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An analysis of low frequency noise from large wind turbines

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Summary

As wind turbines get larger, worries have emerged, that the noise emitted by the turbines would move down in frequency, and that the contents of low-frequency noise would be enough to cause significant annoyance for the neighbors. The sound emission from 48 wind turbines with nominal electric power between 75 kW and 3.6 MW was analyzed.

The apparent sound power, L_{WA} , increases with electric power at a rate close to 3 dB per doubling of electric power. The low-frequency proportion (10-160 Hz) increases more rapidly, and the difference in slope is statistically significant. A comparison of one-third-octave-band spectra shows that the relative noise emission is higher in the 63-250 Hz frequency range from turbines above 2 MW than from smaller turbines. The observations confirm a downward shift of the spectrum.

1 Introduction

Wind turbines get larger and larger, and worries have emerged, that the noise emitted by the turbines would consequently move down in frequency, and that the contents of low-frequency and infrasonic noise would increase and reach a level, where it may be annoying for the neighbors. The daily press frequently reports on rumbling and annoying noise from large wind turbines, and it is often claimed that it propagates quite far. However, the scientific literature on infrasonic and low-frequency noise from large wind turbines is more limited.

This was the background for a Danish project, in which Delta, a consultancy and official acoustics laboratory for the Danish environmental protection agency, would measure and record noise from large wind turbines, and Aalborg University would make listening tests in the laboratory to assess the annoyance and compare it to annoyance from other, more well known, noise sources, e.g. traffic noise. The study would cover the full noise spectrum, but special emphasis would be on low-frequency and infrasonic noise. The study would make use of a special low-frequency exposure facility at Aalborg University (Santillan et al. [1], Pedersen [2]) as well as utilize the university's engagement through decades in research on low-frequency sound and infrasound.

Unfortunately, Aalborg University had to leave the project, before the listening experiments were carried out, because Delta was not able or willing to clarify a number of issues relevant for selecting and documenting recordings for the listening tests. It was also not possible for Aalborg University to get access to all the recordings made, a matter which the authors consider fundamental for a justified

selection of recordings for such tests. Thus, the listening tests have not been carried out, and consequently, this article is confined to analyses and discussions of the physical measurements.

1.1 Outline of study

In the present project, noise from four large turbines was measured, noise data for 44 other small and large turbines was aggregated, and low-frequency sound insulation to sound from the outside of ten normal living rooms was measured. In this article, the data from the project are used to examine the connection between emitted sound power and turbine size. Source spectra are analyzed and discussed, and, in particular, the hypothesis that the spectrum moves towards lower frequencies for increasing turbine size is investigated. Outdoor and indoor spectra at relevant neighbor distances are analyzed and discussed. Measurements and data aggregation were carried out by Delta, and more details may be found in the original reports [3, 4, 5, 6].

2 Methods

2.1 Wind turbines

Forty-eight wind turbines were included in the project. Four prototype turbines with nominal electric power above 2 MW were measured by Delta as part of the project (Turbines 1-4), while data for seven other turbines above 2 MW were taken from measurements made by Delta outside the project (Turbines 5-11) [3, 4]. Data for 37 turbines with nominal power at or below 2 MW were taken from previous measurements made by Delta [5]. Among the small turbines, a few physical turbines appear more than once, representing the turbine measured at different occasions. All turbines were three-bladed with the rotor placed at the upwind side of the tower.

2.2 Emitted sound power

The sound power emitted from the turbines was measured in accordance with IEC 61400-11 [7]. The principle of this standard is to measure the sound on a reflecting board placed on the ground beneath the turbine at a horizontal distance approximately equal to the turbine's total height. The measured sound pressure level is converted to the sound power level of an imaginary point source at the rotor centre that would radiate the same sound in the direction, where the measurement is made. The result is denoted the *apparent sound power level*, where 'apparent' emphasizes that it is not the true sound power, but the power as "seen" in the measured direction.

Apparent sound power level was determined for one-third-octave bands and as total A-weighted level, L_{WA} . In addition, a special low-frequency measure, L_{WALF} , the apparent A-weighted sound power level for the one-third-octave bands 10-160 Hz was derived. A-weighted sound pressure levels for this frequency range, L_{pALF} , are used by the Danish guidelines for low-frequency noise [8].

Data were obtained for all turbines in the down-wind direction, denoted the *reference direction*, at a wind speed of 8 m/s (10 m above ground). This wind speed is often used in noise regulations, and most analyses in the present article were made for this. Turbines 1-4 were also measured at various other wind speeds. For evaluation of the content of pure tones, tonal audibility, ΔL_a , was determined for Turbines 1-4, and to get some insight into a possible directional pattern of the sound radiation, Turbines 1-3 were measured at $\pm 60^\circ$ to the sides of the reference direction and in the

upwind direction, still at the ground. All turbines were measured in the required frequency range of the standard, 50 Hz to 10 kHz, and most turbines were measured down to 31.5 or 25 Hz. Turbines 1-4 were measured down to 4 Hz.

2.3 Outdoor sound pressure levels at neighbors

Free-field sound pressure levels, L_p , for downwind neighbor positions were calculated according to the method given by ISO 9613-2 [9], except that one-third-octave bands were used instead of octave bands.

The direction to neighbors is more horizontal than the direction, in which the apparent sound power level was measured, but in lack of more precise information, the sound power level plus directivity factor, $L_w + D_c$, was replaced by the apparent sound power level, L_{WA} , for the reference direction. The attenuation due to atmospheric absorption, A_{atm} , was calculated using data from ISO 9613-1 [10] for 10° C and a relative humidity of 80 %. The ‘attenuation’ due to ground effects, A_{gr} , was set to -1.5 dB, meaning that 1.5 dB is added to the direct sound from the turbine. The two remaining terms of ISO 9613-2 (attenuation due to a barrier A_{bar} and to miscellaneous A_{misc}) were set to zero. If the slant distance from rotor center to the observation point is denoted d , and the attenuation constant is γ ,

$$L_p = L_{WA} - 20 \text{ dB} \cdot \log_{10} \left(\frac{d}{1 \text{ m}} \right) - 11 \text{ dB} - \alpha \cdot d + 1.5 \text{ dB} \quad (1)$$

This calculation corresponds to the one used in the Danish regulation of noise for wind turbines [11].

2.4 Statistics

Differences are tested in Student’s t-tests. The highest p-values considered significant and are 0.05. In two-sample tests, equal variance is not assumed, thus the Welch’s adaptation of the t-test and the Welch-Satterthwaite degrees of freedom (d.f.) are used. One-sided tests are used, whenever the hypothesis contains a specific direction of the difference, whereas two-sided tests are used elsewhere. As an example, the hypothesis that the spectrum moves down in frequency for increasing turbine size, implies that relative levels for large turbines are higher at low frequencies and lower at high frequencies. Consequently, one-sided tests are used at low and high frequencies, whereas two-sided tests are used in the intermediate frequency range, chosen as 315-1600 Hz.

3 Results and discussion

Three turbines, one at 1650 kW and two at 2.3 MW, were added to the material at a late stage, and one-third-octave data are not available for these, thus only L_{WA} and L_{WALF} are reported. 20-Hz high-pass filters had unfortunately been inserted during some of the measurements (reference, left and right directions for Turbine 1, reference direction for Turbine 3), so, before data processing, the effect of these filters was counteracted by subtracting the filter response from the measured levels in the affected frequency range. High-frequency electrical noise from the frequency converter affected some of the measurements at frequencies above 5 kHz, and data for Turbines 1-4 are thus not reported at these frequencies. Some inconsistencies exist in the data given by Delta in different reports, tables, and figures. The results in the present article are based on the least processed data reported, which mostly means original one-third-octave emitted levels.

3.1 Emitted sound power

3.1.1 L_{WA} and L_{WALF}

Figure 1 shows L_{WA} and L_{WALF} for all turbines as a function of turbine size. The horizontal axis is logarithmic in order to match the vertical decibel axis, which is inherently logarithmic. Simple power relations between emitted acoustic power and nominal electric power of the turbine will thus correspond to straight lines, and regression lines are included in the figure.

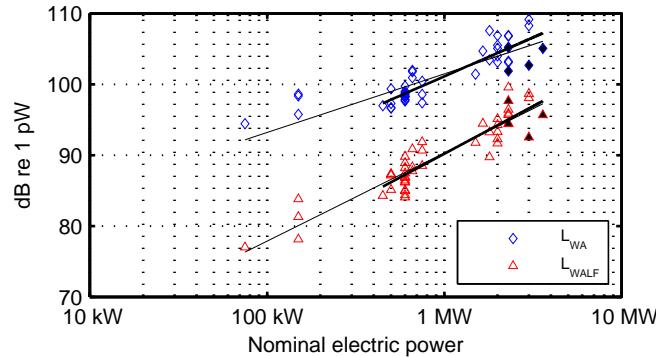


Figure 1. Apparent sound power levels (L_{WA} and L_{WALF}) in the reference direction as a function of turbine size. Wind speed 8 m/s. Regression lines: All turbines included (thin lines), four turbines below 450 kW excluded (bold lines). Black-filled marks are for Turbines 1-4.

It is – not surprisingly – seen that both L_{WA} and L_{WALF} increase with increasing turbine size. It is also noted that L_{WALF} increases more steeply than L_{WA} , meaning that the relative amount of low-frequency noise increases with increasing turbine size. The difference in slope of the regression lines for all data (thin lines) is statistically significant. Since the four smallest turbines may not be representative for modern turbines, regression lines have also been calculated without these turbines (bold lines). The slopes are slightly higher than with all turbines included, and the difference is smaller but still statistically significant.

The relative amount of low-frequency noise can be expressed as $L_{WALF} - L_{WA}$, and a linear regression of this yields a significant positive slope with all turbines included as well as with the four smallest turbines removed.

It is also seen in Figure 1 that there is some variation between turbines of the same size. Turbines of the same size may be of the same or different makes, or, for a few turbines below 2 MW, the same physical turbine measured at different occasions.

3.1.2 One-third-octave band spectra

One-third-octave-band analyses of the apparent sound power are shown in Figure 2.

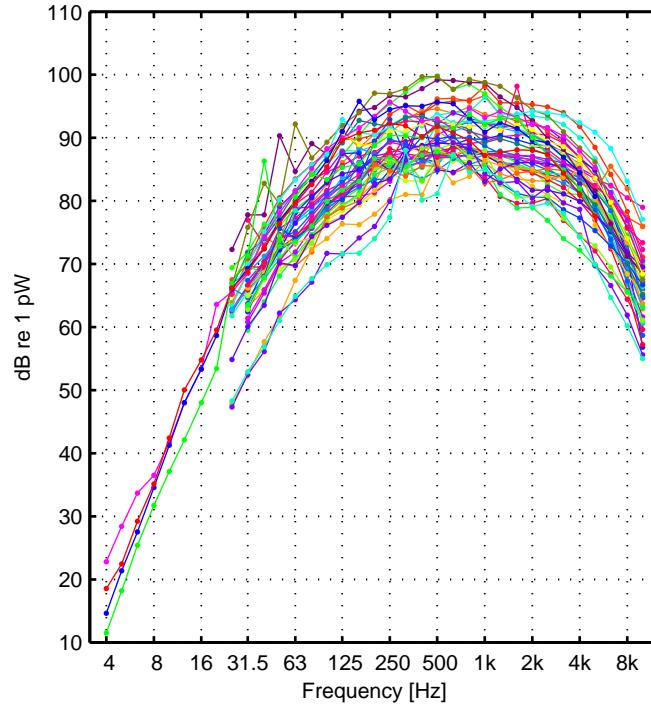


Figure 2. A-weighted apparent sound power levels in one-third-octave bands. 45 turbines with nominal electrical power 75 kW to 3.6 MW.

Regarding the infrasonic part of the spectrum, the G-weighted [12] apparent sound power levels, calculated from the one-third-octave-band levels, are 122-128 dB for the four turbines, where data is available. Even close to the turbines, e.g. in a distance of 150 m from the rotor centre, this will only give G-weighted sound pressure levels of 69-75 dB, which is far below the normal threshold of hearing [13]. This calculation does not account for possible near-field phenomena, e.g. from a closely passing blade.

At frequencies where data are available for all turbines, the level varies between turbines by 20 dB or more. This is to be expected, since the turbines cover a wide range of nominal electric power. In order to show possible spectral differences between turbines more clearly, the one-third-octave-band levels of all turbines have been normalized to the individual turbine's total A-weighted power. The result is shown in Figure 3.

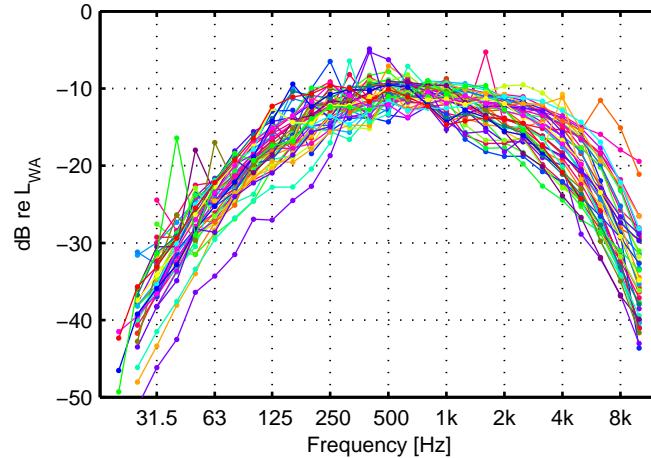


Figure 3. Normalized A-weighted apparent sound power levels in one-third-octave bands. 45 turbines with nominal electrical power 75 kW to 3.6 MW. (Normalized meaning that L_{WA} for the individual turbine has been subtracted all one-third-octave-band levels).

A possible difference in spectrum between small and large turbines was investigated by dividing the turbines into two groups: Turbines up to and including 2 MW, and turbines above 2 MW. Figure 4 shows the mean and the standard error of mean for each of the two groups.

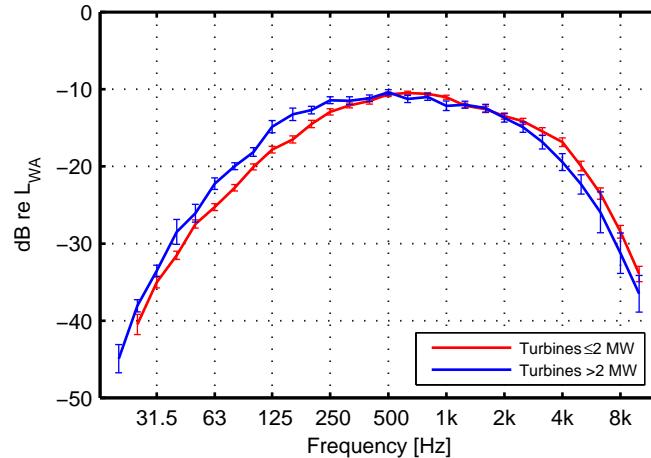


Figure 4. Normalized A-weighted apparent sound power levels in one-third-octave bands, means for two groups of turbines: ≤ 2 MW and > 2 MW. Error bars indicate \pm one standard error of mean.

The spectrum of the large turbines is clearly lower in frequency than that of the smaller turbines. The level difference is significant for all one-third-octave bands in the frequency range 63-250 Hz and at 4 kHz. (If the four smallest turbines are discarded, the difference is significant at the same frequencies plus 5 kHz).

The significant differences between small and large turbines are a moderate 1.5-3.2 dB, but at low frequencies, even small differences may affect human perception of the sound [14]. In addition, if low frequencies have a notable impact on requirements of distance to the neighbors, small differences may have large impact on the needed distance.

Figure 5 shows the mean of turbines up to and including 2 MW and individual turbines above 2 MW. The large turbines lie above the mean of the smaller turbines in virtually every single one-third-octave band below 315 Hz. Some of the turbines

have a peak in one or more one-third-octave bands, which may be due to the presence of tonal components. Tones are likely to have their origin in the turbine mechanics, e.g. the gearbox or secondary equipment such as a generator cooling system (see e.g. Wagner et al. [15]).

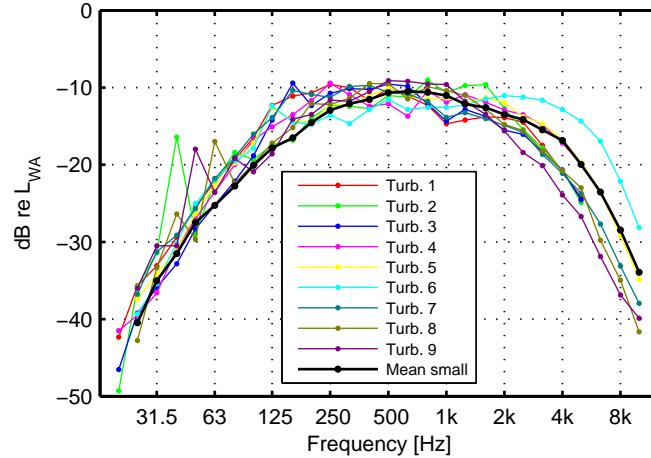


Figure 5. Normalized A-weighted apparent sound power levels in one-third-octave bands, mean of 36 turbines ≤ 2 MW (bold black line) and nine individual turbines > 2 MW.

At high frequencies, the picture is disturbed by an atypical pattern above 2 kHz for Turbine 6. There is no other data available from this turbine, for example for another wind speed or another direction, which could be used to verify that this is really noise from the turbine and not electrical noise as with some other turbines (see introductory remarks of Section 3). If Turbine 6 is disregarded at these frequencies, the large turbines are at or below the mean of small turbines in virtually every one-third-octave band above 2 kHz. The difference between means of the two groups is then significant also for the one-third-octave bands in the 2.5–10 kHz range.

3.1.3 Tonality

The tone analyses show that tones generally vary in level and frequency with wind speed. Figure 6 shows tonal audibility for the most prominent tones of Turbines 1–4.

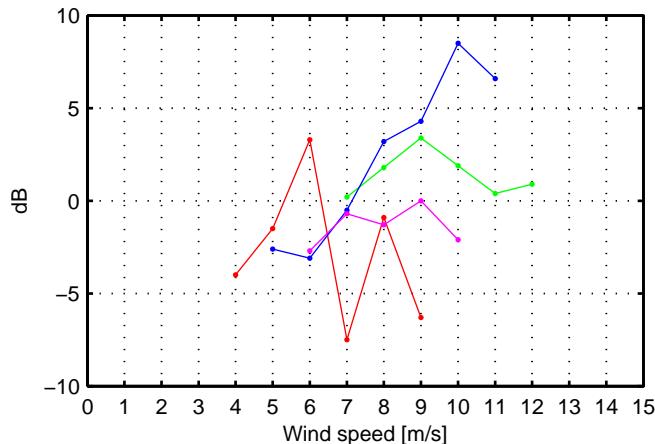


Figure 6. Tonal audibility, ΔL_a , as a function of wind speed for Turbines 1–4, reference direction. Turbine color code as in Figure 5.

Values are below 3-4 dB, except for Turbine 3 at high wind speeds. For Turbines 1 and 3, the data apply to a tone that varies with wind speed around 110-145 Hz, approximately the same frequency range for both turbines. For Turbine 2, the data apply to a tone with a nearly constant frequency around 40 Hz. Turbine 4 has several tones at higher frequencies, and those in the frequency range 800-1400 Hz alternately dominate, depending on wind speed. One-third-octave-band peaks can be identified in Figure 5 for the two turbines with tonality above 0 dB at 8 m/s (Turbine 2, 40 Hz, Turbine 3, 160 Hz).

ISO 1996-2 [16] specifies a tone penalty to be used, when the tonal audibility exceeds 4 dB. National criteria for tone penalty may vary, e.g. Danish regulation requires that the tonal audibility exceeds 6.5 dB, before a penalty is given [17].

Only one turbine exceeds the 4 dB limit and only at high wind speeds, where noise regulation may not apply. It is quite surprising that not even the most distinct tone in the one-third-octave-band spectra, the 40-Hz tone of Turbine 2, results in a tone penalty. This is most likely an effect of the critical band used for tone assessment being very wide at low frequencies. It is outside the scope of the present article to evaluate, if the tones would be perceived as being tonal, despite the lack of tone penalty.

3.1.4 Directivity

Figure 7 shows the directivity of the three turbines measured.

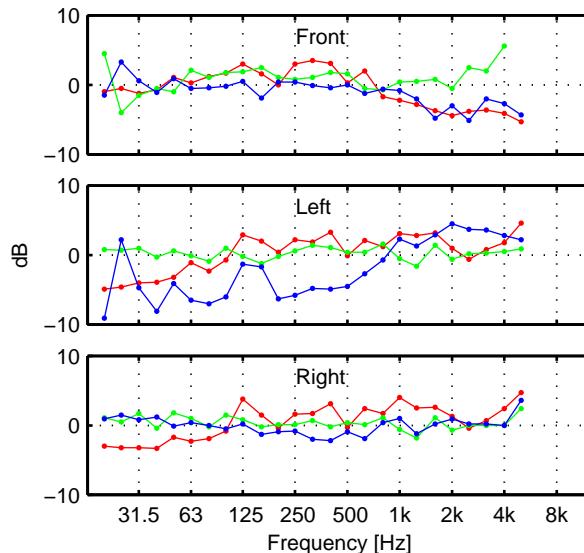


Figure 7. Directivity of Turbines 1-3. Wind speed 8 m/s except for Turbine 2, front, which was measured at 10 m/s (and compared to reference direction at 10 m/s). Data missing for Turbine 2 front at 5 kHz due to electric noise in the measurement. Turbine color code as in Figure 5.

The data differ somewhat between turbines, and it is difficult to find a general pattern. Both higher and lower levels are seen in other directions than the reference. At the lowest frequencies, a low directivity would be expected, but this is not seen in the data. A measured directivity may reflect a true directivity, but if the main noise source is to one side in the rotor plane, e.g. at the down going blade as shown by Oerlemans and Schepers [18] and Oerlemans et al. [19], the measurement in this side is closer to the source, and a false indication of directivity may result.

A possible source of error for the directivity data is that the measurements for the various directions do not always refer to the same period. Each of the other directions was in fact measured together with the reference direction, but they were not all measured at the same time. Only one data set exists for the reference direction, and thus this cannot apply to all directions. At low frequencies, poor signal-to-noise ratio may be responsible for large uncertainty.

The direction from the turbine to neighbors is typically more horizontal than the direction to the measurement positions. In particular, if sound is radiated from synchronous vibrations in blades and/or tower, chances are that radiation will be higher perpendicular to the rotor plane and/or the tower, i.e. close to the horizontal plane. More knowledge is called for on this issue.

3.1.5 Effect of wind speed

Figure 8 shows L_{WA} as a function of wind speed for the four turbines, where data is available.

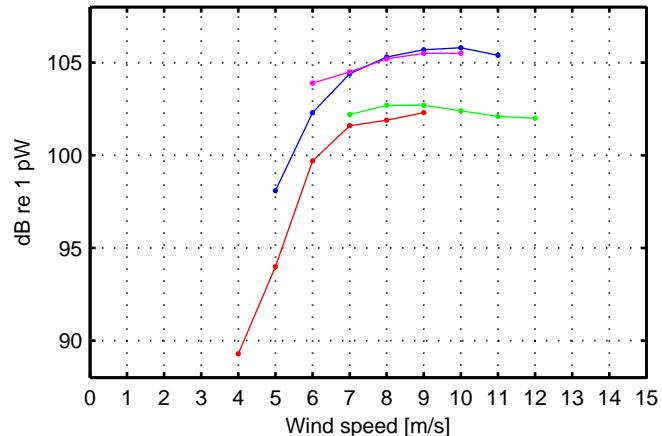


Figure 8. A-weighted apparent sound power level as a function of wind speed for Turbines 1-4. Turbine color code as in Figure 5.

The noise increases with wind speed but levels out or even decreases above 7-8 m/s. The four turbines are all pitch-controlled, and the observation is in line with the reports by Lee et al. [20] and Jung et al. [21] for pitch-controlled turbines.

3.2 Outdoor sound pressure levels at neighbors

For each of the large turbines, the distance needed for the A-weighted sound pressure level to decrease to 35 dB was derived. Pedersen and Waye [22] have shown that around this level, the percentage of highly annoyed persons increases above 5 %, and the percentage of annoyed persons increases above 10 % (Pedersen et al. [23]). Pedersen and Nielsen [24] recommended a minimum distance to neighbors so that the wind turbine noise would be below 33-38 dB. A limit of 35 dB is used for wind turbines, e.g. in Sweden for quiet areas [25]. It is also the evening/night limit for recreational areas in Denmark for industrial noise [26] (but not for wind turbine noise [11]). Table 1 shows the distances for the individual turbines as well as various key figures at the 35-dB distances.

Table 1. Key figures at the distance from a single turbine, where the total A-weighted sound pressure level is 35 dB. Distance is given as slant distance to rotor center, which, for actual turbine heights, is close to horizontal distance.

	Turbine									Mean small
	1	2	3	4	5	6	7	8	9	
Distance [m]	629	647	879	822	678	758	713	1227	1144	453
L_{pA} [dB]	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
L_{pALF} [dB]	28.8	26.7	28.9	27.6	28.0	29.1	28.8	27.0	27.0	24.8
$L_{pALF}-L_{pA}$ [dB]	-6.2	-8.3	-6.1	-7.4	-7.0	-5.9	-6.2	-8.0	-8.0	-10.2
L_{pG} [dB]	59.1	54.5	55.0	58.0						

The minimum distance, where a 35-dB limit is complied with, varies considerably between the large turbines, even when the turbines are relatively equal in size (2.3-3.6 MW). The distance varies from slightly over 600 m to more than 1200 m.

The one-third-octave-band spectra at the same distances are shown in Figure 9.

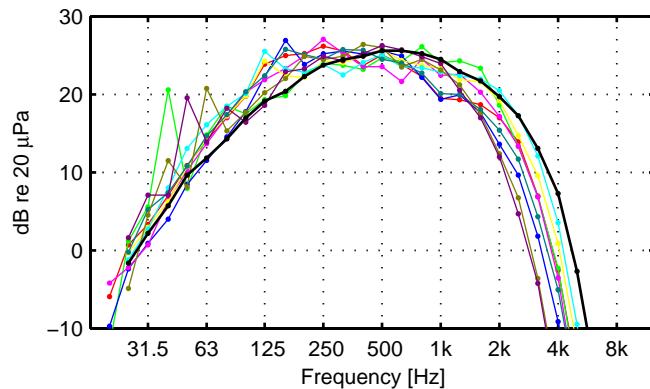


Figure 9. A-weighted one-third-octave-band sound pressure levels at the distance from a single turbine, where the total A-weighted sound pressure level is 35 dB (see Table 1). Turbine color code as in Figure 5.

At these distances, the air absorption plays a role. It affects mainly the high frequencies, and the result is that the shift of the spectrum towards lower frequencies becomes even more pronounced than for the source spectrum (compare with Figure 5).

It is important to note that, for several turbines, the highest one-third-octave-band level is at 250 Hz or lower, even when A-weighted levels are regarded (Figure 9). It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbors, and that the low frequency sound must be treated seriously in the assessment of noise from large turbines.

In many cases, A-weighted outdoor levels in excess of 35 dB are allowed. As an example, for houses outside official residential or recreational areas, Danish regulation allows 44 dB [11]. For visual reasons, the Danish regulation has a setback distance for dwellings of four times the total turbine height, and at this distance, the level is often below 44 dB for a single turbine. However, 44 dB may certainly occur further away than four times the turbine height, when several turbines are together in wind farms.

Table 2 shows distances to small wind farms, where the A-weighted sound pressure level is 44 dB, as well as various key figures at those distances.

Table 2. Key figures at distances, where the total A-weighted sound pressure level is 44 dB. Wind farm with two rows of each 6 identical turbines, 300 m distance between turbines in both directions (200 m for small turbines). Observer point centered at long side. Distance indicated as slant distance to closest turbine.

	Turbine									Mean small
	1	2	3	4	5	6	7	8	9	
Distance [m]	530	546	831	759	585	679	631	1241	1142	393
L_{pA} [dB]	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0	44.0
L_{pALF} [dB]	37.9	35.9	38.1	36.8	37.2	38.3	38.0	36.3	36.3	33.9
$L_{pALF}-L_{pA}$ [dB]	-6.1	-8.1	-5.9	-7.2	-6.8	-5.7	-6.0	-7.7	-7.7	-10.1
L_{pG} [dB]	68.4	63.9	64.6	67.4						

4 General discussion

4.1 Noise versus turbine size

The data material gives a useful overview of the sound power emitted by wind turbines of different sizes, and, with caution, it may be possible to use the data to estimate the apparent sound power level of future, larger turbines. Figure 10 repeats the data for L_{WA} from Figure 1, now with an extrapolation towards higher nominal electric power, and data for the regression line inserted.

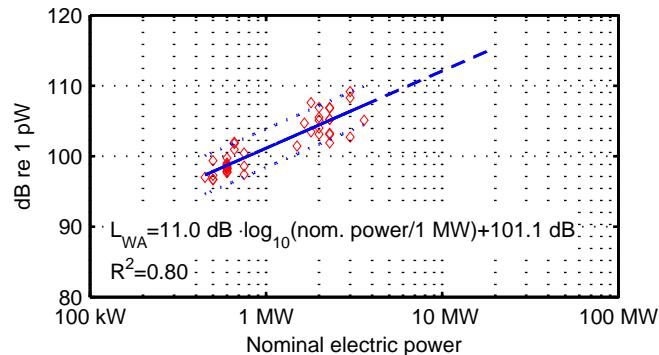


Figure 10. Apparent sound power level (L_{WA}) as a function of turbine size, four turbines below 450 kW excluded, wind speed 8 m/s. Linear regression line, standard error of estimates (s.e.e.) 1.64 dB. Extrapolation dashed, 90 % confidence intervals (dotted) based on s.e.e.

The regression line in Figure 10 corresponds to the following connection between the apparent sound power, P_A , and the nominal electric power, P_E :

$$P_A = \text{constant}_1 \cdot \left(\frac{P_E}{1 \text{ MW}} \right)^{\frac{\text{slope}}{10 \text{ dB}}} \quad (2)$$

where *slope* is the slope of the regression line, and *constant*₁ can be derived from the last term of the regression line. Since the slope is 11.0 dB, the exponent is 1.10, meaning that the apparent sound power increases more than proportionally to the nominal electric power. Thus, to the extent that turbines follow the trend of the regression line, a turbine of double size emits more than the double sound power.

The area *A* of the circle, within which a certain noise limit is exceeded, is of particular interest. The radius of the circle can be found by solving Equation (1) with respect to

d , and, if omitting the atmospheric absorption that mainly has effect at high frequencies and at long distances, it is found that the area is proportional to the apparent sound power. After insertion of Equation (2), it follows that

$$A = \text{constant}_2 \cdot P_A = \text{constant}_2 \cdot \text{constant}_1 \cdot \left(\frac{P_E}{1 \text{ MW}} \right)^{\frac{\text{slope}}{10 \text{ dB}}} \quad (3)$$

where constant_2 depends on the noise limit.

Thus, at the regression line, the noise-occupied area increases more than proportionally to the nominal electric power. This is a remarkable result, when considering today's development with constantly increasing turbine sizes and even, at least in Denmark, replacing many small turbines with few larger. From a noise pollution point of view, this seems as a step back. If the installed nominal electric power is the same, large turbines occupy a larger area with noise than small turbines do.

It must be added that the slope of the regression line is not significantly higher than 10 dB. With a slope of 10 dB, the noise-occupied area is the same for small and large turbines for the same installed nominal electric power.

4.2 Variation between turbines

The data in Figure 10 are based on measurements on single turbines. In order to account for variations between different samples of the same model, somewhat higher apparent sound power levels should be used in project planning. According to IEC 61400-14 [27], manufacturers should declare values that are 1.645 times the standard deviation between turbines higher than the mean of turbines of the given model. This value corresponds to the upper limit of a 90 % confidence interval, meaning that the probability is 5 % that a random sample turbine emits more noise than reflected by the declared value.

The size of the margin thus depends on the variation between turbines of the actual model. The standard deviations in Figure 10 for turbines of the same size and make range from 1.6 to 3.5 dB, when disregarding sizes that comprise repeated measurements on one or more turbines. Since the standard deviation must be multiplied by 1.645 to obtain the margin, it may easily end up in several decibels.

Broneske [28] pointed out that manufacturers often declare values that do not have the safety margin specified in IEC TS 61400-14. It is also the present authors' impression that minimum distances to dwellings are often calculated from noise data that lack an appropriate safety margin. Using data without safety margin, such as mean values for a given turbine model, measurements from a single turbine, or "best guess" for future turbines, gives in principle a probability of 50 % that the actual erected turbine(s) will emit more noise than assumed, and that noise limits will be exceeded, if the project is planned to the limit.

It is noted that small changes in apparent sound power level may result in sizeable changes in distance requirements. As an example, for a single turbine, 3 dB higher apparent sound power level results in a 41 % higher distance requirement.

4.3 Spectrum of large turbines

In Section 3.1.2, the spectral difference between small and large turbines was seen in terms of differences in the normalized apparent sound power levels for certain one-third-octave bands. As an alternative way of regarding this, Figure 11 shows the mean normalized spectra of large and small turbines, but with the data for small turbines shifted one third of an octave down in frequency.

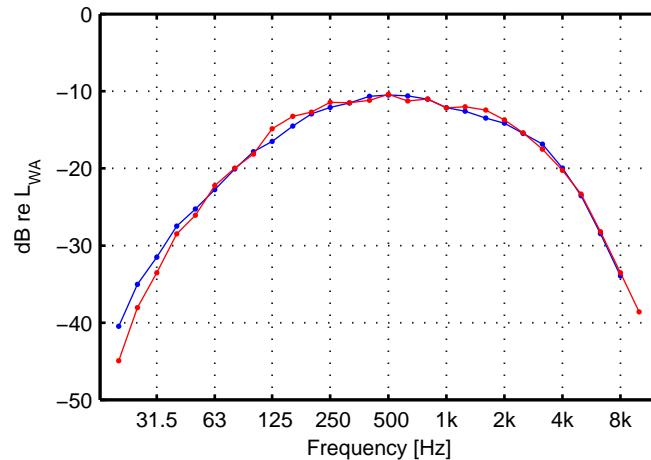


Figure 11. Normalized apparent sound power levels in one-third-octave bands. Mean of two groups of turbines: ≤ 2 MW and > 2 MW, group of turbines ≤ 2 MW shifted one third of an octave down in frequency. (Turbine 6 disregarded above 2 kHz, see Section 3.1.2).

The two curves are very close in the main frequency range, meaning that the spectrum has maintained its shape but shifted about one third of an octave down in frequency from the small to the large turbines (compare with Figure 4). Differences at the lowest frequencies may be real or be the result of uncertainty due to high background noise at these frequencies, a matter that is not fully expounded in the data material.

For the reader who might think that a shift of a single third octave is very modest, it is worth noting that it is the same as the musical interval of a major third, nearly the difference between two adjacent strings on a guitar.

The logarithmic means of the nominal electric power of the small and large turbines are around 650 kW and 2.6 MW, respectively, thus the downward spectral shift of approximately one third of an octave relates to an upward shift of the nominal electrical power by a factor in the order of 4. It would thus be appropriate to suggest a further downward spectral shift of the same amount for future turbines in the 10-MW range.

As a supplement to the linear regression and the extrapolation for L_{WA} in Figure 10, model spectra have been constructed for turbines around 2.5, 5, and 10 MW for possible (and cautious) use in future projects. Figure 12 shows a sixth-order polynomial regression of the mean data for turbines above 2 MW.

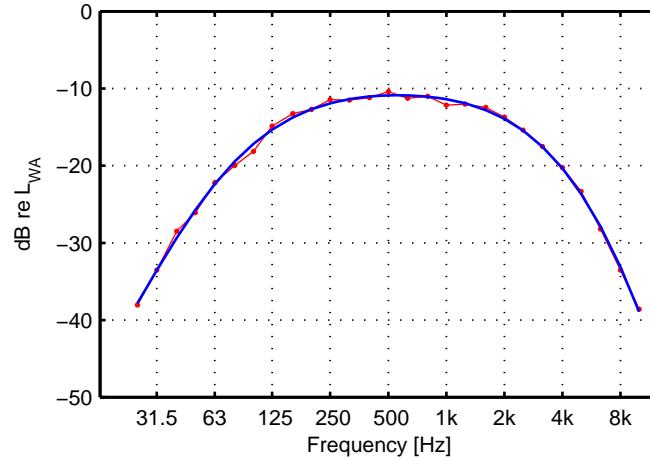


Figure 12. Sixth-order polynomial regression (bold line) for mean of normalized apparent sound power levels (dots and thin line) for turbines with a nominal electric power above 2 MW (Turbine 6 disregarded above 2 kHz, see Section 3.1.2).

4.4 Data from project WINDFARMperception

A study of visual and acoustic impact of wind turbines on residents was carried out by van den Berg et al. [29]. As part of the study (known as project WINDFARMperception), measured spectra of apparent sound power from wind turbines were collected, and 28 octave spectra were selected to represent turbines with nominal electric power in the 80 kW-3 MW range at a wind speed of 8 m/s (10-m height). Only four turbines are above 2 MW, but if three 2 MW turbines are included in the group of large turbines, it is possible to make a relevant comparison of large and small turbines. Figure 13 shows means of turbines < 2 MW and ≥ 2 MW.

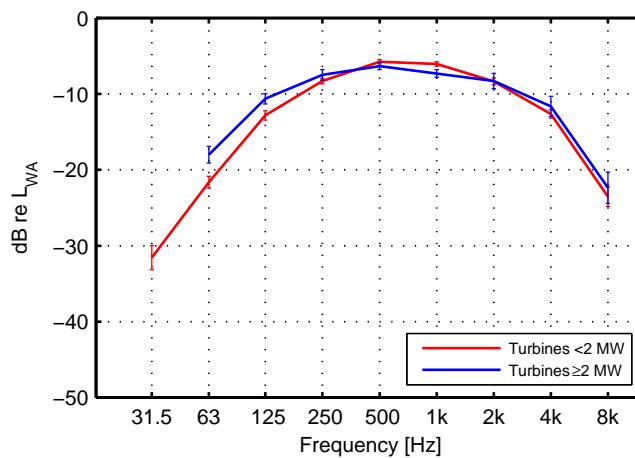


Figure 13. Normalized A-weighted apparent sound power levels in octave bands, means for two groups of turbines: < 2 MW and ≥ 2 MW. Data from van den Berg et al. [29, Appendix D]. Error bars indicate \pm one standard error of mean. (None of the large turbines was measured in the 31.5-Hz octave band).

Also with these data, the low-frequency part is clearly higher for large turbines than for small. The level differences at 63 and 125 Hz are statistically significant.

The differences (3.6 and 2.2 dB) are in the same order of magnitude as the differences in the present investigation (compare with Figure 4). In addition, a comparison with data of the present investigation converted to octave bands shows comparable values in the two investigations, see Figure 14. (There is no overlap in

original data). Data from the two investigations for the same power group are not significantly different at any frequency.

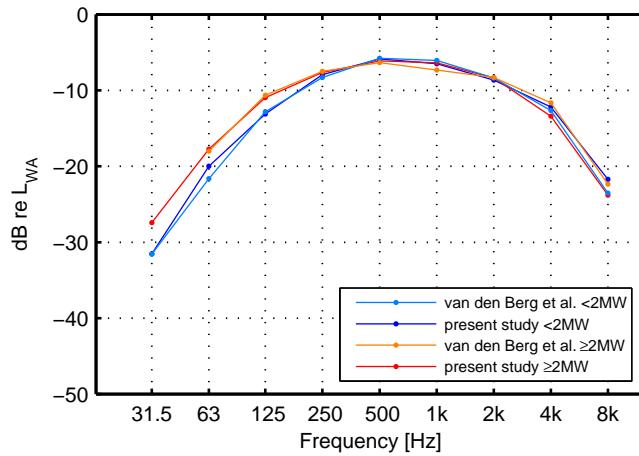


Figure 14. Normalized A-weighted apparent sound power levels in octave bands, means for two groups of turbines: <2 MW and ≥ 2 MW and from two investigations: Present investigation (converted to octave bands) and van den Berg et al. [29, Appendix D].

4.5 Tonal components

Søndergaard and Madsen [3, 30] conclude 1) that the “frequency spectra of the aerodynamic noise from the rotor blades of the largest wind turbines does not deviate significantly from the spectra for smaller wind turbines. This means that for the aerodynamic noise the low frequency range is not more prominent for large turbines than for small turbines”, 2) that the observed “slightly higher relative amount of low frequency noise is mainly caused by gear tones at the frequencies below 200 Hz”, and 3) that this “is not unusual for prototypes and usually the fully developed commercial wind turbines are improved on the noise emission, especially concerning audible tones in the noise”.

However, these conclusions are not substantiated by adequate statistics or other data analyses. The separation of aerodynamic noise and gear noise referred to is not explained, and data are not given. Regarding the development of noise from prototypes to commercial turbines, no data or references are given. If the turbines of the present project are looked upon, it is unclear, whether Turbines 5-11 are prototypes or not, since the turbines are anonymous, and the informations diverge between reports. The original report [3] only specifies Turbines 1-4 as prototypes, but a summarizing report [30] refers to all the turbines above 2 MW as prototypes. If Turbines 5-11 are prototypes, the third conclusion is made without data for large commercial turbines. If Turbines 5-11 are commercial turbines, it is worth noting that also some of these have obvious one-third-octave-band peaks (Figure 5), and that their noise emissions (L_{WA} or L_{WALF}) are not lower than those of Turbines 1-4, perhaps on the contrary (Figure 1).

Regarding reduction of tonal noise, Søndergaard and Madsen refer to the tone penalty as a means in maintaining the reduction, before the turbines are put on the market, and they use expressions like “the necessary tone reduction” [30] and “...reduced to a level where there is no penalty, according to the Danish rules...” [4, 30]. They have evidently overlooked the fact that the results of their tone analyses will not release a tone penalty to any of the turbines (Section 3.1.3).

A closer look at the data reveals that, even when some of the one-third-octave-band peaks at low frequencies are very distinct, the peaks are not in general responsible for the difference between small and large turbines. Figure 15 shows an imagined situation, where all peaks below 200 Hz have been removed from the large turbines by replacing the level at the peaks with levels obtained by linear interpolation between the levels in the two adjacent one-third-octave bands. 1-3 peaks have been removed for each turbine, except for Turbine 4, which does not have peaks in this frequency range. Only removal of the 40-Hz peak of Turbine 2 affects the mean of the large turbines by more than 1.0 dB.

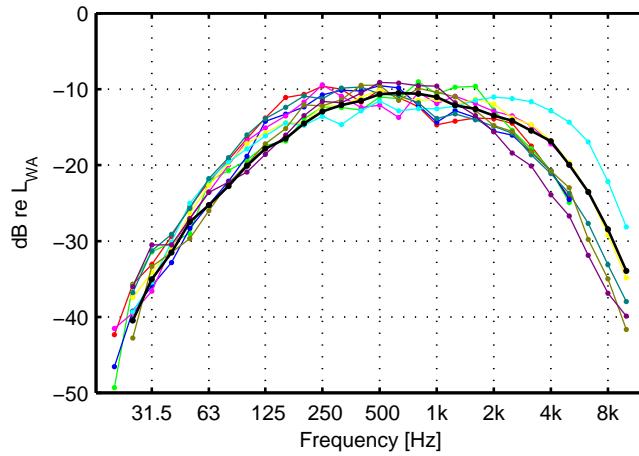


Figure 15. Normalized A-weighted apparent sound power levels in one-third-octave bands, individual turbines >2 MW and mean of 36 turbines ≤2 MW. One-third-octave-band peaks below 200 Hz have been removed from the large turbines by replacing the levels at the peaks by levels obtained by linear interpolation between the levels at the two adjacent one-third-octave-band frequencies. Turbine color code as in Figure 5.

Generally, the large turbines are still above the mean of the small turbines in the low-frequency range. The difference between the means of large (> 2 MW) and small turbines (≤ 2 MW) is still significant in the same one-third-octave bands as they were with the peaks.

The striking similarity with the data by van den Berg et al. [29] (Figure 14) suggests that the mean data for large turbines from the present project, including the tones, are representative for large wind turbines.

4.6 Ground reflection

In the calculations of sound pressure levels at the neighbors, the ground reflection is accounted for by adding 1.5 dB to the direct sound. As mentioned in Section 2.3, the 1.5-dB value is used by Danish regulation. Swedish guidelines add 3 dB to the direct sound (for distances up to 1000 m) [31], a value that also follows from ISO 9613-2 [9] for the 31.5 and 63 Hz octave frequencies, irrespective of the ground surface. During measurements of sound emission from the turbines [7], it is assumed that the ground reflection adds as much as 6 dB to the direct sound. Certainly, a reflecting board is used during measurements, but this has only little effect at low frequencies, where the assumed 6-dB reflection is due mainly to the ground itself.

Possible destructive interference between the direct sound and the ground reflection due to elevation of the receiver above ground will have little impact at low frequencies. As an example, for a source height of 75 m, a distance of 800 m and a receiver height of 1.5 m, the delay between the direct sound and the ground reflection

will only be 0.8 ms, which corresponds to a first dip in the sound transmission at 625 Hz.

On this background, it is reasonable to suspect that the addition of 1.5 dB for the ground reflection is too low at low frequencies, and that higher values up to a theoretical maximum of 6 dB would be more appropriate. Thus, the procedure used to calculate outdoor sound pressure levels at the neighbors is likely to underestimate the low-frequency sound.

4.7 Windows

The measurements of sound insulation were made with closed windows. However, in large parts of the world, many people prefer to sleep with the windows at least slightly open, and WHO recommends that noise limits should permit this [32], 33]. In Denmark, indoor measurements of low-frequency noise are usually made with closed windows, but if the complainant finds the noise as being louder with open windows, measurements should also be made for this situation [34]. It would therefore have been appropriate to measure the insulation also with slightly open windows and to estimate the resulting indoor sound pressure levels accordingly.

4.8 Atmospheric conditions

All previous calculations assume spherical sound propagation, i.e. a 6 dB reduction of sound pressure level per doubling of distance. During certain atmospheric conditions, e.g. with temperature inversion or low-level jets, there may be a sound reflecting layer in a certain height, and thus the propagation beyond a certain distance is more like cylindrical propagation with only 3 dB reduction per doubling of distance. This was observed for low frequencies e.g. by Hubbard and Shepherd [35] and explained e.g. by Zorumski and Willshire [36] and Johansson [37]. Above sea, Swedish guidelines generally assume cylindrical propagation beyond a distance of 200 m [31], a distance supported by data by Bolin et al. [38], who showed reflection in a height in the order of 100-200 m.

With cylindrical propagation beyond 200 m, the following equation applies (for distances above 200 m):

$$L_p = L_{WA} - 20 \text{ dB} \cdot \log_{10} \left(\frac{200 \text{ m}}{1 \text{ m}} \right) - 10 \text{ dB} \cdot \log_{10} \left(\frac{d}{200 \text{ m}} \right) - 11 \text{ dB} - \alpha \cdot d + 1.5 \text{ dB} \quad (4)$$

Table 3 and Figure 16 show key figures and one-third-octave-band spectra, respectively, at the distances from the turbines, where the A-weighted sound pressure level has decreased to 35 dB, assuming cylindrical propagation beyond 200 m.

Table 3. Key figures at distances, where the total A-weighted sound pressure level is 35 dB, cylindrical propagation assumed beyond 200 m. Distance is given as slant distance to rotor center, which, for actual turbine heights, is close to horizontal distance

	Turbine									Mean small
	1	2	3	4	5	6	7	8	9	
Distance [m]	1476	1414	2373	2100	1562	1829	1776	3482	3152	827
L_{pA} [dB]	35,0	35,0	35,0	35,0	35,0	35,0	35,0	35,0	35,0	35,0
L_{pALF} [dB]	29,7	28,2	30,3	29,2	29,4	30,7	30,0	29,7	29,6	25,6
$L_{pALF}-L_{pA}$ [dB]	-5,3	-6,8	-4,7	-5,8	-5,6	-4,3	-5,0	-5,3	-5,4	-9,4
L_{pG} [dB]	60,4	56,2	57,1	60,0						

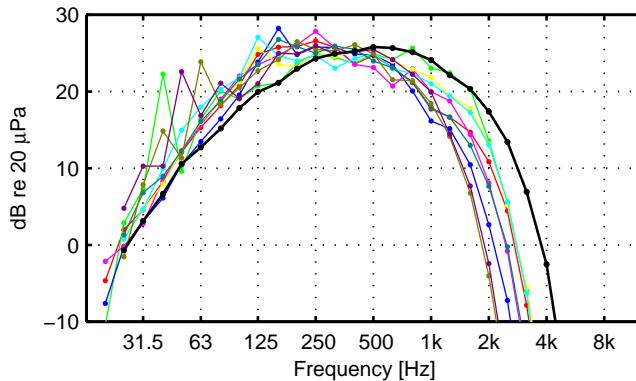


Figure 16. A-weighted one-third-octave-band sound pressure levels at the distance, where the total A-weighted sound pressure level is 35 dB (see Table 3). Cylindrical propagation assumed from 200 m. Turbine color code as in Figure 5.

Much longer distances (1414–3482 m) are needed than with pure spherical propagation, and the low-frequency character of the spectrum has become even more pronounced (compare with Table 1 and Figure 9). Cylindrical propagation may thus explain case stories, where rumbling of wind turbines is claimed to be audible kilometers away. A worst-case scenario combining temperature inversion with a wind park acting as a line source in a certain distance range could theoretically reduce the geometrical attenuation in that range to zero. However, more knowledge is needed about atmospheric conditions and the occurrence of various phenomena.

Also other phenomena related to the atmospheric conditions deserve some attention. It is normally assumed that the wind speed increases logarithmically with increasing height above ground, starting from zero speed at a height equal to the *roughness length* of the ground surface. Thus, knowing the roughness length, the wind speed at all heights can be determined from measurements in a single height. The wind speed in a height of 10 m is used as a reference for measurements of wind turbine noise [7].

However, several studies have shown that actual wind-speed profiles vary a lot and often deviate substantially from the assumed logarithmical profile (e.g. van den Berg [39], Botha [40], Palmer [41], Bowdler [42]). In a stable atmosphere, which often exists at night, variations with height can be much larger than assumed with high wind speed at turbine height and little wind at ground. A large variation of wind speed across the rotor area increases the modulation of the turbine noise, and the normal ‘swish-swish’ sound turns into a more annoying, ‘thumping’, impulsive sound as reported by e.g. van den Berg [43, 44, 45] and Palmer [46]. The effect is more

prominent with large wind turbines, where the difference in wind speed between rotor top and bottom can be substantial. The effect is usually not reflected in noise measurements, which are mainly carried out in the daytime, when the logarithmic profile is more common.

Another consequence of large wind speed variation with height is that the turbine may emit noise corresponding to a high wind speed – and much higher than assumed from the wind speed measured at 10 m – while it is all quiet at the ground. Thus, there is more turbine noise than expected and less wind; hence, the turbine noise will not be masked with natural wind-induced sound, as it might have been with the assumed logarithmic wind profile.

Several authors have argued that the logarithmic wind-speed profile and the 10-m reference height are inadequate with the size of modern turbines (e.g. van den Berg [44], Botha [40], Palmer [41], Almgren et al. [47]), and a revised IEC 61400-11 will use the actual wind speed in the turbine hub height [48]. Wind profiles and statistics for the actual place can then be applied in noise prediction and regulation.

5 Conclusions

The results confirm the hypothesis that the spectrum of wind-turbine noise moves down in frequency with increasing turbine size. The relative amount of emitted low-frequency noise is higher for large turbines (2.3-3.6 MW) than for small turbines (≤ 2 MW). The difference is statistically significant for one-third-octave bands in the frequency range 63-250 Hz. The difference can also be expressed as a downward shift of the spectrum of approximately one third of an octave. A further shift of similar size is suggested for turbines in the 10-MW range.

When outdoor sound pressure levels in relevant neighbor distances are considered, the higher low-frequency content becomes even more pronounced. This is due to the air absorption, which reduces the higher frequencies a lot more than the lower frequencies. Even when A-weighted levels are looked upon, a substantial part of the noise is at low frequencies, and for several of the investigated large turbines, the highest one-third-octave-band level is at or below 250 Hz. It is thus beyond any doubt that the low-frequency part of the spectrum plays an important role in the noise at the neighbors.

The turbines do emit infrasound (sound below 20 Hz), but levels are low, when human sensitivity to these frequencies is accounted for. Even close to the turbines, the sound pressure level is much below the normal hearing threshold, and infrasound is thus not considered a problem with turbines of the investigated size and construction.

The low-frequency noise from several of the investigated large turbines comprises tones, presumably from the gearbox, which result in peaks in the corresponding one-third-octave bands. The tone penalty does not provide a means in having the tones reduced, since they are not sufficiently distinct to release a penalty. The spectral difference between large and small turbines remains statistically significant, even if the one-third-octave-band peaks are removed.

The emitted A-weighted sound power increases proportionally to the nominal electric power, or, most likely, even more. Consequently, large turbines occupy the same – or

possibly even larger – areas with noise, as small turbines do, when they have the same total installed electric power.

There are differences of several decibels between the noise emitted from different turbines of similar size, even if the turbines are of the same make and model. It is therefore not feasible to make calculations down to fractions of a decibel and believe that this hold for the turbines actually set up. A safety margin must be incorporated at the planning stage in order to guarantee that the actual erected turbines will comply with noise limits. An international technical specification exists for this, but it is often not used.

Under certain atmospheric conditions, e.g. temperature inversion, the noise may be more annoying and – in particular the low-frequency part – propagate much further than usually assumed. More knowledge is needed on such phenomena and their occurrence.

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