# Underwater noise from three types of offshore wind turbines: Estimation of impact zones for harbor porpoises and harbor seals

Jakob Tougaard[a] and Oluf Damsgaard Henriksen
*Department of Arctic Environment, National Environmental Research Institute, Aarhus University, Frederiksborgvej 399, DK-4000 Roskilde, Denmark*

Lee A. Miller
*Institute of Biology, University of Southern Denmark, DK-5230 Odense M, Denmark*

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Underwater noise was recorded from three different types of wind turbines in Denmark and Sweden (Middelgrunden, Vindeby, and Bockstigen-Valar) during normal operation. Wind turbine noise was only measurable above ambient noise at frequencies below 500 Hz. Total sound pressure level was in the range 109–127 dB re 1 $\mu$Pa rms, measured at distances between 14 and 20 m from the foundations. The 1/3-octave noise levels were compared with audiograms of harbor seals and harbor porpoises. Maximum 1/3-octave levels were in the range 106–126 dB re 1 $\mu$Pa rms. Maximum range of audibility was estimated under two extreme assumptions on transmission loss (3 and 9 dB per doubling of distance, respectively). Audibility was low for harbor porpoises extending 20–70 m from the foundation, whereas audibility for harbor seals ranged from less than 100 m to several kilometers. Behavioral reactions of porpoises to the noise appear unlikely except if they are very close to the foundations. However, behavioral reactions from seals cannot be excluded up to distances of a few hundred meters. It is unlikely that the noise reaches dangerous levels at any distance from the turbines and the noise is considered incapable of masking acoustic communication by seals and porpoises. © *2009 Acoustical Society of America.* [DOI: 10.1121/1.3117444]

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## I. INTRODUCTION

Noise levels in the oceans have increased considerably since engine powered shipping was introduced in the late 18th century. Until World War II it was not possible to measure absolute noise levels, so only post-World War II recordings of ambient noise are available for comparative studies (Urick, 1983). In a now classic comparative study Ross (1993) found a 15 dB increase in the low frequency ocean ambient noise level between 1950 and 1975. A more recent study shows that the noise level at the continental shelf off the coast of California has increased by 3–10 dB in the frequency range from 20 to 300 Hz from the mid-1960s to the turn of the century (Andrew *et al.*, 2002). Both studies conclude that the most significant source of the increased noise level is increased shipping activity.

Other sources of anthropogenic noise in the ocean include offshore installations to which offshore wind farms have recently been added. Few recordings of noise from wind turbines exist [reviewed by Wahlberg and Westerberg (2005) and Madsen *et al.* (2006)] and little is known about the reactions of marine life to this noise. The possible effects of wind turbine noise on marine mammals and the extent of zones of impact (*sensu* Richardson *et al.*, 1995) are considered in general by Madsen *et al.* (2006). The conclusion was that the zones were small, with audible ranges out to a few kilometers from the turbines under most favorable conditions.

Wind turbine noise has two main sources: air flow and turbulence noise from the wings and machinery noise. The machinery noise stems mainly from the gear box and generator located in the top of the wind turbine tower, the nacelle. The well known whoosh sounds from the wings are the main contributor to in-air noise, whereas machinery noise is the main contributor to underwater noise. Vibrations from the machinery are transmitted from the nacelle through the steel tower into the foundation from which it is radiated into the water column and into the seabed. The air borne noise is almost completely reflected from the water surface, and does not contribute significantly to the underwater noise level. The noise from gearbox and generator contain strong spectral peaks, which are generated from the repetitive contact between gear teeth. Since the turbines are maintained at a constant rate of revolution independent of wind speed, only the height of the peaks and not their location on the frequency axis is affected by increased wind speed.

Known underwater noise levels emitted from operating offshore wind farms are low by any standard (Madsen *et al.*, 2006), but as the offshore wind industry rapidly expands this does not imply that they are necessarily insignificant. High intensity noise sources in the ocean such as noise from individual ships, sonars, and seismic exploration are mostly transient in nature. On the other hand, the lifetime of an offshore wind farm is expected to be at least 20–30 years and associated noise emissions thus constitute an almost permanent

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[a] Author to whom correspondence should be addressed. Electronic mail: jat@dmu.dk

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source of noise year round for many years. As offshore wind power is a new and expanding industry, there is a need to evaluate the possible effects of underwater turbine noise on marine mammals, and a first requirement for this assessment is the availability of good noise recordings from wind turbines.

Richardson *et al.* (1995) provided a common framework for noise impact assessment in the marine environment by introducing the concept of four zones of influence on marine mammal behavior and hearing. These zones are "zone of audibility," "zone of responsiveness," "zone of masking," and "zone of hearing loss, discomfort, and injury." Even though the methods for establishing these four zones for different species and noise sources are not standardized, the concept has resulted in better and more uniform noise related impact assessments. The spatial extensions of the four zones are by their nature very different as they describe different aspects of noise related influences, from the faintest sounds that are just perceptible by the animal to immediately lethal high intensity shock waves. The size of each zone differs from species to species, from individual to individual, and sometimes even for the same individual depending on the physical and behavioral status of the animal.

The zone of audibility is defined as the area where an animal can hear the sound or noise above the background noise level. The extent of this zone is easily defined and thus in principle easy to calculate as it can be found from knowledge of the hearing capabilities of the target species, background noise levels, and sound transmission patterns. In practice, however, lack of accurate measurements of one or more of these parameters may introduce considerable error in estimating the size of the zone of audibility.

Within the zone of responsiveness a target animal will react to a sound or noise with altered behavior. This can be a positive behavior (attraction, investigation, etc.), negative behavior (evasion and startle), or simply changes in ongoing behavior without obvious direction (altered breathing pattern, heart rate changes, etc.). As the zone of responsiveness is related to behavioral reactions by the target species it can only be established using behavioral observations, which in many cases are difficult to obtain. Practical measurements are further complicated by the fact that most animals will display different reactions to noise depending on previous exposure experiences and on the behavioral and physiological states of the animal during noise exposure.

The zone of masking is the area around a noise source where the noise reduces detection of other sounds that are important to the animal in question, such as communication sounds, sounds from prey or predators, and sounds used in orientation and navigation. Masking is defined in psychophysics as an elevation of thresholds for the detection or discrimination of particular sounds without a general effect on the sensitivity of the auditory system. Masking is thus separated from other phenomena such as accommodation (stapedius reflex) and temporary threshold shifts (TTSs) that cause a general reduction in auditory sensitivity following exposure to loud sounds. Accommodation should be considered a behavioral or physiological response, whereas TTS is a commonly adopted criterion defining the extent of the zone of hearing loss, discomfort, or injury (see below).

The zone of hearing loss, discomfort, or injury is usually a small zone close to very loud sound sources where the sound pressures are sufficiently high to inflict temporary or permanent damage to animals, either in their auditory system or in the form of other physiological effects. TTSs of the auditory system have been adopted in recent years as a practical and conservative measure of the lower limit of damaging sound pressures to marine mammals (Kastak *et al.*, 1999; Schlundt *et al.*, 2000; Nachtigall *et al.*, 2003; NMFS, 2003; National Research Council, 2003). Recently, however, Southall *et al.* (2007) suggested the adoption of permanent threshold shift (PTS) as a criterion for defining the zone of injury.

The last three zones, "responsiveness," "masking," and "hearing loss, discomfort, and injury," are of particular interest in the context of management as these describe effects of a noise source and can form the basis for judgments regarding short-term and long-term negative impacts on a particular species. Despite this, the zone of audibility is often used in impact assessment studies to describe worst-case scenarios, partly because this zone can be assessed with the least effort. However, if worst-case scenarios are used uncritically there is a risk of grossly overestimating the size of the zone where sound has a significant impact on the animals in question.

Our study focuses on the extent of impact zones for three different types of offshore wind turbines during normal operation. We discuss the possible effects of wind turbine noise on the hearing of harbor seals (*Phoca vitulina*) and harbor porpoises (*Phocoena phocoena*), which are the most common marine mammal species in the North Sea, the inner Danish waters, and the Baltic Sea.

## II. MATERIALS AND METHODS

Underwater noise was recorded from three different types of wind turbines, denoted as locations 1–3; two Danish and one Swedish offshore wind farm. At location 1 (Middelgrunden, Denmark) underwater noise was recorded at two different wind speeds (1a and 1b). The locations and types of wind turbine are shown in Table I.

### A. Noise measurements and analysis

Broadband digital recordings (100 Hz–150 kHz) of underwater wind turbine noise were made in a preliminary study. As no energy above the background noise was found for frequencies above 10 kHz, broadband recordings were not included in this study.

Portable standard digital audio tape (DAT) recording equipment with appropriate hydrophones and amplifiers were used for noise measurements. Briefly, a sensitive, calibrated hydrophone with a build-in preamplifier (a Brüel & Kjær 8101 or a Reson TC4032) was connected through a low-noise amplifier (B&K Nexus 2693A or an Etec HA01A) to a portable DAT recorder (SONY TCD-D8 or a HHP PDR 1000). Frequency responses of the recording chains were flat (within 3 dB) from 10 Hz to 20 kHz. The distances between

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TABLE I. Description of the three wind farms.

| Name | Position<br>Latitude | <br>Longitude | Turbine type | No. of turbines |
|---|---|---|---|---|
| Middelgrunden offshore wind farm | 55° 40′ N | 12° 40′ E | Bonus 2 MW | 20 |
| Bockstigen-Valar offshore wind farm | 56° 59′ N | 16° 08′ E | WindWorld 500 kW | 5 |
| Vindeby offshore wind farm | 54° 58′ N | 11° 08′ E | Bonus 450 kW | 11 |

the hydrophones and the foundations were measured using either Leica or Bushnell laser binoculars (distometers) and varied between 14 and 40 m. Recording depth was half-way between surface and bottom, i.e., 2.5, 5, and 2 m for locations 1, 2, and 3, respectively.

The complete recording setup was calibrated with a Brüel & Kjær 4223 pistonphone calibrator prior to each recording. The calibration signal was recorded on all DAT-tapes. Recorded sound levels could thus be converted to absolute levels by direct comparison with the reference signal. All other wind turbines within a range of approximately 1000 m were shut down during measurements of noise from a specific wind turbine. Background noise was measured at the same position but with all wind turbines shut down.

The audio range recordings were analyzed on a Hewlett Packard 35670A frequency analyzer (using the analog connection from the DAT recorder) and presented as 1/3-octave levels (TOLs) in $\mathrm{dB_{rms}}$ re 1 $\mu$Pa. Each recording was divided into one section with the wind turbine active, denoted as "turbine noise," and one section with the wind turbine stopped, denoted as "background noise." Turbine and background noise recordings were subjected to identical analysis. The thirty 1/3-octave bands spanning the center frequencies from 12.5 Hz to 10 kHz were analyzed simultaneously. Unless otherwise stated, all references to frequencies in the following refer to 1/3-octave center frequencies.

The recordings from location 1 (a and b) were analyzed with multiple replicates with averaging times of 15 s [the shortest averaging time that can be used for analyzing 20 Hz white Gaussian noise with 95% confidence limits of $\pm 1$ dB is 8 s (Brüel & Kjær, 1985)] and separated by at least 1 min in order to obtain independence between the averages. Wind turbine noise contains small periodical fluctuations due to varying load on the machinery. The period of these is one-third of the rotational speed, due to three wings of the turbines, and is approximately 1 Hz. Several cycles are thus covered within one 15-s averaging period. The total duration of recordings used for analysis at location 1 was 2.25 min at 6 m/s wind speed and 10 min at 13 m/s. Recordings from locations 2 and 3 were analyzed with averaging times of several minutes without replicates.

Statistical analysis was only applied to data from recordings at locations 1a and 1b, as measurements from locations 2 and 3 did not contain multiple replicates. The wind turbine noise levels in 1/3-octave bands were tested against the background noise levels pairwise for all bands (t-test, one-sided, equal variance). $P$-values were Dunn–Sidak-corrected for multiple comparisons (Sokal and Rohlf, 1995).

For all measurements the total sound pressure level of the turbine noise was calculated by addition of TOLs across all 1/3-octave bands.

### B. Estimating the zone of audibility

Noise must be analyzed as "critical band levels" in order to be directly comparable with hearing thresholds for pure tones (Erbe, 2002), where critical bandwidths of the target species are taken into account. As few actual estimates of critical bandwidth are available for marine mammals, and almost none at very low frequencies, the common practice of using 1/3-octave bandwidths as an approximation was adopted (Madsen *et al.*, 2006). This introduces a degree of uncertainty in the estimates, but as turbine noise contains strong tonal components, generated in the gearbox machinery, the critical band levels are not strongly affected by changes in analysis bandwidth.

The zone of audibility was defined based on either the audiogram or the background noise level, depending on which of the two was limiting for detection.

The pure tone audiogram for the harbor seal was taken from the study by Kastak and Schusterman (1998) while that for the harbor porpoise was taken from Kastelein *et al.* (2002). Low frequency hearing for both marine mammals was extrapolated using a slope of approximately 35 dB per decade (Stebbins, 1983; Au, 1993) (see the discussion for further comments).

The turbine noise+background noise in a particular 1/3-octave band was used for calculating the zone of audibility if the combined level was higher than background noise alone in the same band. If the hearing sensitivity was above the background noise in a particular 1/3-octave band, then the zone of audibility was estimated by extrapolating from actual measurements out to the distance at which the turbine noise plus the background noise just equaled the auditory threshold. If the background noise was limiting, the zone of audibility was estimated by extrapolating from measurements out to the range at which the turbine noise equaled the background noise in the particular 1/3-octave band, corresponding to the point where the sum of the turbine noise and the background noise was 3 dB above background noise alone.

A suitable model for transmission loss is critical to both calculations. Due to lack of actual measurements a range was calculated. Upper end of the range was found from a cylindrical spreading loss model (transmission loss equal to 10 log $r$) and lower range was found using transmission loss equal to hyperspherical spreading (30 log $r$) equal to the

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only value for transmission loss actually measured for this type of noise (Madsen *et al.*, 2006).

## III. RESULTS

Measurements of underwater noise (TOLs) from the three different wind turbines and background noise measurements are shown in Fig. 1. Common for all four recordings is that the turbine noise was only detectable above background noise levels at frequencies below 315–500 Hz. Maximum measured noise level was 126 dB re 1 $\mu$Pa TOL at 25 Hz recorded at location 3 (Vindeby) at a distance of 14 m from the foundation. Maximum overall turbine noise level measured (summed across all 1/3-octave bands) was 127 dB re 1 $\mu$Pa (rms) also at location 3 (Table II). The 25 Hz peak in Fig. 1(A) was clearly audible as machinery noise from the wind turbine.

Two measurements at different wind speeds were made at position 1 (Middelgrunden) and from those a pronounced effect of wind speed on noise level was observed. In both spectra a peak is present at 125 Hz, but the sound pressure level was 11 dB higher at 13 m/s wind speed, compared to 6 m/s wind speed [114 dB re 1 $\mu$Pa (rms) TOL vs 103 dB re 1 $\mu$Pa (rms) TOL]. The increase in intensity with wind speed, but constant frequency of the noise, is consistent with the fact that the turbines operate at a constant rate of revolution, irrespective of wind speed.

The strong peak at 25 Hz in the 6 m/s wind speed measurement was not visible in the measurement made at 13 m/s wind speed. This was likely due to a significantly higher background noise at low frequencies in the 13 m/s wind speed recording. The background noise below 50 Hz in recording B at location 1 [Fig. 1(B)] was dominated by heavy shipping noise (clearly audible in the recording) from a nearby deep water shipping lane. The measurements taken at the same position during recording A at location 1 [Fig. 1(A)] were from an unusually quiet day with little shipping traffic in the area. Furthermore the hydrophone used during recording B at location 1 was submerged from a surface float instead of a bottom mount due to rough weather. This is likely to have added to the low frequency noise due to wave-induced motion of the hydrophone.

The noise was not constant over the duration of recordings. For the recordings at position 1 it was possible to calculate percentiles of the noise intensity. 10%, 50%, and 95% percentiles for the noise at 25 Hz and at a wind speed of 6 m/s were 101 dB re 1 $\mu$Pa (rms) TOL, 105 dB re 1 $\mu$Pa (rms) TOL, and 109 dB re 1 $\mu$Pa (rms) TOL. Similar percentiles at 125 Hz and 6 m/s wind speed were 100 dB re 1 $\mu$Pa (rms) TOL, 102 dB re 1 $\mu$Pa (rms) TOL, and 107 dB re 1 $\mu$Pa (rms) TOL. At 25 Hz and 13 m/s these were 113 dB re 1 $\mu$Pa (rms) TOL, 114 dB re 1 $\mu$Pa (rms) TOL, and 116 dB re 1 $\mu$Pa (rms) TOL, respectively.

The zone of audibility can be determined from the results shown in Fig. 1. Together with the turbine noise, audiograms for the harbor seal and the harbor porpoise are shown in Fig. 1. For each 1/3-octave band, the largest difference between turbine noise source level and the audiogram or the background noise, whichever is higher, was determined for

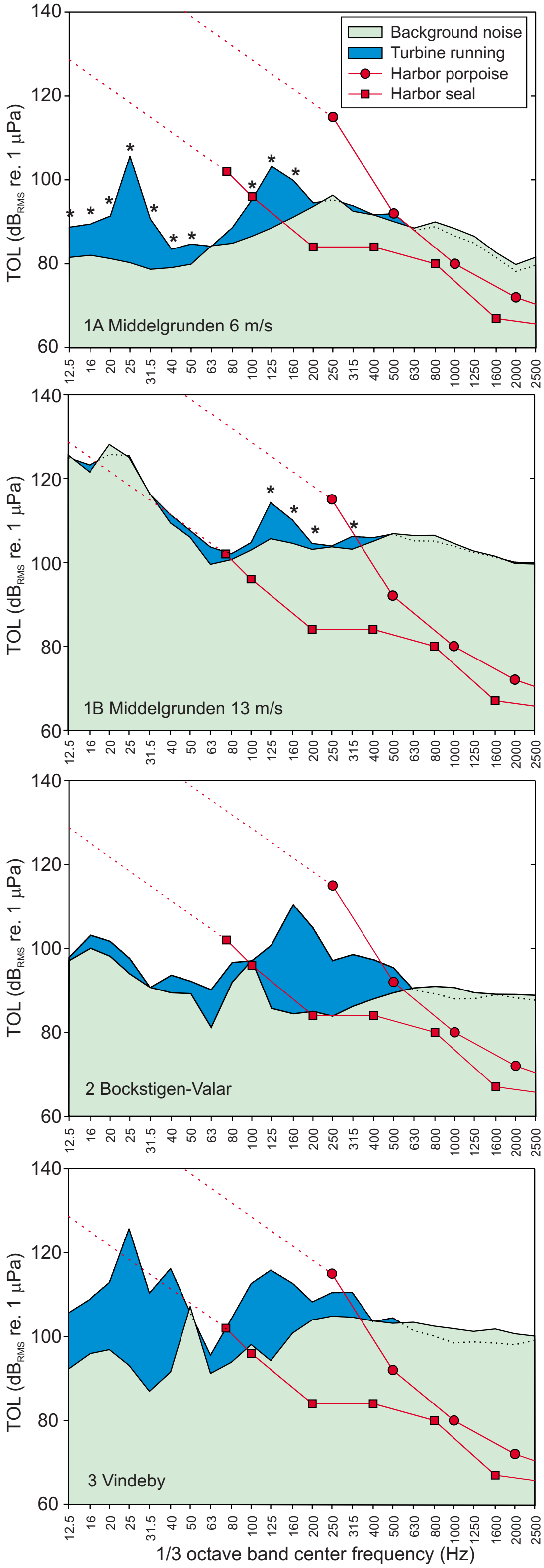

FIG. 1. (Color online) Noise recorded from three different offshore wind turbines given as 1/3-octave levels (TOLs). Background noise was measured at the same position as turbine noise but with the turbine stopped. Turbine and background noise at location 1 were measured at two different wind speeds on two different occasions. * in (A) and (B) indicate 1/3-octave bands where turbine noise was significantly higher than the background noise ($P < 0.05$). Further details on recordings are given in Table II. Included in the figures are the underwater audiograms of a harbor seal and a harbor porpoise (Kastak and Schusterman, 1998; Kastelein *et al.*, 2002). Audiograms were extrapolated to low frequencies with 35 dB/octave (see text).

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TABLE II. Summary of wind turbine noise measurements. Shown are the measuring distance, the wind speed, 1/3-octave bandwidths in which noise was measured, the center frequency of the 1/3-octave band containing the most energy followed by the maximum sound pressure in that band, and the overall sound pressure level of the turbine noise summed over all frequency bands. For each animal, the center frequency of the 1/3-octave band with most audible turbine noise is given (see text for further explanation). This is followed by the decibel difference above background noise, or above the detection threshold of the animal, which ever is largest. The last column for each species shows the extreme values calculated for maximum detection distance range, assuming cylindrical and hyperspherical spreading losses, respectively.

| | | | | | | | | Harbor seal | | | Harbor porpoise | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | Distance (m) | Depth (m) | Wind (m/s) | 1/3-octave bands with turbine noise (Hz) | Overall sound pressure (dB re 1 $\mu$Pa$_{\mathrm{rms}}$) | Peak band (Hz) | Sound pressure (dB re 1 $\mu$Pa$_{\mathrm{rms}}$) | Center frequency (Hz) | Noise level (dB) | Detection distance[a] (m) | Center frequency (Hz) | Noise level (dB) | Detection distance[a] (m) |
| 1a (Middelgrunden) | 20 | 5 | 6 | 12.5–500 | 109 | 25 | 106 | 125 | 11 | 60–460 | 500 | −5 | 19–20 |
| 1b (Middelgrunden) | 40 | 5 | 13 | 40–400 | 122[b] | 125 | 114 | 125 | 8[c] | 70–250 | 315 | −4 | 25–34 |
| 2 (Bockstigen-Valar) | 20 | 10 | 8 | 12.5–500 | 113 | 160 | 110 | 160 | 26 | 140–6400 | 500 | 2 | 31–73 |
| 3 (Vindeby) | 14 | 4 | 13 | 12.5–500 | 127 | 25 | 126 | 125 | 22[b] | 70–2000 | 315 | 2 | 21–47 |

[a] Upper and lower estimates calculated by assuming cylindrical and hyperspherical spreading losses, respectively (see text).

[b] Likely overestimated due to high level of shipping noise.

[c] Limited by background noise rather than hearing threshold.

the harbor seal and the harbor porpoise. These values were used to calculate a range of maximum distance of detection (Table II) under two extreme assumptions regarding transmission loss (3 and 9 dB per doubling of distance, respectively).

The noise from all three turbines is predicted to be barely audible to harbor porpoises in all four recordings. In all cases, the turbine noise just exceeds the pure tone threshold. Thus the maximum predicted detection range is only marginally larger than the actual distance at which the recordings were obtained (Table II).

All turbines are predicted to be clearly audible to harbor seals at the locations where measurements were made as turbine noise in the 1/3-octave band best audible to the seals in all cases were ~10–20 dB above either the pure tone threshold or the background noise, whichever was the highest. The largest zone of audibility for the harbor seal was found at location 2 (Bockstigen-Valar), where the wind turbine TOL at 160 Hz exceeded the audiogram threshold by 26 dB. The predicted range of audibility in this 1/3-octave band is somewhere between 140 m and 6.4 km, strongly depending on assumptions of transmission loss.

## IV. DISCUSSION

Underwater noise from the three different turbines was clearly identifiable above background noise at the distances at which measurements were obtained (14–40 m from foundations). Absolute noise levels were low, however, ranging between 109 and 127 dB re 1 $\mu$Pa (rms) for total noise levels up to 20 kHz.

Based on audiograms from harbor seals and harbor porpoises the noise is predicted to be just audible to porpoises at the distances where measurements were made and audible to harbor seals at distances up to somewhere between several hundred meters to a few kilometers, depending critically on assumptions behind calculations of transmission loss. As discussed below, the noise has, due to the low intensity and the low frequency emphasis, limited if any capability to injure the animals or mask other signals of importance to seals and porpoises. Behavioral reactions to noise from the three turbines are not expected for porpoises and seals unless the animals are in the immediate vicinity of the foundation.

### A. Zone of audibility

The zone of audibility for harbor seals and harbor porpoises was estimated to be between 2.5–10 km and 8–63 m, respectively (Table II), depending on critical bandwidths and under assumption of smallest transmission loss (cylindrical spreading) and for the worst of the four locations studied (Bockstigen-Valar). Harbor seals are thus able to detect the wind turbine noise at considerably longer distances than are harbor porpoises, a reflection of their significantly better low frequency hearing. It is worth noting that the greatest zone of audibility was not found around the most noisy wind turbine (location 3, Vindeby), but rather at location 2 (Bockstigen-Valar). The high source level at location 3 was caused by strong winds (and resulting heavy load on the turbine). The strong winds, however, also increased the wave induced background noise level leaving the extent of the zone of audibility around the wind turbine largely unaffected, as turbine noise to background noise level remains largely unaffected.

#### *1. Transmission loss and near field effects*

Assumptions on transmission loss are central to the calculation of the zone of audibility. In the above calculations an upper and a lower value for the extent of the zone were calculated. The upper extreme was based on a worst case assumption of cylindrical transmission loss (3 dB attenuation per distance doubled). However, true cylindrical spreading is rarely realized under natural conditions and actual measurements at a wind farm not included in this study (Utgrunden offshore wind farm, Madsen *et al.*, 2006) indicated a transmission loss as high as 9 dB per distance doubled. Until more measurements of transmission loss of turbine noise are available, there is thus good reason to consider the upper limit of the audibility ranges in Table II as unrealistic worst case scenarios.

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Additional complications in calculating the audibility ranges could arise from the fact that noise measurements had to be made at short distances from the turbines, probably within the acoustic near field. Transmission loss in the near field is unpredictable due to the large size of the sound producing surface (entire foundation of turbines) and possibly also to Lloyd mirror effects caused by the shallow water. Lloyd mirror effects, however, are probably of minor importance as the sound did not radiate from a point but from the entire turbine foundation, and measurements were made under windy conditions, where the sea surface was rough and thus did not create strong specular reflections. The Fresnel near field generated by the large transducer area may extend out to several times the size of the foundation, i.e., out to distances of several tens of meters. An extension of the Fresnel near field beyond the measuring point would mean that simple geometric spreading cannot be assumed from the measuring point and hence an underestimation of the zone of audibility.

### 2. Auditory sensitivity: Hearing curve extrapolations

Few studies have dealt with hearing at very low frequencies in marine mammals and no thresholds are available for the lowest frequencies found in the turbine noise. In order to access the audibility of the noise, an extrapolation of existing audiogram data is needed. One low frequency audiogram is available for harbor seal (Kastak and Schusterman, 1998). It spans the frequency range from 75 to 6400 Hz, which only partially overlaps with the frequency range of the wind turbine noise. Likewise, a single audiogram with information on low frequency hearing is available for harbor porpoise (Kastelein *et al.*, 2002), covering the frequency range down to 250 Hz. Mammalian audiograms, including those of marine mammals, have in common a characteristic gradual increase in thresholds for low frequencies, with a slope of approximately 35 dB per decade (Stebbins, 1983; Au, 1993). Thus, the audiograms of harbor seal and harbor porpoise were extrapolated by a straight line with a slope of 35 dB per decade for frequencies below 75 Hz for the harbor seal and 250 Hz for the harbor porpoise (Fig. 1). This extrapolation is critical, and especially for species where no data on auditory sensitivity are available, the assumptions regarding audiograms are of utmost importance in estimating the zones of audibility.

### 3. Critical bandwidths

In order to compare broadband noise to an audiogram, the noise level must be stated in critical band levels, describing sound power per critical bandwidth (as done by Erbe and Farmer, 2000), instead of using the standard expression of sound power per 1 Hz bands. Assumptions on the width of the critical bands will affect calculations of the zone of audibility. Narrow critical bands, which may be seen as an adaptation to high-resolution frequency discrimination (Au, 1993), will result in less sensitivity to broadband noise whereas the opposite is true for wide critical bands (Au *et al.*, 2004). Good estimates of critical bandwidths are thus necessary when estimating the possible impact from man-made noise on marine mammals. Not much is known about the critical bandwidths of harbor porpoises and harbor seals at the low frequencies considered in this study. The harbor seal critical bandwidth has been measured by Terhune and Turnbull (1995), and the harbor porpoise estimated indirectly by Popov *et al.* (2006). The critical bandwidth for harbor seals has only been measured for frequencies above 4 kHz, and changes from 1/3-octave at 4 kHz to approximately 1/6-octave at 30 kHz. The critical bandwidth for ringed seals (*Phoca hispida*) (Terhune and Ronald, 1975) and northern fur seal (*Callorinus ursinus*) (Moore and Schusterman, 1987) is less than 1/6-octave in the frequency range between 2 and 30 kHz. Common for these two species is that the critical bandwidth increases for lower frequencies, increasing the sensitivity to broadband noise. Based on these data it is assumed that the critical bandwidth for harbor seals has a pattern similar to the two other pinnipeds and thus is between 1/6- and 1/3-octave wide in the frequency range below 1000 Hz.

Critical bandwidth measurements for cetaceans below 1 kHz are only available for the beluga (*Delphinapterus leucas)* (Johnson *et al.*, 1989). It varies from 1/12-octave at 1 kHz to approximately 2/3-octave at 200 Hz. The critical bandwidth of harbor porpoises was assessed by Popov *et al.* (2006) using auditory brainstem responses with pure-tones both as signals and maskers. In contrast to what is known for all other mammals, the bandwidth of the auditory filters in the harbor porpoise and the Finless porpoise (*Neophocoena phocaenoides*) was found to be approximately constant on a linear scale (constant bandwidth with increasing center frequency). Other mammals, including odontocetes such as bottlenose dolphin (*Tursiops truncatus*) (Johnson, 1968; Au and Moore, 1990) and False killer whale (*Pseudorca crassidens*) (Thomas *et al.*, 1990), have auditory filter bandwidths that are approximately constant on a logarithmic scale (constant ratio of bandwidth to center frequency). The measurements of Popov *et al.* (2006) indicate a constant filter bandwidth of around 3–4 kHz, irrespective of the center frequency in the range 20–150 kHz. Extrapolating to lower frequencies indicates that the critical bandwidth could be as much as several octaves in the frequency range of the turbine noise. As the main energy in the turbine noise is localized at a few prominent tonal peaks, broader filter bandwidths in this range would mean that the turbine noise would be masked by the broadband background noise and thus, if anything, would be harder to detect for the porpoises than the predictions in Table II, based on an assumption of 1/3-octave filter bands.

## B. Zone of responsiveness

As described in the Introduction, the zone of responsiveness is not as straightforward to define and estimate as the zone of audibility and the zone of masking, but must be estimated based on actual observations. A number of studies have addressed the effect of various sound sources on the behavior of seals and porpoises, both in captivity and in the wild (most of these are summarized in Southall *et al.*, 2007). It is difficult to generalize from these studies to the turbine

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noise of this study, but in general no studies have demonstrated significant behavioral reactions at received levels below about 100 dB re 1 μPa rms for odontocetes and about 140 dB re 1 μPa rms for pinnipeds. Due to the poor hearing capabilities of harbor porpoises within the turbine noise frequency range behavioral effects are unlikely, even at close range, simply because they cannot hear the noise, unless very close to the turbine. Harbor seals on the other hand have better hearing, but as summarized by Southall *et al.* (2007) they are more tolerant to underwater noise than odontocetes and it is questionable whether they would experience levels exceeding 140 dB re 1 μPa rms, even if they were next to the foundation. For the three turbines in this study the extent of the zone of responsiveness is thus considered small and insignificant. Other turbines, however, may produce louder noise or more importantly peak energies at higher frequencies. In this case the zones of responsiveness would be larger, but until a better general knowledge of underwater noise for other types of turbines is available, the possibility of behavioral effects should not be dismissed.

### C. Zone of masking

In order for a signal to be masked by noise there must be an overlap between the frequencies of the signal and those of the noise. For a broadband signal to be masked by broadband noise it is reasonable to assume that the noise has to be at the same intensity as the signal (Green, 1969) and if the signal contains strong tonal components, even higher noise levels are needed (Au and Moore, 1990). Harbor seals are very social animals and are known to use a wide variety of communication sounds. Hanggi and Schusterman (1994) and Bjørgesæter *et al.* (2004) reported numerous different underwater sounds, several of which have components in the frequency range below 1000 Hz. All of these display sounds overlap with the wind turbine noise and they could potentially be masked to some degree. However, the broadband nature of the harbor seal sounds, as well as the low intensity of the turbine noise, makes it unlikely that communication signals are masked unless either the calling or the listening seal is located immediately next to the turbine foundation. The zone of masking is thus considered insignificant for harbor seals.

Harbor porpoises use ultrasound for echolocation and communication. Their signals have a peak frequency about 130 kHz and contain virtually no energy below 100 kHz (Møhl and Andersen, 1973; Teilmann *et al.*, 2002). Thus, the reception of these sounds cannot be affected by the turbine noise, which has energy at very low frequencies. The low sensitivity of porpoise hearing at low frequencies (as compared to seals) suggests that passive listening for sounds below 1000 Hz does not play a significant role for the porpoises. Zone of masking is thus considered to be zero for porpoises.

### D. Zone of hearing loss, discomfort, and injury

As described in the Introduction, there is common agreement that the intensity of sounds eliciting TTSs can be used as the lower limit for defining the zone of damage (however, see Southall *et al.*, 2007 on the application of PTSs in impact assessment). TTS elicited by continuous noise exposure has been measured in harbor seals (Kastak *et al.*, 1999). It was found that 20 min of exposure to octave band white noise, 60 dB above the harbor seal hearing threshold at 100, 500, and 1000 Hz center frequencies (i.e., approximately 155, 144, and 140 dB re 1 μPa, respectively) resulted in an average 4.8 dB temporary decrease in hearing sensitivity. These levels are considerably higher than those to which a seal or porpoise will be exposed to when close to wind turbine, and animals remaining even very close to the foundation are unlikely to experience any hearing damage (temporary or permanent). For the types of turbines studied here there is thus no zone in which seals or porpoises are exposed to dangerously high levels of noise.

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