noise annoyance from wind turbines in living areas

Noise from wind turbines can be more or less distinguished depending on the difference between noise from the wind turbine and the background noise. The background noise, for example traffic noise, noise from industries and the whistling in bushes and trees, vary from site to site, but also from day to night. The local environment at the dwelling could also cause a difference in wind speed between the wind turbine and the listener. An example of topographical conditions enlarging the differences in wind speed was described in chapter 3.1. Also less extreme local physical circumstances, as the placing of houses, may shelter the site from wind on the ground, lowering the background noise so that the noise from the wind turbine will be more easily heard.

Only few field studies on noise annoyance among people living close to wind turbines have been carried out. A major study, partly financed by the European Community, was performed in Denmark, the Netherlands and Germany in the beginning of the 1990's [Wolsink et al 1993]. Results from the Danish part of the study were analysed further and presented in a separate report [Holm Pedersen and Skovgard Nielsen 1994]. A Swedish dose-response study was performed 2000 [Pedersen and Persson Waye 2002]. The three studies all explore the correlation between noise exposure from wind turbines (dose) and the noise annoyance among the residents (response), as well as other variables of importance for annoyance. Unfortunately none of these studies has yet been published in refereed journals.

In the European study presented by Wolsink et al [1993], sixteen sites in the three countries comprising residents living within noise levels of 35 dBA were selected. As a certain variance had to be included in the study, residence living at sound pressure levels <25dBA to 60 dBA were chosen, though the major portion or 70% lived within noise levels of 30-40 dBA. The sites comprised a total of 134 turbines: 86 in the Netherlands, 30 in Germany and 18 in Denmark. Most of the turbines were small. Only 20 of them had a power of 500 kW, all the rest were of 300 kW or less.

The results presented were based on a total of 574 interviews: 159 in the Netherlands, 216 in Germany and 199 in Denmark. The response rate is not known. A questionnaire including questions on noise (annoyance, perceived loudness and interference), attitude to wind power, residential quality and stress were used for the interviews. Sound pressure levels were measured on sites, but how these measurements were made is not clear. Sound pressure level strata were calculated with 5 dBA intervals.

Only a weak correlation between sound pressure level and noise annoyance caused by wind turbines could be found (Kendall's coefficient for correlating rank order variables $t=0.09$; $p<0.05$). The proportion annoyed by noise from wind turbines was 6.4% (n=37). The perceived loudness was also low, as well as the interference of noise with various daily activities. Residents complaining about wind turbines noise perceived more sound characteristics ($t=0.56$; $p<0.001$) and reported more interference of daily activities ($t=0.56$; $p>0.001$). The noise produced by the blades lead to most complaints. Most of the annoyance was experienced between 16.00 p.m. and midnight.

Wolsink et al (1993) also evaluated other physical variables and their relation to noise annoyance, e.g. distance between residence and the wind turbine site, location with regard to wind direction, other buildings or natural barriers between the residence and the wind turbine. When adding these variables to the analysis, the objectively measured sound pressure level was no longer significantly related to noise annoyance. Other variables, both subjective and objective, were tried in a multivariate analyse of the level of annoyance of noise from wind turbines. Four variables had an impact of noise annoyance: stress caused by wind turbine noise, daily hassles, perceived effects of wind turbines in the landscape (visual intrusion) and the age of the turbine site (the longer it has been operating, the less annoyance). These four variables explained 53% of the variance of noise annoyance. Variables that had no impact on noise annoyance in the model were e.g. buildings between the residence and the wind turbine or objective sound pressure level. The results should be treated with caution, as the actual level of annoyance among the large majority of the subjects was low.

The Danish part of the study was, as mentioned, presented in a separate report. The 18 wind turbines on the selected sites were rather small; i.e. they had a power of 45 kW to 155kW. The hub height ranged from 18 to 33 meters, with a median of 23 meters. Interviews with 200 residents were performed. The questions agreed on in the European study were used, as well as additional questions. The survey was masked to the respondents as a study on general living conditions. The response rate is not known. A number of objective variables were linked to each respondent, e.g. distance and direction to nearest wind turbine, barriers between residence and turbine, trees or bushes that could mask the noise and a variable called visual angle. The visual angle was measured in degrees from the respondents dwelling to the hub with the ground as the horizontal line. This variable was included as a measure of visual impact. Several noise variables were also added. Sound pressure levels were measured on a ground board at a distance of 1-2 times the hub-height behind the turbine at the same time as the wind was measured at 10 meters height in front of the turbine. Sound pressure levels for each dwelling were then calculated in two ways; not including the influence of barriers and including the influence of barriers. Both reflect downwind conditions at 5 and 8 m/s. The sound was also analysed for tones.

The proportion rather annoyed by noise from wind turbines was 7% (n=14) and the proportion very annoyed was 4% (n=4). The annoyance increased with increasing sound pressure level. At Lr=40dBA (calculated LpA and 5dB added to for audible tones) the mean annoyance was 0.25 at a scale from 0 to 10. Comparing this with the distance and the visual angle, the distance should exceed 300 meters and the visual angle should be less than 3.5 degrees if the annoyance should be kept below 0.25. The angle 3.5 degrees correspond approximately to a distance from the dwelling to the turbine of 16 times the hub-height. A linear regression showed that the objective variable that had the greatest impact on noise annoyance was the visual angle that explained 12% of the variance. Of the variables describing sound properties, the once including LpA (A-weighted sound pressure level) and Lr (5dB added to LpA for audible tones), were also of importance, but to a lesser extend. There was no difference when the sound was calculated for 5 m/s or for 8 m/s. The visual angle and the variables describing sound properties were in turns correlated to each other. Subjective variables were also tried in a linear regression, which showed that whether the turbine noise could be heard or not had the greatest impact on noise annoyance and explained 49% of the variance. Three other subjective variables were also of importance: perception of shadows (r^2=0.23), perception of flicker (r^2=0.25) and the attitude to the turbines' impact on the landscape (r^2=0.23). All these are visual. The conclusion of the authors of the Danish study was that both sound pressure level and visual variables have an impact on noise annoyance.

The Swedish study was performed in Laholm during May-June 2000. The areas chosen comprised in total 16 wind turbines thereof 14 had a power of 600 kW. The study base comprised one randomly selected subject between the ages of 18 and 75 in each household living within a calculated wind turbine sound pressure level of 25 to 40 dBA (n=518).

The annoyance was measured using a questionnaire. The purpose of the study was masked and among questions on living conditions in the countryside, questions directly related to wind turbines were included. Annoyance from several outdoor sources was asked for regarding the degree of annoyance both outdoor and indoor. Annoyance was measured with a 5-graded verbal scale ranging from "do not notice" to "very annoyed". The same scale was used for measuring annoyance from wind turbines specifically (noise, shadows, reflections, changed view and psycho-acoustical characters). The respondents' attitude of the impact of wind turbines on the landscape scenery and the attitude to wind power in general were also measured with a 5-graded verbal scale, ranging from "very positive" to "very negative". Questions regarding living conditions, health, sensitivity to noise and employment were also included. A total of 356 respondents answered the questionnaire, which gave a total response-rate of 69%.

For each respondent calculated A-weighted sound pressure level as well as distance and direction to the nearest wind turbine were obtained. Sound pressure levels (dBA) were calculated at 2.5-decibel intervals for each household. The calculations were done in accordance with [Naturvårdsveket 2001] and reflect downwind conditions. Data of distance between the dwelling of the respondent and the nearest wind turbine, as well as the direction, was obtained from maps.

The correlation between noise annoyance from wind turbines and sound pressure level was statistically significant (r_s=0.399; n=341; $p<0.001$). The annoyance increased with increasing sound pressure level at sound pressure levels exceeding 35 dBA. No respondent stated them selves very annoyed at sound pressure levels below 32.5 dBA (Figure 1). At sound pressure levels in the range of 37.5 to 40.0 dBA, 20% were very annoyed and above 40 dBA 36%. The confidence intervals were though wide; see Figure 1.

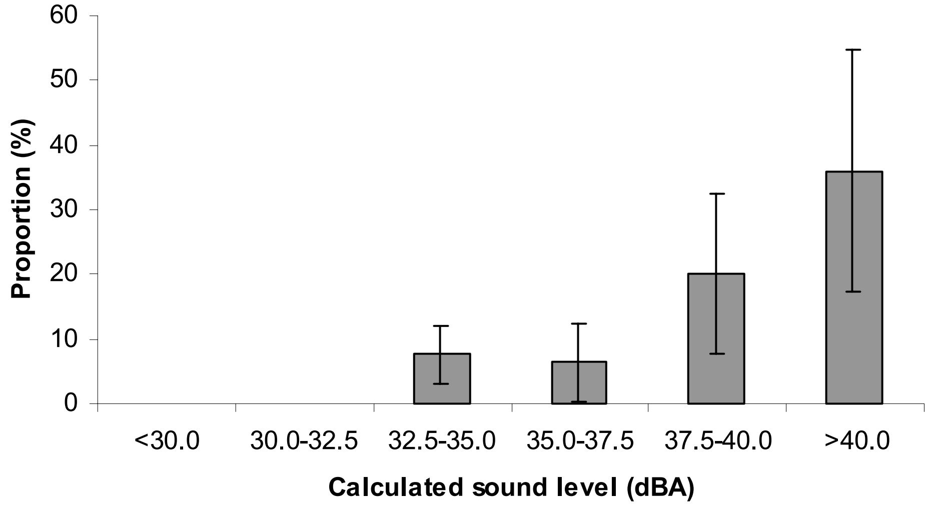

Figure 1. The proportions very annoyed by noise outdoors from wind turbines (95%CI) at different A-weighted sound pressure levels [Pedersen and Persson Waye 2002].

To explore the influence of the subjective factors on noise annoyance, binary multiple logistic regression was used. The analysis showed that the odds for being annoyed increased with 1.87 (95% CI: 1.47-2.38) for each 2.5 dBA increase in sound pressure level. After correction for the individual subjective factors: attitude of visual impact, attitude to wind power in general and sensitivity to noise, the odds for being annoyed decreased to 1.74 (95% CI: 1.29-2.34) for each 2.5 dBA increase in sound pressure level. Only attitude of visual impact had a significant influence on the risk. There was also a statistically significantly correlation between noise annoyance and annoyance of shadows from wind turbines (r_s=0.491; n=339; p<0.001) as well as annoyance of changed view (r_s=0.461; n=340; p<0.001).

The respondents were asked to rate the perception and annoyance of noise from the rotor blades and the noise from the machinery. Noise annoyance from rotor blades and machine were positively correlated to sound pressure level, (r_s=0.410; n=339; p<0.001) and (r_s=0.291; n=333; p<0.001) respectively. At all sound pressure levels, a higher proportion of respondents noticed sound from rotor blades than from the machinery. The same proportion that noticed sound from wind turbines in general noticed sound from the rotor blades. Among those who could notice sound from wind turbines, swishing (33.3%, n=64), followed by whistling (26.5%, n=40) and pulsating/throbbing (20.4%, n=31), were the most common sources of annoyance regarding sound properties.

The proportion rather and very annoyed by noise from wind turbines was small in the first two studies presented above. The annoyance increased with increasing sound pressure level, but the correlation was low. Unfortunately there is no information about proportion annoyed at different sound pressure levels. These percentages would have been interesting to compare with the result of the Swedish study, as the result of this study was different from the results in the two first studies regarding dose-response correlation. In the Swedish study, the proportion very annoyed from wind turbine noise was rather high at sound pressure levels exceeding 37.5 dBA, and a firm correlation between sound pressure level and annoyance was found. All studies find a relation between noise annoyance and visual factors such as visual intrusion and shadows. These factors probably explain part of the noise annoyance. All three studies were performed among residents exposed to rather low sound pressure levels from wind turbines. Still annoyance occurred to some extent. In the noise, the aerodynamic part was found to be the most annoying, stressing the relevance of the sound characteristic, which is also in accordance with previous experimental studies [Persson Waye and Öhrström 2002].

3.3 Perception of noise from wind turbines in wilderness recreational areas

The special soundscape[1] of wilderness recreational areas has been described by a number of authors, e.g. [Miller 2001, Dickinson 2002]. The soundscape differs from site to site and can be very quiet in remote areas, especially when vegetation is sparse (as in the Swedish bare mountain region). In a comparison between different outdoor settings in USA, it was found that the sound pressure level in a suburban area at nighttime was above 40 dBA, along a river in Grand Canyon 30-40 dBA and at a remote trail in the same park 10-20 dBA [Miller, 2002]. The effect of intruding sound should be judged in relation to the natural ambient soundscape. The sound pressure level of the intruding sound must be compared to the sound pressure levels of the background noise. The durability of audibility is another variable of importance for understanding visitors' reactions to noise [Miller 2001].

No studies on noise from wind turbines in wilderness areas have to my knowledge been carried out, but the effect of noise from other sources has been discussed in a few articles. A larger study on noise annoyance from aircraft over-flights on wilderness recreationists was performed in three wilderness areas in USA [Fidell et al 1996]. The areas were chosen specifically for their expected relatively large number of aircraft over-flights. On-site interviews regarding noise annoyance were conducted among visitors. The response rate was 96% (n=920). In addition, more than 2000 h of automated, A-weighted sound pressure level measurements were made as well as forty-six hours of recordings. Out of these, day-night average sound pressure levels (DNL) of visitors' total noise exposure and their exposure to indigenous sound for the time-period of interviewing were estimated.

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[1] One definition of soundscape can be found in "The Handbook for acoustic ecology", Truax, B. (ed) R.C. Publications, Vancouver, Canada. 1978. "SOUNDSCAPE: An environment of sound (sonic environment) with emphasis on the way it is perceived and understood by the individual, or by a society. It thus depends on the relationship between the individual and any such environment."

Table 1. Prevalence of annoyance and estimated cumulative exposure to aircraft noise [Fidell et al 1996]

	%Highly annoyed[2]	Aircraft DNL	Ambient DNL	Total DNL
Golden Trout	12	50 dB	47 dB	52 dB
Cohutta	2	47 dB	52 dB	53 dB
Superstition	1	34 dB	38 dB	39 dB

The results showed that the large majorities (75%-92%) of respondents were not annoyed[3] by noise of over-flights in the three wilderness areas studied. A minority (1%-12%) was highly annoyed. Aircraft that typically produced higher noise levels (low flying jets and helicopters) or operated at shorter slant ranges from observers were reported to be more annoying than small propeller driven aircraft and high altitude jet transports. Little evidence was found that over-flights diminished respondent's overall enjoyment of their visits, nor their intention to return for additional visits. Other aspects of wilderness visits than noise annoyance were of more importance to the visitors than noise from aircraft, e.g. inadequate trail maintenance, crowding, insects and weather. The study was followed up with a telephone survey among visitors from nine wilderness areas in addition to the three selected for the first study. The results were on the whole the same. Fidell and co-workers compared their data with a theoretically derived dosage response relationship between the prevalence of annoyance in residential setting and exposure to general transportation noise. This suggested that respondents engaged in outdoor recreation in three wilderness areas included in the study described themselves as highly annoyed by 7 dB less aircraft noise exposure than would be tolerable in a residential setting.

A quasi-experimental field study on aircraft noise in recreational areas was performed in Norway [Aasvang and Engdahl 1999]. Two groups of people (n=10, n=16) were exposed to aircraft noise in a recreational area close to Fornebu Airport in Oslo and asked to rate their annoyance of noise during a 45-minute section. At the same time the number of over-flights and noise levels were measured. The correlation between noise exposure and annoyance was statistically significant. Of interest for this review is the rating of acceptable annoyance that the subjects were asked to do. Comparing the acceptance with the noise exposure in a linear regression, 50% of the subjects in group-1 considered the noise as not acceptable at sound pressure levels above 60 Laeq (dB). In group-2, who were exposed to less discernible noise events and lower noise levels due to different wind conditions, 50% did not accept sound pressure levels above 50 Laeq (dB). One should be aware of the small number of subjects in each group. Noticeable is that the background noise level for the first group was 40.2 Laeq (dB) and for the second group 42.6 Laeq (dB). Aasvang and Engdahl discussed several explanations of the different outcomes of the two groups. One suggestion was that air flight approach operations are more annoying than departures, even though they resulted in lower sound pressure levels. Due to wind conditions, the exposure of group 2 was dominated by approach operations.

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2 The definition of highly annoyed used in this study has not been found.

3 The definition of not annoyed used in this study has not been found.

Another Norwegian study on aircraft disturbance was carried out as an on-site study in a recreational mountain area [Krog et al 2000]. Daily over-flights were planned together with the Norwegian Air Force so that hikers would be exposed to aircraft noise at different level and different frequency. Interviews with visitors were performed near the end of a walking trail. The purpose of the study was masked, i.e. the study was presented as a general survey about outdoor recreation. A total of 761 respondents participated in the survey. The response rate is not known. Of the respondents exposed to over-flights (n=386), 56% found the aircraft noise very disturbing. When dividing the exposed into four different groups, according to which flying pattern they were exposed to, no differences between the rates of annoyance could be found between the groups. The results also showed that the disturbance due to military aircraft noise increased with increasing age, increasing total noise exposure and increasing duration of time spent on the hike. However, there was no significant difference between the exposed and the unexposed group regarding the overall satisfaction with today's hike. Among the exposed subjects, it was found that the more negative evaluation of military aircraft noise, the higher the likelihood to judge the hike as less positive.

Staffan Hygge has recently in a report for the Swedish National Rail Administration (Banverket) and National Road Administration of Sweden (Vägverket) summarised studies on noise annoyance in recreational areas and national parks [Hygge 2001]. Though the overall proportion of annoyed by aircraft noise is low in many studies, the individual factors are of importance for annoyance. For visitors who seek quietness just hearing any sound from aircraft could be bothering. Hygge also discusses possible cultural differences in acceptance of noise in recreational areas. American studies show a lower proportion of annoyed than studies from Norway and New Zealand. This could be due to the fact that that the non-American studies were done in remote areas which presumable gives a group of respondent with a special profile, seeking quietness. He also discusses other sources of transportation noise and finds an indication that the legitimacy is of importance, e.g. rescue flights are more accepted than sightseeing tours.

Aircraft over-flight is a mobile source of noise in contrary to noise from wind turbines, so the two cannot directly be compared. Noise from wind turbines is more similar to noise from ski lifts. The noise source is stationary and the visitors can usually choose themselves if the like to stay by the noise or move on. Ski lifts are operating at special hours in the winter and they can be assumed to produce noise at comparable sound pressure levels when they are operating. Wind turbines are operating all year around, day and night, but the sound pressure levels vary with the wind and noise is only produced at special conditions.

Some results from the aircraft studies could though be transferred. The expectation of quietness is high among visitors and Fidell et al [1996] estimated that the noise level tolerated in wilderness areas compared to residential areas was 7 dBA lower. The tolerance also depended on the legitimacy of the noise source. Cultural differences in accepting noise should also be discussed. If there were a cultural difference in how noise in recreational areas is accepted, the tolerance would probably be low in Sweden. The visual effect of the wind turbines may be a source of annoyance equal to noise in recreational areas, especially if there is large wide-open space.

3.4 Aspects of health and well-being

According to the definition made by WHO, health is a state of complete physical, mental and social well-being and not merely the absence of infirmity. The WHO Guidelines for Community noise lists specific effects to be considered when setting community noise guidelines: interference with communication; noise-induced hearing loss; sleep disturbance effects; cardiovascular and psycho-physiological effects; performance reduction effects; annoyance responses; and effects on social behaviour [Berglund et al 1999]. Interference with communication and noise-induced hearing loss is not an issue when studying effects of noise from wind turbines as the exposure levels are too low.

No studies have been found exploring cardiovascular and psycho-physiological effects, performance reduction effects and effects on social behaviour specifically with regard to noise from wind turbines. A number of articles have though explored the relationships between exposure of other sources of community noise (road traffic, aircraft, railway traffic) and health effects. Evidence in support of health effects other than annoyance and some indicators of sleep disturbance is weak [Berry et al 1998]. In a Swedish official report Öhrström reviews the effects of community noise in general [Öhrström 1993]. On basis of studies on effects of noise from aircraft and road traffic, she finds that there are some evidences of noise causing psychosocial or psychosomatic nuisance. The effects are related to individual factors (sensitivity to noise and capacity to cope with stress) and to annoyance rather than to sound pressure level. Annoyance itself is though an undesired effect of health and well-being. In a review of studies performed 1993-1998, Lercher et al [1998] evaluated adverse physiological health effects of occupational and community noise. Most of the studies concern sources of noise with higher sound pressure levels than those of wind turbines. Even so, it was difficult to find correlation between exposure and e.g. cardiovascular or immunological effects. In a summery of possible long term effect of exposure to noise done by Passchier-Vermeer the observed threshold for hypertension and ischaemic heart disease was 70 dBA outdoors [Passchier-Vermer 2002]. Transferring the results of these studies, there are no evidences that noise from wind turbines could cause cardiovascular and psycho-physiological effects. However, the overall effect for people living in the vicinity of a wind turbine should be considered (noise annoyance, visual annoyance). The European field study mentioned above indicates that wind turbines could cause stress [Wolsink et al 1993]. Stress is not defined in the report and could be just another aspect of annoyance, but stress could also be one health variable that needs to be investigated further.

Annoyance response is probably the most studied health effect regarding wind turbines. As outlined in chapter 3.2 and 3.3, noise annoyance appears even at low sound pressure levels. Another health effect that may be relevant for people living near wind turbines is sleep disturbance. The WHO guidelines for community noise recommend that the outdoor noise levels in living areas should not exceed 45 dBA Leq at night, measured with the time base 8 hours [Schwela 1998], as sleep disturbance may occur with open windows. The exposure from wind turbines is not known to exceed this limit, but in the Swedish field-study mentioned above [Pedersen and Persson Waye 2002], of the 12 respondents at exposure level 37.5-40.0 dBA who stated them selves disturbed in their sleep by noise, 10 respondents mentioned wind turbines as source. Almost all of them slept with open window. The number of respondents was however too low for conclusions to be drawn and further research is needed.

In a review of health effects of road traffic noise, Rylander finds that there is no research done so far that indicates that environmental noise could provoke psychiatric disease [Rylander 1999]. Noise as a factor of stress, inducing symptoms among sensitive individuals is discussed, as well as the possibility of noise interacting with other environmental strains causing stress. Further research is though needed.

Summarising the findings, there is no scientific evidence that noise at levels emitted by wind turbines could cause health problems other than annoyance. However, sleep disturbances should bee further investigated. As noise from wind turbines has a special characteristic (amplitude modulation, swishing) it may be easily detected in a normal background noise and this may increase the probability for annoyance and sleep disturbance. The combination of different environmental impacts (intrusive sounds, visual disturbance and the unavoidance of the source in the living environment) could lead to a low-level stress-reaction, which should be further studied.

3.5 A comparison of noise regulations in European countries

A summary of limits and regulations regarding noise from wind turbines in some European countries was done by Lisa Johansson in the notes from an IEA topical expert meeting in Stockholm [Johansson 2000]. Her summary has here been updated and expanded.

The recommended highest sound pressure level for noise from wind turbines in Sweden today is 40 dBA outside dwellings (Naturvårdsverket webbplats). In noise sensitive areas as in the mountain wilderness or in the archipelago, a lower value for the highest sound pressure level is preferable. The penalty for pure tones is 5 dBA. In praxis, the sound pressure levels at dwellings nearby a planned wind turbine site are calculated according to [Naturvårdsverket 2001] during the process of applying for a permission to build. Measurements in site are only performed in case of complains and then as measurements of imission at the dwelling of the complainant at wind speeds of 8 m/s at 10 m height.

Denmark has a special legislation governing noise from wind turbines (Bekendtgørelse om støj fra vindmøller BEK nr 304 af 14/05/1991). The limit outside dwellings is 45 dBA and for sensitive areas 40 dBA Leq. Sensitive areas are areas planned for institutions, non-permanent dwellings or allotment-gardens, or for recreation. In case of complaints emission measurements are performed according to the legislation, i.e. on a plate on the ground at a distance of 1-2 times the hub height of the turbine. Noise imission at the dwelling of the complainant is then calculated.

The legal base for noise pollution in Germany is the Federal clean air act from 1974 (Bundes-Immissionschultz-Gesetzes. BimSchG, Germany, 1974). The limited values for the sound pressure levels are defined in TA Lärm (Technische Anleitung Lärm, Germany, 1998).

Table 2. German noise regulations

Area	Day	Night
Industrial Area (Industrigebeit/Gewergebeit)	70 dBA / 65 dBA	70 dBA / 50 dBA
Mixed residential area and industry Or Residential areas mixed with industry	60 dBA	45 dBA
Purely residential areas with no commercial developments (Allgemeines Wohngebeit/Reines Wohngebeit)	55 dBA / 50 dBA	40 dBA / 35 dBA
Areas with hospitals, health resorts, etc.	45 dBA	35 dBA

Calculation of sound propagation is done according to DIN ISO 9613-2. All calculations have to be done with a reference wind speed of 10 m/s at 10 m heights[4].

The French legislation used in the case of wind turbines is the neighbour noise regulation law (Loi n° 92-1444 du 31 décembre 1992: Loi relative à la lutte contre le bruit). This legislation is based on the principle of noise emergence above the background level and there is no absolute noise limit. The permitted emergence is 3 dBA at night and 5 dBA at day. The background noise level has to be measured at a wind speed below 5 m/s. The legislation is not adjusted to wind turbine cases, and in praxis the noise measurements are made at 8 m/s when the wind turbine noise is expected to exceed the background noise levels the most[5].

New regulations on noise including noise from wind turbines were introduced in the Netherlands 2001 (Besluit van 18 oktober 2001, houdende regels voor voorzieningen en installaties; Besluit voorzieningen en installaties milieubeheer; Staatsblad van het Koninkrijk der Nederlanden 487). The limits follow a wind speed dependent curve. For the night the limit starts at 40 dBA at 1 m/s and increases with the wind speed to 50 dBA at 12 m/s. For daytime the limit starts at 50 dBA and for evenings at 45 dBA.

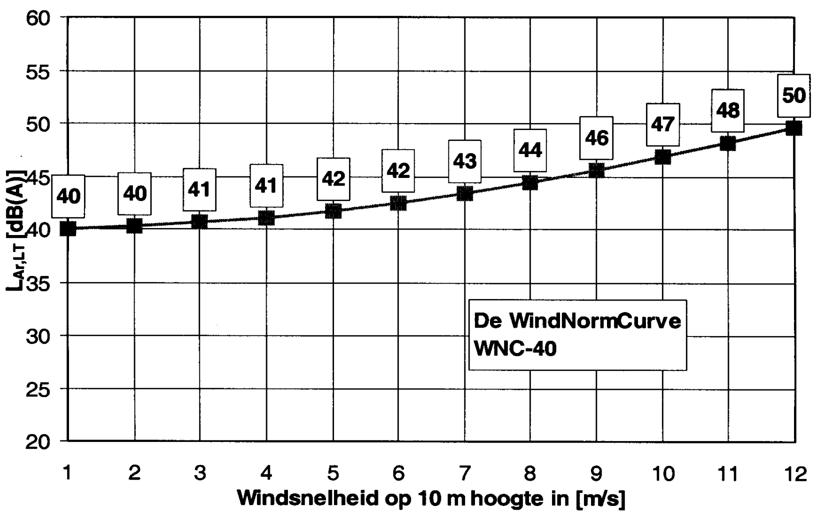

Figure 2. De WindNormCurve. Besluit van 18 oktober 2001, houdende regels voor voorzieningen en installaties; Besluit voorzieningen en installaties milieubeheer; Staatsblad van het Koninkrijk der Nederlanden 487. Bijlage 3.

4 Correspondence with Pamela Ljungberg, Enercon.

5 Correspondence with Karina Bredelles, consultant at ABIES, France

In Great Britain the ETSU-report "The assessment and rating of noise from wind farms" (ETSU for DTI 1996) is referred to by for instance the Scottish Executive Development Department (PAN 45). The report presents a series of recommendations that is regarded as relevant guidance by the authorities. Generally noise limits should be set relative to the background noise and only for areas for which a quiet environment is desirable. More precisely, noise from wind farms should be limited to 5 dBA above background noise for both day- and night-time. The $L_{A90,\ 10\ min}$ descriptor should be used both for the background noise and for the noise from the wind farm. The argument for this is that the use of the $L_{A90,\ 10\ min}$ descriptor allows reliable measurements to be made without corruption from relatively loud, transitory noise events from other sources. A fixed limit for 43 dBA is recommended for nighttime. This is based on a sleep disturbance criterion of 35 dBA. In low noise environments the daytime level of the $L_{A90,\ 10\ min}$ of the wind farm noise should be limited to an absolute level within the range of 35-40 dBA. The actual value chosen within this range should depend upon the number of dwellings in the neighbourhood of the wind farm, the effect of noise limits on the number of kWh generated, and the duration of the level of exposure.

In summery, these regulations are examples of different principles regarding noise from wind turbines. Some states have a special legislation concerning wind turbines, while others use recommendations. Different descriptors as L_{Aeq} or $L_{A90,\ 10\ min}$ are used. The noise level could either be absolute or related to the background noise level. This background noise level could be standardised, measured or related to wind speed.

4. Conclusions

Noise from wind turbines is not at all as well studied as for instance noise from road traffic. As the number of studies is low no general conclusions could be drawn. However, some indications will be listed here.

The reviewed studies above indicate that annoyance from wind turbine noise

- Is to a degree correlated to noise exposure.
- Occurs to a higher degree at low noise levels than noise annoyance from other sources of community noise such as traffic.
- Is influenced by the turbines' visual impact on the landscape.

Wind turbine noise

- Does not directly cause any physical health problems. There is not enough data to conclude if wind turbine noise could induce sleep disturbance or stress-related symptoms.
- Is, due to its characteristics, not easily masked by background noise.
- Is particularly poorly masked by background noise at certain topographical conditions.

Regulations on noise from wind turbines

- Are based on different principles leading to a heterogeneous legislation in Europe.

No conclusions on wind turbine noise in recreational areas could be drawn as no studies on the subject have been found. Other sources of noise studied as aircraft over flights indicate that noise levels tolerated in wilderness areas compared to residential areas are lower, but there is no evidence that this could be transferred to wind turbine noise.

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Noise annoyance from wind turbines – a review

This study summarises present knowledge on noise perception and annoyances from wind turbines in areas were people live or spend recreation time.

Field studies performed among people living in the vicinity of wind turbines showed that there was a correlation between sound pressure level and noise annoyance, but annoyance was also influenced by visual factors such as the attitude to wind turbines impact on the landscape. Noise annoyance was found at lower sound pressure levels than in studies of annoyance from traffic noise.

Regulations on noise from wind turbines are based on different principles. Some states have a special legislation concerning wind turbines, while others use recommendations. Different descriptors as L_{Aeq} or $L_{A90,\ 10\ min}$ are used. The noise level could either be absolute or related to the background noise level. This background noise level could be standardised, measured or related to wind speed.

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