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Danish experiences with measuring wind turbine noise at neighbor dwellings.

Rune Egedal, Sweco: rune.egedal@sweco.dk
Niels F. Christensen, Sweco: nielsfrederik.christensen@sweco.dk
Bo Søndergaard, Sweco: bo.sondergaard@sweco.dk

Summary

This paper investigates measurements conducted in Denmark at neighbour dwellings. The results are based on three studies, two short term and one long term measurement. The paper will summarize the results and experiences gained through the studies. The focus is drawn to the differences in noise level seen at different neighbour dwellings, and hence the influence of the surroundings e.g. the vegetation. Furthermore, the windspeed measured at different positions compared to the measured noise levels are investigated. It is indicated in the studies that it in some cases is possible to measure the noise from wind turbines at the neighbours, but there are several factors that must be accounted for, in order to ensure that the measured noise inherit from the wind turbines.

1. Introduction

In connection with criticism of the Ministry of the Environment's guidelines for documentation of noise from wind turbines through sound power measurements and noise predictions, the Danish Environmental Protection Agency (EPA) has launched a series of studies based on direct measurement of noise from wind turbines at neighbors to wind turbines.
Sweco has conducted two separate studies, where measurements have been conducted during the day period for one site and day and night period for the second site.
The purpose of these studies is to gain knowledge about whether it is realistic to implement documentation of noise from wind turbines through direct measurements at neighbors. Furthermore, whether special noise issues occur outside the wind speed range of 6 m/s to 8 m/s, that the current regulations include, and which may give rise to reassessment of the regulations. Where the first study focuses on more general conditions during the day the second study includes measurements during night time.
Beside the studies conducted for the Danish EPA a third study at a, for Danish circumstances, large windfarm has been conducted.

This paper focuses on the knowledge gained through these three studies. The main points will concern the following:

- Is it possible to measure the noise from the wind turbine at the neighbor dwellings?
- The difficulties experienced during the measurements and data handling.
- Correlation between measured noise and measured windspeed at different positions.

2. General setup and site description

In the following the main characteristics of the three studies will be presented. Starting with the two studies conducted for the Danish EPA, which has similar setups and motivation. Ending with the third study which aim was long term surveillance of noise levels at different dwellings. The project report for study number 2 has been released from the Danish EPA [1] the first study remains to be officially released.

2.1 Study no. 1

For this study a site in western Jutland was investigated. The wind farm consisted of 6 wind turbines with a hub height of 90 meters and a rotor diameter of 120 meters, the combined effect of the wind farm is 36 MW. The turbines are placed on a straight-line oriented north to south. For this study 3 neighbours in different directions were selected, respectively south, north and west of the wind farm. The turbines are situated in a flat terrain surrounded by agricultural land, and scattered vegetation like small and large groups of trees, a site overview can be seen in Figure 1. The distance to the neighbour dwellings varied between 650- to 760 meters from the nearest turbine in the wind farm.

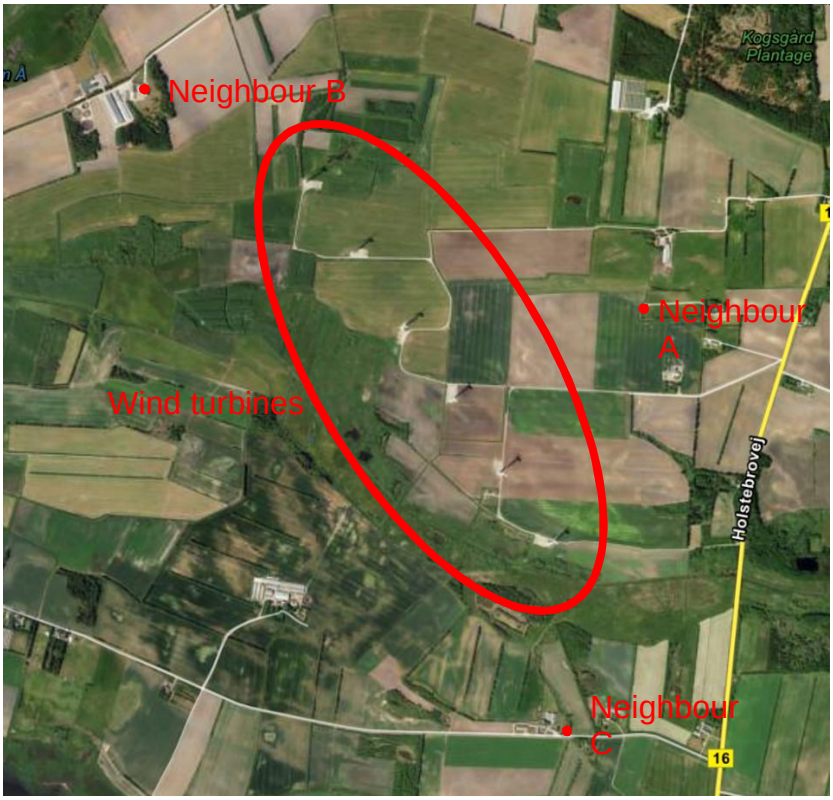

Figure 1: Site overview for study 1.

The measurements were conducted over three different campaigns. Each campaign was conducted at similar times during the day from around 09:00 in the morning to 16:00 in the afternoon. The setup consisted of 3 different positions.

- One position approximately between the nearest wind turbine and the dwelling in question.
- One position outside the dwelling.
- A setup indoors consisting of 3 microphones and measured according to the guidelines described in [2].

Beside the noise measurements the following non-acoustic parameters were obtained:

- Wind speed at one of the neighbours at 10-meter height.
- Operational parameters from the wind farm e.g. produced power, and wind speed at hub height.

2.2 Study no. 2

For this study a site in mid Jutland was investigated. The wind farm consisted of 3 wind turbines with a hub height of 94 meters and a rotor diameter of 112 meters, the combined effect of the wind farm is 9 MW. The turbines are situated on a straight-line oriented north to south. Three neighbours in different directions were selected, respectively east and west of the turbines. The turbines are situated in flat terrain surrounded by agricultural land and scattered vegetation like small and large groups of trees, all three neighbours have larger trees around their dwelling. A site overview can be seen in Figure 2. The distance to the dwellings varied between 650- to 920 meters from the nearest wind turbine.

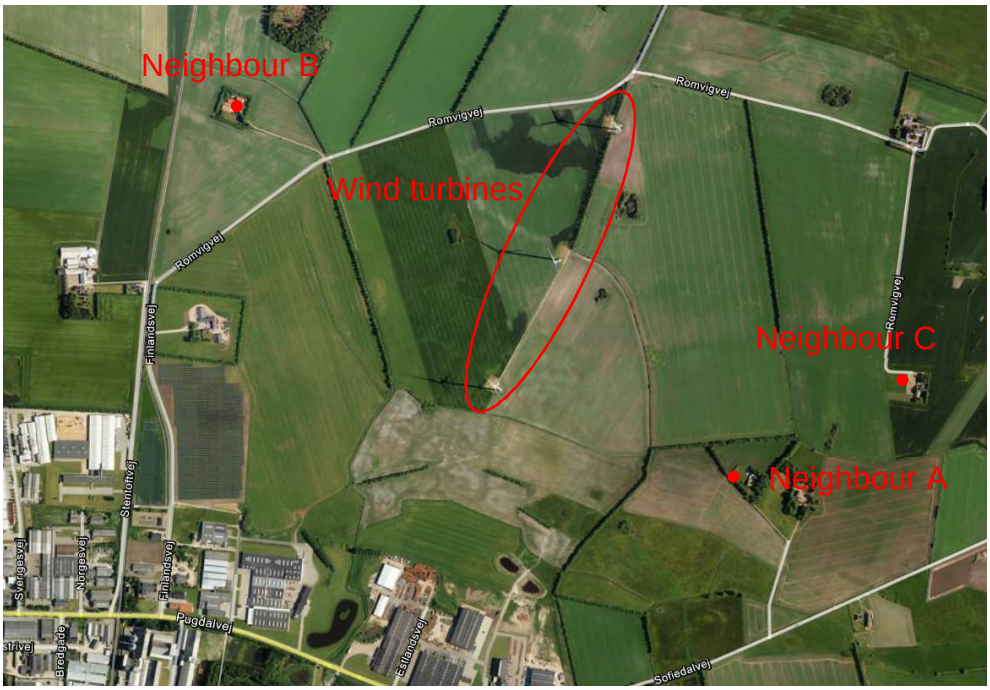

Figure 2: Site overview for study 2

The measurements were conducted like the measurements in study number 1, with the similar positions and data sampling. However, the measurements were conducted over night and until the afternoon the day after, from around 21:00 in the evening until 16:00 the afternoon the day after.

2.3 Study no. 3

This study was conducted near a large wind farm in western Jutland. The wind farm consists of 22 wind turbines with a combined effect of 72,6MW. The turbines are situated in two parallel lines with 11 turbines in each line. For this study eight neighbours were selected located around the wind farm in different directions. The terrain around the wind farm is flat and a large part of the area is agricultural land.

The study was conducted as long-term measurements over a period of 17 days. Microphones were placed at eight different neighbours outside their dwellings. If the residents had special requests on the position of the microphone this was followed. The total A-weighted sound pressure level was recorded at all the neighbours. Beside the sound pressure level, the windspeed at 10-meter height was recorded at two of the neighbours. Operational parameters from the wind farm was not recorded during the measurement. However, operational data from one of the wind turbines has been obtained afterwards as 10 minutes averages and used in this analysis. The wind turbine is situated in the outer limit of the park.

3. Experiences & Results

In the following the results and experiences from the two Danish EPA studies are presented. For comparison two neighbours has been selected showing two different scenarios of neighbour measurements.

3.1 Short term noise measurements (study 1 and 2)

Common to the two studies is that the measurements are conducted over a short period (less than 24 hours). The purpose of dividing the study into several short term measurements is to cover as varying meteorological conditions as possible. The measurements are performed from December to June, so the measurements cover winter, spring and summer.

In Figure 3, one of the measurements campaigns from study no 1 is shown. The light blue (P5) represents the position between the wind turbine and the neighbour. The light green (P4) is the position near the neighbour, and finally the black, red and orange are the three microphones at the indoor position. The pink and blue respectively represents produced power and the normalized windspeed derived from the power curve at hub height

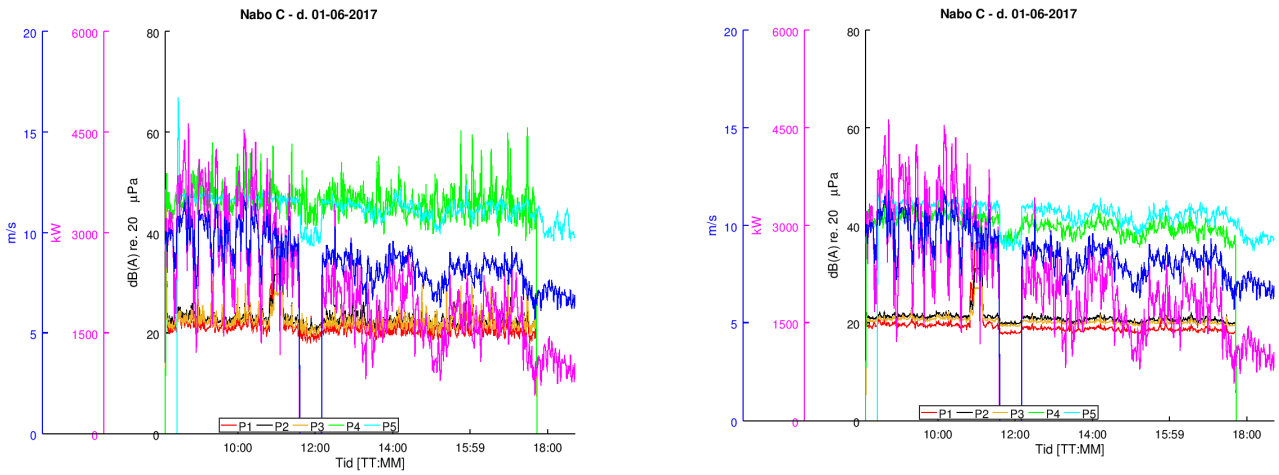

Figure 3: Results of the measurements at neighbor C for study 1. Left L_{pAeq} right L_{A90} 1-minute averages.

It is seen from the left graph in Figure 3 that the noise measured at the neigbour position outdoor is comparable and in some cases higher than the noise measured close to the windturbine. This indicates that the noise measured near the neighbour is contaminated by other spurious noise sources in the area. In order to exclude as much as possible of the spurious noise sources e.g. car passings or activities in the dwelling the noise indicator L_{A90} is chosen as a suitible indicator of the steady noise measured at the nieghbour. On the right side in Figure 3 a time slice is shown with L_{A90} as the indicator. As opposed to the left side the outdoor levels are now more clearly separated. However it is seen that the level at the neighbour and closer to the tubine in some cases are the same. During the measurement the turbines were shut down for a short period, and a drop in the measured noise level at all positions can be seen indicating that the noise from the wind turbines are contributing to the measured noise in all positions.

Noise from wind turbines have a strong correlation with wind speed, therefor the noise measured at the neighbour are compared to the windspeed observed at the wind turbine. In order to show the complexity of the measurements, measurements with high background levels have not been excluded from the plots. The plots are seen in Figure 4, Figure 5 and Figure 6. Kanal 1-3 is indoor, Kanal 4 is outside the house and Kanal 5 is close to the wind turbines.

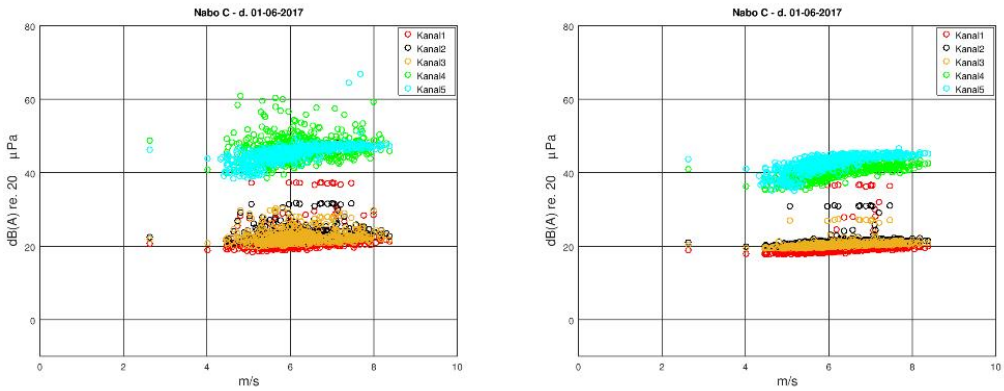

Figure 4: Results of the measurements at neighbor C for study 1. Left L_{pAeq} right L_{A90} 1-minute averages.

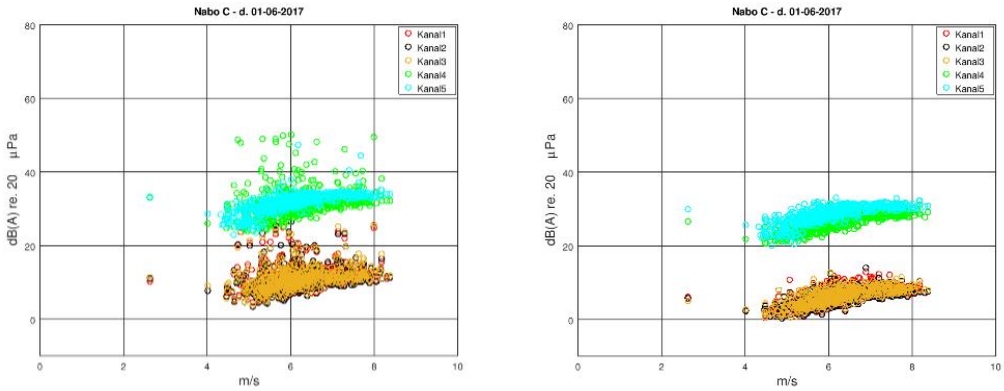

Figure 5: Results of the measurements at neighbor C for study 1. Low frequent levels left L_{pALF} right L_{A90LF} 1-minute averages.

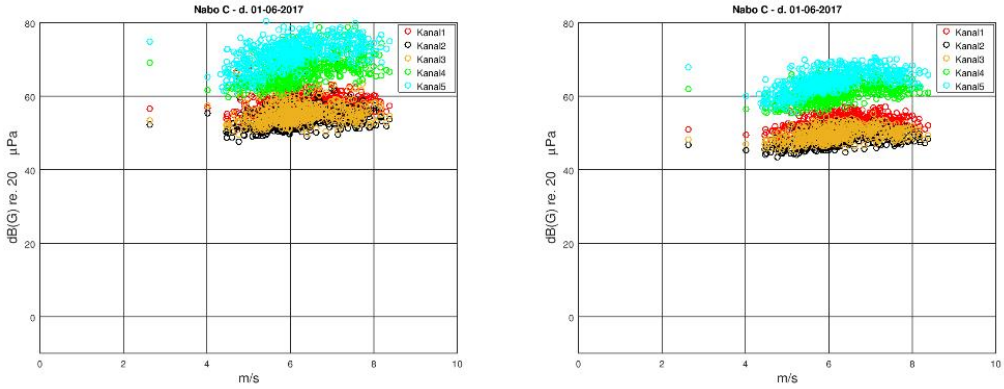

Figure 6: Results of the measurements at neighbor C for study 1. Infrasound (G-weighted) left L_{Geq} right L_{G90} 1-minute averages.

It is seen that there is a correlation between the measured noise levels and the wind speed for all the measurements. For the measurements outdoor light green and light blue, the correlation is visible for all three indicators. The pattern of the measured noise does follow the regular pattern for a pitch regulated wind turbine indicating that the noise is affected by the wind turbine. For the indoor measurements the correlation is weak when using the L_{A90} indicator (probably due to influence from background noise). However, when the L_{pALF}[1] indicator and to some extend L_{pG} is used a correlation is seen even at low levels. This indicates that the background noise in these frequency ranges is low.

To see if the noise is merely a result of increased background noise due to the rise in windspeed and hence more noise from vegetation, the measurement is scrubbed from outliers and afterwards bin analyzed. In Table 1 the results from neighbor C is shown. It is seen that there is a correlation between windspeed and the measured noise level, and that there is a difference between the turbines running or shut down. For the indoor low frequent level and the outdoor L_{A90} level the distance to the background noise is good enough to count the results as liable for the measure of the wind turbine noise at the neighbor, when corrected for background noise.

Windspeed	4 m/s	5 m/s	6 m/s	7 m/s	8 m/s	Background noise
L_{A90} Indoor P1-3	19.3	20.4	21.0	24.2	20.7	19.6
$L_{pA,LF}$ Indoor P1-3	7.5	12.2	12.7	13.4	13.9	8.5
L_{A90} Outdoor P4	36.5	38.5	40.3	41.7	42.3	37.8
L_{pG} Indoor P1-3	53.0	56.8	56.7	58.3	56.7	55.0

Table 1: Bin-analyzed results at neighbor C for study 1, in dB [re 20µPa]. The background noise is representative for 7-8 m/s

For the second study a similar analysis as in study 1 has been conducted. For comparison with the results obtained study 1, and to show the difficulties that can arise for a measurement with a higher degree of influence from background noise.

[1] L_{pALF} is the low frequent part of the A-weighted sound pressure level, given in dB [re 20µPa] for the 1/3 octave bands from 10 Hz to 160 Hz.

As for study 1 the correlation between wind speed and measured noise is investigated. In Figure 7, Figure 8 and Figure 9 the measured levels are shown with light blue for the position closest to the turbine light green for the outdoor position at the neighbour and red, orange and black for the indoor positions at the neighbour. One of the first differences compared to study 1 is that the pattern recognized from a pitch regulated turbine is not clear for the different positions except for L_{A90} for the position closest to the turbine. Instead the measured levels seem to follow a more linear tendency for all the indicators. It is also seen that the level measured outdoor at the neighbour is higher than the measured level close to the turbines for all wind speeds indicating that the measured noise does not inherit from the turbines but from other noise sources.

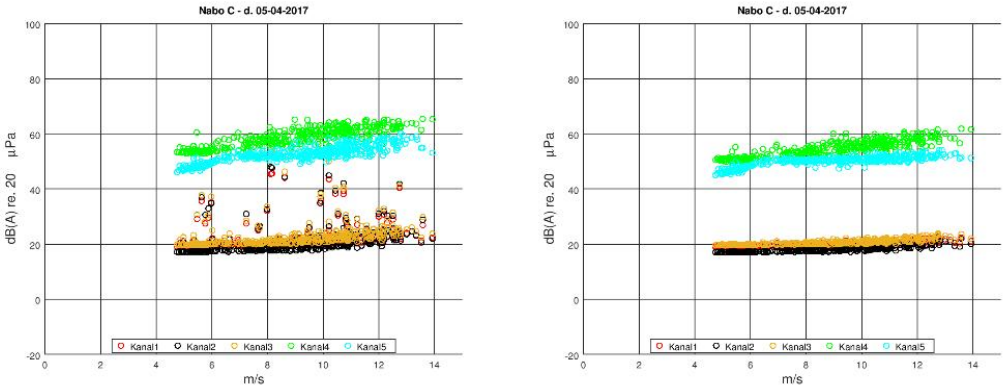

Figure 7: Results of the measurements at neighbour C for study 2. Left L_{Aeq} right L_{A90} 1-minute averages.

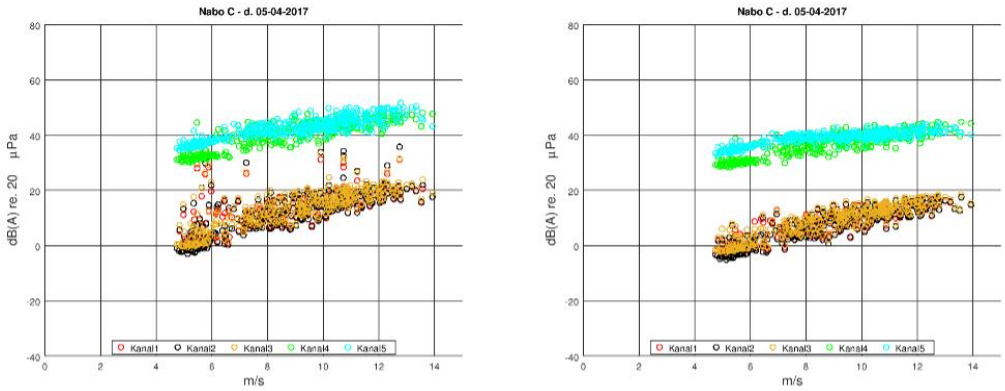

Figure 8: Results of the measurements at neighbour C for study 2. Low frequent levels left L_{pALF} right L_{A90LF} 1-minute averages.

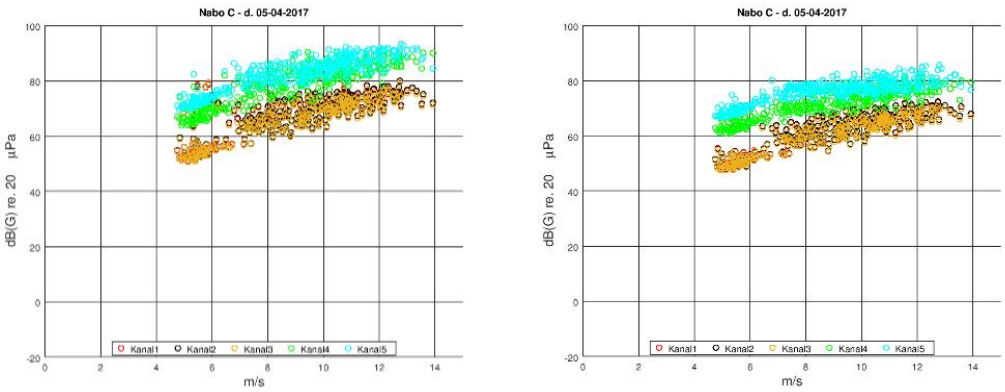

Figure 9: Results of the measurements at neighbour C for study 1. Infrasound (G-weighted) left L_{Geq} right L_{G90} 1-minute averages.

As for study 1 the measured data has been scrubbed for outliers and bin sorted. In Table 2 the result of the analysis is shown. For the indoor indicator L_{A90} the noise with the turbines turned on or off is approximately the same, and hence it is not possible to conclude anything about the noise from the turbines. For the indoor L_{pALF} indicator a difference is seen for low windspeeds. However, as the windspeed rises the difference between the background level and the total level diminishes, and it is difficult to deduct if the noise arises from the turbines, the same occurs for the G-weighted level. For the outdoor L_{A90} level a difference is seen for low wind speeds, but as the windspeed increases the background noise levels reaches the same level as the total level indicating that other noise sources at high windspeeds dominates.

Windspeed	L_{A90} indoor		L_{pALF} indoor		L_{pG} indoor		L_{A90} outdoor	
	Total noise	Bg-noise	Total noise	Bg-noise	Total noise	Bg-noise	Total noise	Bg-noise
3 m/s	18.1	-	0.2	-	46.1	-	33.4	-
4 m/s	18.0	17.9	10.9	-5.6	61.3	43.7	39.1	33.2
5 m/s	18.0	18.0	9.8	-2.7	56.3	46.7	36.4	35.1
6 m/s	18.0	18.0	1.3	4.4	54.7	55.8	42.6	35.6
7 m/s	18.1	18.0	7.8	-3.7	60.0	44.4	47.0	34.1
8 m/s	18.2	18.5	7.0	7.6	60.0	61.0	48.6	52.1
9 m/s	18.5	18.6	10.3	9.3	62.8	62.4	52.1	53.0
10 m/s	18.7	18.7	11.0	9.2	64.4	62.5	53.6	53.9
11 m/s	18.8	18.9	11.3	10.9	65.2	63.9	54.3	54.4
12 m/s	19.0	19.0	11.6	12.6	65.3	66.5	54.9	55.5
13 m/s	19.3	-	13.0	-	66.2	-	56.5	-

Table 2: Bin-analysed results at neighbour C for study 2, in dB [re 20µPa].

As it is seen from the table above it can be difficult to extract valid information on the noise caused by the wind turbine from the background noise. In Figure 10 the background noise is marked with a black cross and total noise with light green in order to compare the levels experienced at the neighbour outdoor position. It is seen that the noise levels for total noise and background noise merges, indicating the complexity of recognizing the turbine at this neighbour for the total noise level.

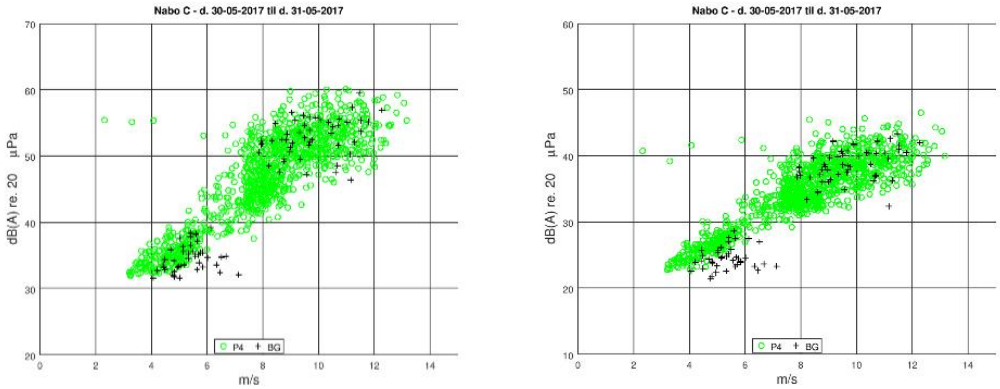

Figure 10: Results from neighbour C for study 2, left L_{A90} right L_{pALF}

From the measurements conducted in the two different studies for the Danish EPA, it is shown that it is, to some extent, possible to measure the noise from the wind turbine at a neighbour position. However, it is also seen that the environment around the neighbour can have an impact on the ability to measure the noise from the turbine at the neighbours. Another parameter that is of high importance is windspeed. As it is seen in the above the noise is correlated with the windspeed, and hence it is important to use the right windspeed in order to

assure that the noise measured is due to the wind turbine and does not inherit from e.g. vegetation or wind induced noise in the house.

3.2 Concerns regarding determination of windspeed (Study 1)

When measuring noise at the neighbour dwellings the windspeed becomes a parameter that can be discussed. Following the Danish EPA statutory order [3] for measuring noise from wind turbines the wind speed is defined through the measured power output of the wind turbine. The determination of the wind speed is under Danish circumstances very important as the noise limits are connected to the wind speeds, 6 and 8 m/s. When measuring at neighbour distance from the wind turbines there are several possibilities for determining wind speed. It can be deduced from one of the turbines, it can be as the average of the wind experienced by the entire wind farm, or it can be measured at the neighbour dwelling at a height of 10 meter or more.
In Figure 11 two different measurements are shown. If there is a good correlation between the measured wind speed at the neighbour and det deduced wind speed from the power produced by the wind turbine, ideally they should form a line with a slope equal to 1. To the left it is seen that the wind experienced at the neighbour does not correspond very well with the wind measured at the turbine, and to the right a tendency is seen towards correlation between the two measured wind speeds.

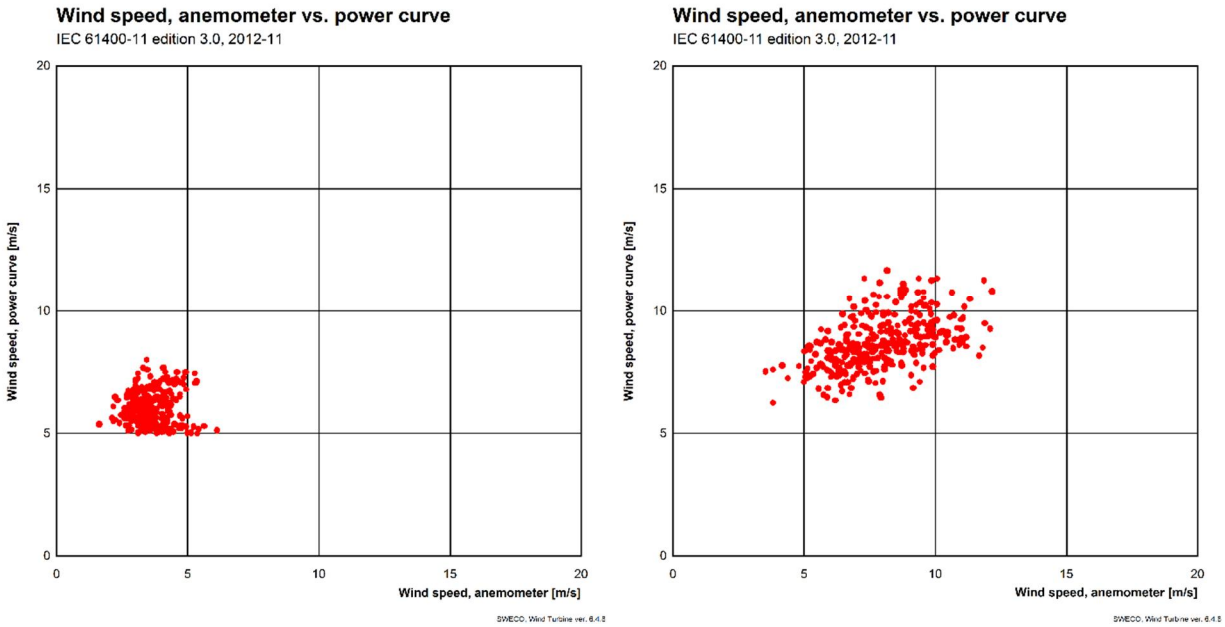

Figure 11: Left, Windspeed at neighbour B, right windspeed at neighbour A. (the measurements were obtained during two different campaigns for study 1)

Moving forward with the windspeed measured at neighbour A, it is possible to link the determined windspeed with the measured noise level at the neighbour. In Figure 12 the measured noise level is shown as a function of the local windspeed at 10 m height at the neighbour (left) and as a function of the windspeed at the wind turbine (right).

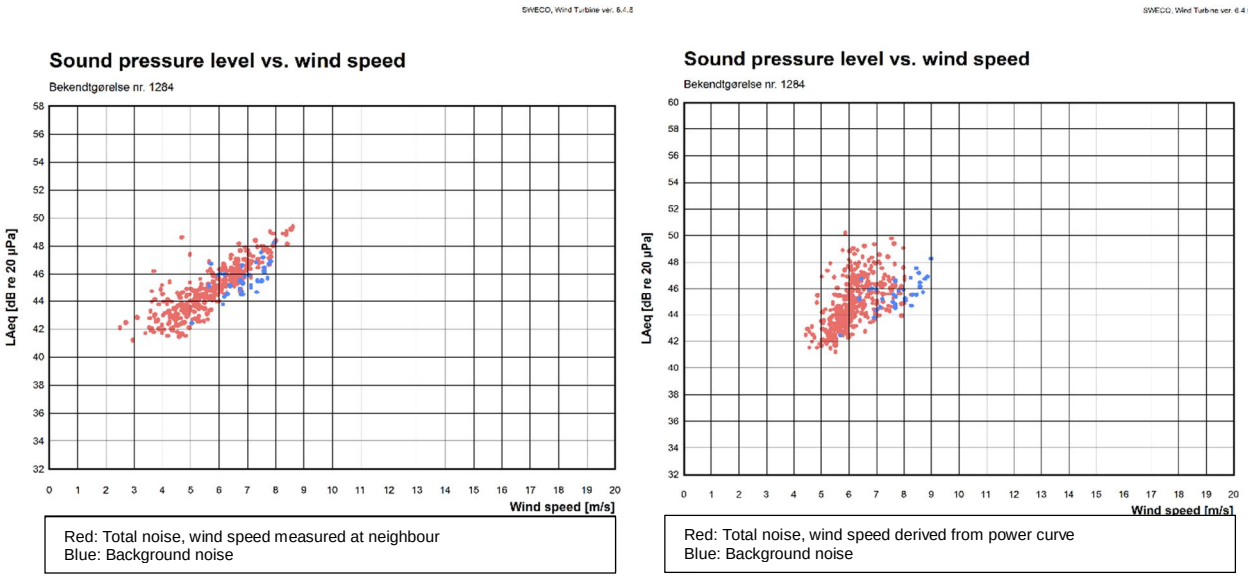

Figure 12: Left, noise as a function of local windspeed. Right, noise as a function of wind turbine windspeed.

It is seen that the noise measured at the neighbour dwelling correlates better with the windspeed measured at the dwelling. This indicates that the noise inherits from other sources than the wind turbines, and most likely from noise caused by the vegetation and/or the surroundings. If the windspeed only was measured at the dwelling it would be possible to draw the wrong conclusion concerning the noise correlation with the wind turbines production. This indicates the necessity of measuring the windspeed at the neighbour and in parallel measure the windspeed at the wind turbines. This will ensure that that the conclusion drawn is fair to the noise produced by the turbines.

4. Long term measurements (study 3)

The third study differs from the two above in duration and data available. For this paper the focus for the third study is on measurement of windspeed and concerns regarding placement of the wind mast. In the full study the noise measured at the eight neighbours have been correlated with the windspeed measured at the neighbours. All averages presented in the following is 10 minutes averages, and the noise indicator is in all cases L_{A90}. The measurements were conducted in April (spring). In the following, measurements at 3 neighbours have been selected. All measures are synchronous over 17 days.

4.1 Wind speed determination.

In Figure 13 the correlation between the wind measured at two different neighbours and the wind turbine is shown. The data from the wind turbine is deduced from hub height to 10 meters. The data is sorted in day/night-bins with night hours defined from 22:00 until 04:00 in the morning. As opposed to the large difference in correlation seen for study 1 this comparison shows a tendency in both cases. However, it is also seen for both cases that the higher windspeeds at the neighbours yields a better correlation with the windspeeds measured at the wind turbine. For neighbour F16 the night data is seen to be higher for the wind turbine than for the measured wind speed at the neighbour which is caused by some periods of high wind shear. For Neighbour No4 it is not as pronounced, however, the tendency is also visible there.

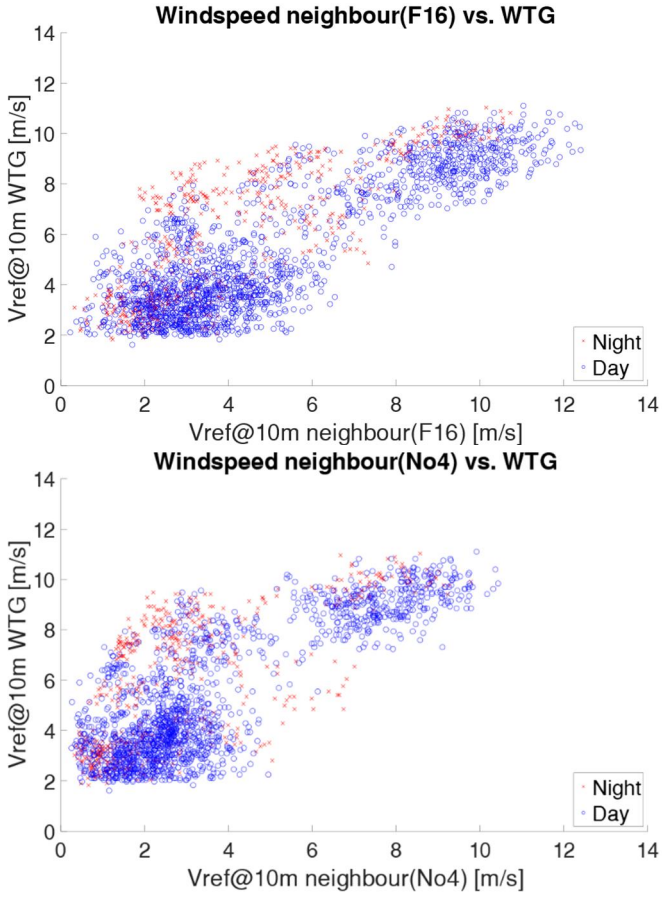

Figure 13: Upper windspeed at neighbour F16 correlated to the turbine wind speed. Lower windspeed at neighbour No4 correlated to the windspeed measured at the same turbine.

To further investigate the difference experienced in Figure 13, the wind direction is considered. In Figure 14 the relative difference in windspeed for the two neighbours is shown together with wind direction. Here 0º designates that upwind is north and 270º that upwind is west.

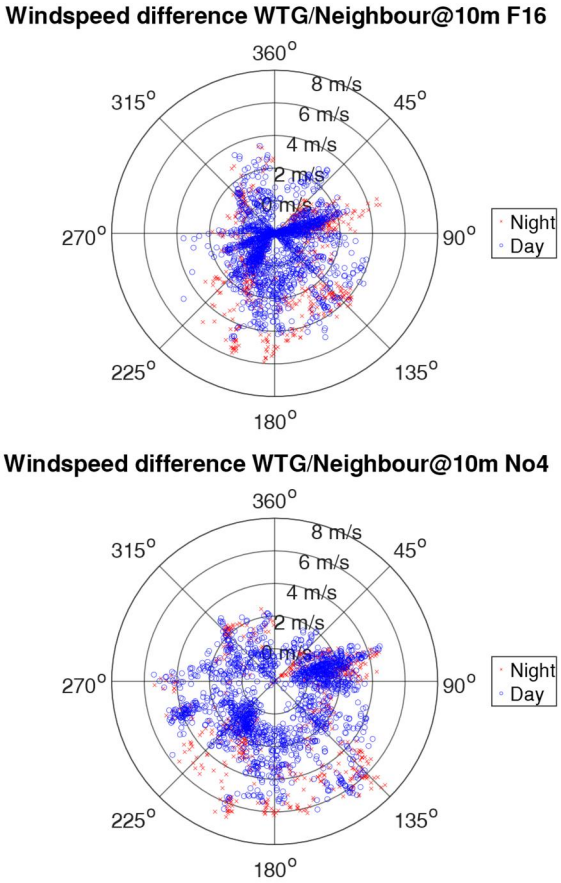

Figure 14: Upper: Relative difference in windspeed neighbour F16. Lower: Relative difference in windspeed neighbour No4.

It is seen for neighbour F16 that the highest differences are reached at night due to high wind shear but for a large part of the day the differences are within 2 m/s. For neighbour No4 the picture is different as the differences are higher, and it is not mainly due to high wind shear as it is seen during both night and day and from approximately 90° and until 270°. The explanation for the higher differences is in this case due to the placement of the wind mast. The wind mast is placed at the neighbour dwelling which is surrounded by small trees. Even though the wind mast is placed free of the trees, their influence is seen in the lower part of Figure 14.

As for study 1 the measured noise at the dwelling is shown as a function of wind speed measured at the wind turbine and at the neighbour. In this study two neighbours with different siting is chosen for comparison (Neighbour F16 and No20). At neighbour F16 there are some low trees and a beech hedge, at neighbour No20 there is low vegetation and an old machinery house. In Figure 15 the measured noise level is shown for the two neighbours as a function of respectively the windspeed at the turbine and at the neighbour. For neighbour F16 it is seen that the noise correlates better with the wind measured at the neighbour dwelling as in study 1. It is also seen that the noise at low windspeeds has an upper level, however when the windspeed increases above 7 - 8 m/s the noise continues to increase. For comparison the noise curve for the wind turbine is introduced in the plot. It is seen that the noise from the wind turbine reaches its maximum at around 7 - 8 m/s, which suggests that the noise measured above 7 m/s most likely does not inherit from the wind turbine, but from other noise sources e.g. the beech hedge.
For the other neighbour, No20, the same comparison is made. Here it is seen that the noise measured tends to follow the pattern of the wind turbine noise to some extent at the higher windspeeds compared to neighbour F16. This might indicate that the noise level measured at neighbour No20 is influenced by noise generated by the wind turbines.

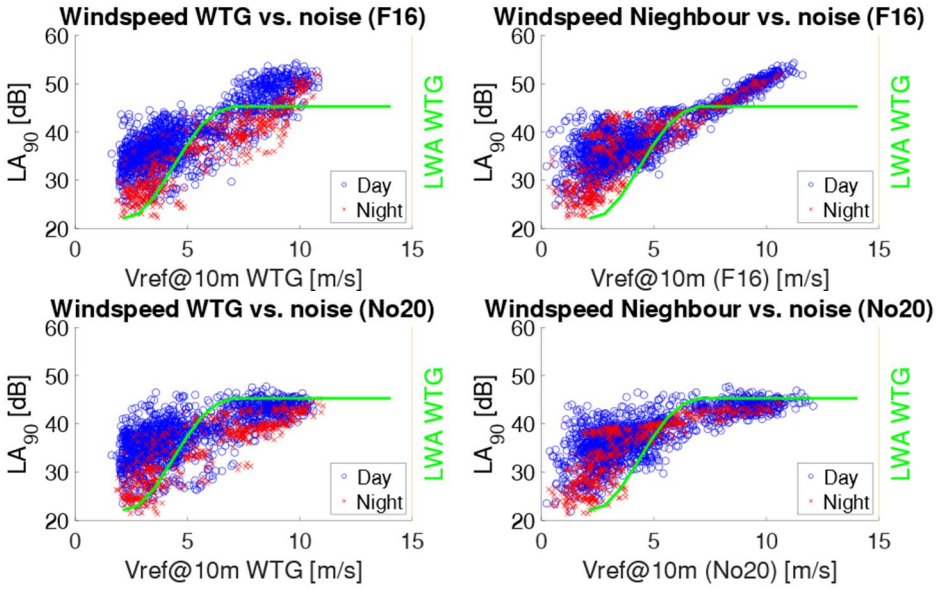

Figure 15: Left, noise as a function of wind turbine windspeed. Right, noise as a function of local windspeed.

Due to the occurrences of high wind shear it is known that the wind turbine in some periods during night hours has experienced higher windspeeds than what has been measured in 10 meters height at the neighbours. In these periods the noise generated at the wind turbine has been at a maximum and the background noise induced by vegetation must be assumed to be on a minimum. In Figure 16 the same data as in Figure 15 is shown, however, only data where the wind turbine has been producing more than 85% of rated power is shown. This is inspired by Payam Ashtiani, Aercoustics Ltd. For the measured noise as a function of the wind speed measured at the neighbour it is seen that the night hours show higher noise levels at low windspeeds, during high wind shear. These measurements could indicate the maximum wind turbine noise level at the neighbour, however due to the lack of background noise measurements from the same period it is not certain that the measured noise inherit from the turbine.

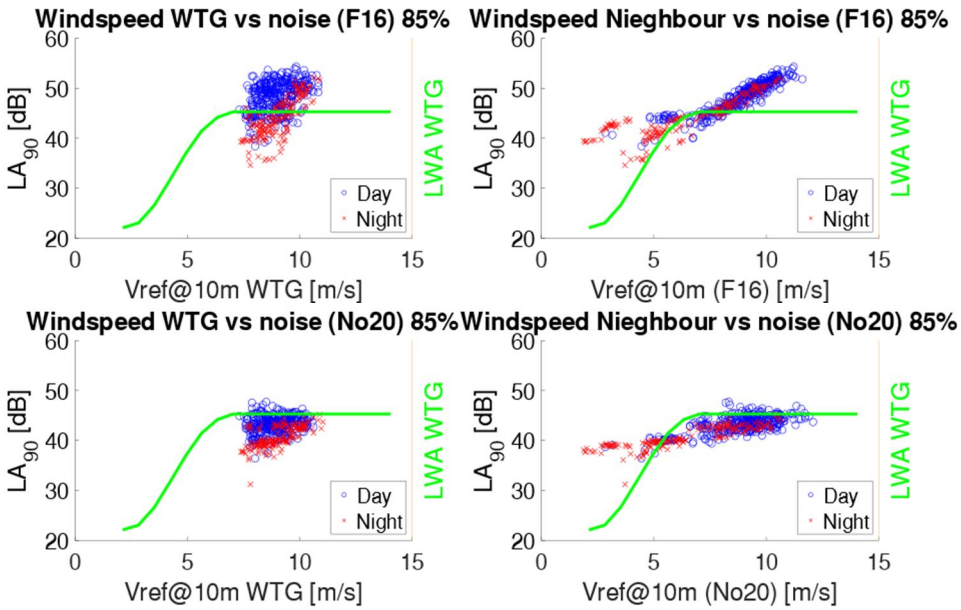

Figure 16: Left, noise as a function of wind turbine windspeed. Right, noise as a function of local windspeed. During a minimum production of 85% of rated power.

From the above it is seen that there are several critical issues when measuring at neighbour distance. The surroundings of the neighbour are decisive of what one can expect to measure at

high windspeeds. A small amount of vegetation such as a beech hedge can introduce high levels of background noise at higher windspeeds and might already introduce it before the wind turbine reaches maximum noise generation. It is also seen that placement of the wind mast is critical in order to assure that there is a good correlation between wind speed measured at the turbine and at the neighbour and at all wind directions. The simultaneous measurement of wind speed ensures that periods with high wind shear and other phenomena's can be detected and accounted for, when drawing conclusions on the noise measured at the neighbour.

5. Conclusions

The two studies conducted for the Danish EPA, shows the difficulties that comes with measuring at neighbour dwellings. The results of the first study show that it is possible to evaluate the noise from a wind farm at a neighbour. The second study on the other hand show that it is or can be difficult to evaluate the noise from a wind farm through measurements at the neighbour dwellings, especially when there is vegetation around the dwellings. In order to secure a good measurement, there are some conditions which should be met before and during measurement:

- The background noise must be evaluated at each dwelling of interest, to secure that a satisfying signal to noise ratio can be achieved (6 dB). This should be investigated both for the outdoor measurement but also for the indoor measurements. Different appliances indoor can give significant contributions to the background noise, e.g. fridges, ventilation, oil furnaces and even clocks.
- During measurements it is important to have several and longer periods where the wind farm is shout down, so that the actual background noise during measurement can be evaluated. It is important to cover the same meteorological conditions for the background noise.
- Operational parameters from the wind farm shall be available during measurement together with windspeed measured at the neighbour dwelling. This is to secure that the measured noise levels can be compared to the expected noise from the wind turbine and vegetation at the dwelling.
- In order to exclude spurious noise sources statistical noise indicators should be used. Knowledge must be established of how to apply the statistical levels especially for low frequency measures. It is however, important to notice that the statistical levels do not exclude continuous noise such as noise caused by vegetation.

For the third study the necessity of windspeed measurements at several positions is shown. The measurements can when correlated with the measured noise levels give valuable information on what may cause the noise measured at the neighbour dwelling. Especially for neighbour F16 the correlation with the local measured windspeed indicates that the noise is induced by vegetation rather than the wind farm. The measurements performed under high levels of wind shear can indicate the level of wind turbine noise at the neighbour. However, it is necessary to have thorough knowledge of the background noise and the representative windspeed and direction for the entire wind farm to ensure that the shear conditions are common for the wind farm.

From what can be derived from the 3 studies there is a strong indication that the Danish method with sound power measurements and a simple prediction method complies with the measurement at relevant Danish distances.

References

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