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Noise from large wind turbines – an update on low frequency noise

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Abstract

Low frequency noise and infrasound from large wind turbines is still a major concern when discussing new wind farms.

New results from the Danish project "Low Frequency Noise from Large Wind Turbines" [1] funded by the Danish Energy Authority, Dong Energy, Vattenfall AB Vindkraft, E.ON Vind Sverige AB, Vestas Wind Systems A/S and Siemens Wind Power A/S is presented.

The study is based on new measurements on large wind turbines representative for the large wind turbines installed in Danish wind farms during the last two years. An evaluation of the development in low frequency noise when comparing to older small turbines is made and differences are discussed.

Methods for evaluation of the low frequency noise impact at residences close to wind turbines are presented. This includes all steps from measurement of noise characteristics of the wind turbines to the calculation of resulting indoor noise levels at nearby residences.

Introduction

Until now only very limited noise data has been available for the discussion of the impact on the surroundings with regard to low frequency noise from modern wind turbines. The work presented here gives a more extensive data material for this discussion.

The main part of the work is carried out as part of the project on "Low Frequency Noise from Large Wind Turbines" [1] that was initiated due to a growing anxiety in the public that new large wind turbines might have a larger impact on the environment, associated with significantly more low frequency noise than experienced from smaller wind turbines already present.

Besides evaluation of the noise emission from large and small wind turbines the project also covers, investigation of noise generation mechanisms at low frequencies, methods for calculation of noise propagation, evaluation of audibility and

masking effects and investigation of annoyance of low frequency wind turbine noise based on listening tests.

This paper will focus on the discussion of development in noise emission from large wind turbines and describe and demonstrate the proposed method for evaluation of low frequency noise at residences close to wind turbines.

Study of low frequency noise emission from large wind turbines

After a period from 2004 to 2007 where only a few new turbines were installed in Denmark, the number of installed turbines increased in 2008, 2009 and 2010.

Table 1 shows the statistics for turbines installed in Denmark during 2008, 2009 and 2010 until end of September 2010 (only turbines with a max capacity larger than 1 MW are shown).

Turbine Max capacity [MW]	Hub height [m]	Rotor diameter [m]	Total height [m]	Installations			Measurements available
				2008	2009	2010	
1.8	80	90	125	0	4	0	3
1.8	107	100	157	0	1	0	0
2.0	60-78	90	105-123	11	1	1	0
2.0	80	90	125	1	0	0	0
3.0	94	112	150	0	0	1	0
3.0	80	90	125	0	6	5	2
2.3	80	93	126.5	17	25	12	5
3.0	98.5	101	149	0	1	0	0
3.6	80	107	133.5	0	3	0	3
3.6	90	107	143.5	1	0	2	1
3.6	90	120	150	0	0	6	1
3.6	90	107	143.5	0	2	0	2
Total				30	43	27	17

Table 1
Turbines with capacity above 1 MW installed in Denmark in the period 2008 until end of September 2010 [2] shown together with the number of new measurements carried out by DELTA on large wind turbines in 2009 and 2010.

In the analysis discussed in the following only measurement data for the turbines above 2 MW are included and it is seen that the available measurements perform a good representative basis for the evaluation.

The total number of installed wind turbines in Denmark taken per ultimo September 2010 with a nominal power between 400 and 2000 kW is 3263 and the average nominal power of these turbines is 800 kW [2]. The 33 small wind turbines included in the following comparisons have an average nominal power of 950 kW. For comparison the 82 large turbines above 2 MW installed in the period 2008-2010 and represented by the new measurement results have an average nominal power of 2500 kW.

The measurements were made in accordance with Danish regulations [3] to verify compliance to these regulations on noise from the wind turbines. The measurement method is compliant with IEC 61400-11 2nd edition (2002).

For the measurements the frequency range was extended to include the low frequency content of the noise according to [1] and as specified in the draft for the 3rd edition of IEC 61400-11. The measurement method with extension of the measurement frequency range down to at least 10 Hz has been used with success for the measurements and is now used as standard for all other measurements carried out on wind turbines. For almost all situations it has been possible to determine the low frequency noise emission with good precision using the proposed secondary wind shield.

All the investigated turbines are placed as part of wind farms in Denmark and all turbines were found to comply with Danish regulations regarding the A-weighted sound immission at dwellings close to the wind farms.

In Figure 1 and Figure 2 sound power levels, L_{WA}, and the low frequency content of the sound power level, $L_{WA,LF}$ are plotted against nominal power for the wind turbines. The plots and analysis includes data for 33 small wind turbines and a total of 22 measurements on large turbines (> 2MW).

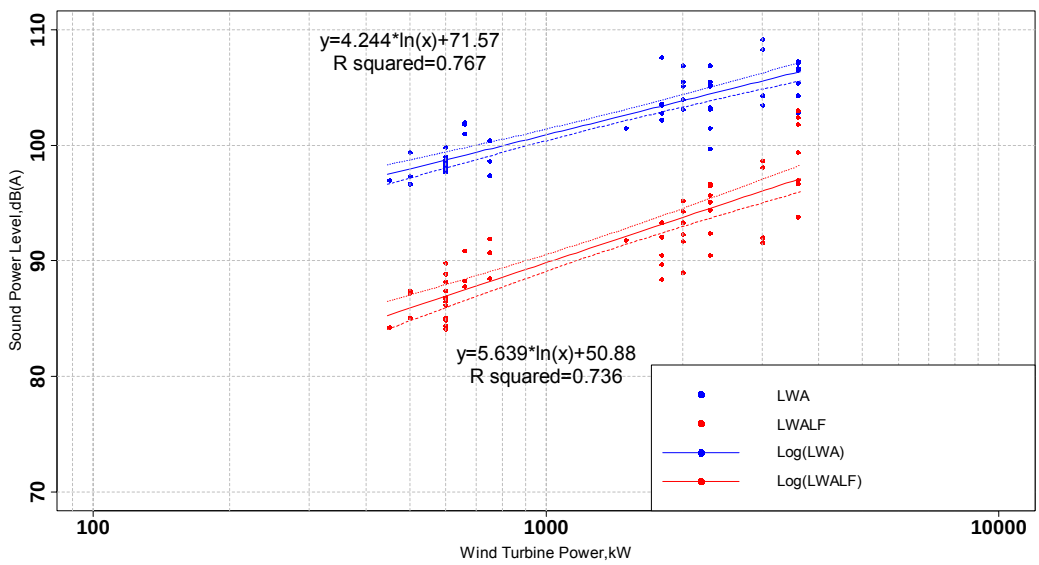

Figure 1
Sound power level L_{WA} and the low frequency sound power level $L_{WA,LF}$ as a function of nominal wind turbine power. The full lines are the regression lines. The dotted lines are the 95% confidence intervals for the regression. Results are included from 33 small turbines and 22 large turbines (> 2MW)

In Figure 1 the regression lines for L_{WA} and $L_{WA,LF}$ are shown. Furthermore the confidence intervals for the lines are shown. The confidence lines show the interval

around the regression lines, where we with a probability of 95 % expect to find the true value for the regression lines.

The statistical analysis[1] shows that the difference in the slope of the two lines is significant. This means that the relative amount of low frequency noise is increasing with increasing wind turbine size. According to the regression shown in Figure 1 a doubling of nominal electrical power will in general increase the sound power level, L_{WA}, by approx. 2.9 dB(A) and the low frequency sound power level, $L_{WA,LF}$, by 3.9 dB(A). This means a relative increase of $L_{WA,LF}$ of 1 dB. The relative increase in $L_{WA,LF}$ from a 1 MW turbine to a 5 MW turbine will be 2.4 dB.

In Figure 2 the data from Figure 1 is presented as the logarithm to the ratios between sound power and electrical power plotted against nominal power for the wind turbines. This shows the relative decrease of total sound power with increasing wind turbines size and the increase of low frequency sound power with increasing wind turbine size.

It is clearly seen from both Figure 1 and 2 that the differences between small and large wind turbines are much smaller than the differences between the individual wind turbine in each electrical power class with regard to total noise emission and to low frequency noise emission. For example the relative general difference in low frequency noise emission from the smallest to the largest turbines is less than 3 dB where a spread in noise emission for the same wind turbine size is up to 9 dB. One of the main reasons for the variation within one wind turbine size is related to the possibility of operating the turbines with different “noise settings” to reduce noise emission.

From this discussion it could also be questioned whether this kind of statistical treatment makes sense and it must be emphasized that use of the general statistical data must be made with caution.

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[1] The regression has been done with a linear model after linearization of the wind turbine power with a natural logarithm. A t-test has been performed on the slope of the regression lines. The analysis showed that the difference between the slopes is significant ($p = 0.009$, $\alpha=0.05$). An analysis of covariance has been performed in order to confirm the previous t-test on the slopes. The results of the analysis of covariance support the results of the t-test ($p=0.01$, $\alpha=0.05$).

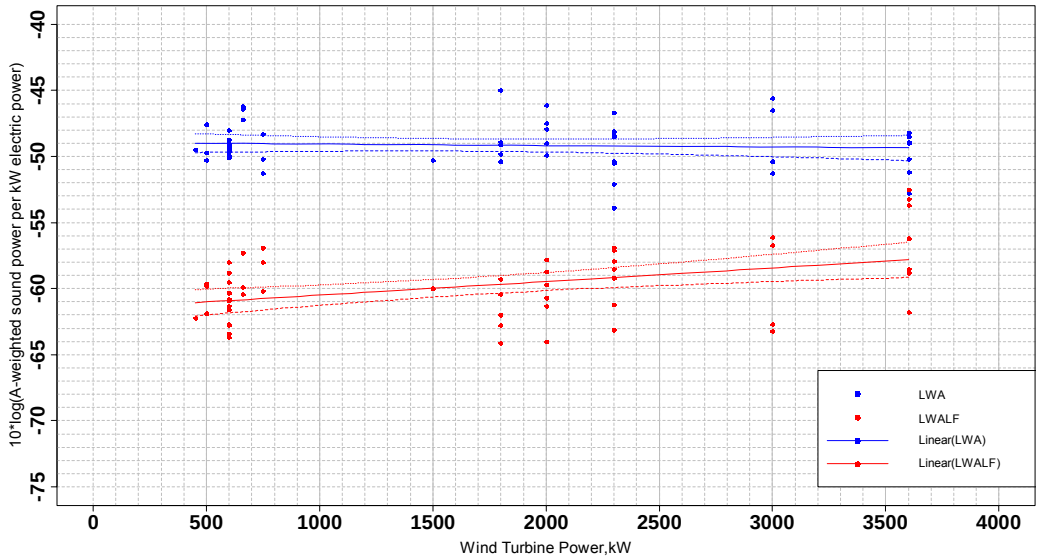

Figure 2
Emitted A-weighted acoustic power per kW electric nominal wind turbine power shown as the logarithm to the ratio between the acoustic sound power and the nominal electric wind turbine power in kW. The full lines are the regression lines. The dotted lines are the 95 % confidence intervals for the regression. Results are included from 33 small turbines and 22 large turbines.

In Figure 3 the A-weighted sound power spectra in 1/3-octave bands are shown for all 17 new measurements mentioned in Table 1.

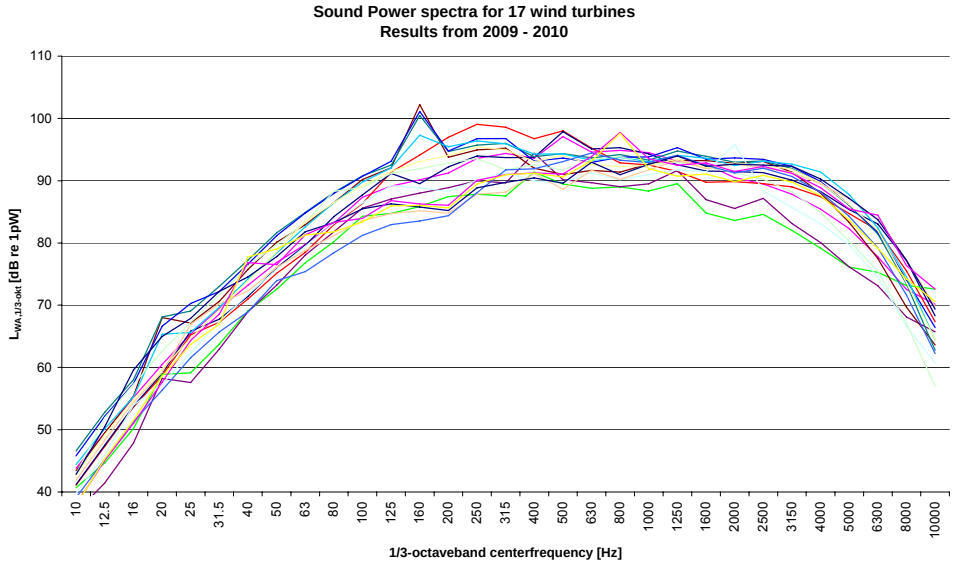

Figure 3
A-weighted sound power spectra for new measurements on newly installed turbines with a nominal power between 1800 and 3600 kW.

In the following only measurements from the 14 turbines with a nominal power capacity above 2 MW are taken into account

In order to decide whether a development of the low frequency noise has occurred all spectra has been normalized to the same A-weighted level, L_{WA} =100 dB re 1pW, making it possible to compare the spectral shape of the noise and evaluate the relative content of low frequency noise for different wind turbines.

For comparison of the spectral contents of the large wind turbines to the small turbines average spectra are used. When averaging the spectra the data are multiplied with a weighting factor for each wind turbine type corresponding to the actual number of installed turbines of different types and size according to the presented statistics in Table 1.

In Figure 4 the normalized spectrum representing the installed wind turbines from 2008-2010 is compared to results from older small turbines.

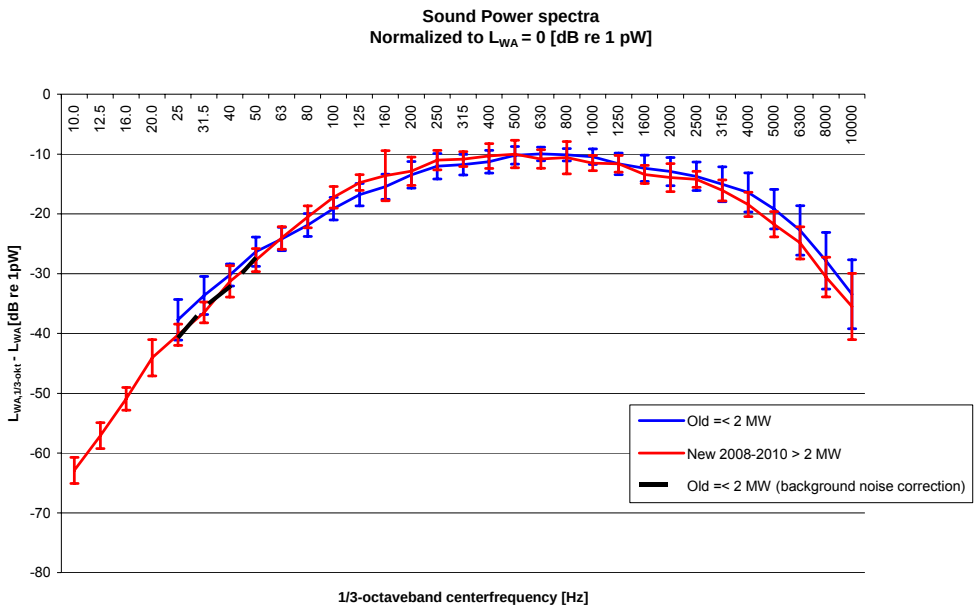

Figure 4
Comparison of A-weighted normalized sound power spectra.
Older small turbines (blue) and the new large turbines representing the turbines installed in Denmark the period 2008-2010 (red). Values for small turbines with estimated background noise correction below 50 Hz (black dotted line). The vertical bars represent plus/minus one standard deviation on the average value for each spectrum.

The old measurements on small wind turbines shown in Figure 4 were made with a higher uncertainty due to the influence from background noise below 50 Hz. From analysis of the old data a best estimate of the potential influence from background noise has been determined. In Figure 4 a corrected mean spectrum for the frequency range below 50 Hz is indicated with the black dashed line. The correction corresponds to -3 dB at 25 Hz, -2 dB at 31.5 Hz, -2 dB at 40 Hz and -1 dB at 50 Hz.

As it can be seen from Figure 4 there is an essential overlap of the standard deviations for the two groups of turbines. As 68 % of the levels of the individual turbines will be found within the interval of +/- one standard deviation this means that you will easily find small turbines with normalized levels that exceed the levels of a large turbine and vice versa. I.e. a certain small turbine may have larger low frequency components than a larger and vice versa.

It is seen that there is a small increase in the relative content of low frequency noise for the large turbines compared to the small for the frequency range 80 – 160 Hz. From the narrowband (fft) noise spectra from the new large turbines shown in Figure 5 it is seen, that tones contributes considerable to the mentioned increase in the low frequency noise emission.

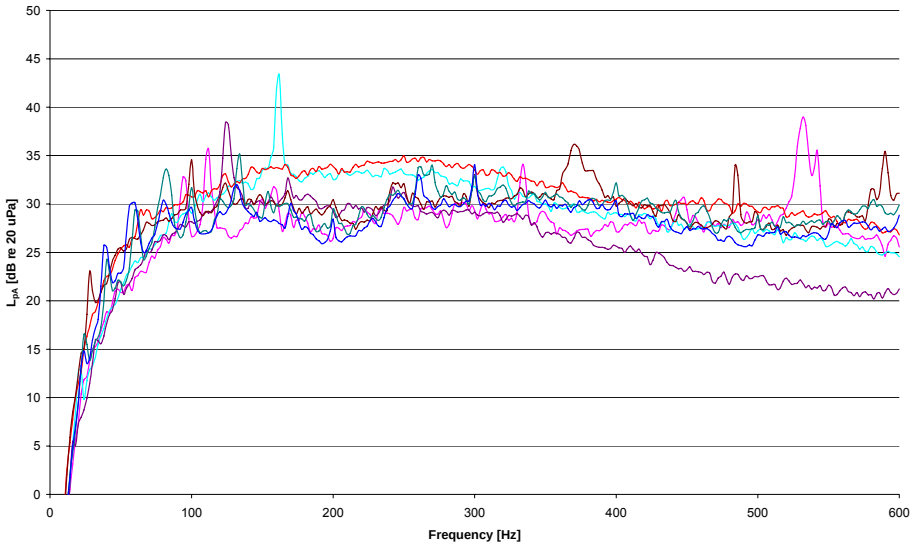

Figure 5
A-weighted narrowband (fft) spectra for 7 different new turbines (>2MW). Frequency spacing 2 Hz.

Method for evaluation of low frequency impact at residences close to wind turbines

To make a reliable assessment of noise from wind turbines in the environment it is necessary to have reliable and applicable methods for determination of the emitted noise, methods for calculation of noise propagation and data for noise insulation of houses.

In Figure 5 a typical situation of sound propagation from a wind turbine to an indoor position at a residence in the vicinity is illustrated. This includes the strength of the wind turbine sound source, the sound attenuation caused by the propagation over distance with influence of the type of landscape and the weather and the sound attenuation due to sound reduction of the building. All put together giving the indoor noise level experienced by the neighbour to the wind turbine.

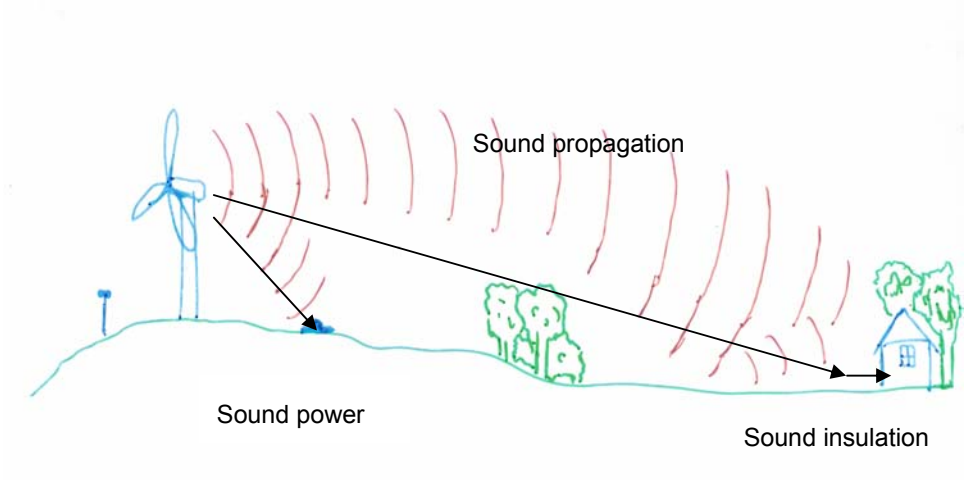

Figure 6
The 3 elements required for noise assessment

The sound power determination for source description was discussed in the previous section.

The calculation of sound propagation from the wind turbine to nearby residences must be made using a model appropriate for handling of both landscape and meteorology at low frequencies and it must also be valid for noise sources placed high above ground level as wind turbines are. In [1] and [4] the Nord2000 propagation model that is chosen for this project is described in more detail. In [4] an extensive validation of the method for specific use on wind turbine noise is presented. The method was field tested under various conditions with very good results.

To be able to perform the indoor assessment of low frequency noise it is necessary to have proper estimation of sound reduction indices for houses. In the project [1] measurements of sound insulations were carried out for a number of houses and rooms. These data have been further investigated, combined with other data sources and treated statistically in order to present a proposal for general sound insulation data for the low frequency range to be used for low frequency noise assessment. The data are published in [5] as values representative for typical Danish dwellings.

The resulting method for assessment of low frequency noise at residences close to wind turbines are then given as follows:

- Measurement of the sound emission from wind turbines performed with extension of the frequency range down to at least 20 Hz (recommended down to 10 Hz). Appropriate measures such as special wind screens must be taken into account to reduce measurement uncertainties at lower frequencies.
- Calculation of sound propagation from turbine to receiver points outdoor at nearby residences made using the Nord2000 sound propagation model.

- Calculation of indoor noise levels using the sound insulation values for houses given in [5].

Indoor low frequency noise levels from wind turbines

To evaluate the noise impact from wind turbines on the surroundings it is relevant to look at the sound pressure levels at distances relevant for the nearest residences close to single wind turbines or groups of wind turbines. Based on the results from Figure 4 a study of this has been made comparing the impact from small and large turbines.

According to Danish regulations a wind turbine cannot be installed closer to the nearest residence than at a distance corresponding to at least 4 times the total height of the wind turbine. This distance is referenced as “the minimum distance”. Another part of the regulations state that the maximum A-weighted sound pressure level at the nearest residences are not allowed to exceed 44 dB(A) in none noise sensitive areas.

Based on these regulations two situations have been chosen for further investigation:
If the noise limits are not exceeded at a distance of 4 total wind turbine heights then it is relevant to compare the two groups of turbines for this distance (for single turbines at this distance). A spectral comparison for this is given in Figure 7.
If the noise limits are just met at four total heights (e.g. for more than one turbine in a wind farm at that distance) then it is relevant to normalize the spectra for the two groups of wind turbines to the same A-weighted level (44 dB(A)) and compare.

Calculations of sound pressure levels at the minimum distance have been made for all turbines using the Nord2000 method, not to underestimate the noise at the lowest frequencies. For the calculations downwind propagation at wind speed 8 m/s at 10 m height over a flat agricultural area are supposed.

In Figure 7 it is seen that at high frequencies the noise is reduced for the large turbines compared to the small ones. This is due to increased air absorption of the sound at the larger minimum distances for the large turbines.

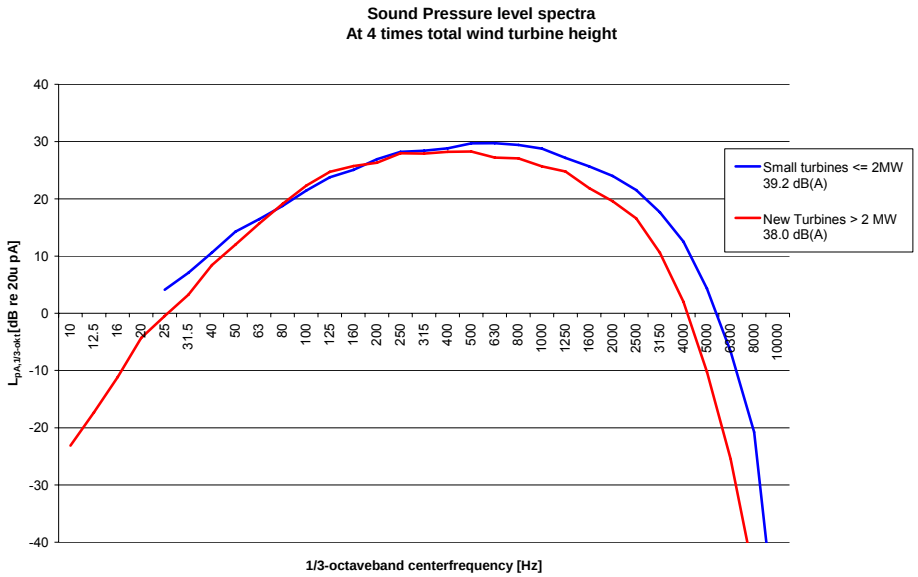

Figure 7
Sound pressure level spectra for new large and old small single turbines at a distance of 4 total heights.

In Table 2 and Table 3 the calculated sound pressure levels L_{pA} and $L_{pA,LF}$ for the two scenarios are presented for both outdoor and indoor situations. For the indoor situation sound reduction values from [5] are used.

Nominal power	**L_{pA} Outdoor**	**$L_{pA,LF}$ Outdoor**	**$L_{pA,LF}$ Indoor**
400 - 1000	39.1	29.7	14.6
1000 - 2000	39.5	30.4	15.3
400 - 2000	39.2	29.9	14.8
>2000 New turbines	38.0	30.4	14.4

Table 2
Noise levels at minimum distance for single wind turbines.
L_{pA}, $L_{pA,LF}$ and $L_{pA,LF}$ – outdoor and indoor in dB re 20 µPa.

Nominal power	L_{pA} Outdoor	$L_{pA,LF}$ Outdoor	$L_{pA,LF}$ Indoor
400 - 1000	44.0	34.6	19.5
1000 - 2000	44.0	34.9	19.9
400 - 2000	44.0	34.7	19.6
>2000 New turbines	44.0	36.5	20.4

Table 3
*Values from table 2**Table** recalculated for a wind farm situation with 44 dB(A) outside the residence. L_{pA}, $L_{pA,LF}$ and $L_{pA,LF}$ – outdoor and indoor in dB re 20 µPa.*

For both scenarios it is seen that the indoor low frequency noise level ($L_{pA,LF}$), that is the most relevant parameter for evaluation of low frequency noise impact at neighbours to wind turbines, only show small differences for the different wind turbine groups.

The scenario with a 44 dB(A) outdoor level could also be realized with a larger number of wind turbines placed at larger distances to the receiver position at the residence. Longer distances between the wind turbines and the receiver position will due to the effect of air absorption result in a damping of the high frequency part of the noise from the wind turbines as it is seen from Figure 7 and thereby increase the relative amount of low frequency noise. This effect will however be the same regardless of the size of the wind turbine.

It is important to mention that the results from the study presented above are based on general average noise data for large and small wind turbines. For evaluation of absolute values at different distances to wind farms the specific data from the involved wind turbines and distances based on the actual wind farm layout must be taken into account.

Example of low frequency noise assessment

Although there is no specific legislation in Denmark at the moment, dealing with low frequency noise from wind turbine noise, the method presented above for assessment of low frequency noise from wind turbines has already been used in situations where wind farm developers would like to ensure about compliance with reasonable low frequency impact at the environment.

In Figure 8 a potential lay out of a wind farm with six 3.0 MW wind turbines are shown. The picture is taken from the calculation model used for prediction of low frequency noise exposure indoor at nearby residences. The landscape contours are modeled as well and taken into account. The six turbines are marked with pink rosettes and the main receiver points are marked in red. Buildings are marked with purple.

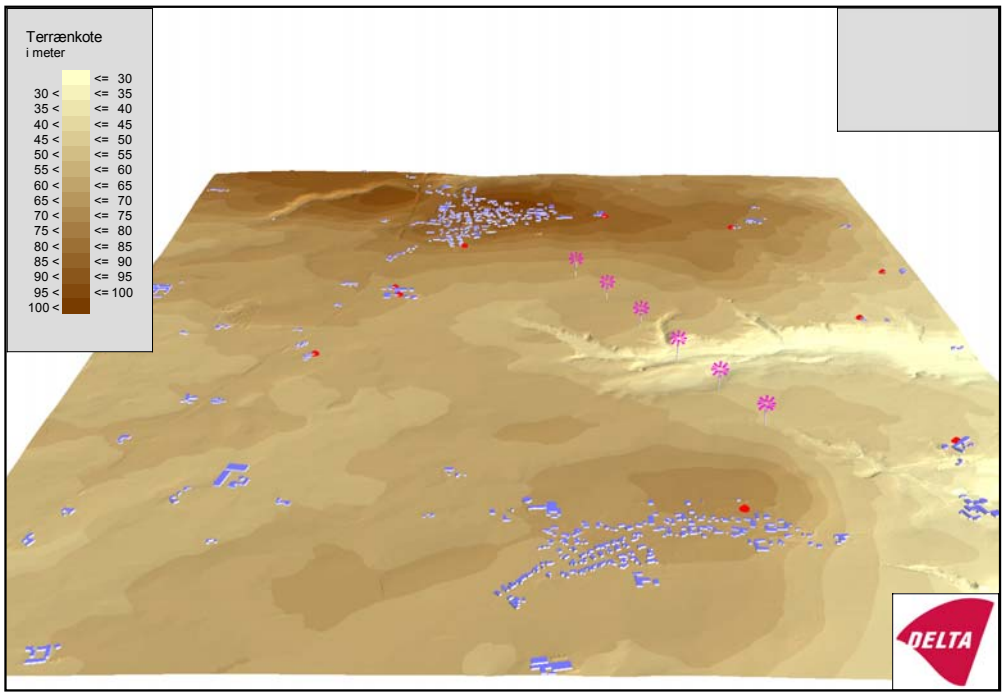

Figure 8
Calculation model for a wind farm with six 3.0 MW wind turbines shown as pink rosettes. Main receiver points at nearby residences are marked with red. Terrain height shown as contours.

Using this model the presented method has been applied using measured sound power levels, Nord2000 for sound propagation and the sound insulation data from [5] to get to the indoor low frequency noise levels. In Figure 9 a contour plot with indoor low frequency noise levels as is expected achieved if a house was placed at the various positions is shown.

Although there are no limits on low frequency noise from wind turbines comparison are often made to guidance limits applicable for industry in Denmark. This limit is at night 20 dB(A) for $L_{pA,LF}$. From Figure 9 it is seen that this limit is respected with some margin for this specific case.

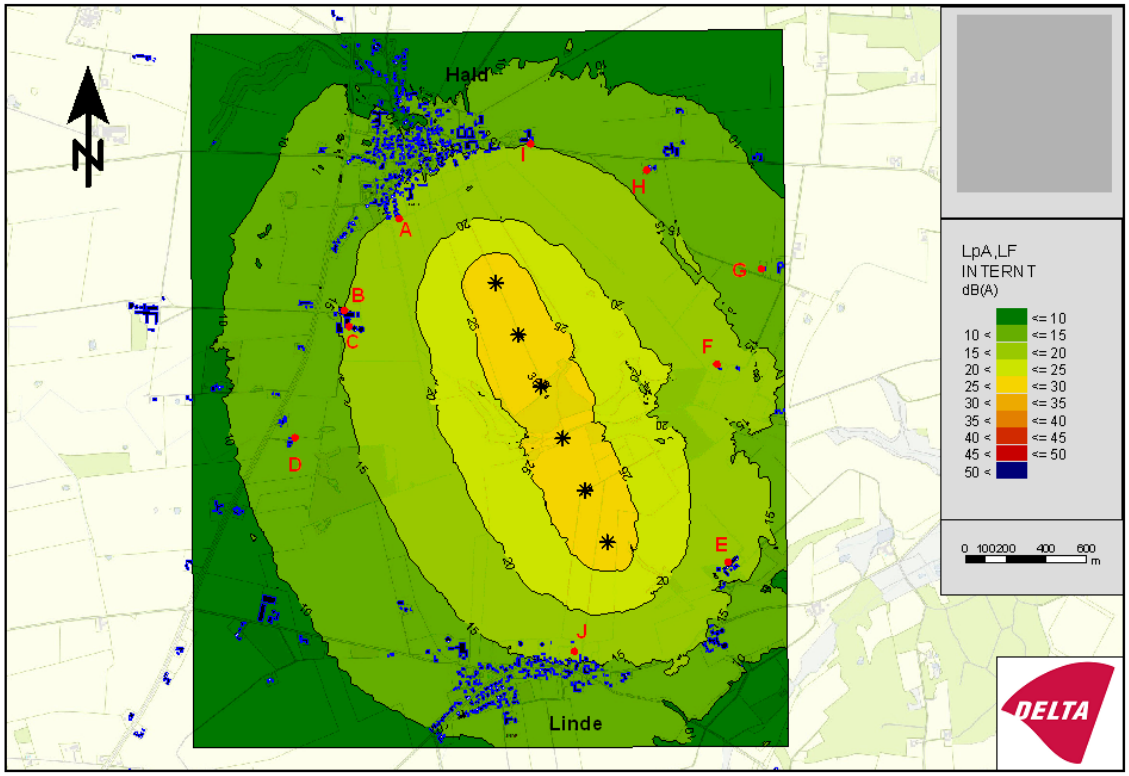

Figure 8
Calculated low frequency noise levels indoor at residences close to a wind farm. $L_{pA,LF}$ shown as colour contours.

Conclusions

Based on new measurement results from large wind turbines it is concluded that large wind turbines do not cause a special problem regarding impact of low frequency noise at residences close to wind turbines.

It is seen that it is important to evaluate each project individually based on the specific data for the project with respect to wind turbine noise data, distances and terrain.

A method for assessment of low frequency noise levels indoor at nearby residences is presented and demonstrated. The method has already been used for specific projects to provide a better and more precise basis for the debate on noise impact caused by these specific wind farms.

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