Perception and annoyance due to wind turbine noise—a dose–response relationship

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Installed global wind power increased by 26% during 2003, with U.S and Europe accounting for 90% of the cumulative capacity. Little is known about wind turbines' impact on people living in their vicinity. The aims of this study were to evaluate the prevalence of annoyance due to wind turbine noise and to study dose–response relationships. Interrelationships between noise annoyance and sound characteristics, as well as the influence of subjective variables such as attitude and noise sensitivity, were also assessed. A cross-sectional study was performed in Sweden in 2000. Responses were obtained through questionnaires ($n=351$; response rate 68.4%), and doses were calculated as A-weighted sound pressure levels for each respondent. A statistically significant dose–response relationship was found, showing higher proportion of people reporting perception and annoyance than expected from the present dose–response relationships for transportation noise. The unexpected high proportion of annoyance could be due to visual interference, influencing noise annoyance, as well as the presence of intrusive sound characteristics. The respondents' attitude to the visual impact of wind turbines on the landscape scenery was found to influence noise annoyance.
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I. INTRODUCTION

Wind turbines generate renewable energy and thus contribute to sustainable development. However, disturbance from wind turbines may be an obstacle for large-scale production (Rand and Clarke, 1990; Ackerman and Söder, 2000). Few studies have so far been directed to the prevalence of disturbance, and existing knowledge of annoyance due to wind turbines is mainly based on studies of smaller turbines of less than 500 kW (Wolsink *et al.*, 1993; Pedersen and Nielsen, 1994).

Global wind power installed at the end of 2003 reached 39 GW according to American Wind Energy Association (2004), an increase of 26% in just one year. United States (7 GW) and Europe (29 GW) account for 90% of the cumulative capacity. In Sweden, more than 600 wind turbines are operating today with a total installed capacity of 0.4 GW, producing 600 GWh per year. They are placed in 84 of Sweden's 290 municipalities both along the coasts and in rural inland areas, concerning a number of people. The goal set up by the Swedish government for 2015 is 10 TWh, leading to an increase of 1600% from today. Most of these new turbines will probably be situated off shore, but as the cost for building on land is considerably lower, the development on land is expected to continue. Already, turbines are being erected near densely populated areas. Preliminary interviews conducted among 12 respondents living within 800 m of a wind turbine, and a register study of the nature of complaints to local health and environments authorities, indicated that the main disturbances from wind turbines were due to noise, shadows, reflections from rotor blades, and spoiled views (Pedersen, 2000).

All wind turbines in Sweden are upwind devices. The most common type is a 600 or 660 kW turbine with three rotor blades, rotor diameter 42–47 m, constant rotor speed 28 rpm (84 blade passages per minute, a blade passage frequency of 1.4 Hz), and hub height of 40–50 m. They often operate singly or in multiple units of 2 to 10. The noise emission at the hub is 98–102 dBA measured at wind velocity 8 m/s at 10 m height. Earlier turbines were often downwind devices and contained low-frequency noise (Hubbard *et al.*, 1983). In contrast to these, modern machines have the rotor blades upwind and the noise is typically broadband in nature (Fig. 1), (Persson Waye and Öhrström, 2002; Björkman, 2004). There are two main types of noise sources from an upwind 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 mechanical noise and tones can be reduced efficiently (Wagner *et al.*, 1996). Aerodynamic noise from wind turbines has a broadband character. It originates mainly from the flow of air around the blades; therefore the sound pressure levels (SPLs) increase with tip speed. Aerodynamic noise is typically the dominant component of wind turbine noise today, as manufacturers have been able to reduce the mechanical noise to a level below the aerodynamic noise. The latter will become even more dominant as the size of wind turbines increase, because mechanical noise does not increase with the dimensions of turbine as rapidly as aerodynamic noise (Wagner *et al.*, 1996).

Previous international field studies of annoyance from wind turbines have generally found a weak relationship between annoyance and the equivalent A-weighted SPL (Rand

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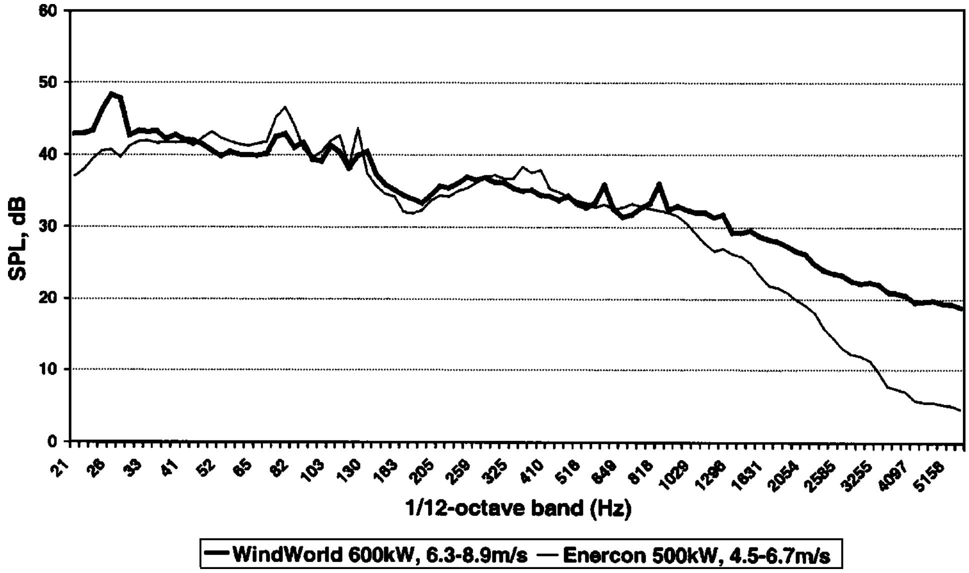

FIG. 1. Frequency spectra of two upwind three-bladed wind turbines recorded at down wind conditions; WindWorld 600 kW and Enercon 500 kW.

and Clarke, 1990; Wolsink *et al.*, 1993; Pedersen and Nielsen, 1994). It is possible that different sound properties, not fully described by the equivalent A-weighted level, are of importance for perception and annoyance for wind turbine noise. Support for such a hypothesis was given in a previous experimental study where reported perception and annoyance for five recorded wind turbine noises were different, although the equivalent A-weighted SPL were the same (Persson Waye and Öhrström, 2002). The results from that study and subsequent experiments suggested that the presence of sound characteristics subjectively described as lapping, swishing, and whistling was responsible for the differences in perception and annoyance between the sounds (Persson Waye and Agge, 2000). The descriptions swishing and whistling were found to be related to the frequency content in the range of 2000 to 4000 Hz (Persson Waye *et al.*, 1998) while the description lapping probably referred to aerodynamically induced fluctuations and was found to best be described by specific loudness over time (Persson Waye *et al.*, 2000). Sound characteristics such as described here could be of relevance for perception and annoyance, especially at low background levels.

It has been suggested that the perception of wind turbine noise could be masked by wind-generated noise. However, most of the wind turbines operating today have a stable rotor speed, and, as a consequence, the rotor blades will generate an aerodynamic noise even if the wind speed is slow and the ambient noise is low. Furthermore, noise from wind turbines comprises modulations with a frequency that corresponds to the blade passage frequency (Hubbard *et al.*, 1983) and is usually poorly masked by ambient noise in rural areas (Arlinger and Gustafsson, 1988).

It has also been shown in previous field studies that attitude to wind turbines is relevant to perceived annoyance (Wolsink *et al.*, 1993; Pedersen and Nielsen, 1994). Such a relationship, however, was not found in an experimental study where the participants were exposed to wind turbine noise (Persson Waye and Öhrström, 2002). The difference could be due to the fact that the subjects in the latter study had very little personal experience of wind turbines generally, or to their lack of visual impression during the noise exposure.

There is clearly a need for field studies to investigate the impact of wind turbines on people living in their vicinity and to further explore the presence of disturbances. In particular, dose–response relationships should be investigated to achieve a more precise knowledge of acceptable exposure levels. As noise annoyance may be interrelated to the presence of intrusive sound characteristics, ambient sound pressure level, and visual intrusion as well as individual variables, all these factors should be taken into account and their relative importance evaluated.

The aims of this study were to evaluate the prevalence of annoyance due to wind turbine noise and to study dose–response relationships. The intention was also to look at interrelationships between noise annoyance and sound characteristics, as well as the influence of subjective variables such as attitude and noise sensitivity.

II. METHOD

A. General outline

The investigation was a cross-sectional study comprising respondents exposed to different A-weighted sound pressure levels (SPL) from wind turbines. Five areas totaling 22 km^2 comprising in total 16 wind turbines and 627 households were chosen within a total area of 30 km^2 (Table I). Subjective responses were obtained through questionnaires delivered at each household and collected a week later in May and June 2000. The response rate was 68.4%. A-weighted SPLs due to wind turbines were calculated for each respondent's dwelling. Comparisons were made of the extent of annoyance between respondents living at different A-weighted SPLs.

B. Study area and study sample

The criteria for the selection of the study areas were that they should comprise a large enough number of dwellings at varying distances from operating wind turbines within a

TABLE I. Description of study areas.

Area	Square km	Wind turbines	Households	Study population	Responses	Response rate (%)
A	3.7	2	89	75	54	72.0
B	4.7	3	44	33	23	69.7
C	8.3	8	70	59	49	83.1
D	3.3	2	393	325	210	64.6
E	2.0	1	31	21	15	71.4
Total	22.0	16	627	513	351	68.4

comparable geographical, cultural, and topographical structure. Suitable areas were found in a municipality in the south of Sweden. More than 40 wind turbines are located in this region, either in small groups with two to five turbines or as single objects. The landscape is flat and mainly agricultural but small industries, roads, and railroads are also present. Most people live in privately owned detached houses in the countryside or in small villages. The wind turbines are visible from many directions. To define the study area, preliminary calculations of sound distribution were made so that the area would include dwellings exposed to similar A-weighted SPL irrespective of the number of wind turbines. Of the 16 wind turbines in the selected five areas, 14 had a power of 600–650 kW, the other two turbines having 500 kW and 150 kW. The towers were between 47 and 50 m in height. Of the turbines, 13 were WindWorld machines, 2 were Enercon, and 1 was a Vestas turbine. Figure 1 shows a $\frac{1}{12}$-octave band spectra of a WindWorld turbine sound recorded 320 m from a turbine in area A at 6.3–8.9 m/s and a spectra of an Enercon turbine sound recorded 370 m from the turbine in area E at 4.5–6.7 m/s. Both recordings were done under downwind conditions.

The study sample comprised one selected subject between the ages of 18 and 75 in each household in the area within a calculated wind turbine A-weighted SPL of more than 30 dB ($n = 513$). The subject with birth date closest to May 20 was asked to answer a questionnaire.

C. Questionnaire

The purpose of the study was masked in the questionnaire; the questions on living conditions in the countryside also included questions directly related to wind turbines. The response of most questions was rated on 5-point or 4-point verbal rating scales. The key questions relevant for this paper were translated into English and are presented in the Appendix. The questionnaire was divided into four sections. The first section comprised questions regarding housing and satisfaction with the living environment, including questions on the degree of annoyance experienced outdoors and indoors from several sources of annoyance, wind turbines included. The respondent was also asked to rate his/her sensitivity to environmental factors, one being noise.

The second section of the questionnaire comprised questions on wind turbines, related to the respondent by the recent development of wind turbines in the community. The response to different visual and auditory aspects of wind turbines as noise and shadows were asked for, followed by questions on frequency of disturbances and experiences during certain activities and weather conditions. Respondents were also asked to describe their level of perception and annoyance related to the wind turbine sounds they could hear, using verbal descriptors of sound and perceptual characteristics. These descriptors were obtained from previous experimental studies were subjects initially verbally described their perception of annoying sound properties for five recorded wind turbine sounds (Persson Waye and Öhrström, 2002). This, together with some given adjectives, resulted in a total of 14 adjectives that were rated on unipolar scales with regard to annoyance. In this field study, the original descriptors were complemented with regionally used phrases. Several questions on attitude to wind turbines were also included.

The third section of the questionnaire concerned health aspects such as chronic illnesses (diabetes, tinnitus, cardiovascular diseases, hearing impairment) and general well-being (headache, undue tiredness, pain and stiffness in the back, neck or shoulders, feeling tensed/stressed, irritable). Respondents were asked questions about their normal sleep habits: quality of sleep, whether sleep was disturbed by any noise source, and whether they normally slept with the window open. The last section comprised questions on employment and working hours.

D. Calculations and measurements of noise exposure

For each respondent, A-weighted SPLs (dB) were calculated as the sum of contributions from the wind power plants in the specific area. The calculations were made with calculation points every fifth meter. The calculations followed the sound propagation model for wind power plants adopted by the Swedish Environmental Protection Agency (2001) and used as a basis for granting of building permission. The model assumes downward wind of 8 m/s at 10-m height. The calculation model is slightly different depending on the distance between the source and the receiver. For the cases in this study the following equation was used:

$$L_A = L_{WA,corr} - 8 - 20\lg(r) - 0.005r, \tag{1}$$

where r is the distance from the source to the receiver in meters. The atmospheric absorption coefficient is estimated to be 0.005 dB/m. $L_{WA,corr}$ is a modified sound power level of the wind power:

$$L_{WA,corr} = L_{WA} + k \cdot \Delta v_h. \tag{2}$$

TABLE II. Study sample, study population, and response rate related to sound category (dBA).

Sound category	<30.0	30.0–32.5	32.5–35.0	35.0–37.5	37.5–40.0	>40.0	Total
Study sample	25	103	200	100	53	32	513
Study population	15	71	137	63	40	25	351
Response rate	60.0%	68.9%	68.5%	63.0%	75.5%	78.1%	68.4%

L_{WA} is the A-weighted sound power level of the wind power plant, which in this study was given by the manufacturer; k describes how the sound power level varies with the wind speed at 10 m height and

$$\Delta v_h = v_h\left(\frac{\ln(H/z_0)}{\ln(h/z_0)}\,\frac{\ln(h/0.05)}{\ln(H/0.05)} - 1\right), \tag{3}$$

where v_h is the wind speed at 10-m height, H the height of the hub, h is 10 m, and z_0 the surface roughness length. In these calculations, $z_0 = 0.05\,\mathrm{m}$ (fields with few buildings) was used and therefore no value of k was needed. The SPL calculated this way is an estimate for the equivalent level for a hypothetical time period with continuous performance at downwind conditions 8 m/s at 10-m height.

To verify the calculations, to record frequency spectra, and to study background sound, a mobile caravan equipped with a sound level meter (Larson & Davis type 820), digital audio tape recorder (Sony TCD-D8 DAT), and meteorological instruments (Davis Weather Monitor type II) was used. The mobile station was placed on different sites of the study area. Both the meteorological instruments and the noise recording instruments were computer controlled and directed remotely via a cellular phone. The microphone was attached on a vertical hardboard facing the noise source. The equipment and procedures are thoroughly described by Björkman (2004). The sound pressure levels measured on the reflecting plane were corrected by -6 dB to present the free field value. The ambient sound pressure level varied from 33 dB $L_{\mathrm{Aeq,5\,min}}$ to 44 dB $L_{\mathrm{Aeq,5\,min}}$. The variations were mainly due to the amount of traffic within a 24-h time period. The lower background levels typically occurred during evening and nights.

The respondents were classified into six sound categories according to the calculated wind turbine A-weighted SPL at their dwelling. Table II shows the number of respondents living within each sound category and also the study sample and response rate for each sound category.

Data for the distance between the dwelling of the respondent and the nearest wind turbine were obtained from property maps, scale 1:10 000. The distance differed within each sound category, depending on the number of wind turbines in the area—the larger number of wind turbines, the shorter distance at the same A-weighted SPL. Table III shows the relationship between distance and A-weighted SPL. Two values are given for each category: the range and the median interval.

E. Statistical treatment of data

Due to the fact that most of the data were categorical (ordered or nonordered) and not continuos data, and therefore no assumptions on probability distribution could be made, nonparametric statistical methods were used, all described by Altman (1991). Data from verbal rating scales were calculated as proportions with 95% confidence intervals. When relevant, the two highest ratings of annoyance (rather annoyed and very annoyed) were classified as annoyed and the three lower ones as not annoyed (do not notice, notice but not annoyed, and slightly annoyed). In the analysis of attitude, negative and very negative were classified as negative; in the analysis of sensitivity, rather sensitive and very sensitive were classified as sensitive. More advanced statistical analyses were carried out using SPSS version 11.0. Relationships between variables were evaluated using Spearman's nonparametric rank correlation (r_s). Pearson's chi-square (chi2) was used to test that all sound categories contained the same proportion of observations. To evaluate differences between two unmatched samples of observations on an ordinal scale (e.g., comparing men and women's answers on a 5-graded verbal rating scale), the Mann–Whitney test was used (z_{MW}); a nonparametric test equivalent to the t test, but based on ranks (Altman, 1991). All significance tests were two-sided and p-values below 0.05 were considered statistically significant. When exploring several relationships at the same time, 1 out of 20 calculations would be classified as statistically significant by chance. This risk of mass significance was avoided using Bonferroni's method when appropriate, reducing the p-value considered statistically significant by dividing it with the number of correlations calculated at the same time (Altman, 1991).

Binary logistic multiple regression was used to study the impact of different variables on annoyance of wind turbine noise (annoyed–not annoyed). Sound category was used as the dose variable. Logistic regression is a method used to make a nonlinear function into a linear equation, using odds rather than straightforward probability. The equation is

TABLE III. Distance between dwelling and nearest wind turbine related to sound category (dBA).

Sound category	<30.0	30.0–32.5	32.5–35.0	35.0–37.5	37.5–40.0	>40.0
Range (m)	650–1049	550–1199	450–1099	300–799	300–749	150–549
Median interval (m)	850–899	750–799	550–599	450–499	350–399	300–349

TABLE IV. Characteristics of the respondents given as proportions of respondents in each sound category (dBA) and in total.

Sound category	<30.0	30.0–32.5	32.5–35.0	35.0–37.5	37.5–40.0	>40.0	Total
n	15	71	137	63	40	25	351
Gender: Male (%)	27	35	39	50	50	48	42
Residence: Detached houses/farms (%)	100	83	61	100	97	96	81
Occupation: Employed (%)	67	59	58	53	69	67	60
Sensitive[a] to noise (%)	62	44	49	53	58	50	50
Negative[b] to wind turbines (%)	8	10	11	18	20	8	13
Negative[b] to visual impact (%)	43	33	38	41	40	58	40
Long-term illness (%)	20	29	28	16	30	24	26
Age: Mean	46	47	47	50	48	48	48
(SD)	(13.3)	(13.7)	(14.3)	(14.6)	(13.1)	(14.3)	(14.0)

[a]Sensitive consists of the two ratings: rather sensitive and very sensitive.
[b]Negative consists of the two ratings: rather negative and very negative.

$$\ln\left(\frac{p}{1-p}\right)=b_0+b_1x_1+b_2x_2+\cdots, \tag{4}$$

where, in this case, p is the probability of being annoyed by noise from wind turbines, x_1–x_n are the variables put into the model, and b_1–b_n are the logarithmic value of the odds ratio for one unit change in the respective variable (Altman, 1991). A relevant measurement of explained variance using nonparametric statistics is Nagelkerke pseudo-R^2 (Nagelkerke, 1991).

To estimate how consistently the respondents answered to questions measuring similar response, Cronbach's alpha (Miller, 1995) was calculated as a testing of the internal consistency reliability of the questionnaire. Five of the questions regarding wind turbine noise were compared: annoyance outdoors, annoyance indoors, annoyance of rotor blades, annoyance of machinery, annoyance as a describing adjective. Demographic data on age and gender of the population in the four parishes in the study area were collected from local authorities. The study population was compared to these demographical data, parish-by-parish, and divided into 10-year categories for age and gender, as well as in total.

III. RESULTS

A. Study population

The overall response rate was 68.4%, ranging from 60.0% to 78.1% in the six sound categories (Table II). No statistically significant differences in variables related to age, gender, or employment were found among sound categories (Table IV). A statistically significant difference was found between sound categories as to whether respondents lived in apartments or detached houses (chi2=62.99, df=5, $p<0.001$). Overall, most of the respondents (80%) lived in privately owned detached houses or on farms. The remaining lived in tenant-owned or rented apartments. The latter were more frequent in sound category 32.5–35.0 dBA (Table IV). However, there was no statistically significant difference between the respondents living in privately owned detached houses or on farms, on one hand, and those living in tenant-owned or rented apartments, on the other hand, regarding subjective factors, when correcting for requirements to avoid mass significance. Most of the respondents did not own a wind turbine or share of a wind turbine (95%, $n=335$). No statistically significant differences in variables related to noise sensitivity, attitude, or health were found between the different sound categories.

The mean age in the study population was 48 years (SD =14.0) (Table IV) which did not differ statistically significantly from the demographic data (45 years, SD=15.2). The proportion of women in the study population was slightly higher than in the demographic data; in the study population, 58% women and 42% men (Table IV), compared to 49% women and 51% men in the demographic data. However, no statistically significant differences were found between men and women regarding perception and annoyance due to wind turbine noise, noise sensitivity, or attitude to wind turbines. Differences between genders were found regarding well-being. Women suffered more often from headache ($z_{MW}=-3.243$, $n=328$, $p<0.001$), undue tiredness ($z_{MW}=-3.549$, $n=327$, $p<0.05$), pain and stiffness in back, neck or shoulders ($z_{MW}=-3.312$, $n=331$, $p<0.001$), and tension/stress ($z_{MW}=-3.446$, $n=328$, $p<0.001$).

B. Main results

The proportion of respondents who noticed noise from wind turbines outdoors increased sharply from 39% ($n=27$, 95%CI: 27%–50%) at sound category 30.0–32.5 dBA to 85% ($n=53$, 95%CI: 77%–94%) at sound category 35.0–37.5 dBA (Table V). The proportion of those annoyed by wind turbine noise outdoors also increased with higher sound category, at sound categories exceeding 35.0 dBA. The correlation between sound category and outdoor annoyance due to wind turbine noise (scale 1–5) was statistically significant ($r_s=0.421$, $n=341$, $p<0.001$). No respondent self-reported as annoyed at sound categories below 32.5 dBA, but at sound category 37.5–40.0 dBA, 20% of the 40 respondents living within this exposure were very annoyed and above 40 dBA, 36% of the 25 respondents (Table V).

To explore the influence of the subjective factors on noise annoyance, binary multiple logistic regression was used (Table VI). Eight models were created, all containing sound category as the prime variable assumed to predict noise annoyance. The three subjective factors of attitude to visual impact, attitude to wind turbines in general, and sensitivity to noise were forced into the model one-by-one, two-by-two, and finally all together. In the first model only noise

TABLE V. Perception and annoyance outdoors from wind turbine noise related to sound exposure.

	<30.0 n=12 %(95%CI)	30.0–32.5 n=70 %(95%CI)	32.5–35.0 n=132 %(95%CI)	35.0–37.5 n=62 %(95%CI)	37.5–40.0 n=40 %(95%CI)	>40.0 n=25 %(95%CI)
Do not notice	75 (51–100)	61(50–73)	38(30–46)	15(3–23)	15(4–26)	4(19–57)
Notice, but not annoyed	25(1–50)	24(14–34)	28(20–36)	47(34–59)	35(20–50)	40(19–57)
Slightly annoyed	0	14(6–22)	17(10–23)	26(15–37)	23(10–35)	12(19–57)
Rather annoyed	0	0	10(5–15)	6(0–13)	8(−1–16)	8(19–57)
Very annoyed	0	0	8(3–12)	6(0–13)	20(8–32)	36(17–55)

exposure was used as the independent variable. The Exp(b) was 1.87, i.e., the odds for being annoyed by noise from wind turbines would increase 1.87 times from one sound category to the next. When adding the subjective factor of attitude to visual impact as an independent variable, the influence of the noise exposure decreased, but was still statistically significant. The pseudo-R^2 increased from 0.13 to 0.46, indicating that the new model explained 46% of the variance in annoyance. Adding the two remaining subjective factors did not improve the model as the coefficients did not reach statistical significance.

Noise from rotor blades was reported as the most annoying aspect of wind turbines. Of the respondents, 16% ($n=54$, 95%CI: 12%–20%) were annoyed by noise from rotor blades. Changed view (14%, $n=48$, 95%CI: 10%–18%), noise from machinery (9%, $n=33$, 95%CI: 6%–12%), shadows from rotor blades (9%, $n=29$, 95%CI: 6%–11%), and reflections from rotor blades (7%, $n=22$, 95%CI: 4%–9%) were also reported.

C. Attitude and sensitivity

Almost all respondents (93%, $n=327$, 95%CI: 91%–96%) could see one or more wind turbines from their dwelling or garden. When asked for judgments on wind turbines, the adjectives that were agreed on by most respondents were ‘‘environmentally friendly’’ (79%), ‘‘necessary’’ (37%), ‘‘ugly’’ (36%), and ‘‘effective’’ (30%). Only the word ‘‘annoying’’ (25%) was judged higher among those in higher sound categories than among those in lower sound categories ($z_{MW}=-3.613$, $n=351$, $p<0.001$).

The high judgment of the word ‘‘ugly’’ corresponds to the outcome of the attitude questions. Of the respondents, only 13% ($n=44$, 95%CI: 9%–16%) reported that they were negative or very negative to wind turbines in general, but 40% ($n=137$, 95%CI: 34%–44%) that they were negative or very negative to the visual impact of wind turbines on the landscape scenery (Table IV).

All correlations between sound category, noise annoyance, and subjective factors are shown in Table VII. Noise annoyance was correlated to both sound category and the three subjective factors, strongest to attitude to the wind turbines' visual impact on the landscape. The subjective factors were also correlated to each other, except for general attitude and sensitivity to noise. Of all the respondents, 50% ($n=169$, 95%CI: 45%–55%) regarded themselves as rather sensitive or very sensitive to noise (Table IV).

When comparing those annoyed by wind turbine noise and those not, no differences were found regarding the judgments of the local authorities, with the exception of perceived opportunity to influence local government ($z_{MW}=-2.753$, $n=300$, $p<0.005$). Those annoyed reported negative changes to a higher degree ($z_{MW}=-5.993$, $n=307$, p

TABLE VI. Results of multiple logistic regression analyses with 95% confidence intervals.

	Variables	b	p-value	Exp(b) (95%CI)	Pseudo-R^{2a}
1	Noise exposure	0.63	<0.001	1.87(1.47–2.38)	0.13
2	Noise exposure	0.55	<0.001	1.74(1.29–2.34)	0.46
	Attitude to visual impact	1.62	<0.001	5.05(3.22–7.92)	
3	Noise exposure	0.62	<0.001	1.86(1.45–2.40)	0.20
	Attitude to wind turbines	0.56	<0.001	1.74(1.30–2.33)	
4	Noise exposure	0.63	<0.001	1.88(1.46–2.42)	0.18
	Sensitivity to noise	0.56	<0.005	1.75(1.19–2.57)	
5	Noise exposure	0.55	<0.001	1.73(1.28–2.33)	0.46
	Attitude to visual impact	1.66	<0.001	5.28(3.26–8.56)	
	Attitude to wind turbines	−0.10	0.319	0.91(0.64–1.28)	
6	Noise exposure	0.57	<0.001	1.77(1.30–2.40)	0.47
	Attitude to visual impact	1.59	<0.001	4.88(3.08–7.72)	
	Sensitivity to noise	0.22	0.344	1.25(0.79–1.96)	
7	Noise exposure	0.63	<0.001	1.88(1.45–2.45)	0.24
	Attitude to wind turbines	0.58	<0.001	1.78(1.32–2.41)	
	Sensitivity to noise	0.59	<0.005	1.80(1.22–2.67)	
8	Noise exposure	0.56	<0.001	1.76(1.29–2.39)	0.47
	Attitude to visual impact	1.63	<0.001	5.11(3.10–8.41)	
	Attitude to wind turbines	−0.10	0.597	0.91(0.64–1.29)	
	Sensitivity to noise	0.21	0.373	1.23(0.78–1.94)	

[a]Nagelkerke (1991).

TABLE VII. Correlation between noise annoyance, sound category (dBA) and the subjective variables. Statistically significant correlations in boldface. To avoid the risk of mass significance $p<0.008$ were required for statistical significance.

	Sound category	Attitude to visual impact	Attitude to wind turbines	Sensitivity to noise
Noise annoyance	**0.421**	**0.512**	**0.334**	**0.197**
Sound category	⋯	**0.145**	0.074	0.069
Attitude to visual impact		⋯	**0.568**	**0.194**
Attitude to wind turbines			⋯	0.023
Sensitivity to noise				⋯

<0.001); 83% compared to 37% among those not annoyed. Of the 138 respondents who reported negative changes overall, 41% ($n=57$, 95%CI: 33%–50%) specified wind turbines in the response to an open question.

D. The occurrence of noise annoyance

Among those who noticed wind turbine noise ($n=223$), 25% ($n=47$, 95%CI: 18%–31%) reported that they were disturbed every day or almost every day and 17% ($n=33$, 95%CI: 12%–23%) once or twice a week. Annoyance was most frequently reported when relaxing outdoors and at barbecue nights.

Perception of wind turbine noise was influenced by weather conditions. Of the respondents who noticed wind turbine noise, 54% stated that they could hear the noise more clearly than usual when the wind was blowing from the turbines towards their dwelling. Only 9% reported that the noise was heard more clearly when the wind was from the opposite direction. The noise was also more clearly noticed when a rather strong wind was blowing (39%), but 18% reported that the noise was more clearly noticed in low wind. For warm summer nights, 26% noticed the noise more clearly than usual.

E. Sound characteristics

There was a statistically significant correlation between sound category and annoyance due to noise from rotor blades ($r_s=0.431$, $n=339$, $p<0.001$) and from the machinery ($r_s=0.294$, $n=333$, $p<0.001$). In all sound categories, a higher proportion of respondents noticed noise from rotor blades than from the machinery (Fig. 2). The proportion who noticed noise from rotor blades was similar to the proportion of respondents who noticed wind turbine noise in general. Noise from rotor blades was noticed in lower sound categories than noise from the machinery, i.e., it could be heard at a greater distance. However, comparing the numbers of annoyed with the numbers of those who could hear noise from the two sources, respectively, both noises were almost equally annoying. Of the 215 respondents who noticed noise from rotor blades, 25% ($n=54$, 95%CI: 19%–31%) were annoyed. Of the 101 respondents who noticed noise from the machinery, 30% ($n=30$, 95%CI: 21%–39%) were annoyed.

Among those who noticed noise from wind turbines, swishing, whistling, pulsating/throbbing, and resounding were the most common sources of annoyance according to verbal descriptors of sound characteristics (Table VIII). These descriptors were all highly correlated to noise annoyance. All other verbal descriptors of sound characteristics were also statistically significantly correlated to noise annoyance, but to a lower degree. When analyzing annoyance due to noise from rotor blades, the strongest correlated verbal descriptor of sound characteristics was swishing ($r_s=0.807$, $n=185$, $p<0.001$), which can be compared to noise annoyance due to noise from the machinery—which had the highest correlation with scratching/squeaking ($r_s=0.571$, $n=133$, $p<0.001$).

F. Indoor noise annoyance and sleep disturbance

A total of 7% of respondents ($n=25$, 95%CI: 5%–10%) were annoyed by noise from wind turbines indoors. Forty-five percent ($n=24$, 95%CI: 32%–59%) of those who were annoyed by noise from wind turbines outdoors were also

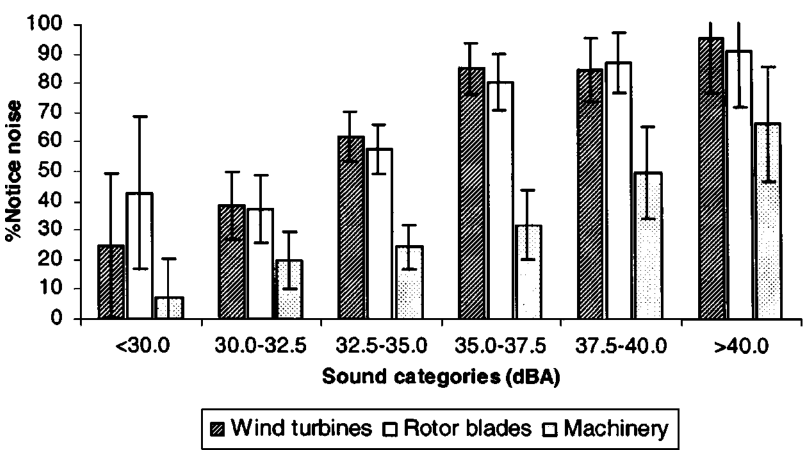

FIG. 2. Proportions with 95% confidence intervals of perception outdoors due to noise (notice but not annoyed, slightly annoyed, rather annoyed, very annoyed) from wind turbines, from rotor blades, and from machinery, related to sound categories.

TABLE VIII. Verbal descriptors of sound characteristics of wind turbine noise, based on those who noticed wind turbine sound ($n=223$). Statistically significant correlations in boldface. To avoid the risk of mass significance $p<0.0062$ were required for statistical significance.

	Annoyed by the specified sound character	Correlation to noise annoyance
Swishing	33%(27%–40%)	**0.718**
Whistling	26%(18%–33%)	**0.642**
Pulsating/throbbing	20%(14%–27%)	**0.450**
Resounding	16%(10%–23%)	**0.485**
Low frequency	13% (7%–18%)	**0.292**
Scratching/squeaking	12% (6%–17%)	**0.398**
Tonal	7% (3%–12%)	**0.335**
Lapping	5% (1%–8%)	**0.262**

annoyed indoors. There was a statistically significant correlation between indoor annoyance and sound category ($r_s=0.348$, $n=340$, $p<0.001$).

Regarding sleep disturbance, 23% ($n=80$, 95%CI: 18%–27%) of respondents stated that they were disturbed in their sleep by noise. Several sources of sleep disturbance, such as road traffic, rail traffic, neighbors, and wind turbines, were reported in an open question. At lower sound categories, no respondents were disturbed in their sleep by wind turbine noise, but 16% ($n=20$, 95%CI: 11%–20%) of the 128 respondents living at sound exposure above 35.0 dBA stated that they were disturbed in their sleep by wind turbine noise. Of those, all except two slept with an open window in the summer. No statistically significant correlations were found between sleep quality in general and outdoor noise annoyance, indoor noise annoyance, attitude to visual impact, attitude to wind turbines in general, or sensitivity to noise.

IV. DISCUSSION

A. Method

The results were based on the questionnaire survey and calculated A-weighted SPL. The purpose of the study was masked in order to avoid other factors such as attitude and ownership influencing the answers. The survey method is well established and has been used in several previous studies exploring annoyance due to community noise (e.g., Öhrström, 2004).

The results indicate a high validity for the questionnaire. The questions detected annoyance by odor from industrial plants in the area where the biogas plant is located [of those annoyed by odor from industrial plants, 83% ($n=19$) lived close to the biogas plant]; it also detected annoyance by noise from trains in the areas where the train passes [all of the respondents who reported that they were annoyed by noise from railway traffic ($n=12$) lived in areas where the railway passed]. There was a high correspondence between the responses to the general question of noise from wind turbines at the beginning of the questionnaire and the more specific questions later (alpha: 0.8850, $n=326$), also indicating high reliability of results.

The response rate at the different sound categories ranged from 60.0% to 78.1%, with the overall mean 68.4% and the dropout fairly equally distributed over sound categories. The distribution of age in the study population was similar to that of the demographic data for the area, but the proportions of women were somewhat higher than expected, especially in the lower sound categories. It has previously been shown that annoyance is not related to gender (Miedema and Vos, 1999) and as this study found no differences between men and women regarding noise annoyance and attitude to wind turbines, the higher proportion of women in the study population presumably had no impact on the results. A rather high proportion, 50%, of respondents self-reported as rather or very sensitive to noise. Other field studies in Sweden on annoyance due to road traffic noise in urban areas have found a lower proportion of noise-sensitive persons; for example, Matsumura and Rylander (1991) reported 25% of the respondents as noise sensitive in a road traffic survey ($n=805$). The difference might reflect preference of living environment, indicating that noise sensitive individuals prefer a more rural surrounding or that people living in areas with low background noise levels might develop a higher sensitivity to noise.

The calculated A-weighted SPL reflected downwind conditions assuming a wind speed of 8 m/s. Over a larger period of time, the direction and speed of the wind will vary and hence affect the actual SPL at the respondent's dwelling. It is likely that these variations, seen as an average over a longer period of time, in most cases will result in lower levels than the calculated SPL. Several unreliabilities related to the calculations might have led to an over- or underestimation of the dose levels. However, this error would not invalidate the comparison between respondents living at different SPL. Another source of error is that no account was taken of the physical environment around the respondent's house (e.g., location of patio or veranda, presence of bushes and trees in the garden). The actual SPL that the respondent experienced in daily life might therefore differ from the calculated, leading in most cases to an overestimation of the calculated dose.

B. Results

The results suggest that the proportions of respondents annoyed by wind turbine noise are higher than for other community noise sources at the same A-weighted SPL and that the proportion annoyed increases more rapidly. A comparison between established estimations of dose–response relationships for annoyance of transportation noise (Schultz, 1978; Fidell *et al.*, 1991; Miedema and Voss, 1998; Miedema and Oudshoorn, 2001; Fidell, 2003) and an estimation of a dose–response relationship for wind turbine noise, based on the findings in this study, are shown in Fig. 3. All curves are third order polynomials. The established curves describing annoyance from transportation noise are based on a large amount of data, and the wind turbine curve on only one study, so interpretations should be done with care. An important difference between studies of transportation noises and wind turbine noise is however where the main annoyance reaction is formed. For most studies of transportation noises

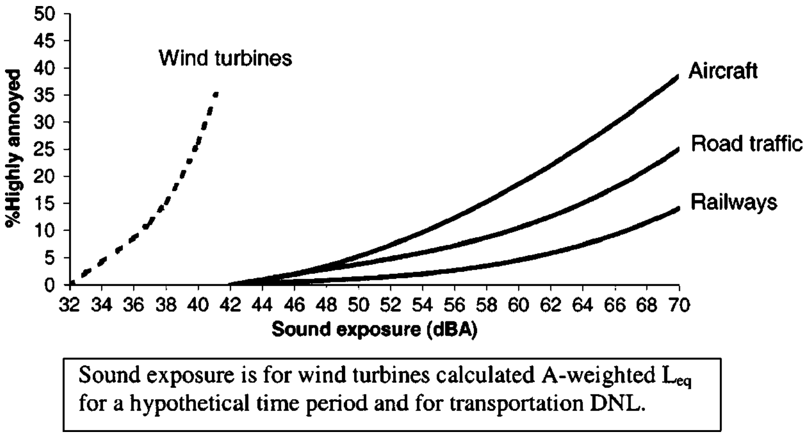

FIG. 3. A comparison between the dose–response relationship for transportation noise estimated by third order polynomials suggested by Miedema and Oudshoorn (2001) and wind turbine noise (dotted line). The latter ($\%HA=4.38*10^{-2}(LEQ-32)^3-2.413*10^{-1}(LEQ-32)^2+2.4073(LEQ-32)$) were derived using regression based on five points interpolated from sound categories used in this study and the assumption that "very annoyed" in this study equals "highly annoyed" (Miedema and Voss, 1998).

it can be assumed that annoyance is formed mainly as a reaction to the sound pressure levels perceived indoors, and hence the actual noise dose should be reduced by the attenuation of the façade. For wind turbine noise the main annoyance reaction is formed when spending time outdoors. The actual difference in noise dose could therefore, at least partly, explain the comparatively higher prevalence of noise annoyance due to wind turbines. However, this factor does not explain the steep gradient.

Another factor that could be of importance for explaining the seemingly different dose–response relationships is that the wind turbine study was performed in a rural environment, where a low background level allows perception of noise sources even if the A-weighted SPL are low. Wind turbine noise was perceived by about 85% of the respondents even when the calculated A-weighted SPL were as low as 35.0–37.5 dB. This could be due to the presence of amplitude modulation in the noise, making it easy to detect and difficult to mask by ambient noise. This is also confirmed by the fact that the aerodynamic sounds were perceived at a longer distance than machinery noise.

Data obtained in this study also suggest that visual and/or aesthetic interference influenced noise annoyance. Support for this hypothesis can be found in studies evaluating auditory-visual interactions (Viollon *et al.*, 2002). In one field-laboratory study, subjects evaluating annoyance due to traffic noise were less annoyed if a slide of a visually attractive street was presented together with the noise, as compared to the same noise level presented together with a visually unattractive street. The difference in noise annoyance amounted to as much as 5 dBA (Kastka and Hangartner, 1986). The hypothesis was also supported by the logistic multiple regression analyses in the present study, where the visual variable attitude to visual impact had a significant impact on the model. However, although the inclusion of the variable increased the pseudo-R^2, the influence of noise exposure was still a significant factor for noise annoyance. A general prediction of the visual influence on noise annoyance, however, can not yet be made with any certainty as both attenuating (Kastka and Hangartner, 1986) and amplifying effects (e.g., Watts *et al.*, 1999) have been detected.

The high prevalence of noise annoyance could also be due to the intrusive characteristics of the aerodynamic sound. The verbal descriptors of sound characteristics related to the aerodynamic sounds of swishing, whistling, pulsating/throbbing, and resounding were—in agreement with this hypothesis—also reported to be most annoying. The results for the sounds of swishing and whistling agree well with results from previous experimental studies (Persson Waye *et al.*, 2000; Persson Waye and Agge, 2000; Persson Waye and Öhrström, 2002), while pulsating/throbbing in those studies was not significantly related to annoyance.

Most respondents who were annoyed by wind turbine noise stated that they were annoyed often, i.e., every day or almost every day. The high occurrence of noise annoyance indicates that the noise intrudes on people's daily life. The survey was performed during May and June when people could be expected to spend time outdoors, and the results therefore reflect the period that is expected to be most sensitive for annoyance due to wind turbine noise.

A low number of respondents were annoyed indoors by wind turbine noise. Some of the respondents also stated that they were disturbed in their sleep by wind turbine noise, and the proportions seemed to increase with higher SPL. The number of respondents disturbed in their sleep, however, was too small for meaningful statistical analysis, but the probability of sleep disturbances due to wind turbine noise can not be neglected at this stage.

Noise annoyance was also related to other subjective factors such as attitude and sensitivity. These results correspond well with the results from other studies regarding community noise (e.g., noise from aircraft, railways, road traffic, and rifle ranges). In a summary of 39 surveys performed in ten different countries, the correlation was 0.42 between dose and response, 0.15 between exposure and attitude, 0.41 between annoyance and attitude, −0.01 between exposure and sensitivity, and 0.30 between annoyance and sensitivity (Job, 1988). Corresponding numbers from this study are presented in Table VII and show a noteworthy similarity.

Two aspects of attitude were explored in the present study. Attitude to the visual impact of wind turbines on the landscape scenery was more strongly correlated to annoyance than the general attitude to wind turbines. The four most supported adjectives queried in the survey were environmentally friendly, necessary, ugly, and effective, thus giving the picture of a phenomenon that is accepted, but not regarded as a positive contribution to the landscape.

Previous studies of community noise have found that people who tend to be consistently negative could be predicted to be more annoyed by a new source of noise (Weinsten, 1980). More recent studies on community noise have included additional aspects and suggest conceptual models describing individual differences in the terms of stress, appraisal, and coping (Lercher, 1996). In the case of annoyance due to wind turbine noise, the findings suggest that individual differences others than attitude and sensitivity could influence the variation of noise annoyance. Respondents annoyed by wind turbine reported negative changes in their neighborhood to a higher degree than those not annoyed and stated that they had little perceived opportunity to influence local government. The importance of these parameters for noise annoyance due to wind turbines should be further studied.

C. Conclusions

A significant dose–response relationship between calculated A-weighted SPL from wind turbines and noise annoyance was found. The prevalence of noise annoyance was higher than what was expected from the calculated dose. It is possible that the presence of intrusive sound characteristics and/or attitudinal visual impacts have an influence on noise annoyance. Further studies are needed, including a larger number of respondents especially at the upper end of the dose curve, before firm conclusions could be drawn. To explore attitude with regard to visual impact, some of these studies should be performed in areas of different topography where the turbines are less visible. There is also a need to further explore the influence of individual and contextual parameters.

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APPENDIX: QUESTIONNAIRE

Key questions from the questionnaire used in the study. Questions with the main purpose to mask the intention of the questionnaire and standard questions on socio-economic status and health are not shown here. Translated from Swedish.

Section I

—How satisfied are you with your living environment? (very satisfied, satisfied, not so satisfied, not satisfied, not at all satisfied)

—Have there been any changes to the *better* in your living environment/municipality during the last years? (no, yes) State which changes.

—Have there been any changes to the *worse* in your living environment/municipality during the last years? (no, yes) State which changes.

—State for each nuisance below if you notice or are annoyed when you spend time *outdoors* at your dwelling: odor from industries, odor from manure, flies, noise from hay fans, noise from wind turbines, railway noise, road traffic noise, lawn mowers. (do not notice, notice but not annoyed, slightly annoyed, rather annoyed, very annoyed)

—State for each nuisance below if you notice or are annoyed when you spend time *indoors* in your dwelling: odor from industries, odor from manure, flies, noise from hay fans, noise from wind turbines, railway noise, road traffic noise, lawn mowers. (do not notice, notice but not annoyed, slightly annoyed, rather annoyed, very annoyed)

—How would you describe your sensitivity to the following environmental factors: air pollution, odors, noise, littering? (not sensitive at all, slightly sensitive, rather sensitive, very sensitive)

Section II

—Can you see any wind turbine from your dwelling or your garden? (yes, no)

—What is your opinion on the wind turbines' impact on the landscape scenery? (very positive, positive, neither positive nor negative, negative, very negative)

—Are you affected by wind turbines in your living environment with regard to: shadows from rotor blades, reflections from rotor blades, sound from rotor blades, sound from machinery, changed view? (do not notice, notice but not annoyed, slightly annoyed, rather annoyed, very annoyed)

—If you are annoyed by noise, shadows and/or reflections from wind turbines, how often does this happen? (never/almost never, some/a few times per year, some/a few times per month, some/a few times per week, daily/almost daily)

—If you hear sound from wind turbines, how would you describe the sound: tonal, pulsating/throbbing, swishing, whistling, lapping, scratching/squeaking, low frequency, resounding? (do not notice, notice but not annoyed, slightly annoyed, rather annoyed, very annoyed)

—Have you noticed if sounds from wind turbines sound different at special occasions: when the wind blows from the turbine towards my dwelling, when the wind blows from my dwelling towards the turbine, when the wind is low, when the wind is rather strong, warm summer nights? (less clearly heard, more clearly heard, no differences, do not know)

—Are you annoyed by sound from wind turbines during any of the following activities: relaxing outdoors, barbecue nights, taking a walk, gardening, other outdoor activity? (do not notice, notice but not annoyed, slightly annoyed, rather annoyed, very annoyed)

—Do you own any wind turbines? (no, yes I own one or more turbines, yes I own shares of wind turbines)

—What is your general opinion on wind turbines? (very positive, positive, neither positive nor negative, negative, very negative)

—Please mark the adjectives that you think are adequate for wind turbines: efficient, inefficient, environmentally friendly, harmful to the environment, unnecessary, necessary, ugly, beautiful, inviting, threatening, natural, unnatural, annoying, blends in.[1]

[1]Developed by Karin Hammarlund, Department of Human and Economic Geography, Göteborg University, Sweden, and used with her permission.

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