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Assessment of low-frequency noise from wind turbines in Maastricht[1]

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1 Preface

The noise from a planned wind-farm project at Lanakerveld in Maastricht has been evaluated in several reports. Boukich and Koppen[1] studied alternative projects, and Koppen[2] made additional analyses including analyses of low-frequency noise. Koppen[3] analyzed the optimized and selected project comprising four Vestas V112-3.0 MW turbines with 119 meter hub height. A special analysis of low-frequency noise in the selected project was made by Koppen[4]. Upon request from local residents, an additional analysis of low-frequency noise was made by Koppen[5] taking into account information given in an article by Møller and Pedersen[6] as well as new regulations of low-frequency noise from wind turbines in Denmark[7]. Subsequently, the City Council of Maastricht has requested the present report in particular addressing certain questions. Unfortunately, only the latest Dutch report[5] was made available in English, but employees of the City Council and Arcadis Nederland BV have been very helpful answering questions. In addition, we have used original noise measurements[8] and data sheets[9,10].

The report is public and may be re-distributed as a whole.

2 Introduction

A brief introduction to low-frequency sound is relevant.

Sound and noise can be characterized by their frequency. The range from 20 Hz to 20 kHz (20 cycles per second to 20,000 cycles per second) is usually called the normal hearing range or the audio frequency range. Sound with frequencies above 20 kHz is denoted ultrasound and cannot be heard by humans.

Sound with frequencies below 20 Hz is denoted infrasound. It is usually understood that also infrasound cannot be heard, but this is wrong. Infrasound is audible at least down to 1 or 2 Hz, provided that the sound pressure level is sufficiently high. The sound is perceived with the ears, usually giving a feeling of pressure at the eardrums.

The 20-200 Hz range is denoted the low-frequency range. Slightly different limits are sometimes used, e.g. 10-160 Hz.

[1] Prepared for the City Council of Maastricht, ISBN 978-87-92328-82-3, Aalborg University, 10. April 2012.

Everyone knows from his everyday surroundings the perception of hearing sound at low and infrasonic frequencies. Typical low-frequency sound sources are ventilation systems, compressors, idling trucks and the neighbor's stereo. Infrasound at an audible level is usually found on the car deck of a ferry and when driving a car with an open window. However, infrasound is most often accompanied by sound at other frequencies, so the experience of listening to pure infrasound is not common.

For a thorough review of the human hearing at low and infrasonic frequencies, see Møller and Pedersen[11].

The level of the infrasound produced by modern wind turbines is so low that the sound cannot be perceived by humans even close to the turbines[6]. Much higher levels occur elsewhere in our daily environment, e.g. in transportation.

Low-frequency wind turbine noise is usually described as humming or rumbling. It may have a more or less pronounced tonal character, e.g. in terms of tones that fluctuate and vary in level and/or pitch, or of tone-like pulses excited with regular or random intervals. The feeling of pressure at the eardrums is also reported. It is characteristic that the noise varies a lot in time and with wind and other atmospheric conditions.

The rate of modulation of the low-frequency noise from wind turbines (and higher frequencies as well) is often in the infrasonic frequency range, e.g. the blade passage frequency, and the noise may thus be mistaken as infrasound, even when there is little or virtually no infrasound present.

3 Specific questions

The questions asked by the City Council are considered in each their subsection. The full list is given in Annex A.

3.1 Effects of Low Frequency Noise have been researched a lot. On which aspects does the research (approach) of Møller and Pedersen differ from that of other researchers?

It is true that many investigations have studied effects of low-frequency noise in general. However, only few studies have addressed low-frequency noise from wind turbines specifically.

Møller and Pedersen[6] did not investigate effects of low-frequency noise but focused on the physical noise from wind turbines, such as emitted sound power, its frequency distribution, propagation to neighbors and transmission into neighbor houses.

The approach of Møller and Pedersen does not differ from that of other researchers. Most measurements were made according to international standards, and conventional statistical methods were used in the analyses. Possible annoyance from low-frequency noise was evaluated from its audibility and contribution to the total noise as well as standard criteria used for other noise sources.

The investigation reported by Møller and Pedersen was to our knowledge the first study focusing on the relationship between low-frequency noise and turbine size. The measurements were made by the consultancy company Delta, who published the data in un-reviewed project reports by Søndergaard and Madsen[12,13,14] and Hoffmeyer and Søndergaard[15]. Madsen and Pedersen[16] added emission data from 17 new turbines of 1.8 to 3.6 MW. The added data were included in an updated report by Møller et al.[17] with essentially the same results and conclusions as those by Møller and Pedersen[6] however based on a larger material.

Differences do exist between the results by Delta and by us, but they are mainly moderate. Some of Delta's findings are not clearly reflected in their conclusions, though. Larger differences exist between the results and the interpretations given in press releases from Delta, The Danish Environmental Protection Agency (EPA) and the wind power industry, which might be claimed to underrate some of the findings and possible adverse effects of wind turbine noise.

At this place it is relevant to mention that Møller and Pedersen also analyzed Dutch measurements of wind turbine noise originally published by van den Berg et al.[18]. Virtually the same levels and the same differences between small and large turbines were found as in the Danish measurements.

It is recommended that readers make themselves acquainted with our original publications[6,17].

3.2 What are the main effects of Low Frequency Noise (LFN) on humans and when specifically do these effects occur?

Noise with prominent low-frequency components may affect human health and well-being to a larger extent than noise without such components.

At low frequencies, the loudness increases more steeply above the hearing threshold than at higher frequencies (see e.g. Whittle et al.[19], Møller and Andresen[20], Bellmann et al.[21], ISO 226[22]). Thus, a sound moderately above threshold may be perceived not only loud but also annoying (Andresen and Møller[23], Møller[24], Inukai et al.[25], Subedi et al.[26]). Since there is a natural spread in hearing thresholds between individuals, a low-frequency sound that is inaudible or soft to some people may be loud and annoying to others.

Low-frequency sound is particularly annoying, when it occurs alone or with low levels of sound at higher frequencies. This means that it is usually more annoying indoors than outdoors, since the high frequencies are more attenuated by the sound insulation of the house than the low frequencies are. Also it is often more annoying in the evening and at night, when it is otherwise quiet.

Prolonged exposure to audible low-frequency sound may cause fatigue, headache, impaired concentration, sleep disturbance and physiological stress as indicated by increased levels of saliva cortisol (see. e.g. Berglund et al.[27], Bengtsson et al.[28], Waye et al.[29], Waye et al.[30]).

There is no reliable evidence of physiological or psychological effects from infrasound or low-frequency sound below the hearing threshold (see e.g. Berglund and Lindvall[31]).

(The above paragraphs are partly quoted from Bolin et al.[32] and Møller and Pedersen[11]).

3.3 The Danish Government has changed the regulations for erecting wind turbines as a result of your research. Is that correct? And if so, what specific changes have been made?

The Danish regulations are given in a statutory order on noise from wind turbines[7]. The order was updated in 2011 to include specific rules for the low-frequency part of the noise (being effective by 1. January 2012).

3.3.1 Background

At the previous revision of the statutory order on wind turbine noise in 2006, the Danish EPA stated that regulation of low-frequency wind turbine noise would not be needed, because the general 20 dB indoor limit applied to other sources would automatically be complied with, when the normal outdoor noise limits were observed.

In fact, the EPA's own data showed the opposite[33], and during the following years, an increasing pressure was put on the EPA from neighbors, who complained about low-frequency noise from wind turbines. Moreover, scientific results supported the need for regulation, most recently the publications from Delta[16] and Aalborg University[6,17].

In October 2010, a report from Aalborg University revealed serious errors in the noise sections of the Environmental Impact Assessment (EIA) for a prestigious Danish test center for large wind turbines[34]. The law establishing the center had to be revised, and the handling of noise from wind turbines in the EPA attracted political attention in Parliament. The Minister of the Environment promised to introduce limits for low-frequency wind turbine noise.

3.3.2 Low-frequency limit

The general (i.e. not for wind turbines) Danish limit for low-frequency noise in dwellings is an indoor A-weighted sound pressure level of 20 dB (evening and night) and 25 dB (day). Only frequencies in the 10-160 Hz frequency range (third-octave frequencies) are included. The level is measured as the power average of the levels in three positions, of which two are in the living areas of the room, where the noise complainant perceives the noise as particularly loud. The third position is near a room corner (1-1.5 m height, 0.5-1 m from the walls). Due to the power averaging process, the final result is close to the level in the appointed high-level positions.

With the updated order, the 20 dB limit applies also for wind turbines at wind speeds of 6 and 8 m/s (wind turbines run around the clock).

Unlike for other noise sources, the low-frequency noise is not measured but calculated from measurements close to the turbine of the emitted sound.

The indoor sound pressure level L_{pA} is calculated using the following equation:

$$L_{pA} = L_{WA,ref} - 20\text{ dB} \cdot \log_{10}\left(\frac{d}{1\text{ m}}\right) - 11\text{ dB} + \Delta L_g - \Delta L_a - \Delta L_\sigma$$

$L_{WA,ref}$ is the apparent sound power level in the reference direction, basically measured according to IEC 61400-11[35], d the distance from the nacelle to the neighbor, ΔL_g correction for the ground reflection, ΔL_a

the air absorption equal to $\alpha_a \cdot d$, where α_a is the absorption coefficient, and ΔL_σ the sound insulation. ΔL_g, α_a and ΔL_σ are given in a table quoted here as Table 1.

Table 1. Constants used in the Danish regulation for calculating indoor low-frequency noise $L_{pA,LF}$.

Frequency (Hz)	10	12.5	16	20	25	31.5	40	50	63	80	100	125	160
ΔL_g (land) (dB)	6.0	6.0	5.8	5.6	5.4	5.2	5.0	4.7	4.3	3.7	3.0	1.8	0.0
ΔL_g (sea) (dB)	6.0	6.0	6.0	6.0	6.0	5.9	5.9	5.8	5.7	5.5	5.2	4.7	4.0
ΔL_σ (dB)	4.9	5.9	4.6	6.6	8.4	10.8	11.4	13.0	16.6	19.7	21.2	20.2	21.2
α_a (dB/km)	0	0	0	0	0.02	0.03	0.05	0.07	0.11	0.17	0.26	0.38	0.55

Calculations are made for the third-octave frequency bands 10-160 Hz and the levels summarized to give the A-weighted low-frequency sound pressure level $L_{pA,LF}$.

3.3.3 Comments to the low-frequency regulation

Based on the existing knowledge of the effects of low-frequency noise on humans, we consider the chosen limit of 20 dB for the A-weighted level of the 10-160 Hz frequency range as a reasonable limit.

In the new Danish statutory order for wind turbines, the noise is not measured but calculated. This need not be a problem, if the calculations are correct. But they are not.

The main problem is the sound insulation tabled in the statutory order. The values are based on measurements in 26 Danish houses published by Hoffmeyer and Jakobsen[36]. Unfortunately, these measurements were wrong.

The issue is that sound at low frequencies varies within a room – usually by many decibels – and as mentioned in Section 3.3.2, the level should – briefly explained – be measured, where the annoyed person finds it loudest. The sound insulation must be measured the same way in order to be applicable for calculations of relevant indoor levels from outdoor levels. But it was not. The indoor measurements were simply made at arbitrary positions that were not selected for a high level. Thus the obtained values of sound insulation are too high.

Figure 1 shows an example of the sound distribution in a room. Each frame shows the sound distribution in a given height, and the color scale gives the sound pressure level (scale at the right).

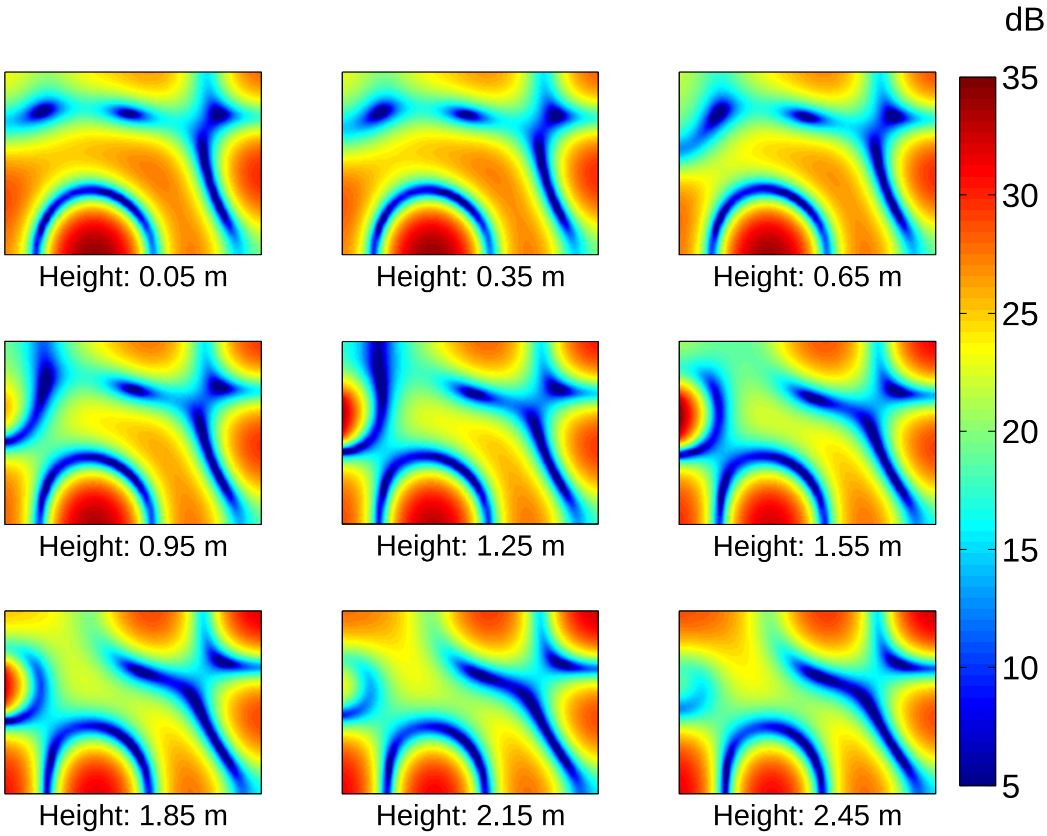

Figure 1. Example of simulated sound distribution in a room (5.0 m x 3.6 m x 2.5 m; L x W x H). The sound is a 112-Hz pure tone. The sound enters through a 90 cm x 90 cm opening (assumed window) at the left end wall. Probably as a surprise to many, this is not where the highest levels are found, which is at the lower side wall.

As seen, there are large areas with sound pressure levels of more than 25 dB, while less than 10 dB may be measured in other areas. The figure applies to an extreme situation with a pure tone in an empty room, but variations of 30 dB with pure tones and 20 dB with third-octave-band noise are not uncommon in real furnished rooms.

Together with a Swedish colleague, we pointed out the error in Hoffmeyer and Jakobsen's data[36] in a commentary[37] in the scientific journal where the measurements were published.

In a reply[38] to the commentary, Danish EPA employee Jakobsen seems to be of the opinion that it makes no difference, whether the measurements are made in the loudest areas or not. This is obviously wrong. The first author Hoffmeyer of the original publication did not sign the reply, and despite of many requests it has not been possible to clarify, whether he shares the views expressed in Jakobsen's reply.

Based on their measurements, Hoffmeyer and Jakobsen[36] proposed sound insulation data to be used for calculation of indoor low-frequency noise from wind turbines. Due to the measurement error, these values are too high. For the Danish regulation, values were increased even further by 2.2-4.1 dB depending on frequency.

As a result, the calculation of the Danish regulation gives values that underestimate the low-frequency noise that would be measured in neighboring houses.

The magnitude of the error is estimated to be around 5 dB, see Annex B.

Even when an error of 5 dB might seem small, it is far from being negligible. As mentioned in Section 3.2, the loudness and annoyance increase more steeply above threshold than at higher frequencies. This means that when the level is a few decibels above the 20 dB limit, the consequences are more severe, than if a limit at higher frequencies is exceeded by the same amount. Most people will hear a sound at 20 dB, and some will find it annoying. Few people would probably accept 25 dB in their home at night and hardly anyone would accept 30 dB.

In the argumentation for the new regulation, the EPA says*: "The Danish EPA finds that there will be a substantial noise nuisance, if the low-frequency indoor noise exceeds 20 dB in the evening and night. The perceived annoyance from low-frequency noise increases strongly, when the noise reaches above 20 dB".*[39] (Our translation).

3.3.4 Limits for the general noise

To complete the description of the Danish regulation, calculations and limits for total noise should be briefly mentioned.

The limits for total wind turbine noise were not modified in the update. The limits are outdoor A-weighted levels of 39 dB in residential areas except for residences in the open countryside, where the limit is 44 dB. These limits apply at a wind speed of 8 m/s at a height of 10 m. At a wind speed of 6 m/s, limits of 37 and 42 dB apply, respectively. The low set of limits also applies to recreational areas and areas for various institutions.

Unlike for other noise sources, the noise is not measured at neighboring dwellings, but measurements close to the turbines of the emitted sound are used to calculate theoretical outdoor sound pressure levels at the neighbors.

The noise is calculated using the same formula as for the indoor low-frequency noise, except that the sound insulation ΔL_σ is omitted. 1.5 dB is used for the ground reflection ΔL_σ (3.0 dB over sea), and absorption coefficients α_a for the full frequency range are given in a table quoted here as Table 2.

Table 2. Absorption coefficients used in the Danish regulation for calculating outdoor total sound pressure level L_{pA}.

Frequency (Hz)	50	63	80	100	125	160	200	250	315	400	500	630
α_a (dB/km)	0.07	0.11	0.17	0.26	0.38	0.55	0.77	1.02	1.3	1.6	2.0	2.4
Frequency (Hz)	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
α_a (dB/km)	2.9	3.6	4.6	6.3	8.8	12.6	18.8	29.0	43.7	67.2	105	157

3.4 Regarding the Arcadis Report, have the calculations and assessment of Low Frequency Noise been made correctly with respect to the Danish method and standards? If not, in what respect do they differ? Will recalculation lead to substantially different results?

We have the following comments to the Arcadis report[5].

Table 2 of the report has a data point for the relative spectrum at 20 Hz, which is reported to be from the article by Møller and Pedersen[6] (Table III). However, our article does not have data at this frequency. In the other end of the low-frequency range, for some odd reason, Table 2 does not include the frequencies 125 and 160 Hz.

Likewise, in the calculations, Arcadis used data points at 10, 12.5, 16 and 20 Hz allegedly from our article, where data points do not exist at these frequencies. Furthermore, the data point at 20 Hz used in the calculations is not the same as given in Table 2.

However, the extra data points have been given reasonable values, and since the noise at these lowest frequencies does not contribute much to the total low-frequency level, their exact value has only marginal impact on the final result. Nevertheless, the addition of data points to the Møller and Pedersen data should, of course, have been explained and discussed in the Arcadis report.

Except for this, the understanding and use of the Møller and Pedersen data are correct.

Also the understanding and use of the Danish regulation for low-frequency noise are correct. We have checked the calculations of low-frequency noise at the four selected neighbor positions and get the same results.

It should be noted that the 20-dB limit was actually exceeded in three of the four calculated positions in all scenarios and in all four positions in one scenario, which is not fully reflected in Table 3, where figures are rounded to nearest integer decibel. In Denmark, the limit is an absolute limit, which may not be exceeded.

Arcadis seems to be unaware of the measurement error in the insulation measurements behind the data of the Danish statutory order. Despite that this has been pointed out in the scientific literature, it may be considered excusable, since the order itself does not inform about the origin of the data.

3.5 In your opinion, is the noise spectrum referred to as Arcadis acoustic study in Tables 1 and 2 a realistic worst case scenario for calculating LFN effects produced by 3 MW wind turbines? If not, why not and can you indicate what the correct assumptions will be? Will this lead to substantially different results?

No, the spectrum of the original Arcadis study in these tables (Koppen[5], first rows of Table 1 and 2) does not represent a worst-case scenario. It may be so for the relative source level at certain frequencies, but not for all frequencies, and not for the final result, the noise at the neighbors.

We do not know the exact derivation of the Arcadis relative spectrum from the non-translated previous Dutch reports (Koppen[2,4]), but worst-case aspects have not been involved in the derivation of the two other relative spectra, and the final results of using the three sets of data are very similar (Koppen[5], Table 3).

The data by Møller and Pedersen[6] are estimates based on measurements of turbines of various size and models. The model is a best-fit model of the actually measured data without additions to account for uncertainty and variation between turbines.

Furthermore, the averaging by Møller and Pedersen disguises tones or tone-like components that typically appear in single frequency bands for a specific model, but in different bands for different models. Due to room resonances, such tonal or tone-like noise components may be particularly loud and annoying in certain houses and/or rooms.

There is an unavoidable variation in noise emission between turbines, even of the same model. The probability that a given delivered turbine emits more noise than an average turbine – or for that matter, any randomly chosen measured turbine – of the same model, is in principle 50%.

For planning purposes, the noise emission should therefore be specified according to IEC TS 11400-14[40]. This document uses measurements on several similar turbines and takes into account the variation between turbines to obtain the *declared apparent sound power level* L_{Wd} for the model. This is the level of the apparent sound power that will only be exceeded by 5% of the production. Using such values would yield a scenario, which could reasonably well be denoted as "worst-case".

The "Vestas V112" scenario of Tables 3 is indeed derived from measurements on a single turbine[8]. Even when the levels have been marginally adjusted to meet the specified total noise in Vestas' data sheet[9], this does not make it a worst-case scenario. Vestas does not refer to IEC TS 11400-14 or otherwise claim or document that their values are the maximum emitted sound power for samples of the production. When seen across the measured wind speeds, their data sheet values are in fact close to the measured levels for the single measured turbine. (See also Section 4.1).

How much higher values will be in a worst-case scenario, depends on the variation between turbines, and since this is not specified for the actual model, we can only give general information. Møller et al.[17] estimated a value of 2.6-4.8 dB to be added to the average of turbines to achieve levels according to IEC TS 11400-14. Part of this variation, may though stem from differences between similar turbines running in different modes, a matter which was not fully expounded in the data at our disposal. Only turbine producers have the full information on turbine settings and should provide the information, e.g. by using IEC TS 11400-14. The values mentioned apply to the total noise and not particularly to the low-frequency noise.

Experience from a recent Danish project with eight Vestas V90-3.0 MW turbines has shown that the measured sound power levels[41] exceed the anticipated levels from the Environmental Impact Assessment (EIA)[42], and several turbines now run in noise-reduced modes to fulfill noise requirements. The turbines were built before the new Danish regulations, but the measurements show that they fulfill the new low-frequency requirements[43]. Nevertheless, there are heavy complaints from neighbors, and it is our impression that high emissions in the 50-Hz third-octave band are of importance. The nearest neighbor is 545 meters from the closest turbine. The data sheet noise specifications for the V90-3 MW turbine[44] are very close to those of the V112-3 MW, although marginally lower for most wind speeds. It should be emphasized that we have no reason to believe that such problems are specific to Vestas turbines.

The source data used by Arcadis for the "Vestas V112" scenario (Koppen[5], Table 3 third row), i.e. relative spectrum levels from the measurements of the V112-3.0 MW turbine applied to data sheet values for the total noise of V112 and V80 turbines, can be considered realistic and likely.

These data will therefore be used for calculations in the remaining part of this report. Since the Arcadis report only displays values up to 160 Hz, values for the full frequency range are given in Annex 3. Data for the V112 turbine are also given in graphical form in Figure 2.

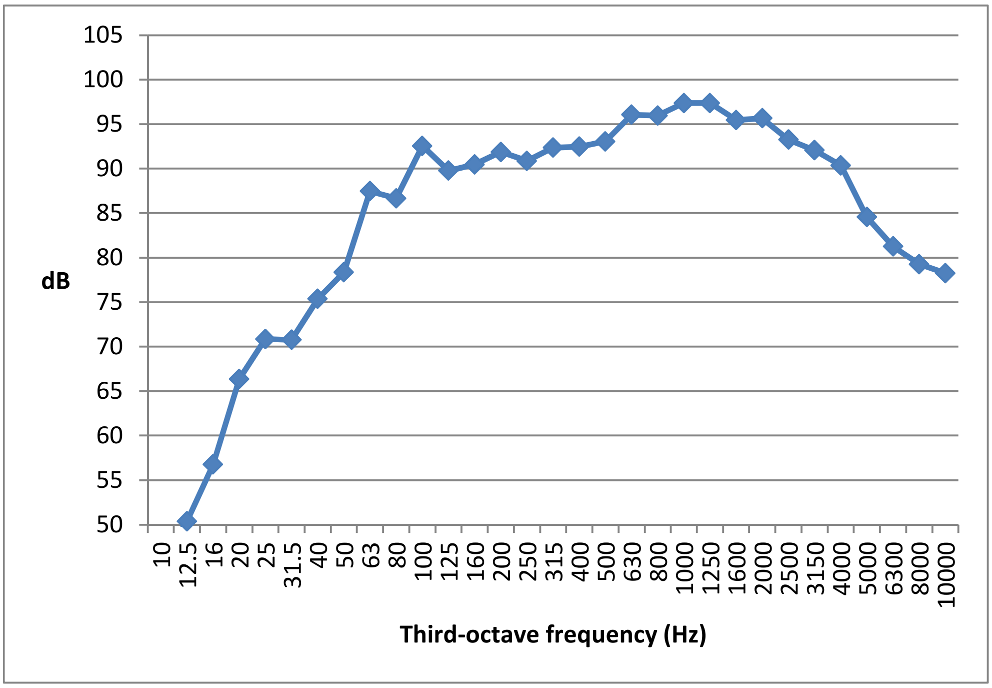

Figure 2. Third-octave apparent sound power levels for Vestas V112-3.0 MW turbines used in the calculations.

It is noted that there are peaks at 63 and 100 Hz, suggesting tones or tone-like noise in these frequency bands.

It should be emphasized that all calculations of noise at the neighbors in this report include noise from the proposed new turbines as well as the existing Belgian turbines.

3.6 Is it possible to indicate the expected LFN that will be produced by the planned four wind turbines of type Vestas V112 3MW, hub height 119 m.

It is possible to indicate a realistic and likely (not worst-case) scenario for the low-frequency-noise exposure at the neighbors.

For that purpose, source data explained in Section 3.5 and shown in Figure 2 and Annex C are used. For the sound transmission, the Danish regulation[7] (Section 3.3.2) is used and results are corrected with the estimated 5-dB error due to the sound insulation measurement error (Section 3.3.3 and Annex B).

Because of differences in sound insulation, not all houses will have the same indoor noise, and higher sound pressure levels than calculated will be observed in some houses. It is the expressed objective of the Danish regulation that higher levels will be observed in 33% of the houses[39]. Hoffmeyer and Jakobsen[36] had otherwise proposed that the calculated level should only be exceeded in 10-20% of the houses. In the following, calculations have also been made with their proposed sound insulation data (results likewise corrected by the estimated 5-dB measurement error).

These calculations offer a credible estimate of the indoor low-frequency noise to be exceeded in the 33% respectively 10-20% poorest-sound-insulated houses. The calculations do not account for deviations in the noise emitted from the actually erected turbines (Section 3.6) (including their directional pattern), deviations in the emitted sound from the existing Belgian turbines (including their directional pattern), differences in building style and sound insulation between Dutch and Danish houses, possibly open windows and variation in atmospheric conditions.

Table 3 gives calculated outdoor and indoor levels for the four neighbor positions chosen by Arcadis[5].

Table 3. Calculated outdoor and indoor sound pressure levels at selected neighbor positions. The indoor data are levels exceeded in the 33% respectively 10-20% poorest-sound-insulated houses. Wind speed 8 m/s.

Neighbor position	Outdoor L_{pA} (dB)	Indoor L_{pALF} (dB)	
		Danish regulation†	Hoffmeyer and Jakobsen†
7: new homes Malberg	45.1	25.3	28.1
7B: Toustruwe, Malberg	44.0	24.4	27.2
17: Kantoorweg	45.2	25.2	27.9
18: Europark, Belgium	46.2	26.1	28.9

† corrected with the estimated 5-dB error due to the sound insulation measurement error (Section 3.3.3 and Annex B)

It is seen that, depending on position, outdoor levels of 44.0-46.2 dB are expected. For the indoor low-frequency noise, levels of 24.4-26.1 dB or more are expected in 33% of houses (column Danish regulation) and 27.2-28.9 dB or more in 10-20% of houses (column Hoffmeyer and Jakobsen).

To give an idea of how far away the 20-dB indoor limit is exceeded, 20-dB noise contours for the indoor low-frequency noise have been calculated. The contours are shown on an open street map (Figure 3) and on an ortophoto (Figure 4) (Microsoft Bing Aerial).

The contours can also be seen online, where it is possible to switch between map and aerial view, and to zoom and move around with the cursor. It is also possible to use street view and e.g. see the existing Belgian turbines in different perspectives. Internet address: http://tinyurl.com/d7ht7xh.

It is seen that the 20-dB limit will be exceeded in a very large area with many dwellings and not only at the nearest neighbors. It should be remembered that the loudness increases more steeply above the hearing threshold than at higher frequencies as mentioned in Section 3.2, and that "*The perceived annoyance from low frequency noise increases strongly when the noise reaches above 20 dB*" (quote from Danish EPA[39] as mentioned in Section 3.3.3).

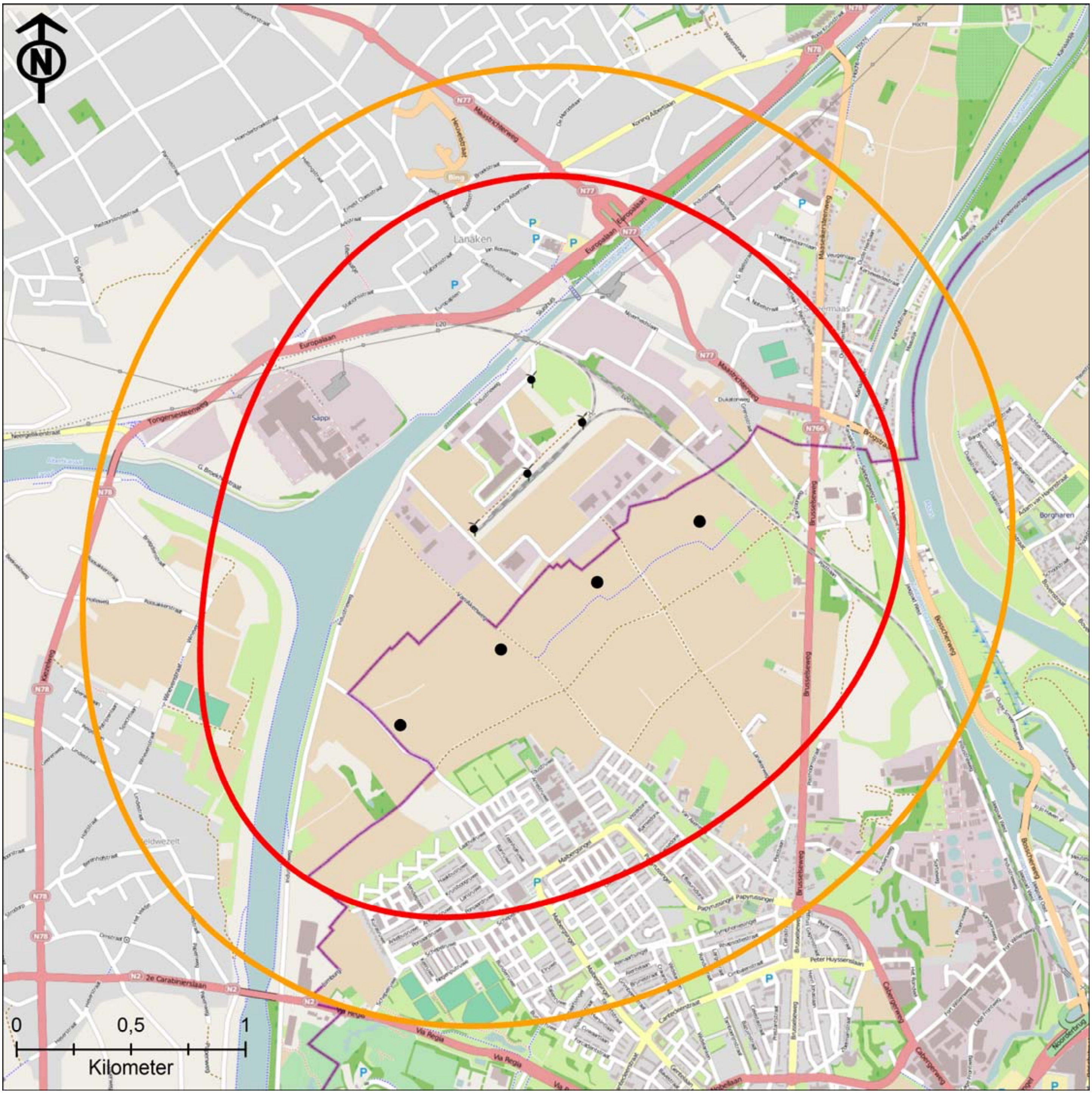

Figure 3. Contours where the 20-dB indoor low-frequency limit is exceeded in the 33% or 10-20% poorest-sound-insulated houses (red and orange line, respectively). Wind speed 8 m/s. See text for calculation details.

Figure 4. Contours where the 20-dB indoor low-frequency limit is exceeded in the 33% or 10-20% poorest-sound-insulated houses (red and orange lines, respectively). Wind speed 8 m/s. See text for calculation details.

4 General comments to the project

All questions asked (Annex A) and thus the preceding sections have dealt with low-frequency noise. However, we find it appropriate to add some general comments.

4.1 Total noise outdoors

The Dutch noise limits for wind turbine noise[45,46] are based on the day-evening-night concept, L_{den}, the long-term (yearly) equivalent level, where noise in the evening is given a penalty of 5 dB and noise in the night a penalty of 10 dB. This concept was developed to allow traffic noise with a typical 24-hour pattern to be characterized by a single figure. However, such diurnal pattern does not exist for wind turbines, since wind turbines run around the clock, and we do not find it suitable to characterize wind turbine noise by L_{den}. Also Pedersen[47] argued against using of L_{den} for wind turbine noise.

Since most complaints relate to the wind turbine noise in the evening and at night, we appreciate that there is an additional Dutch limit for the level at night L_{night}. However, this limit also applies to a yearly average, which allows more noise at some nights, if there is less noise at other nights. This is not the way the human organism works, though. If we are disturbed by noise in the night, we cannot take advantage of the fact that, after a while – tomorrow, after some days, maybe a week – there will be nights with less or no noise. It is our conviction that limits should apply to the actual noise in situations that occur regularly.

In Denmark and Sweden, noise limits apply to calculated noise levels at a wind speed of 8 m/s (10 m height). (In Denmark additional lower limits exist at 6 m/s). Wind at 8 m/s occurs less often in the actual area around Maastricht than in most parts of Denmark, thus there are arguments for using the noise emission at a lower wind speed than 8 m/s, e.g. 6 m/s. However, with the proposed turbines (large rotor, high tower), it makes only a marginal difference, in fact the measured noise at 7 m/s was higher than at 8 m/s[8]. Figure 5 shows the emitted noise as a function of wind speed as measured by Delta[8] and as given in the data sheet[9]. At low wind speeds, up to 1.2 dB more was measured than given in the data sheet, while up to 1.4 dB less was measured at high wind speeds.

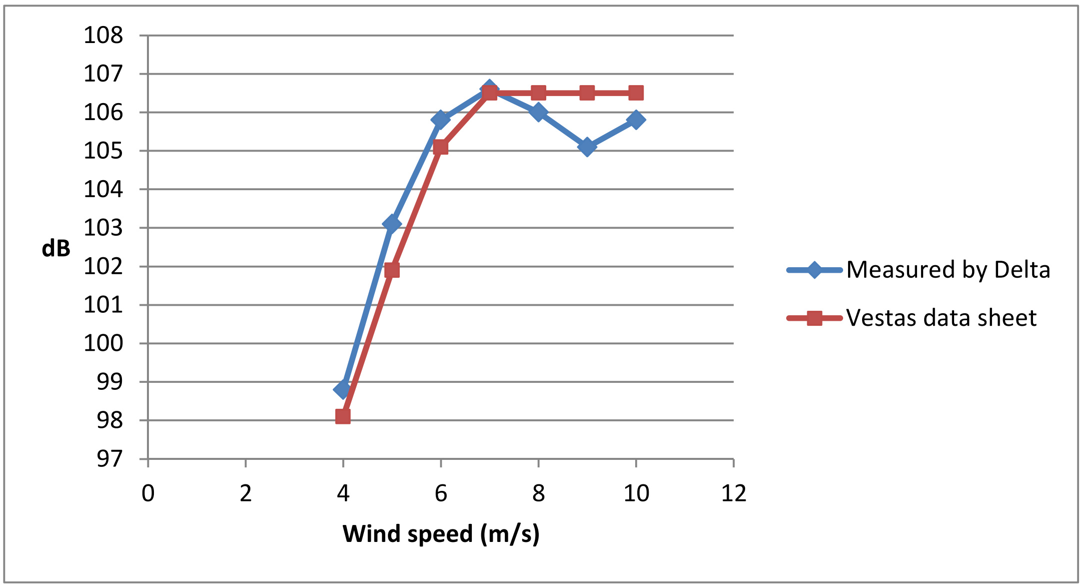

Figure 5. Apparent sound power level L_{WA} as a function of wind speed as measured by Delta[8] and as given in data sheet by Vestas[9].

Further, the three most acknowledged dose-response curves, including Dutch curves, have been made with calculated noise at a 10-m-height wind speed of 8 m/s as the independent variable (Pedersen and Waye[48]; Pedersen and Waye[49]; van den Berg et al. [18] and Pedersen et al.[50]). We have therefore chosen to calculate the noise for a wind speed of 8 m/s.

As mentioned in Section 3.3.4, the limits in Denmark at 8 m/s are 39 dB in dwelling areas and 44 dB at dwellings in the open land. In Sweden, general limits are 40 dB at dwellings, however 35 dB in areas with low background noise[51]. The project area is claimed to be already marked by industry, which argues for using the slightly higher Dutch night limit of 41 dB with calculated levels at 8 m/s. Dose-response curves indicate 23-24% rather/fairly or very annoyed at 41 dB calculated level at 8 m/s (interpolated from Pedersen et al.[50], Figure 2).

Contours of 39, 41 and 44 dB at a wind speed of 8 m/s have been calculated using the propagation calculation of the Danish regulations. Results are shown on an open street map (Figure 6) and on an orthophoto (Figure 7) (Microsoft Bing Aerial). (Source spectra as described in Section 3.5 and given in Annex C).

Also these contours can be seen online. Internet address: http://tinyurl.com/cwv76ke.

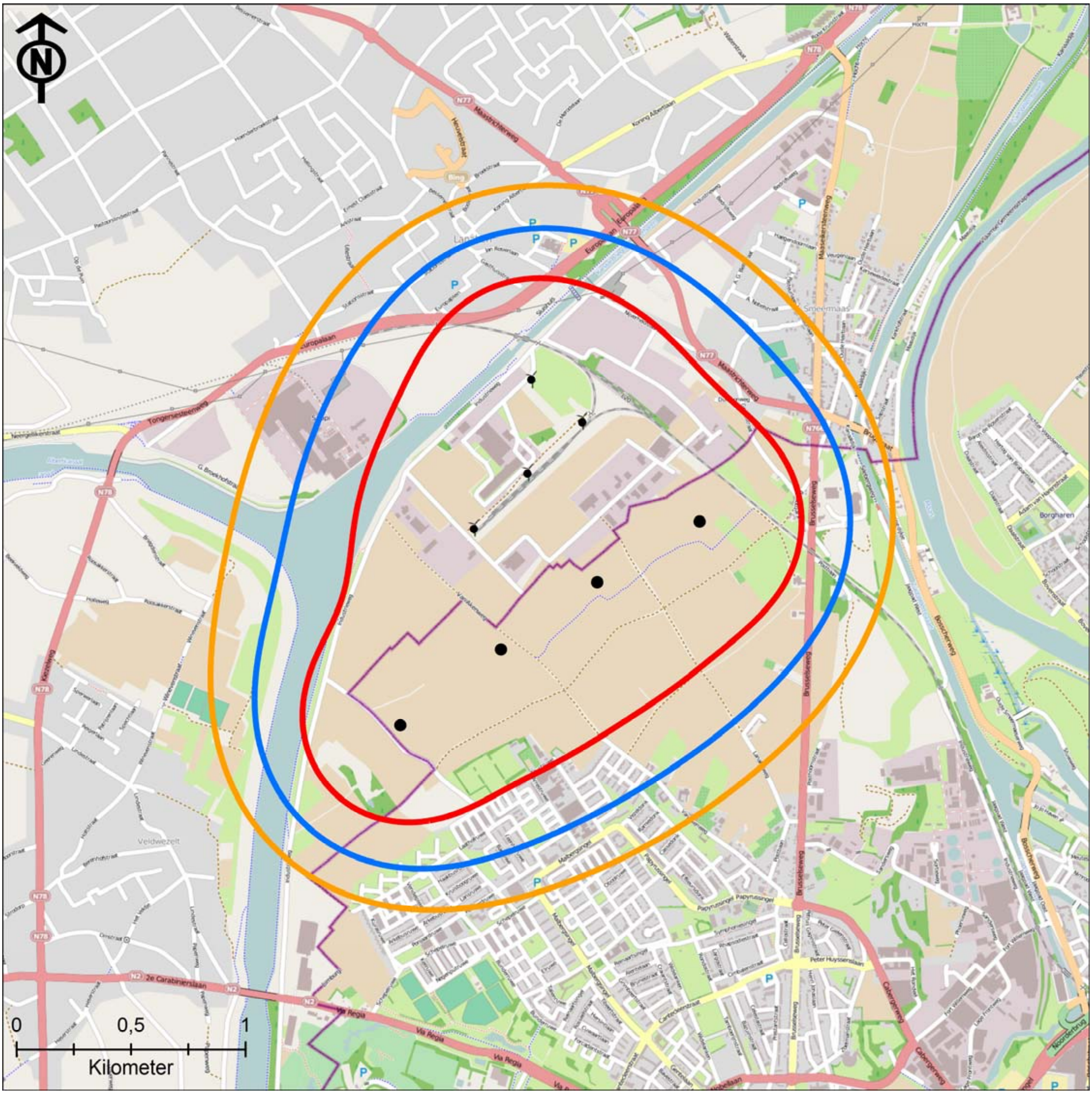

Figure 6. Contours for outdoor A-weighted sound pressure levels of 39 dB (orange line), 41 dB (blue line) and 44 dB (red line) using the propagation calculation of the Danish regulation. Wind speed 8 m/s.

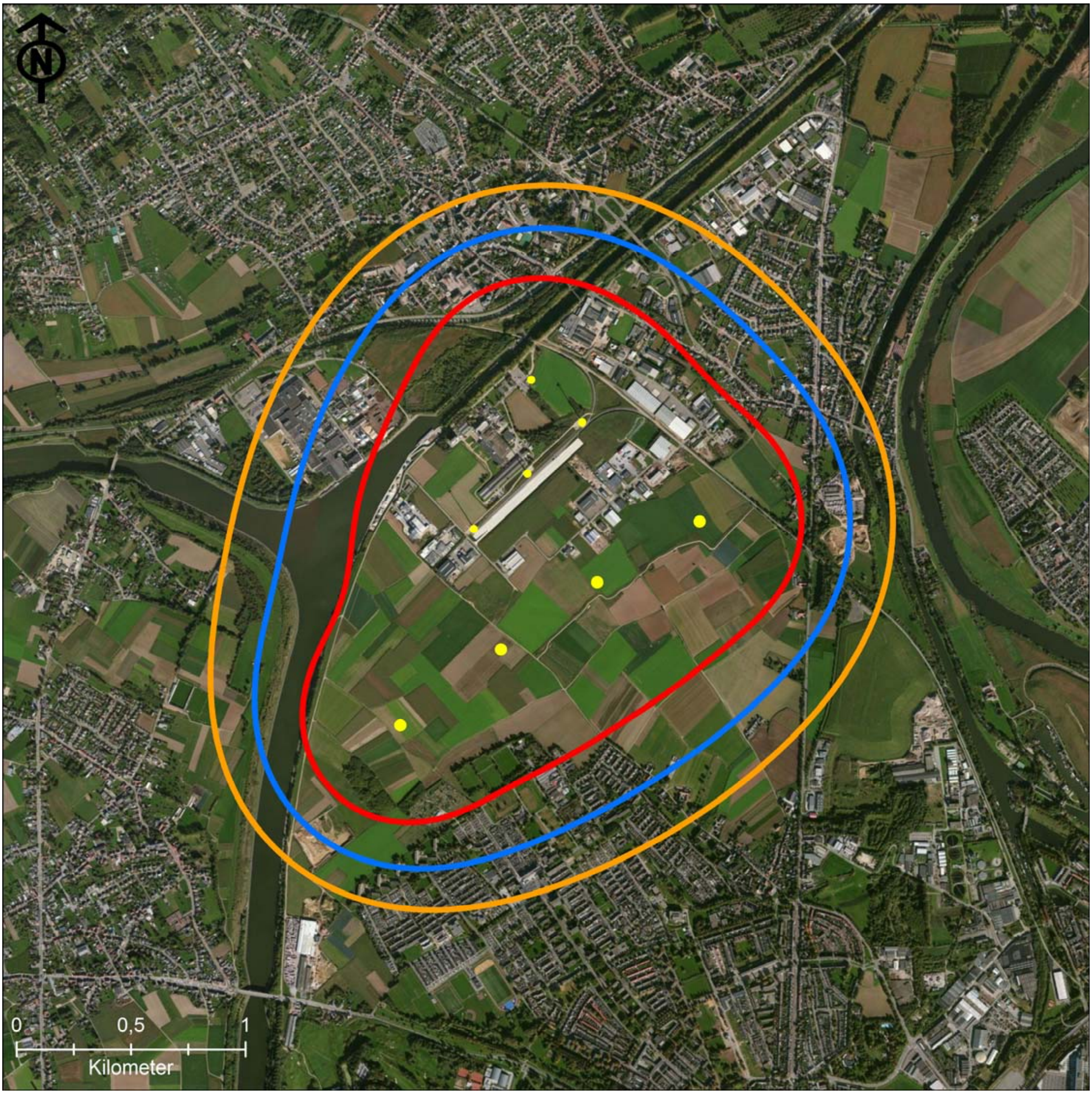

Figure 7. Contours for outdoor A-weighted sound pressure levels of 39 dB (orange line), 41 dB (blue line) and 44 dB (red line), using the propagation calculation of the Danish regulations. Wind speed 8 m/s.

Noise spectra at the four positions selected by Arcadis[5] are shown in Figure 8.

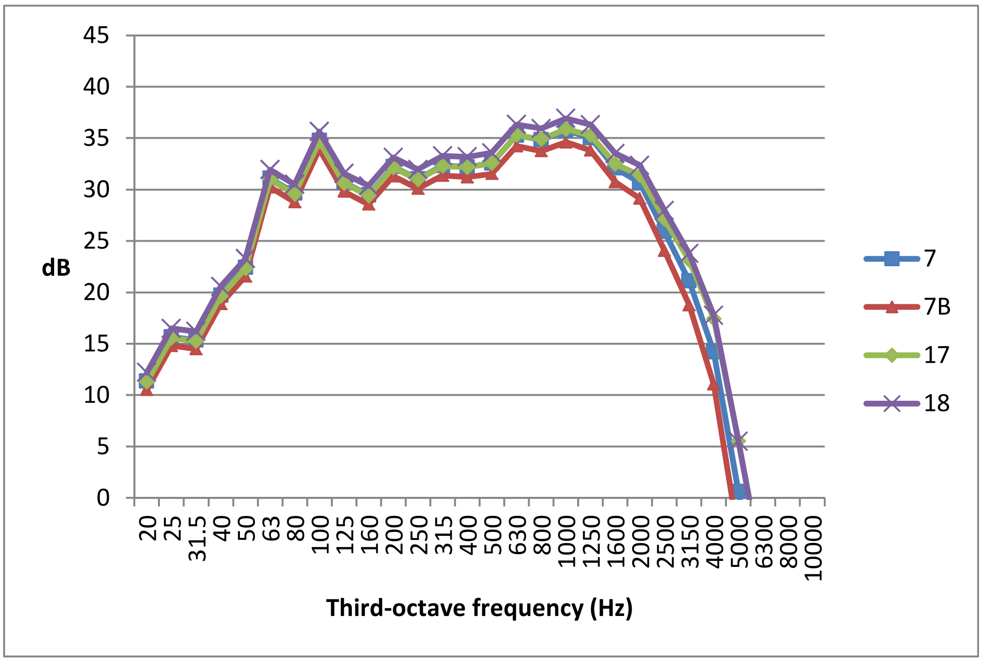

Figure 8. Third-octave spectra of the calculated outdoor A-weighted noise at four selected positions by Arcadis[1,5]: 7 (new homes Malberg), 7B (Toustruwe, Malberg), 17 (Kantoorweg) and 18 (Europark, Belgium). Total A-weighted sound pressure levels L_{pA} are 45.1, 44.1, 45.2 and 46.2 dB, respectively. Distances to nearest turbine are 467, 546, 381 and 385 m. Wind speed 8 m/s.

The peaks at 63 and 100 Hz are more prominent than in the source spectrum, since at these distances the higher frequencies have been attenuated by the sound absorption of the air.

4.2 Additional comments

In addition to the formal questions raised and given in each of the subsections of Section 3, we were asked to address certain aspects if possible (see Annex A). Most of these aspects have obviously been mentioned already, and a few more will follow here along with other comments.

One subject is the state of repair of wind turbines and the noise production. We have no specific knowledge of this, but it seems to be generally agreed that the noise may increase with improper maintenance and also normal wear of the mechanics and the blades.

Another matter is the height of the turbines and its possible influence on the noise. The turbine tower is extraordinary high and the rotor diameter large for 3.0 MW turbines, which is probably needed to achieve an adequate power production with the low wind conditions of the actual area.

A specific problem with large turbines is that actual wind speed profiles vary a lot and often deviate substantially from the normally assumed logarithmical profile (see, e.g. van den Berg[52], Botha[53], Palmer[54] and Bowdler[55]). In a stable atmosphere, which often exists at night, variations with height can be much larger than assumed with high wind speed at the turbine height and little wind at the 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[56,57] and Palmer[58]. The effect is more prominent with turbines with large rotors, 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 issue regarding atmospheric conditions is that it is often claimed to reflect a worst-case situation, when downwind propagation is assumed for calculations of neighbor noise. This is barely true, though. It is correct that noise is usually more attenuated in upwind conditions, and most people have everyday experience with this. The effect is due to bending of the sound waves from refraction in the atmosphere, which causes upwind shadow zones. However, for noise sources of the height of large wind turbines, shadow zones are normally further away than usual noise contours, including those given in this report.

It is also our experience that complaining neighbors do not explicitly mention downwind conditions as the worst situation. Sometimes, nuisances are mentioned as being more severe in other wind directions, which may be explained by a directional pattern of the turbine combined with its orientation to the neighbor.

It is also relevant to mention that in Denmark there is an absolute minimum distance to dwellings – irrespective of the noise – of four times the total height of the turbine to prevent that the turbines appear too gigantic and intrusive at the neighbor's place. Since the total height of the planned turbines is 175 meter, the absolute minimum distance in Denmark would be 700 meter.

5 Concluding remarks

- Arcadis' understanding and use of our data are correct, except for a few minor issues. Also their understanding and use of the new Danish regulation of low-frequency noise are correct.
- However, the calculation of the new Danish regulation underestimates the indoor low-frequency noise. Where the 20 dB limit is just met, real measurements will give values that exceed the limit by several decibels in many houses.
- A creditable calculation of the proposed project shows that the indoor low-frequency noise will exceed 20 dB in many houses in a large geographical area.
- This is important, since the perceived annoyance from low-frequency noise increases strongly, when the noise exceeds 20 dB.
- Prolonged exposure to audible low-frequency sound may cause fatigue, headache, impaired concentration, sleep disturbance and physiological stress.
- The calculations use the most likely values of emitted noise and do not represent worst-case scenarios. There is no margin to account for uncertainty and/or increased noise during ageing of the turbines.
- We do not consider noise limits (such as the Dutch) based on yearly averages as suitable for wind turbine noise. In common actual situations, Dutch and Danish limits for the total outdoor noise in dwelling areas are exceeded in many locations.
- In Denmark, there is a minimum set-back distance – irrespective of noise – of four times the turbine height, i.e. 700 meter for turbines proposed.

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Annex A. Questions from the City of Maastricht

1. Effects of Low Frequency Noise have been researched a lot. On which aspects does the research (approach) of Møller and Pedersen differ from that of other researchers?

2. What are the main effects of Low Frequency Noise (LFN) on humans and when specifically do these effects occur?

3. The Danish Government has changed the regulations for erecting wind turbines as a result of your research. Is that correct? And if so, what specific changes have been made?

4. Regarding the Arcadis Report, have the calculations and assessment of Low Frequency Noise been made correctly with respect to the Danish method and standards? If not, in what respect do they differ? Will recalculation lead to substantially different results?

5. In your opinion, is the noise spectrum referred to as Arcadis acoustic study in Tables 1 and 2 a realistic worst case scenario for calculating LFN effects produced by 3 MW wind turbines? If not, why not and can you indicate what the correct assumptions will be? Will this lead to substantially different results?

6. Is it possible to indicate the expected LFN that will be produced by the planned four wind turbines of type Vestas V112 3MW, hub height 119 m.

If possible, please address the following in your answer:

a. Applicable Dutch and Belgian laws and regulations and recent jurisprudence;
b. The standards with respect to noise (Lden and Lnight) in Belgium and the Netherlands, how these standards came about (legal history) and how the description 'special circumstances' as referred to in the Activities Decree is being put into practice;
c. The low and high-frequency noise and the standards applicable to it;
d. The noise spectrum of the wind turbine, the tonal and pulsating noise;
e. The aspects relating to cumulation with the existing companies and wind turbines in Belgium;
f. The (provisional) results of the noise measurement of the existing situation in Lanakerveld[1];
g. Reliability of measurements as opposed to calculations based on computer models;
h. The wind speed in relation to the noise production of the four turbines;
i. The acoustic study of low-frequency noise and the Danish standard;
j. The state of repair of the wind turbines and the noise production;
k. The multi-year wind statistics of the KNMI, the shaft height of the wind turbine and the noise production (source level);
l. The wind speed in the evening/night at a great height and the noise production (source level);
m. The autonomous development of Albertknoop and Lanakerveld and its effect on the total noise production;
n. The determination of the maximum source level by the supplier and the guarantees of the maximum source level given by the supplier;
o. The relationship between the shaft height of the wind turbines and the low-frequency noise;

[1] These measurements have not been available during preparation of the present report

Annex B. Estimation of the error by using Hoffmeyer and Jakobsen's insulation data

Pedersen et al. [59] have found that a 3D-corner measurement method is useful in finding levels near the maximum low-frequency levels, people are exposed to in rooms. This is supported by data from Brunskog and Jakobsen[60], who simulated the sound field in 100 room/frequency combinations and found that the 3D-corner method hits quite centrally the maximum levels, which inhabitants are exposed to in the open areas of the room (their Tables 3 and 4, mean error below 1 dB).

In parallel measurements in nine rooms, mean differences of 0.3-9.6 dB depending on frequency were seen between the 3D-corner method and the procedure used by Hoffmeyer and Jakobsen[36] (measurements reported by Hoffmeyer and Søndergaard[15] and by Hoffmeyer[61], respectively).

An estimated error in the middle of this range, i.e. 5 dB, is thus proposed for the total indoor low-frequency sound level. This is a conservative estimate, since the main contributions are usually from frequencies at 50 Hz or above, and at these frequencies differences are about 5 dB or higher.

A difference of the same order of magnitude is supported by Pedersen et al.'s own measurements in three rooms (their Figure 20).

Finally, Moorhouse and Ramadorai [62] found that the power average of measurements in a low number of arbitrary positions as in the ISO 140 series[63] underestimates the true room power average by 2-3 dB or more at frequencies below 125-160 Hz. ISO 140 has five positions, Hoffmeyer and Jakobsen only three. Pedersen et al. found that the high-level areas are 3-4 dB above the true room power average. Consequently, this also leads to a conservative estimate of 5 dB for the error from using Hoffmeyer and Jakobsen's data.

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Annex C. Spectra of emitted sound used in calculations

Frequency distributions of emitted noise are not available from the producer. Relative spectrum values from measurements of the V112-3.0 MW[8] turbine have therefore been applied to the data sheet values for the total noise of the V80-2.0 MW[10] and V112-3.0 MW[9] turbines. This is the same procedure as used by Arcadis[5]. See also Section 3.5.

Table 4. Source spectra used for the V80-2.0 MW and V112-3.0 MW turbines and the background data. All data are given as A-weighted sound power levels in decibels.

	Measured for V112 at 8 m/s		Data sheet 8 m/s	
			V80	V112
Total L_{WA}	**106.0**		**105.2**	**106.5**
Frequency		Relative	**Used in calculations**	
10	45.2	-60.8	44.4	45.7
12.5	49.9	-56.1	49.1	50.4
16	56.3	-49.7	55.5	56.8
20	65.9	-40.1	65.1	66.4
25	70.4	-35.6	69.6	70.9
31.5	70.3	-35.7	69.5	70.8
40	74.9	-31.1	74.1	75.4
50	77.9	-28.1	77.1	78.4
63	87.0	-19.0	86.2	87.5
80	86.2	-19.8	85.4	86.7
100	92.1	-13.9	91.3	92.6
125	89.3	-16.7	88.5	89.8
160	90.0	-16.0	89.2	90.5
200	91.4	-14.6	90.6	91.9
250	90.4	-15.6	89.6	90.9
315	91.9	-14.1	91.1	92.4
400	92.0	-14.0	91.2	92.5
500	92.6	-13.4	91.8	93.1
630	95.6	-10.4	94.8	96.1
800	95.5	-10.5	94.7	96.0
1000	96.9	-9.1	96.1	97.4
1250	96.9	-9.1	96.1	97.4
1600	95.0	-11.0	94.2	95.5
2000	95.2	-10.8	94.4	95.7
2500	92.8	-13.2	92.0	93.3
3150	91.6	-14.4	90.8	92.1
4000	89.9	-16.1	89.1	90.4
5000	84.1	-21.9	83.3	84.6
6300	80.8	-25.2	80.0	81.3
8000	78.8	-27.2	78.0	79.3
10000	77.8	-28.2	77.0	78.3