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The ocean wave noise masking effect on wind turbine noise audibility

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ABSTRACT

In Denmark and several other countries noise is regulated as absolute levels, hence the audibility of the noise source is not directly handled.
In most countries, including Denmark, wind turbines are often set up in rural areas. Denmark is a flat, windy and in general densely populated country, but the rural areas are less populated and has longer distances between dwellings, and so it is easier to comply with the setback distances and noise demands. Coincidently some of the windiest parts of Denmark are also rural areas.
In the rural areas some of the common sources of noise is vegetation or waves, which masks other environmental noise sources. The effect of masking from vegetation and/or waves has not been studied in much detail in Denmark.
The aim of this article is to gather meteorological, wave and sound data from waves at the Danish west coast and compare this data to estimated offshore wind turbine noise.

1. INTRODUCTION

Denmark is a windy, densely populated and flat country surrounded by water, where the highest natural points are approximately 170 m above sea level. The authors paper at the wind turbine noise conference in Dublin in 2023 [1] show that the largest wind resources typically are in the least populated areas of Denmark which also are the areas where most wind turbines are installed. Consequently, some of the areas where wind turbines are installed and have been installed are areas where the background noise level is dominated by not man-made noise sources such as vegetation noise and wave noise + sounds from birds etc. It should be noted that even though these areas are some of the least populated areas in Denmark, dwellings are still spread all over the area. This leads to the fact that distances between dwellings and wind

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turbines are relatively small. This is originally investigated in Denmark in [2], and the current article and [1] follows up on the work.

2. DANISH REGULATION FOR WIND TURBINES

The current regulation for noise from wind turbines in Denmark is from 2019 [3]. In short, it states that the cumulative noise level from all relevant wind turbines may not exceed the following limits:

- At the most noise-exposed point in outdoor living area no more than 15 metres from dwellings in the open countryside:
  - (a) **44 dB(A)** at a wind speed of **8 m/s** (10 m height).
  - (b) **42 dB(A)** at a wind speed of **6 m/s** (10 m height).
- At the most noise-exposed point in areas with noise-sensitive land use:
  - (a) **39 dB(A)** at a wind speed of **8 m/s** (10 m height).
  - (b) **37 dB(A)** at a wind speed of **6 m/s** (10 m height).

The total low frequency noise from wind turbines at wind speeds of 6 and 8 m/s (10 m height) may not exceed **20 dB(A) indoors** in neither dwelling in the open countryside nor indoors in areas with noise-sensitive land use. The low frequency noise level is the A-weighted level of the noise in the frequency range defined by the 1/3-octavebands from 10 Hz to 160 Hz, including both.

The noise level at these points is calculated based on sound power level measurements with a prescribed noise propagation method, where there is a method both for noise propagation over land and over water. For the indoor low frequency noise level there are defined sound insulation values both for regular houses and for summer cottages (with a lower sound insulation). The regulation also describes how to handle tonality content in the wind turbine noise.

3. OFFSHORE WIND TURBINES

There are in Denmark much debate about wind turbines, and an often-heard argument is "Wind turbines should be put up out in the ocean instead of on land". And truly the coastline of Denmark is 8750 km long which should be related to a total area of 43094 km^2 [5]. As with much else related to wind energy Denmark was the first country in the world to install a wind farm offshore, the Vindeby Offshore wind farm [6]. Since then, many wind turbines has been installed offshore, at the moment a total capacity of 2300 MW [7] (onshore 4700 MW).

In Denmark there are noise regulation both for onshore and offshore wind turbines; and contrary to onshore wind turbines noise complaints about noise from offshore wind turbines seems not to be of much focus. In Denmark the dominant wind direction is from west, from the North Sea. Therefore, also much onshore wind is and have been installed on the Danish west coast. However, the North Sea is not only powerful in terms of wave energy, but the sound level from the ocean is also significant. The west coast of Denmark is also a popular tourist destination, and close to the sea many summer houses/cottages are located, see examples in Figure 1.

4. MEASUREMENT SETUP AND DATA SOURCES

In Denmark most noise sources are regulated as absolute levels and is based on sound power levels and predicted levels, and as a result there is much knowledge about the noise levels from sources of noise, but little knowledge about background noise. To obtain better knowledge about the wave / wind / sound relationship it was obvious to study it at and near the beach close to the Danish wind turbine test center Høvsøre, since there is both large met masts at the test center and a buoy installed in the ocean approximately 4 km west of the beach at Fjaltring which is approx. 3 km NNW of the northernmost of the wind turbines in test center Høvsøre. Supplementary inspiration was found in the work from Bolin [10].

Figure 1 Examples of Danish summer houses / cottages behind and in the sand dunes at 'Vesterhavet' (The North Sea). Pictures from [8-9].

4.1. Mereological and wave data

Wind speed from one of the Høvsøre met masts and wave height from the buoy is correlated in Figure 2, which are data from July – November 2023 and March – April 2024. The figure shows that for eastern wind even high wind speed only generates small waves, where for wind from the other 3 wind directions it takes a wind speed of 10 - 12 m/s in 115 m height to generate 2 m high waves, as H1-3, which is defined as average wave height of the highest 1/3 of all waves. In this article it has been chosen to use this parameter as the primary parameter to describe the wave size.

The met masts log quite many data, including the wind speed at many altitudes. It is here chosen to focus on the data from 115 m height, since it approximates the nacelle height of many Danish onshore wind turbines. BEK135 supplies an equation for calculating from nacelle height to the standardized 10 m height (equation 1.1.1) which is identical to equation D.1 in the international standard for sound power level for wind turbines [4]. This equation assumes a roughness length of 0.05 e.g. farmland with some vegetation. Utilizing the equation, the goal of a wind speed at 10 m height equivalent to 6-8 m, equalize a wind speed of 8.8-11.7 m/s at 115 m height.

Recordings of wave sound was performed on three days: the 26th of March from 9 – 17 o'clock, the 5th of April 2024 from 6 – 10 o'clock and the 23rd of April 2024 from 6 – 10 o'clock. Numerous meteorological data for these three days is shown in Figure 3. The data is from the met mast and the buoy supplemented with information about water level (measured at Thorsminde which is approximately 10 km south) and wind speed and wind direction (also measured at Thorsminde at a height of 16 m). Table 1 summarises the conditions during the recordings.

Table 1: Table of conditions during the recordings. The wind speed at 10 m height is calculated by the equation from BEK 135 mentioned above.

Date	**Wind speed**		**Wind direction**		**Wave**		**Water level**
	@111m	**@10m**			**Height**	**Period**	
	[m/s]		**[º]**		**[m]**	**[s]**	**[cm]**
26th of March	5-10	3.4-6.8	115-150	ESE-SSE	0.5-0.6	4.0 – 2.8	-35 - +20
5th of April	5-8	3.4-5.5	220-150	SW-SSE	1.5-1.2	5.1 – 4.1	8 - 24
23rd of April	10-12	6.8-8.2	265-250	WSW	1.0-1.3	3.5 – 3.9	-23 - +5

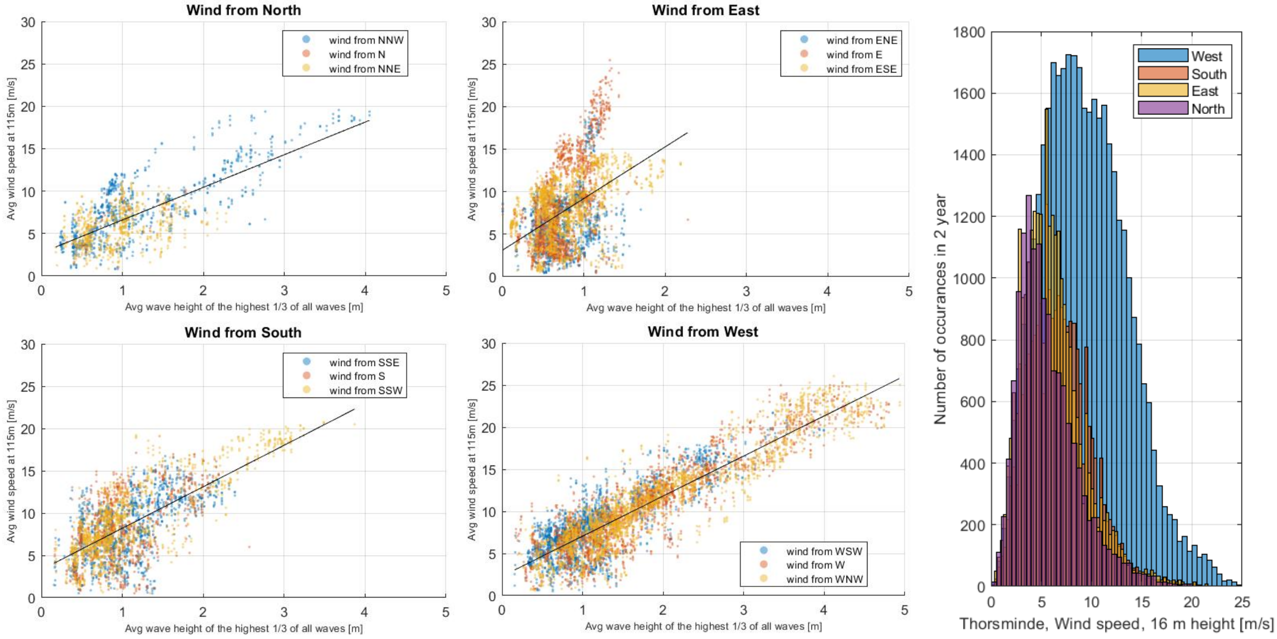

Figure 2 Left: Relationship between Høvsøre met mast wind speed and buoy wave height. Right: Number of occurrences of wind direction and wind speed for 2 years data.

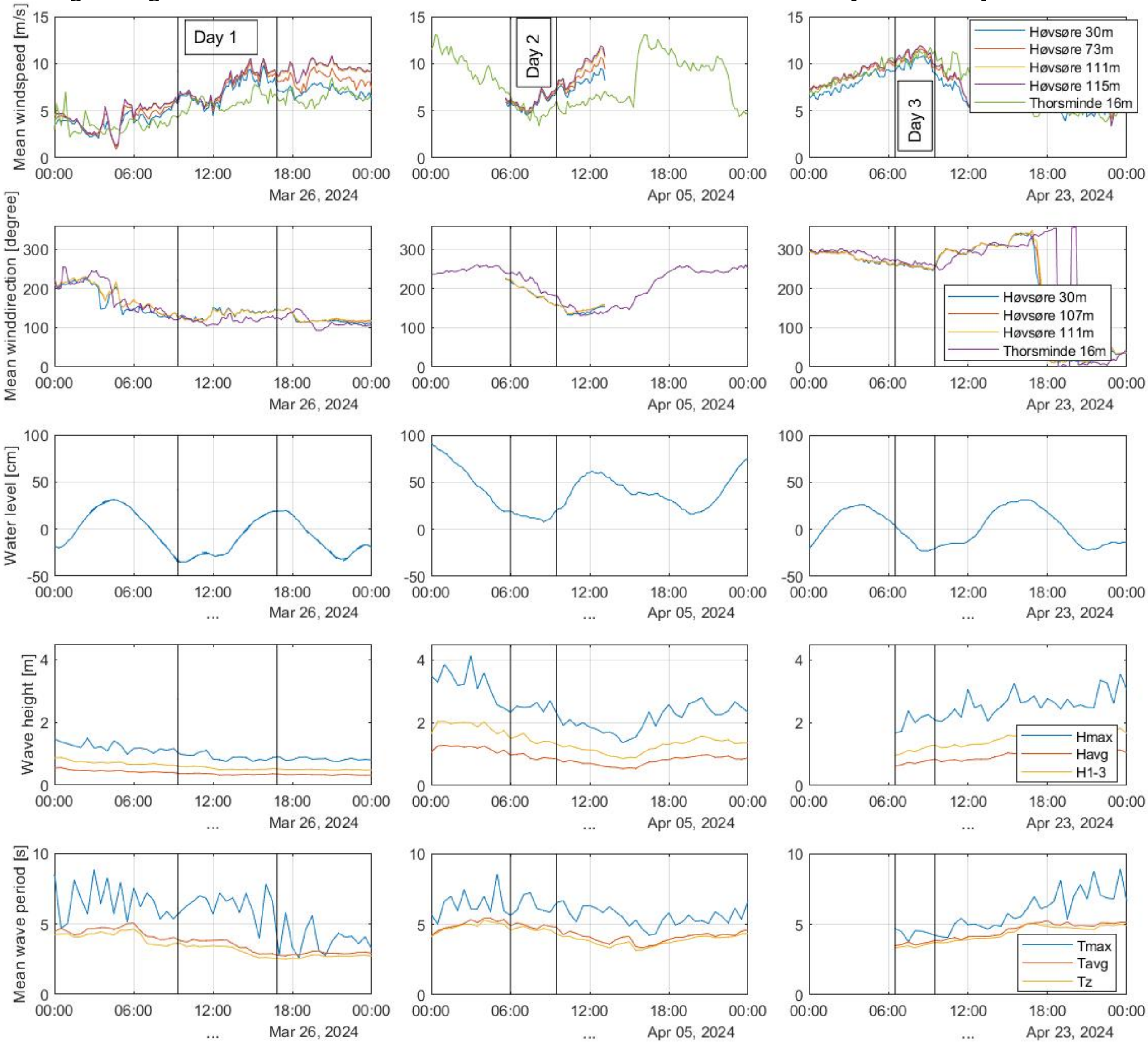

Figure 3 Logged conditions for the days where the sound was recorded.

4.2. Setup and positions

Recordings was performed at positions both south and north of Høvsøre, in areas far enough away from the turbines so the turbines are not audible, but close enough for the wind speed from the met masts to be relevant. From the northern positions there are approximately 3 km to the nearest wind turbine at Høvsøre, where the distance is approximately 2.6 km to the nearest wind turbine from the southern positions. Figure 4 shows elevation map with the microphone positions, and indication of shoreline and position of the Høvsøre wind turbines.

For the recordings a B&K 2250 SLM was used, and both a primary and secondary wind shield was used to avoid wind noise as much as possible. The microphone was mounted on a tripod at 1.5 m, and approximately 10-minute length recordings was measured in each position. For the analysis a train analysis was done, and then the 10 x 10 second recordings with lowest L_{Aeq} were used for further processing, where an arithmetic average is taken. This method was used as a quick method to avoid other noise sources, especially traffic on the road just behind the sand dunes at the southern positions. Originally a multichannel system was planned, but in the end the B&K 2250 was chosen since it was an agile way to record many positions. Since the recordings was supervised it was possible to position the microphone quite close to the water, since a quick reaction was possible should the waves be larger than anticipated.

Figure 5 shows 3D maps with the elevation of the sand dunes together with microphone positions, and indication of shoreline and position of the Høvsøre wind turbines. Photos of some of the microphone positions are shown in Figure 6 and Figure 7.

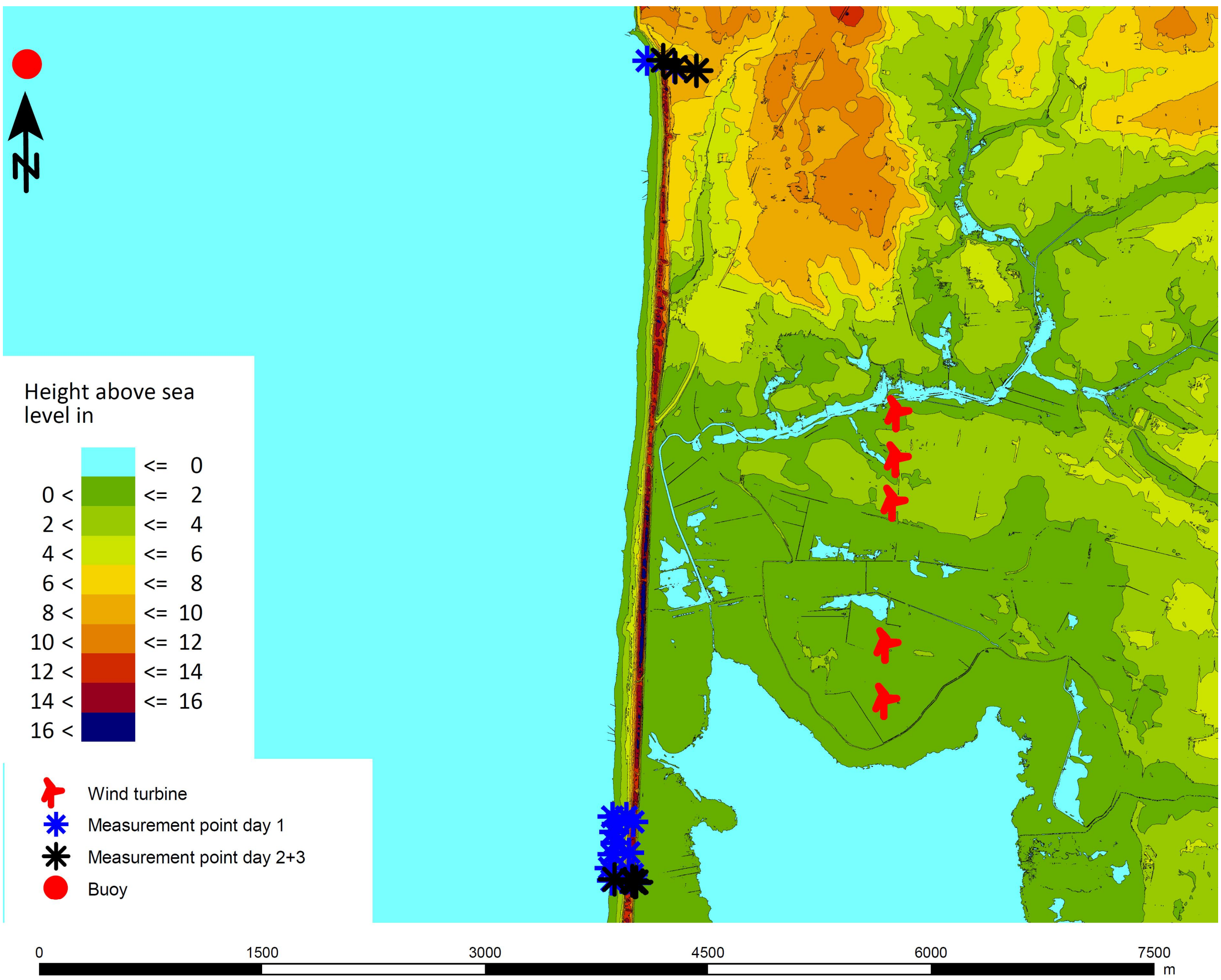

Figure 4 Map with height contour lines, and mics and wind turbines. The met masts are approximate 400 m west of each turbine.

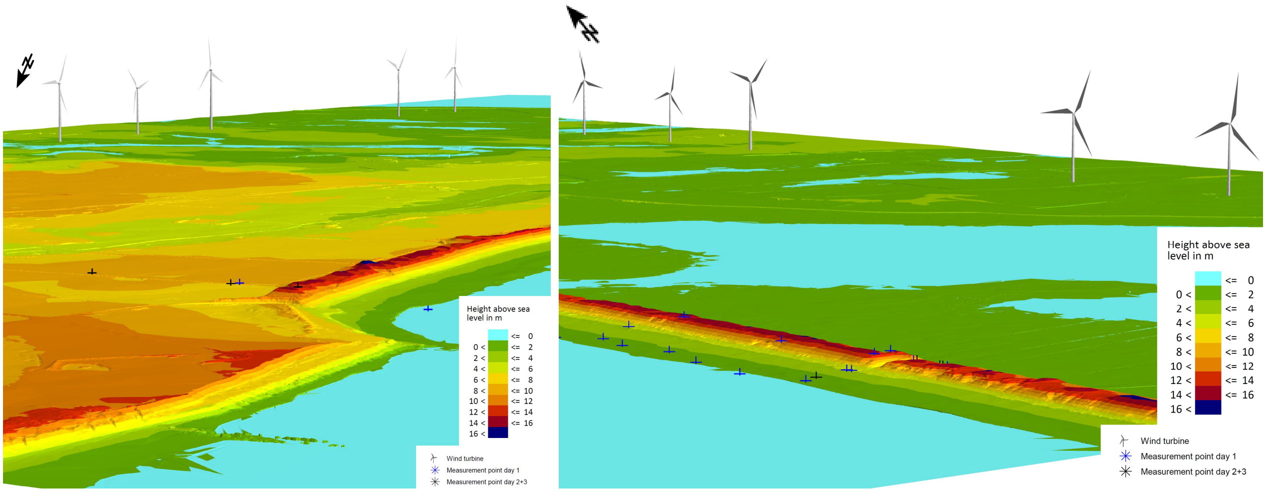

Figure 5.: Left and right: 3D plot from respectively the northern and southern position, where both the position of the turbines and microphone positions are shown, together with height representation of the sand dunes.

Figure 6 Photos from the shoreline: Top: Day 1, Middle: Day 2, Bottom: Day 3.

Figure 7. Top: Photo from Day 3 from behind the sand dunes at position South. Middle: Photo from Day 2 behind the sand dunes at position North. Bottom: Photo from Day 3 at the top of the sand dunes at position North.

5. RESULTS

The analysed result of the recordings is shown in Figure 8 for the three measurement days.

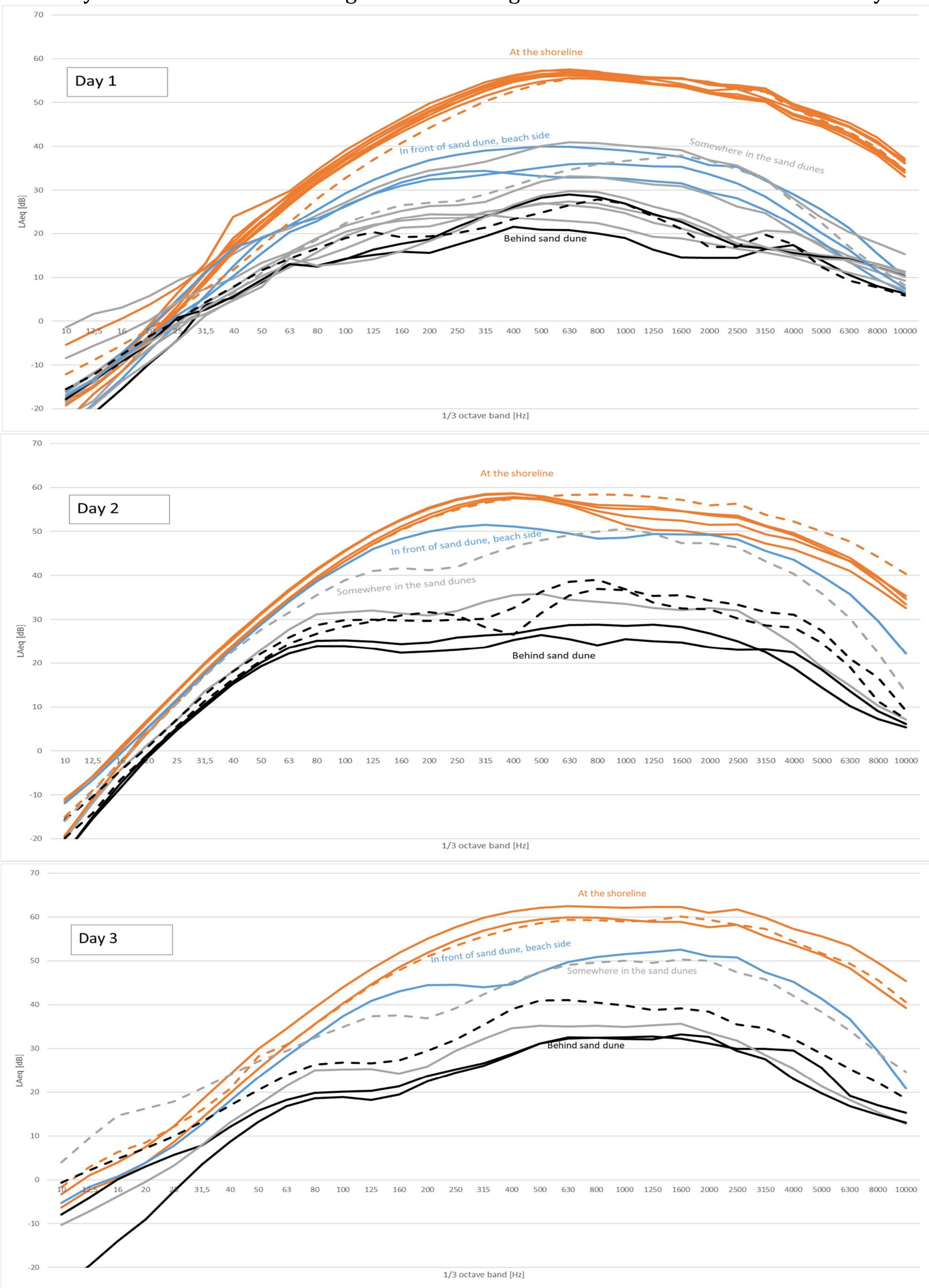

Figure 8. Analysed results. No dash = Southern position. Dash = Northern position.

Generally, the lowest levels typically are found behind the sand dunes and the highest values at the shoreline, whereas the levels measured in the sand dunes are somewhere in between. Large variation is seen at the lowest frequencies (primarily below 31.5 Hz), indicating that these results are somewhat influenced by wind induced noise in the microphone despite the double wind screen. This is especially for Day 3.

Selected measured levels are shown in Figure 9 and Figure 10 together with a typical spectrum from wind turbines, based on information at the disposal from Allan Jensen/Rambøll [11]. The spectrum is based on sound power levels for typical wind turbines in this example installed 10 km offshore. The propagation to the shore is then based on the Danish BEK135 for offshore wind turbines, and both an outdoor spectrum (50 Hz – 10 kHz) is calculated together with an indoor spectrum (20 Hz – 160 Hz) utilizing the summer house level difference from BEK135. For the indoor spectrum the level has been adjusted to be L_{paLF} = 20 dB, i.e. the limit value in the Danish regulation. In the figures it has been chosen to only show the levels at the shore and levels behind the sand dunes, to not to have too much information in the figures. The recordings have been performed un-weighted. For the analysed results it has been chosen to apply the A-weighting, to correspond to the Danish regulation for wind turbine noise.

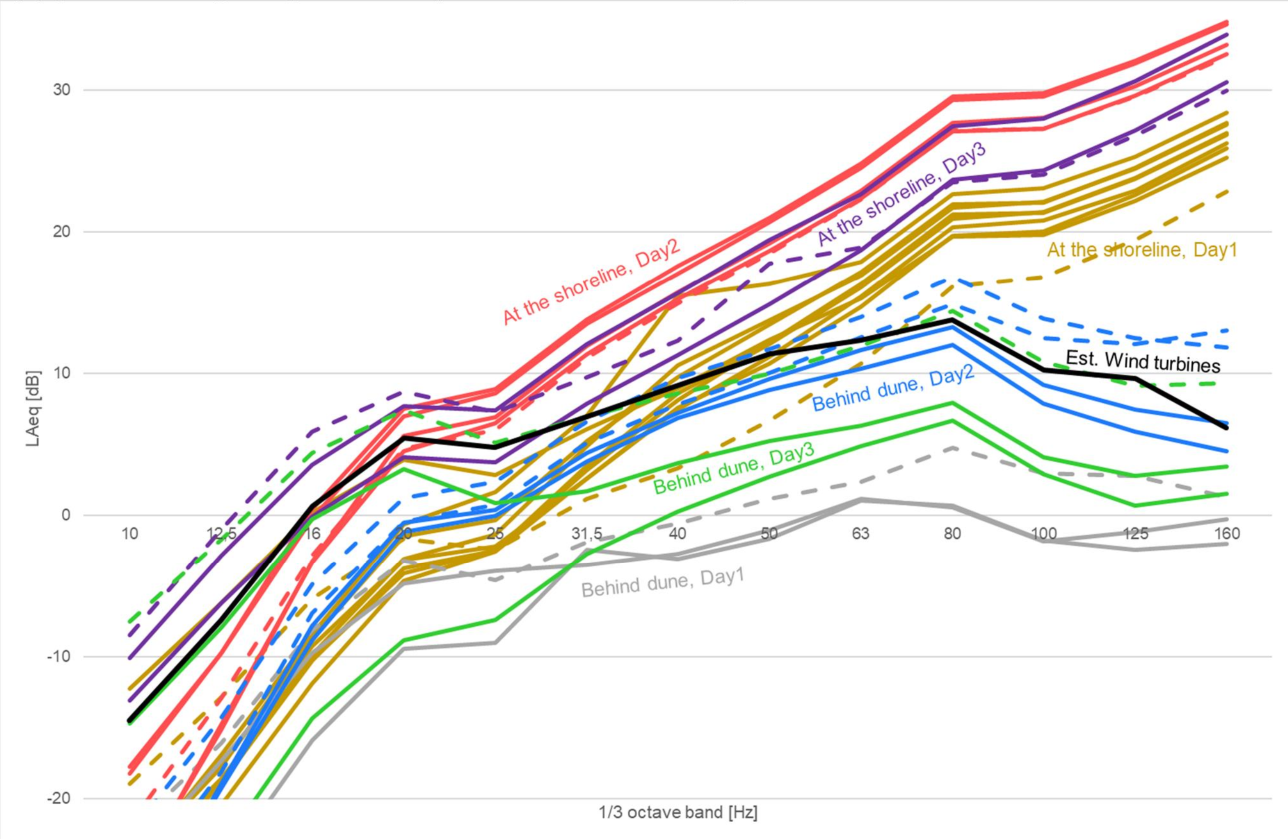

Figure 9. Calculated indoor levels, 1/3 octave band frequencies up to 160 Hz

For the indoor low frequency figure, the level of the estimated wind turbine corresponds well to the measured levels for frequencies above 40 Hz behind the sand dunes for Day 2 and for the northern position for Day 3, where the measured levels behind the sand dunes for the other recordings are approximately 10-15 dB lower. For the lowest frequencies a large variation in the results is shown, where the estimated wind turbine level is in the top quarter.

For the levels outdoor, Figure 10, the 1/3 octave band levels for the wind turbine quickly drops for higher frequencies than 315 Hz, which is primarily due to the air absorption. For the same reason, the indoor low frequency noise regulation is typically the dimensioning limit for offshore wind turbines, whereas the estimated levels in the 'normal' frequency area is typically never close to the limit. To illustrate this, 3 estimated wind turbine spectra is shown in the figure, which are all based on the same spectrum, but adjusted to either indoor L_{paLF} = 20 dB, outdoor L_{Aeq} = 39 dB or outdoor L_{Aeq} = 44 dB, i.e. the limit values in the Danish wind turbine noise regulation.

For this article it is primarily the L_{paLF} = 20 dB spectrum which is relevant, which will be referred to as the wind turbine spectrum unless otherwise mentioned. When comparing the measured wave levels to the estimated wind turbine spectrum it can be seen that the level behind the sand dunes for southern position for Day 2 is comparable, however only for frequencies up to 200 Hz, where for higher frequencies the spectrum for the wind turbines quickly drops lower and at 1kHz the difference is 20-40 dB compared to the levels behind the sand dunes. Below 200 Hz for the northern position for Day 2 and 3 behind the sand dunes the levels are 5-10 dB higher than the wind turbine spectra, where for behind the sand dunes the southern position for Day 3 and all positions for Day 1 the level is below the estimated wind turbine spectra. All levels at the shoreline are at the same level or higher than the estimated wind turbine spectra.

Interestingly Day 3 is the one with the highest wind speed, and a wave height comparable to Day 2 so it is a bit surprising that the sound level in general is lower for Day 3 than for Day 2, but it also fitted with the subjective assessment at site.

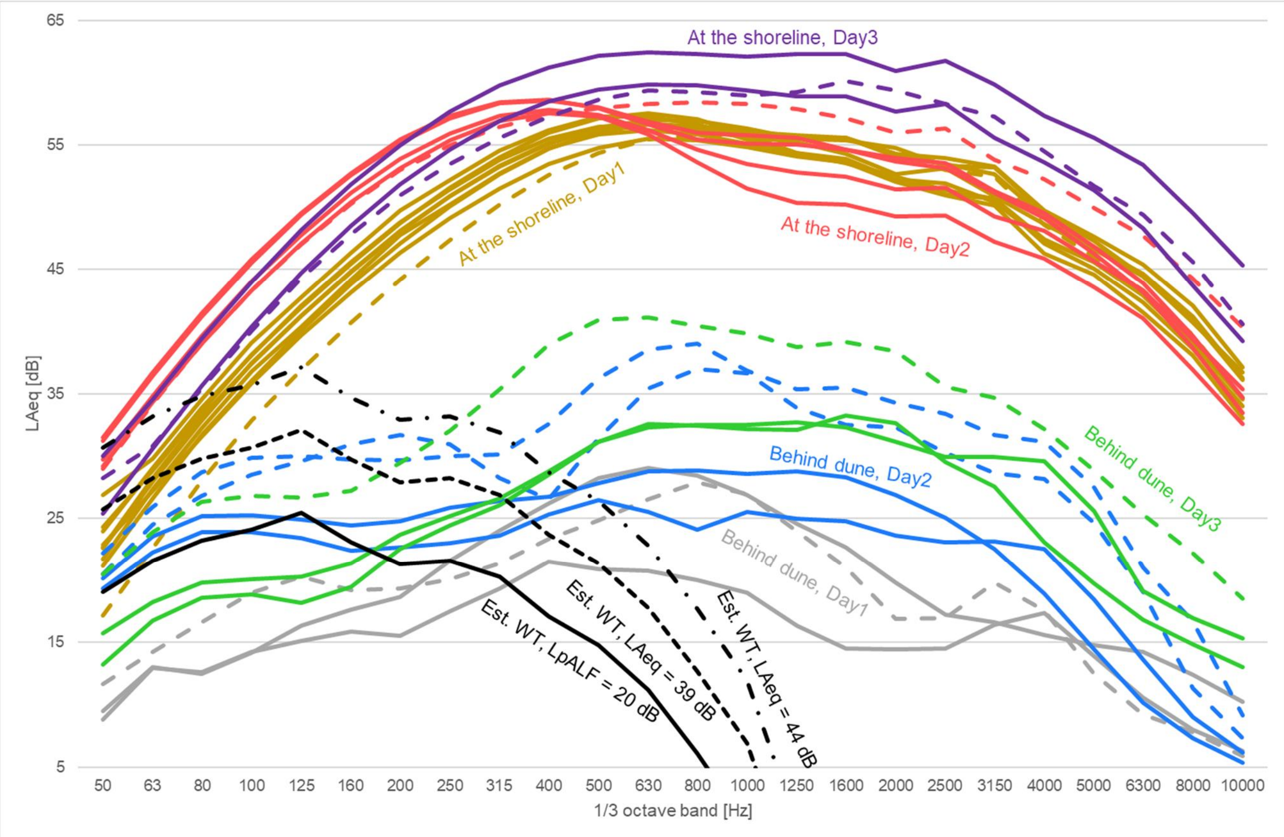

Figure 10. Selected outdoor sound/noise levels compared to estimated wind turbine spectrums, adjusted either to an indoor level of L_{pALF} = 20 dB, an outdoor level of L_{Aeq} = 39 or an outdoor level of L_{Aeq} = 44 dB.

6. MASKING

Regarding masking a recent report [12] summarized the following (translation from Danish by the author):

It is rather important if the noise from for example a wind turbine can be heard due to other noise, from for example traffic, vegetation noise or wave noise, e.g. whether it is masked more or less by other noise sources. Masking by tones or narrow noise bands is well described and an objective analysis method is described in the Danish regulation for wind turbine noise [3]. Masking *by wideband noise by other noise is not so investigated and depends on several factors. Reference [13] compile knowledge of different situations, which can occur in relation to wind turbines. It is differentiated between stable relations, where the wind turbine noise and the background noise can be compared directly, and unstable relations, where the two noise types vary independent of each other. In summary it is concluded:*

- *For stable relations: The wind turbine noise is considered as masked, if the levels of the critical bands of the A-weighted wind turbine noise is more than 2 dB below the levels for the critical bands of the A-weighted background noise.*
- *For unstable relations: If the noise from the wind turbine is to be considered always below the masking threshold, the maximum levels (with time weighting F) of the wind turbine noise shall be compared to the minimum levels (for example as L95) of the background noise following the same criteria as above.*

7. FINAL COMMENTS AND CONCLUSIONS

The primary aim was to gather meteorological, wave and sound data for waves at the Danish west coast, specifically close to the Høvsøre wind turbine test center, because at this position meteorological and wave data is already logged and can be extracted.

The goal was to perform surveyed recordings in several wind conditions specifically around 6-8 m/s at 10 m height. Weather forecasts was monitored, and recordings was performed on three days with different weather conditions.

Recordings of the sound of waves was performed in multiple points; some at the shoreline, some in the sand dunes and some behind the sand dunes.

The recorded levels were compared to an estimated wind turbine spectrum, based on typical wind turbine sound power levels, and propagated 10 km to land following the prescribed methods in the Danish regulation for offshore wind turbine noise, BEK135.

It is found that:

- Due to air absorption the estimated wind turbine spectra primarily consists of sound below 315 Hz. For the same reason the noise limit which is relevant is the indoor low frequency level of L_{pALF} = 20 dB.
- The BEK135 specifies both level differences for ordinary houses and for summer houses. Since summer houses has the lowest sound insulation, it has chosen to focus on the summer houses.
- The estimated wind turbine spectrum adjusted to achieve an indoor low frequency level of L_{pALF} = 20 have a level comparable to the recorded wave sound for some situations, where in other situations the level is either lower or higher. It is therefore assumed that the wind turbine sound would be masked in some of the measured situations and measurement positions, but not in all.
- It was desired to perform recordings also for wave height as H1-3 up to 2 m, but that did not occur during the recordings. Following Figure 2 a wave height 2 m should correspond to a wind speed at 10 m height of 8 m/s.
- It should also be noted that this study is based on 3 measurements at 2 nearby beaches, which is compared with an estimated wind turbine spectrum. It is suggested that the study be extended with more data and more measurements, preferably a long-term measurement campaign.

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