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Noise from wind turbines and health effects - Investigation of wind turbine noise spectra

Lars Sommer Søndergaard
DELTA Acoustics, Agro Food Park 13, 8200 Aarhus N, Denmark
E-mail: lss@delta.dk

Claus Backalarz
DELTA Acoustics, Venlighedsvej 4, 2970 Hørsholm, Denmark
E-mail: cb@delta.dk

Summary
The Danish Cancer Society is conducting an objective register based cohort study of whether noise from wind turbines can cause health problems. The study is investigating connections between noise levels from all land based Danish wind turbines with registered health problems for neighbours to wind turbines and are utilizing the unique combination of the Danish health register and a long history of wind turbines. The study includes occupants at all dwellings/houses which potentially can hear one or more wind turbines. The calculation of the noise levels are performed by DELTA based on weather statistics provided by the Technical University of Denmark. The noise calculation is executed each hour for all Danish land based wind turbines connected to grid in the years 1982-2013. The used calculation method is the Nord2000 method developed by DELTA and other Nordic institutes. Basis for the noise calculation is a study of results from wind turbine noise measurement reports during 1982 to 2013. The measurement methods have changed over the years, and the measurements are not necessarily performed for the frequency range, frequency resolution and wind speeds which are interesting for this study. This paper describes how data is collected to form the 100 classes of wind turbines, which forms the basis for calculations of the contribution of noise at the neighbours. Each class contains one third sound power spectra at wind speeds from 3 to 14 m/s and an assessment of the tonality and validity of the results in each of the classes.

1. Introduction

The project aims to investigate both short and long term exposure to wind turbine noise on the health. More specifically whether noise from wind turbines can be associated with increased risk of cardiovascular disease and whether prolonged exposure to wind turbine noise increases the risk of heart disease, diabetes, increased consumption of prescription of drugs for high blood pressure, sleep problems and depression and if the exposure to noise from wind turbines during pregnancy is associated with increased risk of low birth weight. Denmark is densely populated and has been a pioneer in setting up wind turbines since 1980. This combined with unique national registers of addresses of all Danish citizens since 1971 and a variety of health registers (among other things all hospital admissions for cardiovascular disease) makes it possible to track all Danes who have lived near wind turbines during 1982 to 2013.

2. Onshore wind turbines in Denmark

The Danish Energy Agency and Energinet.dk have established a register of all Danish wind turbines. This register is updated monthly, and contains information on all wind turbines from 1980 including the exact location of each wind turbine (geographical coordinate), date of grid

connection, cancelation date for decommissioned turbines, manufacture, type, hub height and diameter of rotor blades. The registry contains data for approximately 4,700 wind turbines in operation and 2,500 cancelled wind turbines.

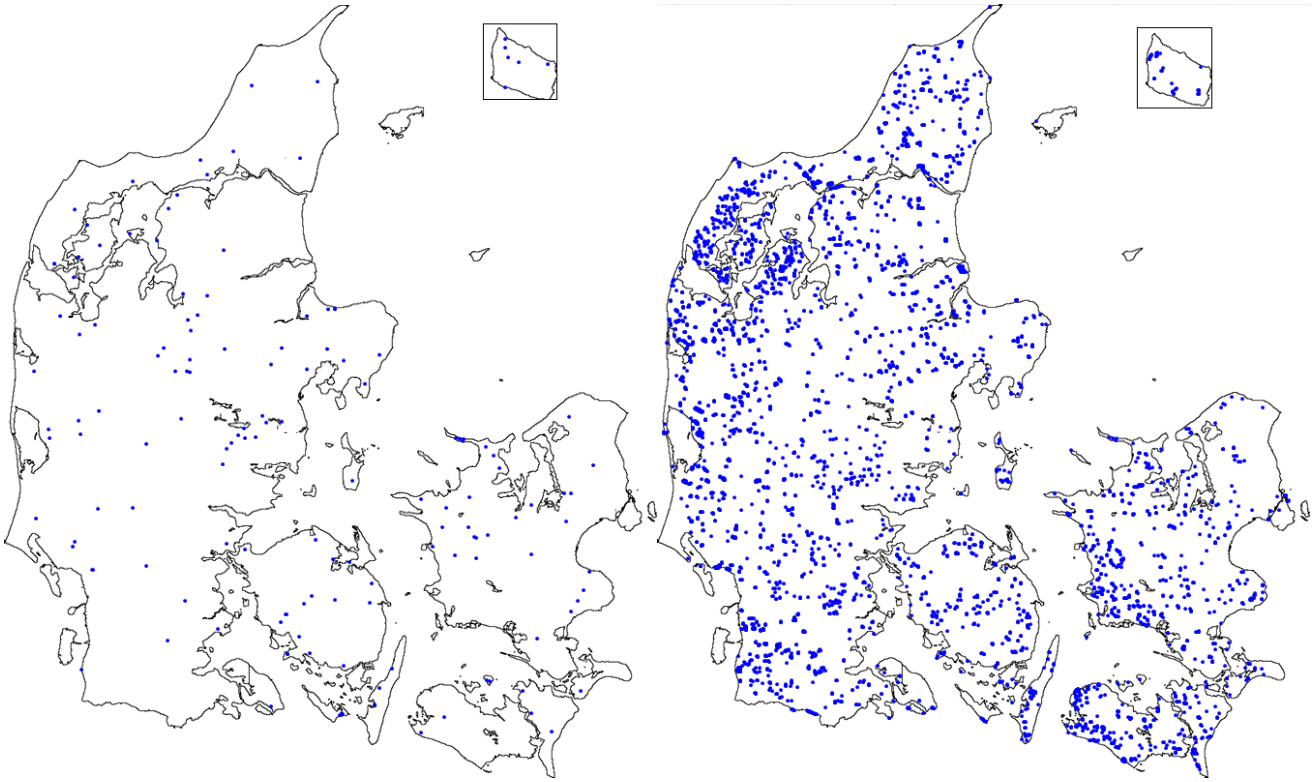

Figure 1

Onshore wind turbines in Denmark. Left: Position of wind turbines connected to grid January 1st 1982. Right: Position of wind turbines connected to grid December 31st 2013.

In figure 1 is shown a map of onshore wind turbines connected to grid the 1st of January 1982 and again 32 years later the 31st of December 2013. These maps show all onshore wind turbines – both small and large wind turbines. As can be seen wind turbines has been erected in most of Denmark, but especially near western coastlines which has the strongest wind.

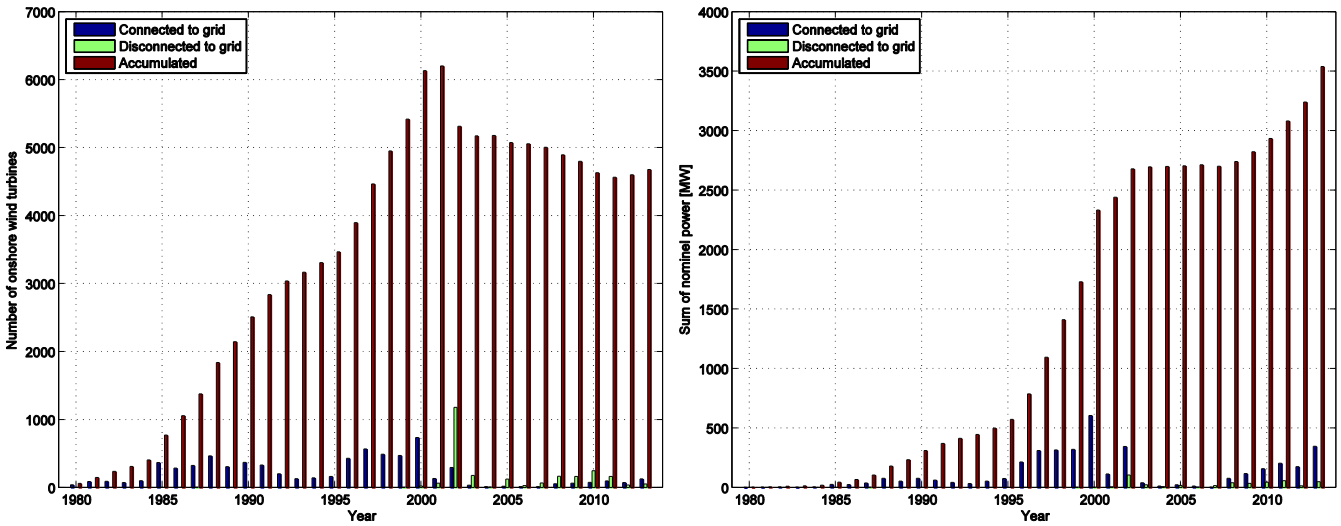

Figure 2
Statistics of onshore wind turbines in Denmark. Left: Number of wind turbines connected to grid. Right: Sum of nominal power of the wind turbines connected to grid.

In the years 1980-2000 there were numerous wind turbine manufacturers each with typically only a few wind turbine types, and where generally the wind turbines were small with a low nominal power. Over the years the wind turbines has grown in size and electrical power and typically in recent years a newly erected wind turbine is either; 1. Large (>2MW) and typically produced by either Siemens or Vestas or 2. Small (<100 kW) and produced by a number of manufacturers.

Since 1980 approximately 7200 wind turbines has been connected to grid in Denmark, where approximately 2500 of them has been decommissioned again (most of them to make room for newer and/or larger wind turbines). In figure 2 it can be seen that the number of wind turbines has grown steady until around year 2000 where the number of wind turbines has decreased, but even with fewer wind turbines the total nominal power keeps growing.
In figure 3 it can be seen that the average wind turbine connected to grid generally grows.

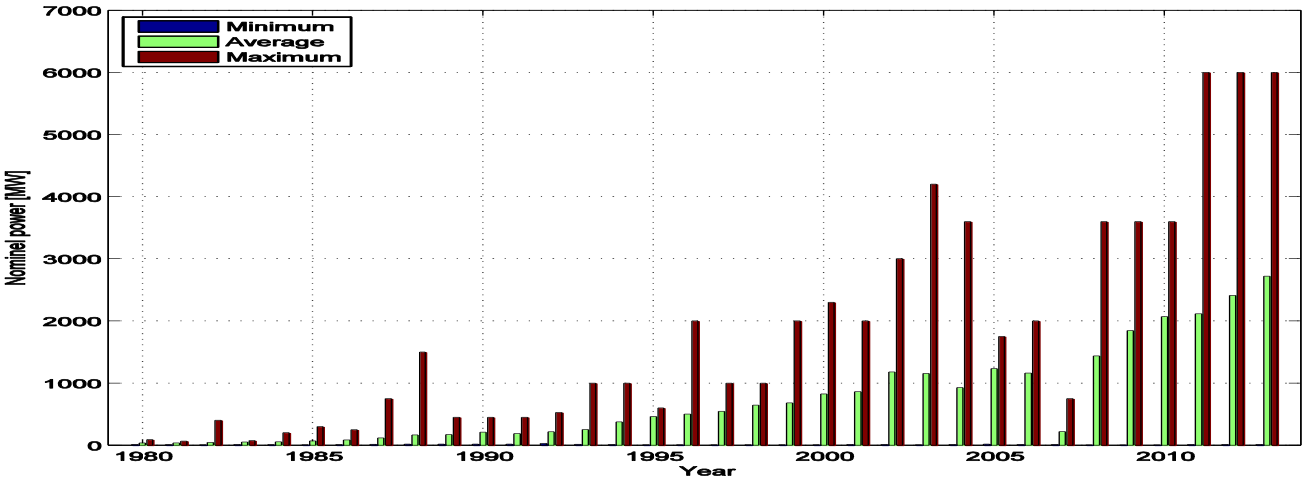

Figure 3
Average, minimum and maximum nominal power for a wind turbine connected to grid a given year

3. Wind turbines and measurement methods

The data material for this investigation is a large number of noise measurements performed on wind turbines primarily erected in Denmark. Over the years between 1980 to now wind turbines has changed largely, both in size but also layout of the blades, the drivetrain and controlling the wind turbine. Measuring equipment has also improved rapidly, and the measurement methods for wind turbine noise has also improved encompassing both the updated wind turbines and using the improved measurement systems. The included data in this document are measured according to one of methods described in reference [6 to 10]. Mostly for smaller wind turbines the noise development versus wind speed can be described as linear – at least in the wind speed range normally measured.
The wind speed of 8 m/s (referenced at 10 m height) are the common thread for most standard noise measurement on wind turbines in Denmark – old as new. Most reports contain also a frequency spectrum in some form. It however varies largely how low frequencies are included, and whether the resolution of the spectra is in 1/1-octave bands or 1/3-octave bands. In the following all wind speeds will be references to 10 m height.
A short description of the primary of the methods (where the measurement method in general is identical):

- Statutory order number 304 from 1991 [7] (in the following referenced as BEK 304) assumes a linear relationship for the noise development, which is used for calculating the noise level at 8 m/s. Reports typically shows a 1/1 octave band sound power level and the slope of the linear relationship for the development of the sound power level. Typical frequency reported frequency range is between 63 Hz and 8 kHz.
- IEC 61400-11:Ed.2.1 [10] Assumes a 4th order regression to describe the noise development (bin analysis if poor fit). Reports typically a 1/3 octave band sound power

level for wind speeds 6 to 10 m/s and a frequency range between 50 Hz to 10 kHz. In recent years often a frequency range down to 10 Hz is reported.

- Statutory order number 1518 from 2006 [8] (in the following referenced as BEK 1518) Uses bin analyses for the wind speeds 6 and 8 m/s. 1/1 octave band sound power levels in the frequency area 63 Hz to 8 kHz is required, but often 1/3 octave band sound power levels in the frequency range 10 Hz to 10 kHz is reported.
- Statutory order number 1284 from 2011 [9] (in the following referenced as BEK 1284) Uses bin analyses for the wind speeds 6 and 8 m/s. 1/3 octave band sound power levels in the frequency area 20 Hz to 10 kHz is required, but often data down to 10 Hz is reported.

In figure 4 is shown the measured noise levels (measured in a distance equal to the total height of the wind turbine) for both a small and a large wind turbine. To the left is shown measurement result for a small wind turbine and to the right for a large wind turbine. In the figure is shown both total noise and background noise. Additionally is on each figure shown the result of 1st order regression, 4th order regression and bin analysis. It can be seen that the 1st order regression (linear noise development) is a fair fit of the total noise from the small wind turbine, where the linear fit for the large wind turbine is poor. The 4th order regression is a fair fit for both turbines, but only for the wind speed range where data exists. The bin analysis is generally also a fair fit for both turbines as long as there is a sufficient amount of data.

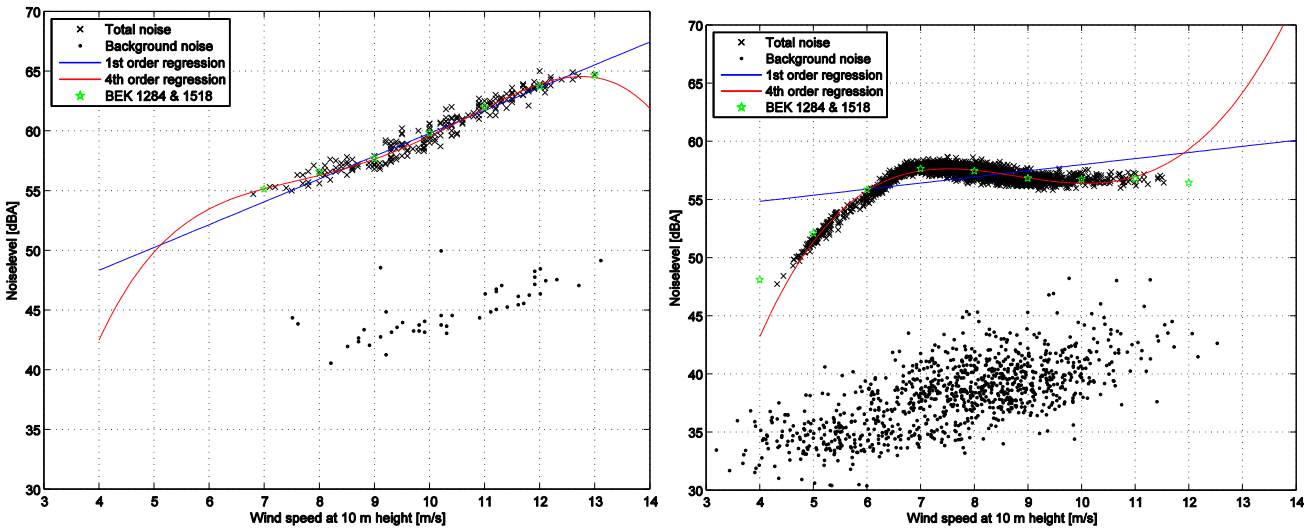

Figure 4
Measured noise development for two random wind turbines together a 1st order regression, a 4th order regression and bin analysis. Left: Small wind turbine (< 1 MW). Right: Large wind turbine (> 2 MW)

4. Existing (old) wind turbines

The investigation for data representing existing and old wind turbines will be based on reference [1], [2] and [3] – supplemented by extra data from DELTA's archives.

4.1 General spectra for older wind turbines

As a part of the introduction of Statutory order number 1284 [9] in 2011 a guideline to the Statutory order was written [1]. When calculating the noise contribution levels at receivers positions all relevant neighbour wind turbines must be included. An investigation was conducted to provide a table with data to use if the noise levels of the relevant neighbour wind turbines were not known [2].
Sound power spectrums for approximately 130 existing Danish wind turbines was sorted into 9 classes based on nominal power – from 0 kW to 2 MW, where data for domestic wind turbines are also included in the lowest class. Each class is based on between 6 to 35 reports with an average of 14 reports pr. class. The reports suggest general 1/3-octave sound power

spectrums for the 9 classes for 6 and 8 m/s (referenced 10 m height) in the frequency range 10 Hz to 10 kHz, where some data are based on regression. The classes are listed in table 1.

Class no	Nominal power	Class no	Nominal power	Class no	Nominal power
1	[0 kW – 100 kW[	4	600 kW	7	]750 kW – 1000 kW[
2	]100 kW – 300 kW]	5	660 kW	8	[1000 kW – 2000 kW[
3	]300 kW – 600 kW[	6	750 kW	9	2000 kW

Table 1
Overview of the classes described in [1] and [2].

The suggested data are based on the 90 percentile of the 1/3 octave spectra in order not to underestimate the noise level. However an average spectrum is also found for each class which will be used in this study. In figure 5 the sound power level spectra for the 9 classes are shown for the wind speeds 6 and 8 m/s.

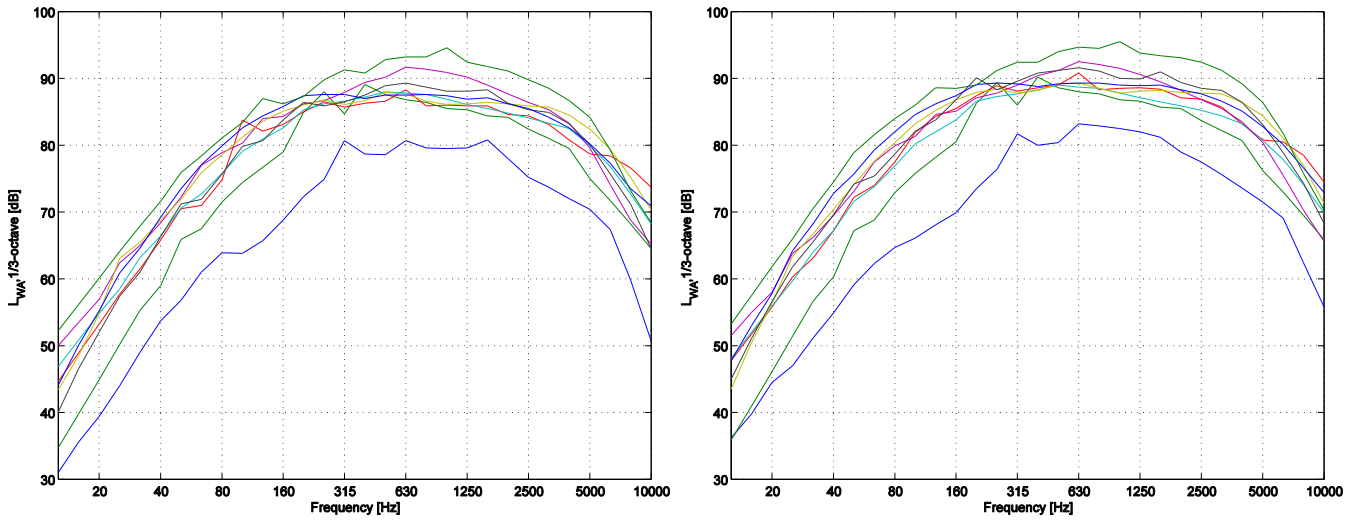

Figure 5
Average 1/3 octave sound power level spectra from reference [2]. Left: Data for wind speed at 6 m/s. Right: Data for wind speed at 8 m/s

4.2 Noise catalogue for older wind turbines in Denmark

As mentioned in section 4.1 a list with 1/3 octave spectra were found to be used for calculating the noise contribution for relevant existing neighbour wind turbines. Using the 90 percentile might not be representative for all wind turbines in each class and another investigation was performed in order to build a more extensive list with relevant noise spectra [3] for as many wind turbines as possible. Data was collected for approximately 300 wind turbines for 89 different wind turbine types erected in Denmark. Some of the wind turbine types have been combined in the data analysis to a final number of 75 different wind turbines types, each based on between 1 to 19 wind turbines with an average of 4 wind turbines pr. class. For each of the 75 wind turbine classes are described 1/1-octave sound power spectrums for 6 and 8 m/s in the frequency range 63 Hz to 8 kHz. Only wind turbines which are not sold anymore by manufacturers are included in the data material. The nominal power for the described 75 classes ranges from 11 kW to 2.75 MW. The spectra are shown in figure 6.

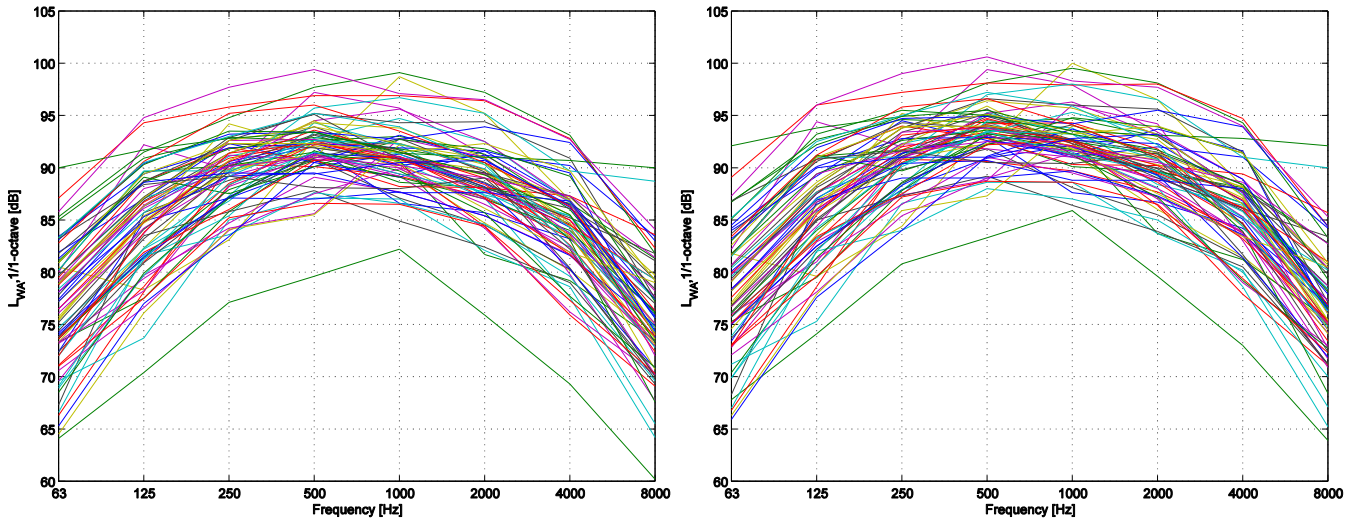

Figure 6
1/3 octave sound power level spectra from reference [3]. Left: Data for wind speed at 6 m/s. Right: Data for wind speed at 8 m/s.

4.3 Noise spectra for other wind speeds than 6 and 8 m/s

The noise spectra shown in section 4.1 and 4.2 are only reported for 6 and 8 m/s which is the wind speeds the noise spectra is typically reported in Denmark. In [2], [3] and [4] are assumed a linear noise development for other wind speeds. Reference [4] describes that at higher and lower wind speeds the correlation can be different, and for turbines with two generators, the switching between the two generators can result in a significant change of noise development at the wind speed where the switching occurs. It is assumed in this study that the noise development for small wind turbines is linear and that the frequency distribution behaves in the same way at the different wind speeds. This is probably not always correct, but the frequency distribution by other wind speeds than 6 and 8 m/s are mostly unknown or only sporadically reported. Probably the spectra changes especially for the highest wind speeds, and especially also when switching between generators. This is not methodically reported. For the reports DELTA has checked the linear noise development has a good fit with the measured values. The majority of these reports has primarily data around and close to 8 m/s, but a few also has data at high and low wind.

In order to describe spectra at other wind speeds than 6 and 8 m/s the difference in the reported 6 and 8 m/s spectra are used to calculate spectra at other wind speeds following the method described in [2] and [3]. For data described in section 4.2 the energy in the 1/1 octave bands will be divided into the relevant 1/3 octave bands and combined with interpolation to ensure a smooth spectrum, however still ensuring the same energy in each 1/1 octave band. For the low frequency part of the data from section 4.2 data from the relevant class in section 4.1 will be used.

By combining knowledge from section 4.1 and 4.2 1/3 octave band spectra in the frequency range 10 Hz to 10 kHz can be calculated/estimated, where two examples of the frequency distribution of two random wind turbine classes is shown in figure 7. The greater the difference in wind speed is compared to 8 m/s (and 6 m/s) the greater the uncertainty of the data is.

As a result the standard deviation grows with the difference in wind speed to 8 m/s (and 6 m/s).

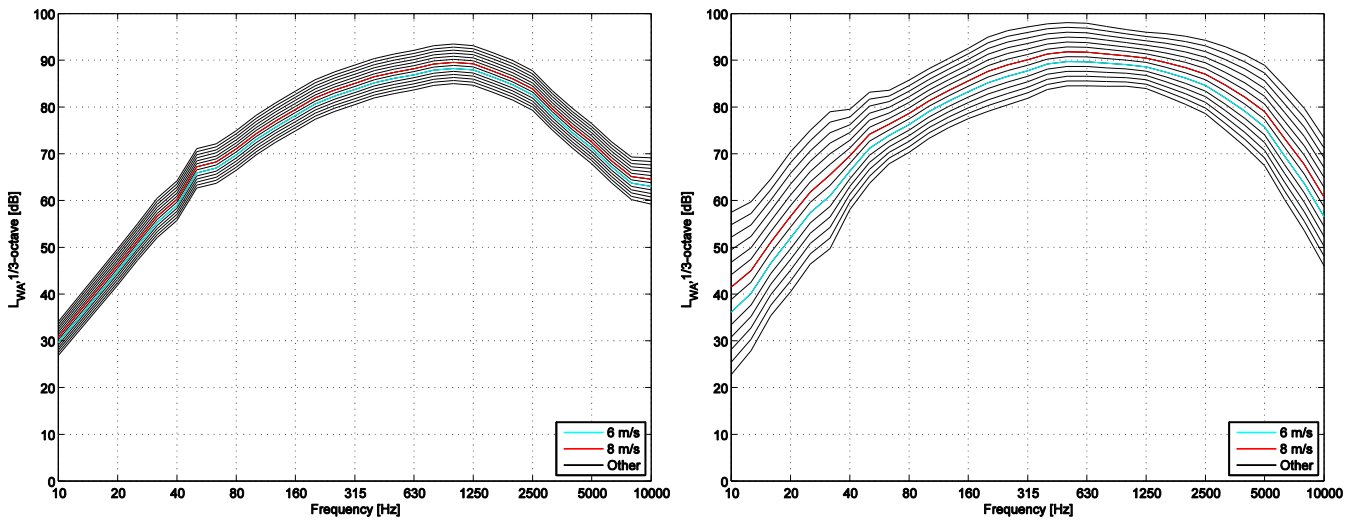

Figure 7
Calculated 1/3 octave sound power level spectra for wind speeds from 2 – 14 m/s for two randomly selected classes. The blue line shows the spectra at 6 m/s and the red line the spectra at 8 m/s.

5. New wind turbines

Data on new wind turbines are primarily based on data from DELTA's archives supplemented by received measurement reports. Data are from measurement reports according to [8], [9] and [10].

5.1 Large wind turbines

For large new wind turbines DELTA has performed a large number of measurements both according to the Danish methods [8] and [9] but also according to the IEC method [10]. The data for this analysis continues the investigation reported in [5] where additional data has been included. Noise from a total of 111 different wind turbines has been included in the study primarily measured by DELTA, but a few received measurement reports have been included as well. Some of the turbines are measured in different operating modes. Some turbines are measured over several days of measurement to catch wind speeds both about 6 m/s and 8 m/s. In total 156 measurements are included. Figure 8 shows the distribution of these measurements on wind speeds. The figure shows that the two distributions are very similar, so the comparison of the two types of wind turbines at different wind speeds can be done on a consistent basis.

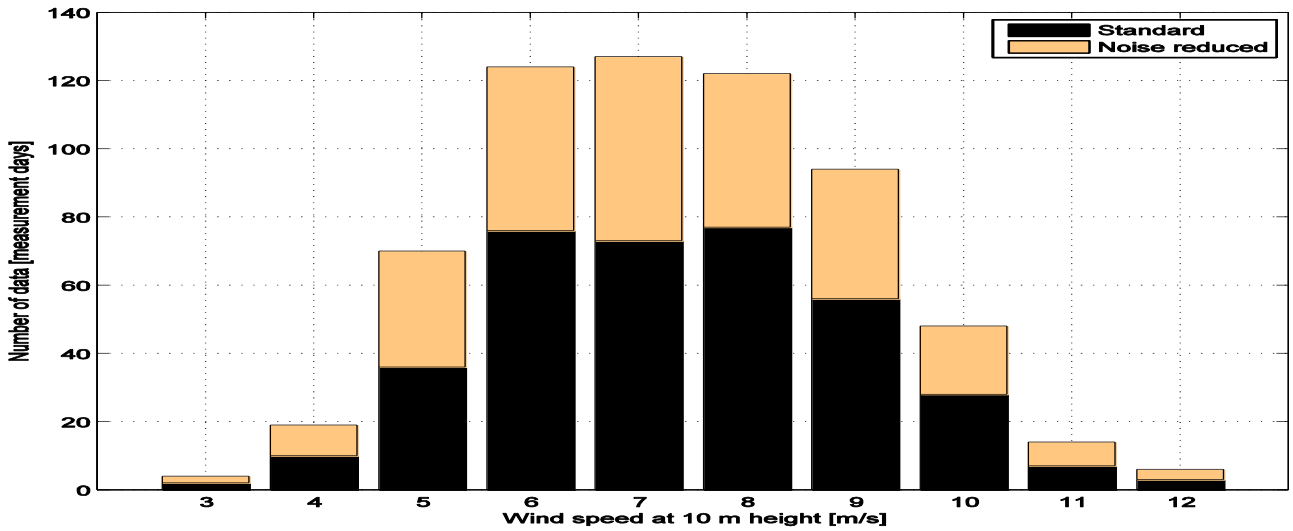

Figure 8
Number of measurements for noise reduced wind turbines and standard wind turbines for different wind speeds.

Primarily measurements covering a wide wind speed range are selected. For most measurements only data at 6 and 8 m/s was initially reported, for the other wind speeds similar analysis is conducted and 1/3 octave band spectra are calculated for as large a wind speed as possible. A few data does not meet all of the requirements of [8] and [9], but is included if a further validation estimates that the deviation is not believed to influence the outcome. In figure 9 is shown the 1/3 octave band frequency spectrum for 6 and 8 m/s for all the data.

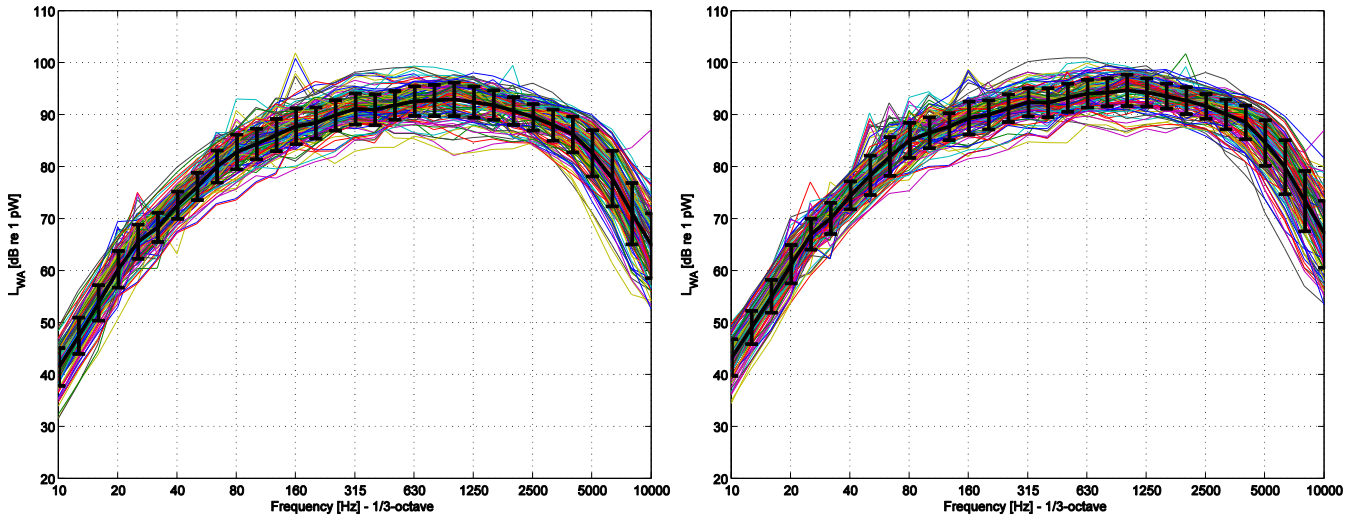

Figure 9
1/3 octave band frequency spectrums for all wind turbines used in section 5.1. Left: Data for wind speed at 6 m/s. Right: Data for wind speed at 8 m/s.

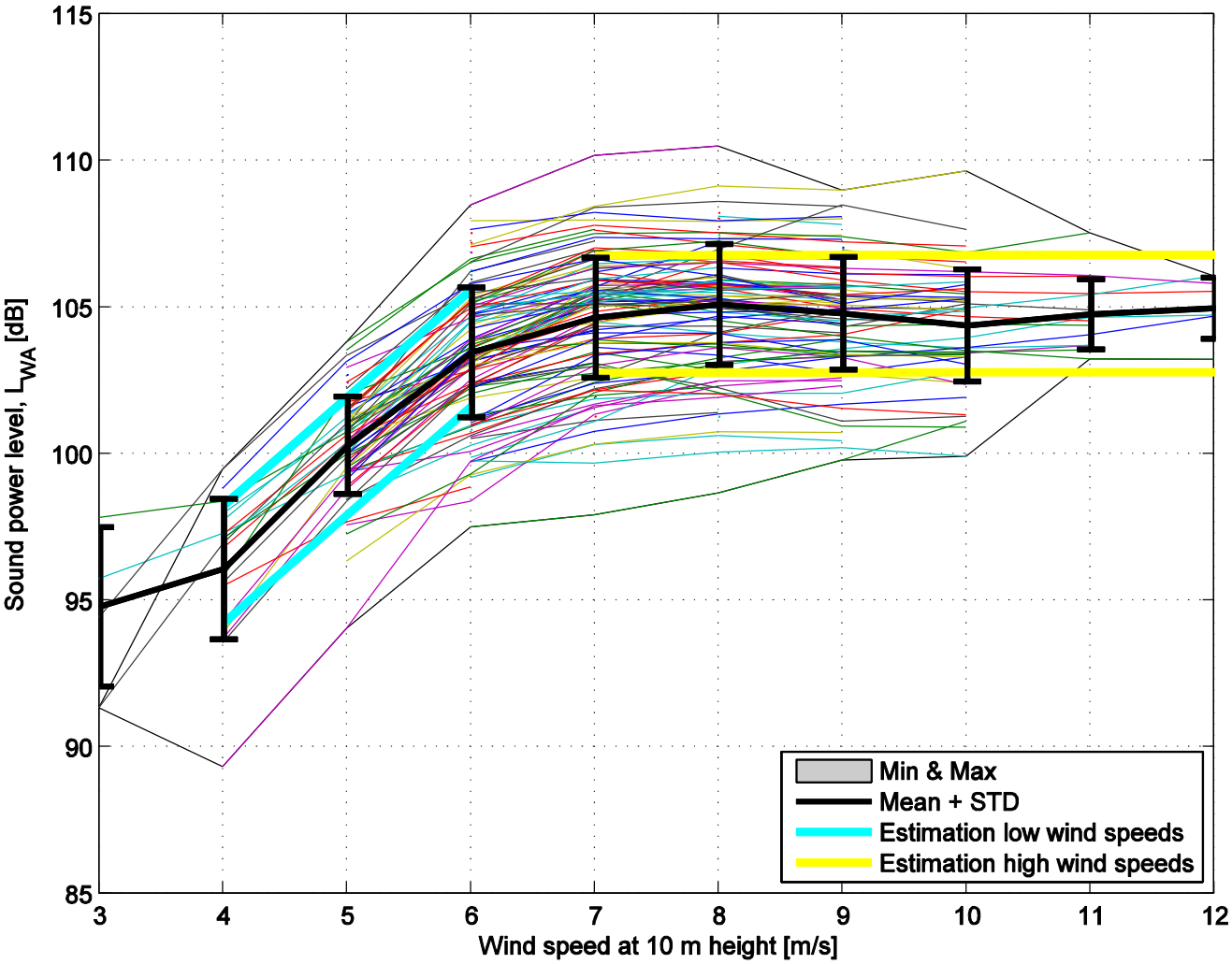

Figure 10
Noise distribution for different wind speeds for large wind turbines

Data was obtained in the wind speed range 3-12 m/s, with most data from 5-9 m/s. In general the noise from the wind turbines increases up to approximately 7 m/s, where it for higher wind speeds is approximately constant. In figure 10 is shown the noise distribution for each wind speed bin centre. The thin coloured lines shows data for each measurement, where the grey area marks the minimum and maximum of the data. A thick black line shows the average value together with the standard deviation. It can be seen that data below 7 m/s can be represented by a linear regression (shown with thick blue lines) and that data from 7 m/s and up can be represented by another linear regression (shown with thick yellow lines).

Data is divided into 6 classes which together represent the majority of the wind turbines erected in Denmark since approximately 2006. Each class is divided into two subclasses, one with noise reduced wind turbines and the other with standard wind turbines. To represent the remaining wind turbines the last class contains all data, again divided into noise reduced and standard wind turbines. The amount of data differs for each class, where especially the wind speed distribution differs. To obtain data for all wind speeds for each class from 3 to 14 m/s linear regression is used on the group of data below 7 m/s and again on the group of data from 7 m/s and up. This is used to find a noise development for each class for each wind speed from 3 to 14 m/s.
Accordingly all frequency spectra below 7 m/s are grouped together and normalized to the same total sound power level where after an average 1/3 octave band frequency spectrum is calculated to represent the low wind speeds. The same method is used for data with wind speeds from 7 m/s and up.
Finally for each wind speed with no or only one data set the average frequency spectra for either low or high wind speed is used adjusted to the noise development found above. All data are visually inspected to ensure validity of the data.

5.2 Domestic wind turbines

For the domestic wind turbines the procedure in general are identical to the procedure followed for new wind turbines (see section 5.1), except that a linear relationship is found for all wind speeds as for with the old/existing wind turbines. DELTA has measured noise from a number of domestic wind turbines. These data are supplemented with received data.

6. Data validity

For all spectra are calculated a standard deviation (either in the referenced reports or calculated on data). For a wind speed with only one spectrum or with no spectra a standard deviation cannot be calculated. Instead a value is calculated based on available data. In the calculation a “penalty” is added representing the distance to wind speeds with measured data.

6. Tonality number

For all wind turbine classes are indicated a tonality number based on available reports. In Danish legislation tonality are primarily assessed at a distance from the wind turbine equal to the total height of the turbine (referred to as the IEC distance) and sometimes also at neighbour distance. For this investigation the following indicators are used:

- -1: No knowledge whether this turbine class has audible tones
- 0: No clearly audible tones at IEC distance is found for this wind turbine class
- 1: There are cases with clearly audible tones at the IEC distance, but no cases are known of clearly audible tones at neighbour distance
- 2: There are cases of clearly audible tones at neighbour distance

The assessment of tonality is performed according to reference [11] and for old turbines generally evaluated around 8 m/s. Since 2006 the assessment are generally evaluated around 6 and 8 m/s. Generally there is no knowledge of the tonal content at other wind speeds.

Not all reports contain assessment of tonality, which especially is the case for the oldest measurement.

7. Conclusions

Noise regulation for wind turbines in Denmark are based on sound power level measurements primarily following the statutory orders 304, 1284 or 1518 [7, 8 and 9], which are comparable with the IEC 61400-11 [10]. Measurements are performed in a distance from the wind turbine approximately equal to the total height of the wind turbine.

Combining reference [2], [3] and [5] with additional noise data 100 wind turbine classes are formed with noise data for 1/3 octave band sound power level spectra for wind speeds from 3 to 14 m/s referenced 10 m height. For each 1/3 octave band for each wind speed are found a validity value, which describes the validity of the data. Additionally for each class are described a tonality value, which add information of tonality around 6 and 8 m/s (if known).

The classes are:
Class 1-9: Based on reference [1] and [2]
Class 10: Domestic wind turbines
Class 11-86: Based on the 75 classes in reference [3]
Class 87-100: New wind turbines

The 100 classes are then used to calculate the noise from the approximately 7200 onshore wind turbines in Denmark in the years 1982 to 2013.

The noise development for different wind speeds for the 100 classes are shown in figure 11.

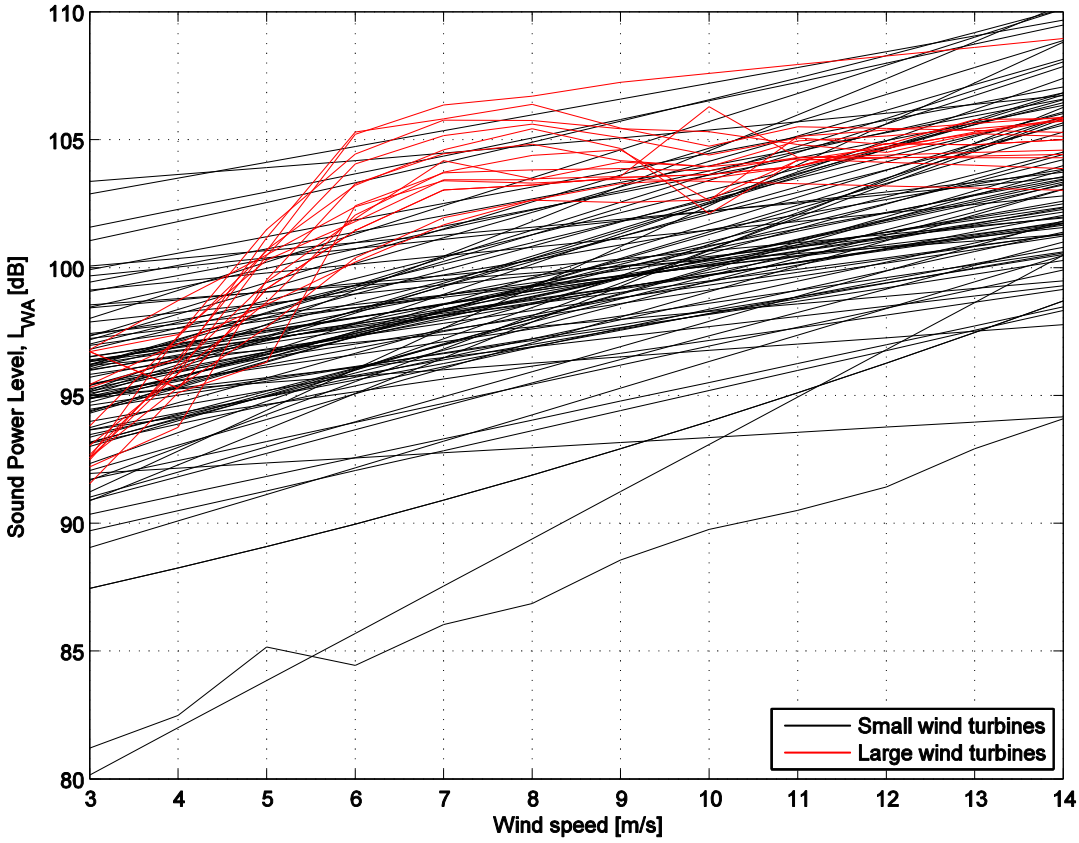

Figure 11
Sound power level for the 100 classes for wind speeds from 3 to 14 m/s

References

[1] Danish Environmental Protection Agency, *Støj fra vindmøller (Noise from wind turbines)* – Guideline from the Danish Environmental Protection Agency no. 1, 2012 (in Danish).
[2] Søndergaard, B / Danish Environmental Protection Agency, *Generelle data om støjen fra ældre vindmøller (General data about the noise from older wind turbines)* – Environmental Project no. 1398 from 2011 from the Danish Environmental Protection Agency (in Danish).
[3] Søndergaard, B / The Danish Wind Turbine association et all, *Støjkatalog over ældre vindmøller i Danmark (Noise catalog for older wind turbines in Denmark)* – June 2014. Grontmij (in Danish).
[4] Jakobsen, J / The Reference Laboratory for the Danish Environmental Protection Agency, *Støj fra vindmøller (Noise from wind turbines)* – Information no. 22. 1994 (in Danish)
[5] Søndergaard, L / DELTA / Danish Environmental Protection Agency, *Støj fra vindmøller ved andre vindhastigheder end 6 og 8 m/s (Noise from wind turbines at other wind speeds than 6 and 8 m/s)* April 2014 (in Danish).
[6] Letter from the Danish Environmental Protection Agency to Danish Counties, municipalities etc. May 3 1988 (in Danish)
[7] *Statutory Order on Noise from Wind Turbines*; Statutory Order no. 304 of 14. May 1991 (in Danish).
[8] *Statutory Order on Noise from Wind Turbines*; Statutory Order no. 1518 of 14. December 2006 (in Danish)
[9] *Statutory Order on Noise from Wind Turbines*; Statutory Order no. 1284 of 15. December 2011 (in Danish. English translation can be seen at http://www.mst.dk/NR/rdonlyres/E8562E10-2B2D-4BF3-BAE0-A265C5A0B86E/0/engelsk_vindmoellebekendtgoerelse.pdf).
[10] IEC 61400-11 Ed. 2.0 IDT *Wind turbine generator systems – Part 11: Acoustic noise measurement techniques*
[11] Danish Environmental Protection Agency, *Guidelines for Measurements of Environmental Noise*, 6/1984 (in Danish), Nov. 1984.