TAIWANESE WHITE DOLPHINS AND OFFSHORE WIND FARMS

Scientific Report from DCE – Danish Centre for Environment and Energy No. 245 2017

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Abstract: Taiwan has proposed development of offshore wind energy in the Eastern Taiwan Strait, which is home to the endemic and critically endangered Taiwanese white dolphin (*Sousa chinensis taiwanensis*). The most significant source of disturbance from offshore wind is noise from percussive piling on turbine foundations. The direct impact on Taiwanese white dolphins from construction and operation of offshore wind farms in the Taiwan Strait is considered to be manageable by appropriate mitigation measures (most importantly by application of air bubble curtains during percussive piling of turbine foundations) and within limits, that will not further endanger the population of dolphins. However, considering and handling possible knock-on effects from changes in use of the areas, including consequences for bycatch rates in fisheries, is critical in order to secure the long-time survival of the Taiwanese white dolphin.

Keywords: Offshore wind farms, underwater noise, Taiwan, *Sousa chinensis taiwanensis*

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1 Foreword

The Government in Taiwan has decided that nuclear power will be phased out by 2025 and instead develop offshore wind energy to cover the gap in energy supply. Consequently, Taiwan has set an ambitious goal of 3,000 MW nominal power installed by 2025.

Most of the proposed sites for this offshore wind development are located in the eastern part of the Taiwanese Strait. These coastal waters along the west coast of Taiwan are home to the endemic and endangered Taiwanese white dolphin (*Sousa chinensis taiwanensis*). This report was commissioned by Copenhagen Infrastructure Partners (CIP). It contains background information about the effects of offshore wind farms on small cetaceans in general, centred around the last 20 years of experience from the large development of offshore wind in European waters, especially when it comes to effects of underwater noise on harbour porpoises (*Phocoena phocoena*). It further discusses how this extensive experience, also with respect to mitigation of effects, can be applied to the case of the Taiwanese white dolphin.

This report is not part of the legally required EIA-documents and thus has no official status within the projects proposed by CIP. It is intended as an independent expert assessment, and will be subject to evaluation by other experts, including the Eastern Taiwan Strait *Sousa* Technical Advisory Working Group.

2 Summary

Taiwan has proposed an ambitious offshore wind energy plan, with the aim of installing 3000 MW capacity by 2025. A significant part of the designated licence blocks are located in the coastal waters on the west coast of Taiwan. These waters are also home to the endemic and critically endangered Taiwanese white dolphin (*Sousa chinensis taiwanensis*).

Potential impact from installing and operating offshore wind farms in the waters just outside the dolphin habitat is therefore subject to detailed impact assessments, in order to assure that the pressure on the already endangered dolphins is not increased even more by the offshore wind farm construction. A key factor of potential impact is underwater noise.

The most significant noise source in construction of offshore wind farms is percussive piling on turbine foundations. Unmitigated pile driving noise has been shown to cause behavioural reactions in harbour porpoises at distances of tens of kilometres, and can potentially cause hearing damage in animals closer to the foundation. The potential impact of pile driving in a project proposed by the company Copenhagen Infrastructure Partners (CIP) in the area Xidao is assessed in this report. Three different frameworks for regulating pile driving noise were used in this assessment: the German, Danish and NOAA / NMFS guidelines, and were carried out on basis of the commitments of CIP. During the EIA-process CIP has strongly committed to assure that single strike sound exposure level (SEL_{SS}) 750 meter from the foundation does not exceed 160 dB re. 1 μPa^2s, unweighted. This will most likely be ascertained by means of bubble curtains that attenuates the sound radiated the pile driving. CIP has also committed to conduct only one pile driving at a time in the Changhua wind farm areas that CIP is developing, eliminating cumulative impacts from multiple noise sources.

Irrespective of which framework is used, the assessment shows that dolphins more than 750 m from the pile driving will not be at risk of acquiring permanent hearing loss (PTS) and that dolphins inside the core dolphin habitat (roughly within the 10 m depth contour) will be outside the zone where behavioural reactions to the noise is anticipated. The above guidelines differ in assessment of risk of temporary hearing loss (TTS). The German and NOAA / NMFS guidelines indicate no risk of TTS outside the 750 m zone and the Danish guidelines indicate a moderate risk. However, as the Danish guidelines do not factor in the high attenuation at higher frequencies provided by the bubble curtain, the latter assessment is likely to overestimate the impact.

The likelihood of any masking effects of the pile driving noise is considered negligible within the dolphin habitat. Likewise is the anticipated noise from operating turbines so low that it is inaudible more than about hundred meters from the foundations.

The direct impact on Taiwanese white dolphins from construction and operation of offshore wind farms in the Taiwan Strait is thus considered to be manageable by appropriate mitigation measures and within limits, that will not further endanger the population of dolphins. However, the possible knock-on effects from anticipated and unanticipated changes especially to the local

fishery and thus dolphin bycatch rates have not been included in the assessment. Considering and handling these effects, including possible mitigations to reduce bycatch, is critical in order to secure the long-time survival of the Taiwanese white dolphin.

3 Proposed projects

Taiwan has designated a substantial number of licence blocks intended for development of offshore wind energy. All licence blocks are located within the 50 depth contour and the economic exclusive zone (EEZ) off the Taiwanese west coast (figure 3.1), with the majority being in the Changhua region.

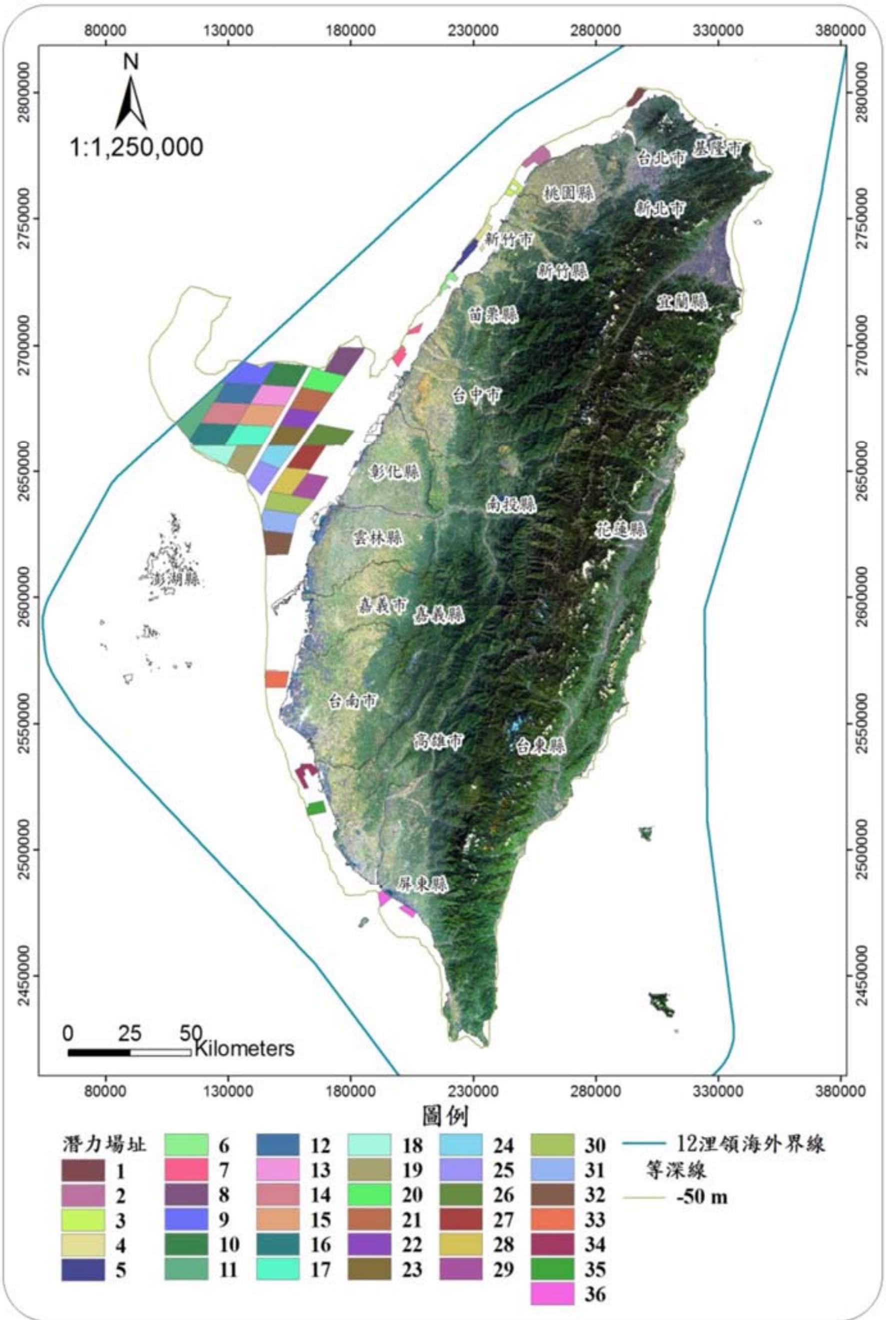
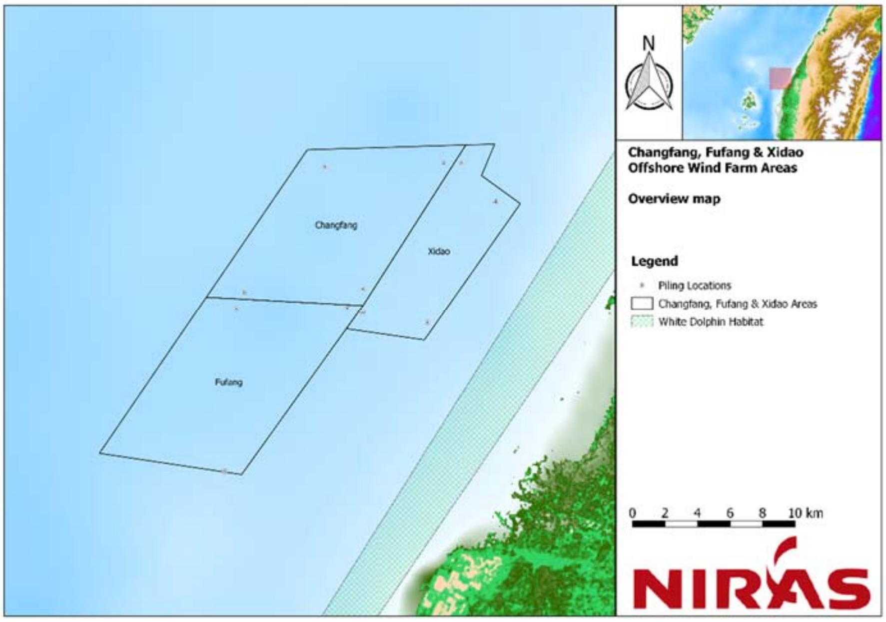


Figure 3.1. Map of waters around Taiwan with indication of the first tentative designation of licence blocks for offshore wind farms. Some licence blocks have been skipped through later consultations and the shape of others have been modified. Blue line indicate economic exclusive zone (EEZ) and light green line indicate the 50 m depth contours.

Copenhagen Infrastructure Partners (CIP) have proposed development of offshore wind in the three areas in the Changhua region: Changfang, Fufang, and Xidao (numbers 27, 28 and east of 27, on figure 3.1, respectively). The current location and extent of the three areas are shown in figure 3.2. The eastern extent of the area has been modified to remain outside the 30 m depth contour and approximately 3 km outside the white dolphin habitat (bluegreen area in figure 3.2).

Figure 3.2. Overview of the outline of the proposed offshore wind farms in the Changfang, Fufang and Xidao areas, located off the western coast of Taiwan. Circles indicate pile driving locations used in modelling. Exact placement and number of turbines is to be decided. The approximate extent of the white dolphin core habitat is indicated by the blue-green area parallel to the coast.



The exact number of turbines, their size and position inside the areas has not been decided yet. It is expected that the turbine size will be 6MW nominal capacity or larger (up to 12MW) and mounted on so-called jacket foundations (figure 3.3). Jacket foundations are expected to be four-legged platforms fastened into the seabed by steel piles, which are piled through the hollow legs of the platform (jackets) 50-80 m into the seabed (figure 3.4).

Figure 3.3. Typical example of 6 MW turbines mounted on jacket foundations. Source: Block Island offshore wind farm, US.

Piles are installed by percussive piling, by means of a large hydraulic hammer, typically operated from a jack-up rig. The typical turn-around time for pile driving is around one day per jacket foundation.

The turbines are expected to be installed with a separation of 800 – 1500m depending on the turbine size and the exact layout. The result will be a very open layout (figure 3.5).

Figure 3.4. Photo of jacket foundation after piling, showing the steel piles in the jackets, through which they were piled into the seabed. Source: Block Island offshore wind farm, US.

Figure 3.5. Example of operational offshore wind farm (DanTysk, German Bight). Yellow platform in the foreground is the transformer station, which connects cables from all turbines with the main cable to shore. Distance between rows of turbines is roughly 1 km. Source: Vattenfall.

4 The Taiwanese white dolphin

Numerous species of odontocetes are found in the Taiwan Strait, including coastal species such as finless porpoise (*Neophocoena phocaneoides*), bottlenose dolphin (*Tursiops truncatus*) and rough-toothed dolphin (*Steno bredanensis*). Also deep-water species such as Blainville's beaked whale (*Mesoplodon densirostris*) and pygmy sperm whale (*Kogia breviceps*) are reported from strandings (Wang et al. 2015b).

The most relevant species in relation to offshore wind farms in the eastern Taiwan Strait, however, is the Taiwanese white dolphin (*Sousa chinensis taiwanensis*), a subspecies of the indo-pacific humpback dolphin (Wang et al. 2015a).

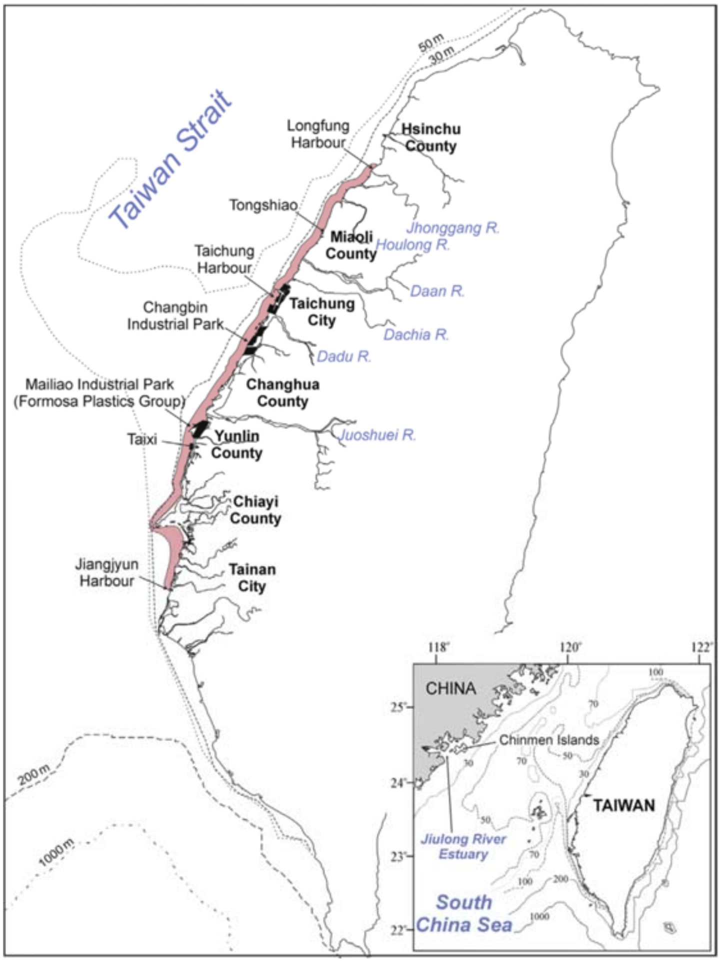


Figure 4.1. Distribution range (in pink) of the Taiwanese white dolphin. From Wang et al. (2016a)

4.1.1 Ecology and population status

The Taiwanese white dolphin has, in line with other white dolphin subpopulations, a very limited coastal habitat. It is exclusively found along the eastern shore of the Taiwan Strait. Here the dolphins are almost exclusively found in shallow waters, less than 20 m deep and within an approximately 100 km long stretch of water (Wang et al. 2007, Dares et al. 2014). See figure 4.1.

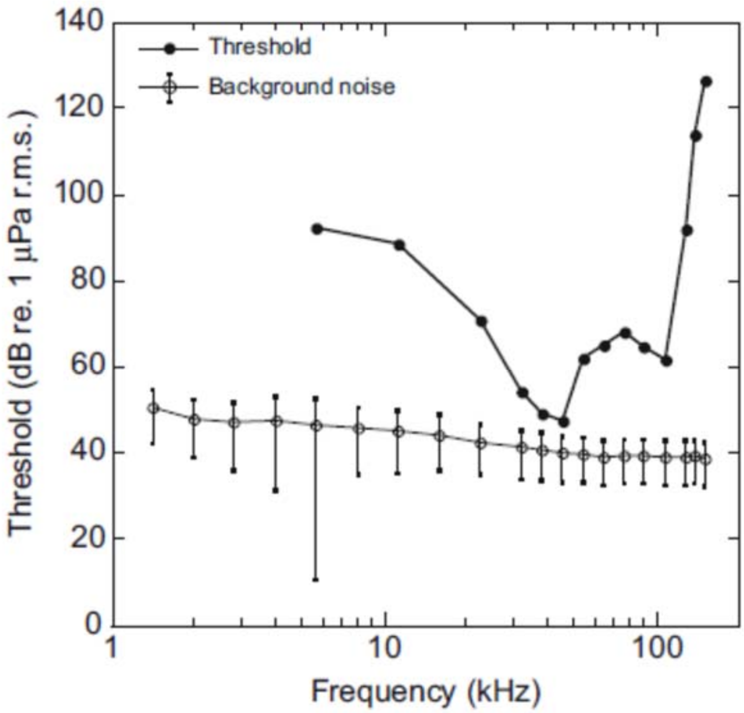
Even though there is a similar population on the western shores of the Taiwan Strait, photo id studies have shown that there is no exchange between the two populations on either side of the deeper parts of the strait (Wang et al. 2016b), supporting the claim that the Taiwanese subspecies is indeed genetically isolated from the other white dolphins.

Surveys indicate that the total population size is significantly smaller than 100 animals (Wang et al. 2012) and the conservation status has been assessed as critically endangered (Reeves et al. 2008).

4.1.2 Auditory physiology and vocalisations

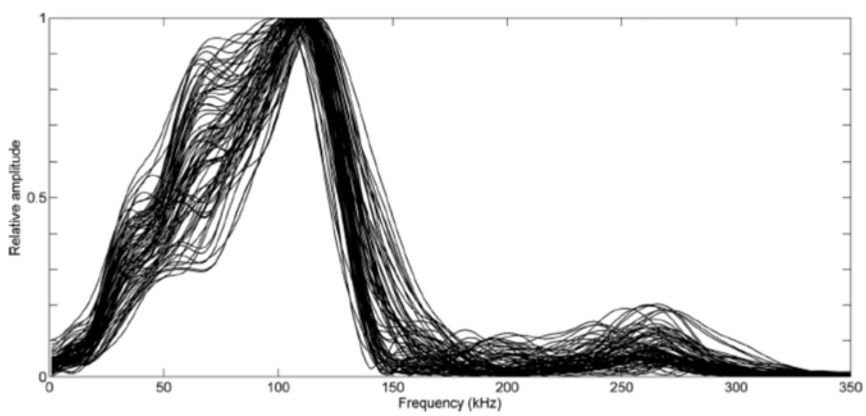
Comparatively little work has been done on the auditory physiology of humpback dolphins. One audiogram has been obtained from a Chinese white dolphin in captivity (Figure 4.2; Li et al. 2012). This shows a typical odontocete shape, with best hearing in the ultrasonic range 20 kHz to above 100 kHz.

Figure 4.2. Audiogram from a single white dolphin. Source: Li et al. (2012).



Echolocation signals from Chinese white dolphins were recorded by Fang et al. (2015). These signals are broadband signals with peak energy above 100 kHz, but significant energy down to 20 kHz (figure 4.3), typical of small delphinids and consistent with classification of the species as a mid-frequency cetacean (sensu Southall et al. 2007).

Figure 4.3. Individual and superimposed power spectra of on-axis echolocation clicks from white dolphins (Fang et al. 2015).



White dolphins, like other typical mid-frequency cetaceans, use whistles for communication (figure 2.3). These whistles are found in the frequency range approximately 3 kHz to 15 kHz (Wang et al. 2016c, Hoffman et al. 2017).

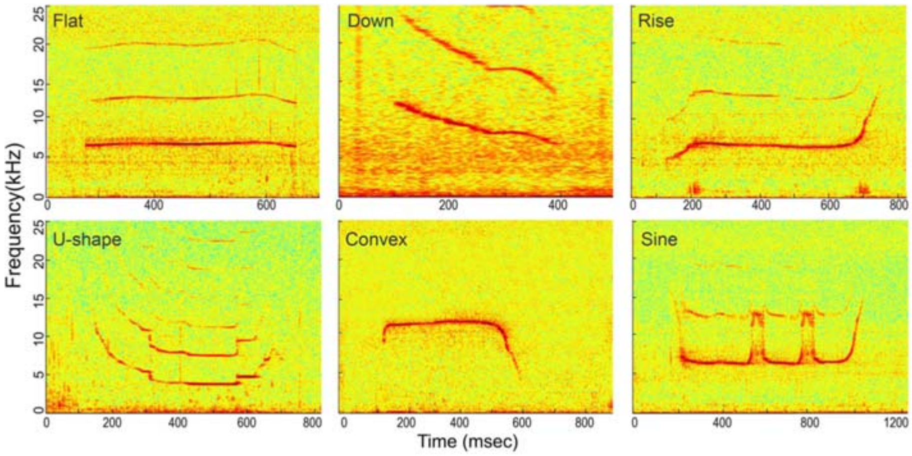


Figure 4.4. Examples of spectrograms of communication whistles of Indo-pacific humpback dolphins. Main energy is in the frequency range approximately between 4 kHz and 15 kHz. From Wang et al. (2016c).

Although the information on the auditory physiology of white dolphins is limited, the little, which is known, is consistent with what is known from other shallow-water, coastal dolphins and supports that in the absence of better data, experimental results from well-studied species such as bottlenose dolphins can be used in first approximations.

5 Detrimental effects of underwater sound

Underwater noise has long been recognised as a major source of human disturbance to marine mammals (e.g. reviews by Richardson et al. 1995, National Research Council 2003, Hildebrand 2009). From early on (Richardson et al. 1995) effects have been divided into injury (including hearing loss), disturbance of behaviour, and masking of communication and other sounds. Additional, but less well-studied effects are physiological effects, including increase in stress hormone levels (e.g. Wright et al. 2016) and non-auditory effects, mediated by the vestibular system or otherwise (Steevens et al. 1999 for an example).

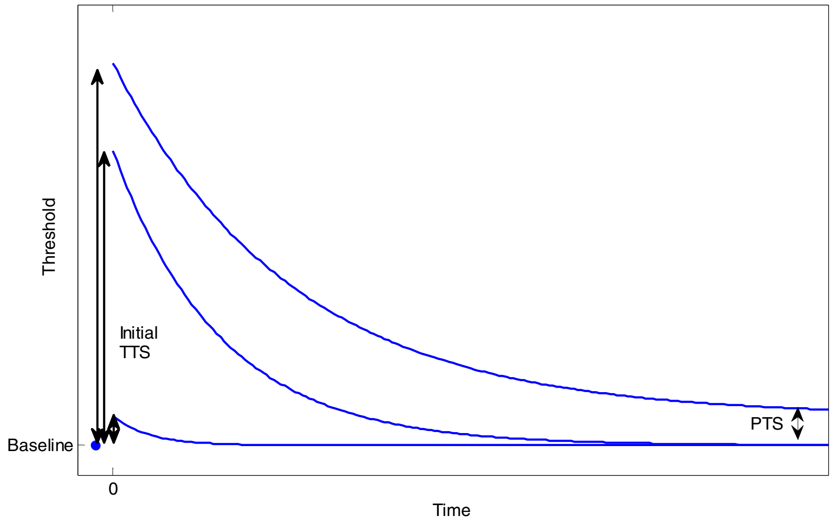
5.1 Hearing loss

For marine mammals it is generally accepted that the auditory system is the most sensitive organ to acoustic injury, meaning that injury to the auditory system will occur at lower levels than injuries to other tissues (Southall et al. 2007). Noise induced threshold shifts are in the same way accepted as precautionary proxies for more widespread injuries to the auditory system. A noise induced threshold shift is a temporary or permanent reduction in hearing sensitivity following exposure to loud noise (For example commonly experienced by humans as reduced hearing after a rock concert). Temporary threshold shifts (TTS) disappear after some time, how long depending on the severity of the impact. Small amounts of TTS will disappear in a matter of minutes, extending to hours or even days for very large TTS. A schematic illustration of the time course of TTS is shown in Figure 5.1. The amount of TTS immediately after end of the noise exposure is referred to as initial TTS. It expresses the amount by which the hearing threshold is elevated and is measured in dB. The larger the initial TTS, the longer the recovery period.

At higher levels of noise exposure, the hearing threshold does not recover fully, but leaves a smaller or larger amount of permanent threshold shift (PTS, see Figure 5.1). This permanent threshold shift is a result of damage to the sensory cells in the inner ear (Kujawa and Liberman 2009). An initial TTS of 40 dB or higher is generally considered to constitute a significantly increased risk of generating a PTS (reviewed in National Marine Fisheries Service 2016). Lower levels of TTS can, if repeatedly induced, also lead to PTS (Kujawa and Liberman 2009), which is also well known in humans.

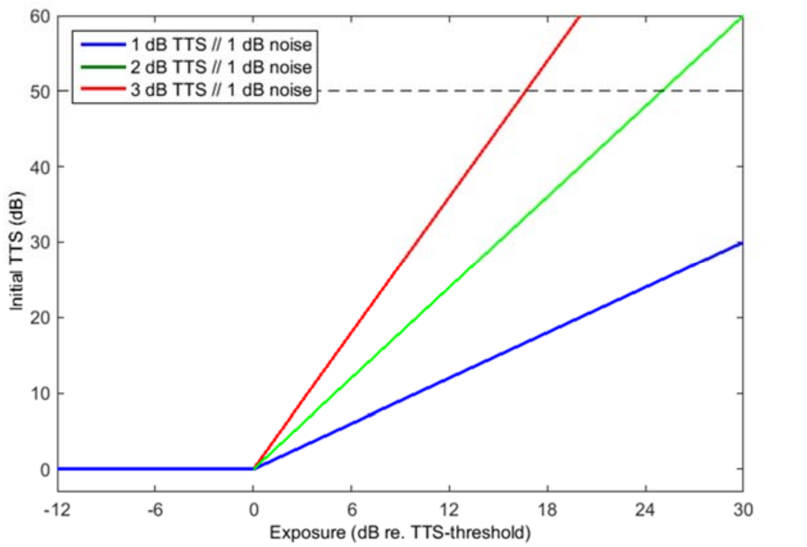
Central for assessment of risk of auditory injury are thus thresholds for inducing TTS and PTS. Deriving such thresholds has been the subject of a large effort from many sides (see reviews by Southall et al. 2007, Finneran 2015). No current consensus on general thresholds for TTS and PTS can be said to exist. Matters are simplified somewhat, however, if one restricts to only one type of sound, such as pile driving noise and limits the discussion to only species for which sufficient data is available. A comparatively large effort has gone into investigating TTS caused by low frequency noise, including from pile driving, in small cetaceans, such as harbour porpoises, bottlenose dolphins and belugas (*Delphinapterus leucas*). TTS is in general localised to frequencies around and immediately above the frequency range of the noise inducing the TTS (often referred to as the fatiguing noise). This means that TTS induced by low frequency noise typically only affects the hearing at low frequencies (Kastelein et al. 2013).

Figure 5.1. Schematic illustration of the time course in recovery of TTS. Zero on the time axis is the end of the fatiguing noise. The threshold returns gradually to baseline level, except for very large amounts of initial TTS where a smaller, permanent shift (PTS) may persist. As the figure is schematic, there are no scales on the axes. Time axis is usually measured in hours to days, whereas the threshold shift is measured in tens of dB. From Skjellerup et al. (2015).



As PTS thresholds for ethical reasons cannot be measured by direct experiments, the agreed approach to estimate thresholds for PTS is by extrapolation from TTS thresholds to the noise exposure predicted to induce 40-50 dB of TTS and thus a significant risk of PTS. This extrapolation is not trivial, however, as it is complicated by the fact that the relationship between exposure and amount of initial TTS is not proportional (see e.g review by Finneran 2015). Thus, one dB of added noise above the threshold for inducing TTS can induce more than one dB of additional TTS, see Figure 5.2. The slope of the TTS growth-curve differs from experiment to experiment and slopes as high as 4 dB of TTS per dB of additional noise has been observed in a harbour porpoise (Lucke et al. 2009).

Figure 5.2. Schematic illustration of the growth of initial TTS with increasing noise exposure. Three different slopes are indicated. Note that the real curves are not necessarily linear. Broken line indicate threshold for inducing PTS, assumed to be at 50 dB initial TTS. From Skjellerup et al. (2015).



Two aspects of TTS and PTS are of central importance in assessments. The first aspect is the frequency spectrum of the noise causing TTS / PTS, which leads to the question of how to account for differences in spectra of different types of noise through frequency weighting, which is discussed below (5.1.1). The second aspect is the cumulative nature of TTS / PTS. It is well known that the duration of exposures and the duty cycle (proportion of time during an exposure where the sound is on during intermittent exposures, such as pile driving) has a large influence on the amount of TTS / PTS induced, but no simple model is available that can predict this relationship accurately (see 5.1.2).

5.1.1 Frequency weighting

Animals do not hear equally well at all frequencies. Substantial uncertainty, however, is connected to the question of how this fact should be incorporated into assessing risk of inflicting TTS and PTS. Southall et al. (2007) proposed that frequencies should be weighted with a fairly broad weighting function (M-weighting) which only excludes energy at very low and very high frequencies, well outside the range of best hearing for the animals. Separate weighting functions were developed for different groups of marine mammals. Others have proposed a more restrictive weighting with a weighting filter function resembling the inversed audiogram (Terhune 2013, Tougaard et al. 2015, National Marine Fisheries Service 2016) or other intermediate weightings, with increased emphasis on higher frequencies over lower, less audible frequencies (Finneran and Schlundt 2013). As long as this issue remains unsettled, it is unclear how frequency weighting should be performed and much caution should be taken when extrapolating results from one frequency range to another (Tougaard et al. 2015).

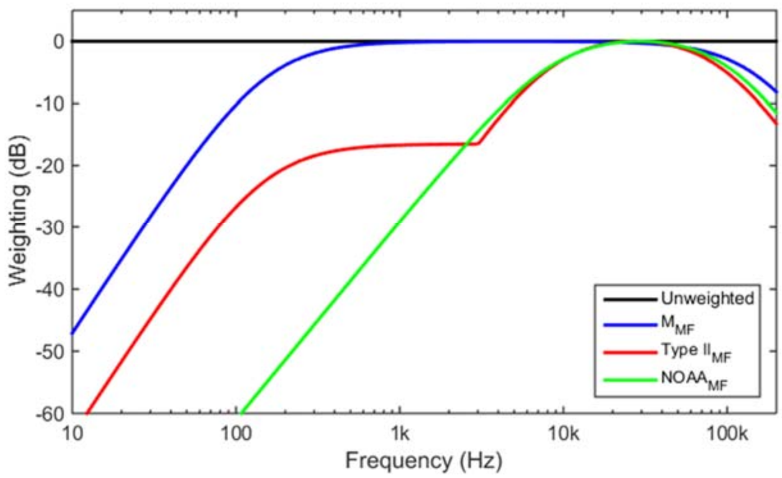


Figure 5.3. Examples of frequency weighting curves proposed for mid-frequency cetaceans. Sources: Southall et al. (2007), Finneran and Jenkins (2012), and National Marine Fisheries Service (2016)

5.1.2 Equal energy hypothesis

A substantial effort has gone into quantifying sound levels required to elicit TTS in marine mammals. The initial experiments were primarily conducted on bottlenose dolphins, belugas and California sea lions (*Zalophus californianus*) (all reviewed by Southall et al. 2007), but recently also a large number of results are available from other species, most notably harbour porpoises (see comprehensive review by Finneran 2015). The initial recommendations of Southall et al. (2007) reflected an uncertainty as to what single acoustic parameter best correlated with amount of TTS induced and resulted in a dual criterion: one expressed as instantaneous peak pressure and another as acoustic energy of the sound (integral of pressure squared over time, see below). In the reviews of Tougaard et al. (2015) and Finneran (2015) this uncertainty is no longer present and it is generally accepted that everything else being equal the amount of TTS correlates better with the acoustic energy than with the peak pressure. The acoustic energy is most often expressed as the sound exposure level (SEL), given as:

$$SEL = 10 \log \int_0^T \frac{p^2(t)}{p_0^2} dt \qquad \text{Equation 5.1}$$

Where p(t) is the instantaneous pressure at time t of a signal of duration T and p_0 is the reference pressure (1 µPa, in water). The unit of SEL is thus dB re. 1µPa²s. It is possible to show that this unit is indeed a unit of energy, being proportional to Jm^{-2} by means of a constant depending on the acoustic impedance of water.

The integration period T should equal the duration of the fatiguing noise up to some limit. This limit is debated. In human audiometry it is customary to use 24 hours, in conjunction with the sensible assumption that people are often exposed to loud noise during their workday and then spend the night resting in a quiet place. This assumption is less relevant for marine mammals, but the 24 h maximum was also applied in a precautionary approach by Southall et al. (2007) and retained by National Marine Fisheries Service (2016), stressing that it is likely to be very conservative (in the sense that it leads to overprotection). However, an experiment with harbour porpoises (Kastelein et al. 2016) indicate that the integration time should be at least several hours.

5.1.3 TTS and PTS thresholds for small odontocetes

Numerous studies on TTS in small cetaceans are available (for a complete list up to 2015 see Finneran 2015). Several authors have derived generalised TTS and PTS thresholds for use in assessments and regulations. Three of these sets of thresholds are of particular relevance to white dolphins and pile driving noise, and are described below. They are summarised in table 5.1

Table 5.1. Thresholds for development of TTS and PTS possibly relevant for Taiwanese white dolphins and pile driving. See text for further explanation.

Reference	TTS	PTS	Comment
German Federal Ministry for the Environment and Nuclear Safety (2013)	160 dB re. 1 µPa²s (unweighted)	Not given	Single strike SEL Developed for porpoises
National Marine Fisheries Service (2016)	170 dB re 1µPa²s (24h, MF-weighted)	185 dB re 1µPa²s (24h, MF-weighted)	Cumulated over 24 hours Impulsive noise
Skjellerup et al. (2015), Skjellerup and Tougaard (2016)	175 dB re 1µPa²s (unweighted)	190 dB re 1µPa²s (unweighted)	Developed for porpoises Cumulated over single pile driving operation

German regulatory threshold

The regulation of noise from pile driving operation in German waters (German Federal Ministry for the Environment and Nuclear Safety 2013) was developed specifically to protect harbour porpoises against TTS. The basis for this was Lucke et al. (2009), who measured TTS in a porpoise induced by exposure to airgun pulses. These pulses, generated by a small 20in³ sleeve gun, has a duration and frequency spectrum not unlike pile driving noise. TTS was induced by single air gun pulses at an unweighted received SEL of 164 dB re. 1 µPa²s. In a precautionary approach, the German threshold was subsequently set to 160 dB re. 1 µPa²s, unweighted, and to be evaluated on single pulses, which is the lowest level set by any regulatory body to date. No threshold for PTS has been estimated in the German guidelines.

There are two important issues related to the German TTS threshold. The first is the fact that it is specified as an unweighted (broadband) level, which means that the regulation does not take into account the hearing abilities of the animals. Recent compilations of results from TTS-studies on porpoises (Tougaard et al. 2015) and odontocetes at large (Finneran 2015, National Marine Fisheries Service 2016) have noted that noise at higher frequencies, where the hearing of odontocetes is better, have a higher capacity to induce TTS than lower frequencies typically dominant in pile driving noise. The recommendation is thus to use an appropriate weighting function with roughly the shape of an inverted audiogram (National Marine Fisheries Service 2016). As the German threshold is based on unweighted levels, there is a risk that this regulation severely underestimates the effectiveness of bubble curtains. Bubble curtains are very effective at attenuating noise above 1-2 kHz and less effective at frequencies below 200 Hz, where the peak energy typically is (Figure 5.4).

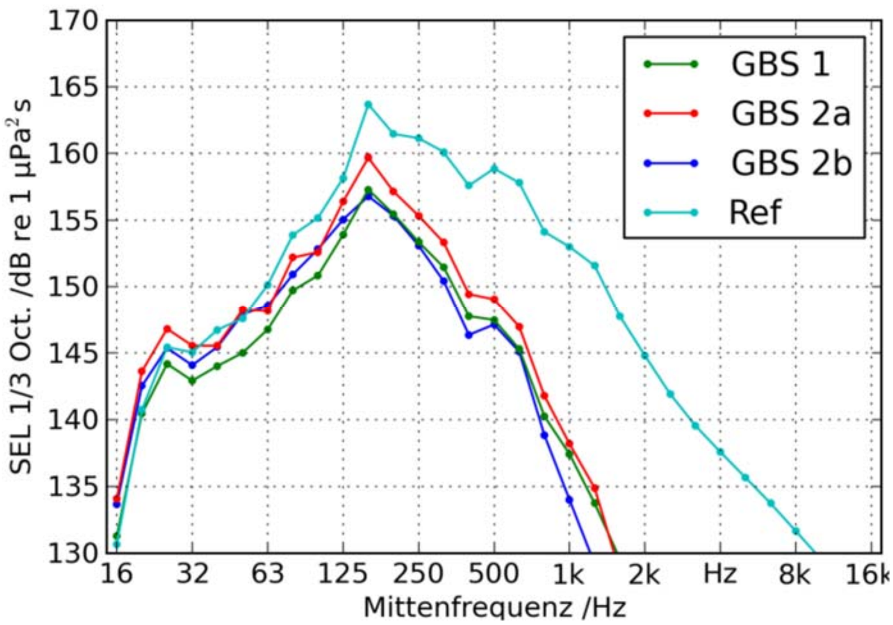


Figure 5.4. Median third-octave band spectra of pile driving noise measured 750 m from pile driving at the GlobalTech 1 offshore wind farm (tripod foundations). Spectra are shown without bubble curtain (Ref) and three different configurations of the bubble curtain. From Nehls and Bellmann (2016).

Figure 5.5 illustrates the difference between evaluation of the effect of bubble curtains on unweighted and weighted levels, respectively. The effect of the bubble curtain is the same in both cases: predominantly attenuating noise above 1 kHz, but in the unweighted spectra the overall level (sum of all third-octave bands) is affected very little, whereas there is a pronounced effect on the weighted spectra (2.3 dB vs. 25.9 dB, respectively; Tougaard and Dähne 2017). Note that the y-axis is logarithmic (due to the dB scale), which means that sum of all third-octave bands is almost entirely dominated by the band with the highest level. The result is that the peak in the weighted spectra shifts from 4-5 kHz without bubble curtain to about 200 Hz with bubble curtain, whereas the peak in the unweighted spectra remains unchanged around 200 Hz.

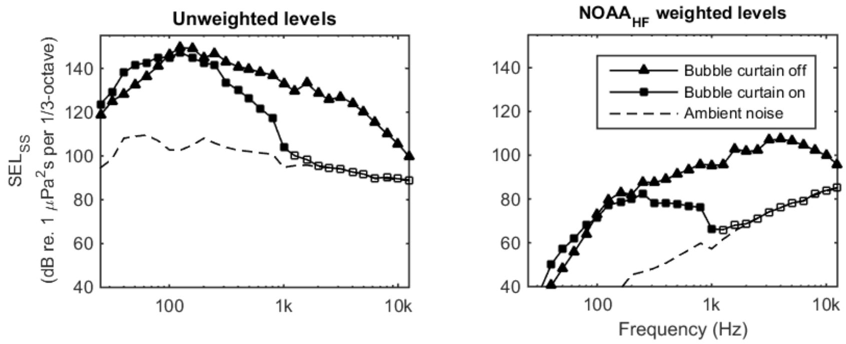


Figure 5.5. Effect of applying the weighting curve recommended by National Marine Fisheries Service (2016) to spectra of pile driving noise (6 m diam. monopile) with and without a double bubble curtain. Open symbols indicate levels dominated by ambient noise rather than pile driving noise. From DanTysk offshore wind farm (Tougaard and Dähne 2017).

The second issue with the German regulation is that it uses a threshold based on an experiment with a single pulse (an airgun pulse, Lucke et al. 2009), whereas the pile driving noise is a very long sequence of pulses. A later study

(Kastelein et al. 2015) measured TTS in a porpoise after exposure to a 1 hour sequence of pile driving pulses and reported a considerably higher threshold at 180 dB re. 1 $\mu Pa^2 s$, unweighted and cumulated over all pulses (SELcum). A range of experiments supports the conclusion that thresholds for single pulses, intermittent pulses / noise, and continuous noise cannot be compared directly and thus that the simple assumption that total noise SEL determines the TTS induced (the equal energy hypothesis described above) cannot explain all variation seen in experimental results. Other studies with longer sounds in the low frequency range (1-4 kHz; Kastelein et al. 2012, Kastelein et al. 2013, Kastelein et al. 2014) have thus resulted in significantly higher thresholds than the threshold of Lucke et al. (2009). There is yet no full understanding of this difference between single, short impulses and longer signals, but it could be related to the recent demonstration of a rapid reduction in hearing sensitivity in dolphins after being conditioned to a loud noise by a warning signal (Nachtigall and Supin 2014). This could explain why the noise exposure experienced by the inner ear to a single transient noise could be significantly higher than to a longer noise or a repeated series of pulses, as the animal, upon perceiving the first part of the noise, consciously or unconsciously reduces the sensitivity of the ear. Functionally, this is to some degree equivalent to the stapedial reflex of terrestrial mammals, which contracts the stapedius muscle in the middle ear when a loud and potentially damaging sound is heard, but it is unknown how this mechanism works in cetaceans.

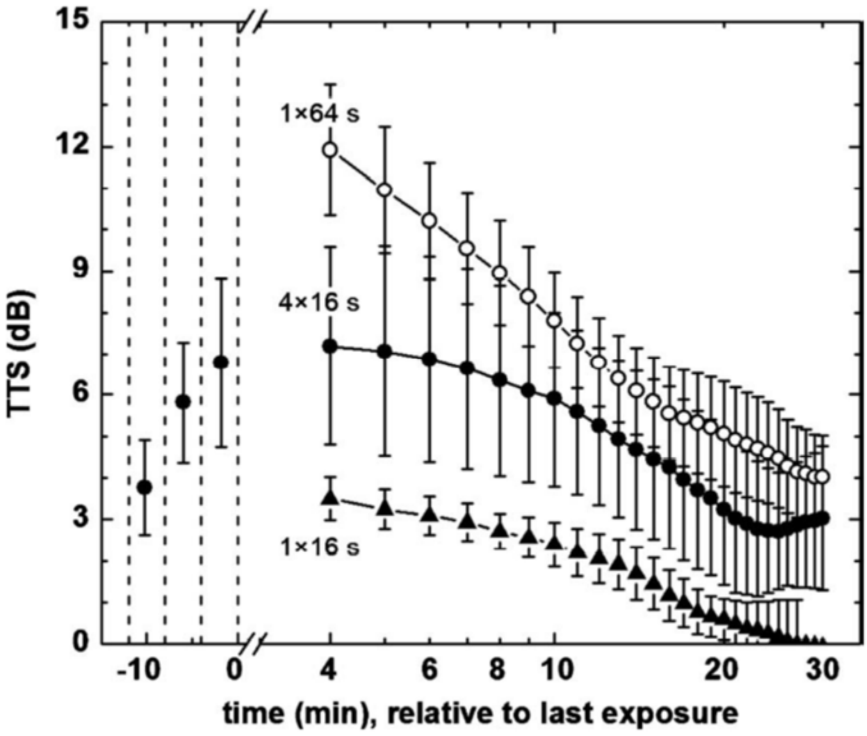


Figure 5.6. TTS in a bottlenose dolphin after exposure to either one 16 s pulse (triangles), four 16 s pulses (closed circles) and one 64 s pulse (open circles). From Finneran et al. (2010).

Another problem rooted in ignoring the repetitive pulses of a real pile driving, is the cumulative impact of many, closely spaced pulses. Finneran et al. (2010) showed in an experiment with single noise pulses, repeated noise pulses and continuous noise that the amount of TTS induced by repeated pulses is higher than the TTS caused by a single pulse, demonstrating that impact is accumulated across pulses (figure 5.6). However, the TTS induced by the multiple pulses was less than the TTS induced by a continuous noise signal with the same total energy as the pulse train, demonstrating that there is some recovery from TTS between pulses.

Together, these factors (lack of frequency weighting and no integration across pulses) pull in opposite directions in the German regulation. The threshold based on just a single pulse (Lucke et al. 2009) is most likely too low, when applied to pile driving and thus lead to an overestimate of the impact. Alongside this is the lack of an auditory frequency weighting likely to result in a large underestimation of the beneficial effects of the bubble curtain. On the other hand, the lack of integration of energy across the repeated pulses lead to an underestimation of impact. It is not yet possible to compare these effects quantitatively and thus determine whether the net result is an over- or underestimation of the effect.

Danish Energy Agency guidelines

The Danish Energy Agency guidelines for pile driving were designed to incorporate the cumulative impact across the repeated pile driving pulses and incorporates a model for taking the fleeing of animals into account (Skjellerup et al. 2015). The thresholds were later updated by Skjellerup and Tougaard (2016) in the light of the results of Kastelein et al. (2015). However, as Skjellerup and Tougaard (2016) found reasons to believe the threshold given by Kastelein et al. (2015) was too high, they reanalysed the data of Kastelein et al. (2015) in a precautionary approach and ended with an unweighted threshold for TTS in harbour porpoises of 175 dB re. 1 μPa^2s, cumulated across all the pile driving strikes used to install one pile. In line with the practice by Southall et al. (2007) the PTS threshold was extrapolated by adding 15 dB to the TTS threshold, i.e. 190 dB re. 1 μPa^2s, unweighted.

In the same way as for the German guidelines, the Danish guidelines do not employ frequency weighting, which means that by using these criteria the beneficial effects of a bubble curtain is likely to be significantly underestimated, i.e. the impact is likely to be significantly overestimated by this approach to assessment, when bubble curtains are used.

NOAA/NMFS guidance

Based on a comprehensive review of the entire literature on TTS and PTS in marine mammals this guidance was developed on the basis of measured TTS onset thresholds (National Marine Fisheries Service 2016). These thresholds were combined with all available information on auditory sensitivity in marine mammals (audiograms) to create appropriate frequency weighting curves and TTS-growth curves. Analysis was separated into several species groups: for cetaceans high-frequency species (including porpoises), mid-frequency species (most odontocetes, including humpback dolphins), and low-frequency species (baleen whales). Weighted onset TTS thresholds were derived for each species group for impulsive sounds (including pile driving) and non-impulse sounds, respectively and from the TTS-growth functions onset PTS thresholds were estimated as the sound exposure level required to elicit 40 dB of TTS, which was considered indicative of a significantly increased risk of developing PTS.

All thresholds are specified as cumulative SEL and in line with the recommendations of Southall et al. (2007) the integration time is 24 hours.

In contrast to the German and Danish guidelines, the NOAA / NMFS guidelines handles both the issues of frequency weighting and summation across multiple pulses. The calculation of cumulative impact over 24 hours, irrespective of the temporal structure of the fatiguing noise will inevitably lead to an overestimation of impact, especially in cases where there are larger time gaps in the noise, where the simple cumulative approach fails to incorporate any recovery from TTS (full or partial) in the gaps between exposure. This clearly applies to pile driving on a jacket platform, where typically four piles are piled one at a time and with a break between piles to allow for positioning of the next pile and the hydraulic hammer.

Concern has also been raised over such issues as pseudoreplication and lack of consideration of variance (Wright 2015), but overall the thresholds are based on more experimental evidence and thorough data analysis than the two other approaches and accordingly should be given high weight in assessments.

5.1.4 Consequences of TTS and PTS for the dolphins

The long-term effects of various degrees of temporary or permanent hearing loss on long-term survival and reproductive success of marine mammals is unknown. It is thus difficult to assess how these impacts may affect the population of dolphins. Intuitively, as PTS is graded, there should be a lower level, below which the hearing loss is so small that it is without long-term consequences for the animal. This is supported by the observation that also dolphins seem to experience natural, age-related hearing loss (presybycusis; Ridgway and Carder 1997, Houser and Finneran 2006, Li et al. 2013). Large hearing losses, however, will inevitably affect the ability of the animal to carry out its normal range of behaviours and hence cause a decrease in fitness. Although this may not directly lead to the death of the individual, it may reduce the life span and reproductive success of the animal.

TTS and PTS primarily affects hearing around and immediately above the frequency range of the fatiguing noise. In a study with playback of pile driving sounds to harbour porpoises, the TTS developed at 4 kHz and 8 kHz, but not at 16 kHz or 128 kHz (Kastelein et al. 2015). For white dolphins, this means that any TTS induced by pile driving is unlikely to affect the echolocation abilities, but TTS could potentially affect detection ranges for communication sounds and acoustic cues from the environment.

In general, however, there is very limited knowledge on the natural variation in hearing abilities in wild dolphins (Houser and Finneran 2006) and how hearing loss may affect the fitness of the animals.

5.2 Disturbance of behaviour

Permanent or temporary damage to marine mammal hearing may not necessarily be the most detrimental effect of noise. Noise levels below the TTS threshold may affect and alter the behaviour of animals, which can carry implications for the long-term survival and reproductive success of individual animals, and thereby ultimately on the population status (National Research Council 2003). See also Figure 5.7. Effects can occur directly from severe reactions as for example panic or fleeing (negative phonotaxis), by which there is an increased risk of direct mortality due to for example bycatch in gill nets (as suggested for porpoises in response to military sonar exercises; Wright et al. 2013) or separation of dependent calves from mothers. More common, however, is probably less severe effects where animals are displaced from habitats, or their foraging or mating behaviour disrupted due to noise.

However, at present the knowledge about how immediate, short-term behavioural changes translate into population level effects is very incomplete for marine mammals, and to a degree where inference to population level is not possible. At present, it is therefore not possible to derive exposure limits based on management objectives for the conservation status of a population and assessment can only be based on the immediate disturbance from the noise.

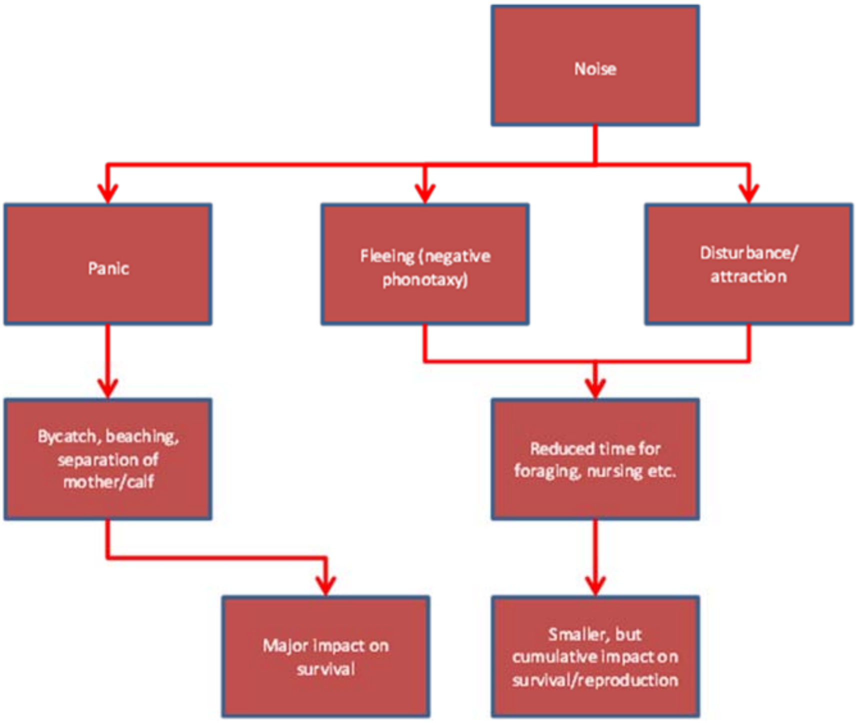


Figure 5.7. Schematic illustration of mechanisms by which noise-induced changes to behaviour can lead to effects on short-term and long-term survival and reproduction (fitness) in marine mammals. From Skjellerup et al. (2015).

5.2.1 Thresholds for behavioural disturbance

There is less consensus on common thresholds when it comes to behavioural reactions. Three different frameworks are listed in Table 5.2 and will be used in the assessment in section 7.

Table 5.2. Thresholds for behavioural reactions possibly relevant for Taiwanese white dolphins and pile driving. See text for further explanation.

Reference	Threshold	Comments
NOAA/NMFS interim guidance[1]	160 dB re. 1 μPa (unweighted)	Integration time presumed to be over one pulse
German Federal Ministry for the Environment and Nuclear Safety (2013)	140 dB re. 1 μPa^2s (unweighted)	Single strike SEL Developed for porpoises
Tougaard et al. (2015)	45 dB above hearing threshold	Developed for porpoises

1) http://www.westcoast.fisheries.noaa.gov/protected_species/marine_mammals/threshold_guidance.html

NOAA/NMFS interim guidance

The review by Southall et al. (2007) compiled a large body of experimental results on behavioural reactions of cetaceans to various types of underwater noise. They failed to establish common thresholds, however. Thus, the only available threshold for regulatory purposes in the US is the interim guidance by NOAA / NMFS, which gives a sound pressure level (L_{eq}) of 160 dB re. 1 μPa as the threshold for behavioural disruption. This level is unweighted and the duration over which the rms-average should be calculated is not given, but for impulsive sounds it makes some intuitive sense to use the duration of the pulse. The actual experimental support for this threshold is limited. See National Marine Fisheries Service (2003), however.

German guidelines

According to the German guidelines (German Federal Ministry for the Environment and Nuclear Safety 2013), a behavioural reaction can be expected in harbour porpoises when the single strike SEL exceeds 140 dB re. 1 µPa²s (unweighted). This threshold is based partly on observations in a captive porpoise (Lucke et al. 2009), which responded to noise levels above 145 dB re. 1 µPa²s; and partly on observations of displacement of harbour porpoises during pile driving in the North Sea, where reactions have been observed at ranges in excess of 20 km. At these ranges, the estimated received level was between 139 and 152 dB re. 1 µPa²s (Dähne et al. 2013).

Danish approach

No guidelines have been adopted by Danish Agencies yet, but recommendations can be found in Tougaard et al. (2015). Threshold for behavioural response (fleeing) in harbour porpoises is estimated by Tougaard et al. (2015) to be 45 dB above the hearing threshold, where the noise level is expressed as L_{eq} (rms-average) computed over a time interval of 125 ms, reflecting the integration time of the porpoise auditory system (Kastelein et al. 2010).

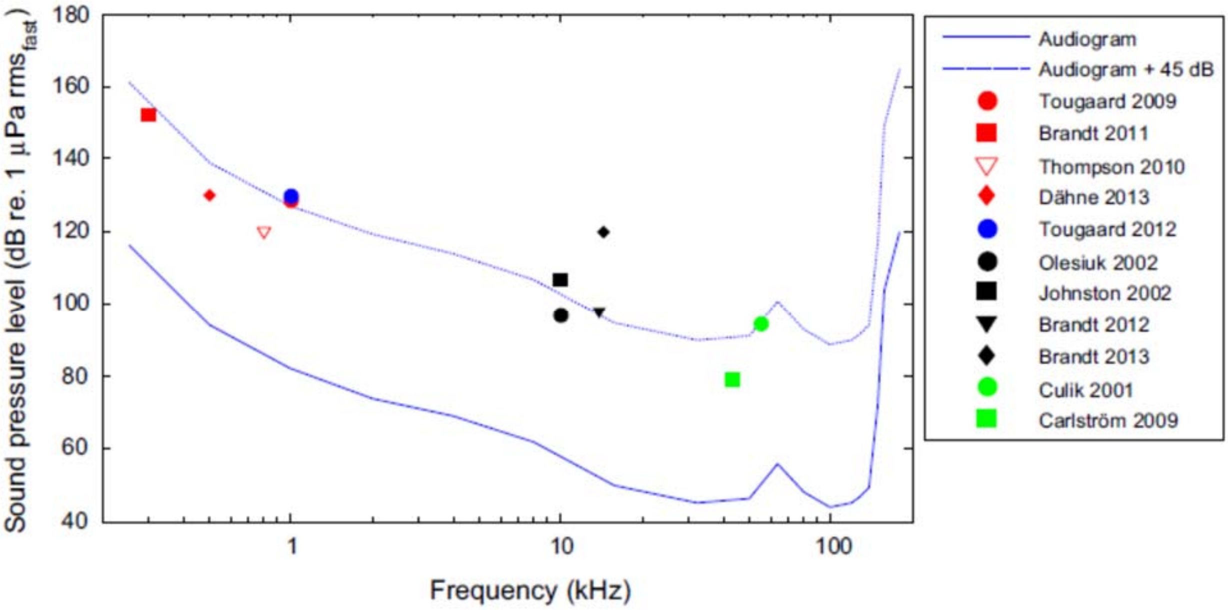


Figure 5.8. Thresholds for behavioural reactions of porpoises to different types of sound. Red symbols: pile driving noise (without bubble curtains), blue: simulated pile driving, black: seal scarers, green: net pingers. Thresholds have been converted into the common metric $L_{eq\text{-}125\ ms}$, i.e. rms average over 125 ms (rms$_{fast}$ in figure legend). Solid line is the harbour porpoise audiogram (Kastelein et al. 2010). Broken line is the audiogram offset by 45 dB on the y-axis. For references to experiments see source: Tougaard et al. (2015).

5.3 Masking

Masking is the phenomenon that noise can negatively affect the ability of an animal to detect and identify other sounds. The masking noise must be audible, roughly coincide with (within tens of milliseconds), and have energy in roughly the same frequency band, as the masked sound.

The current level of understanding of conditions where masking occur outside strictly experimental settings in captive animals is very low. Even less is known about how masking may affect short-term and long-term survival of individuals. See Erbe et al. (2016) for a current review.

6 Experience with wind farms and porpoises in European waters

Figure 6.1. Harbour porpoises in front of the British Offshore wind farm Gunfleet Sands. Photo courtesy of Colm O'Laoi.

Development of offshore wind farms began in Europe in the 1990'ties, developing at a steady pace after the construction of the two first large-scale offshore wind farms in 2002 and 2003 (demonstration projects Horns Rev and Nysted, Denmark. See figure 6.2. An important part of these demonstration projects was conduction of impact studies to describe and quantify effects on the environment (for review see Danish Energy Authority 2006). Other countries have followed this tradition, which have resulted in a wealth of experience gained on the effects and methods to mitigate these (e.g. Wollny-Goerke and Eskildsen 2008).

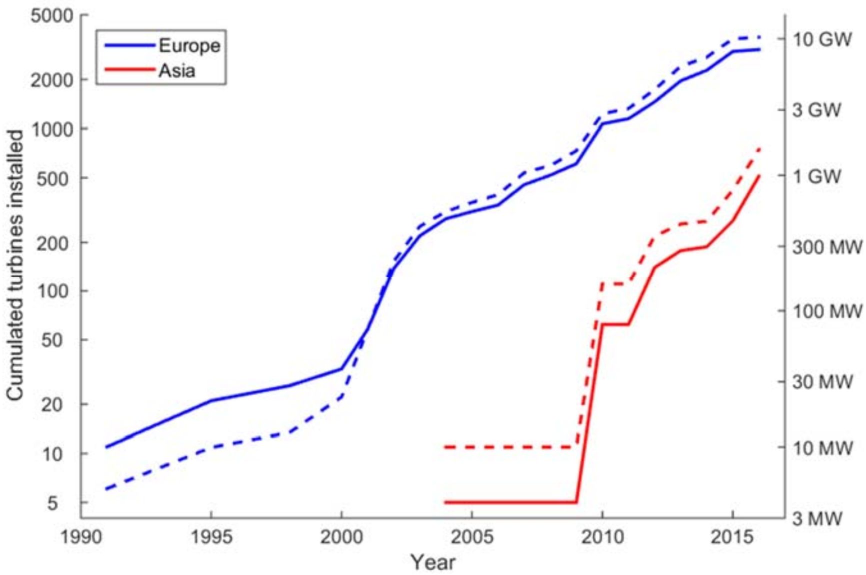


Figure 6.2. Development of offshore wind in Europe and Asia, expressed as cumulative number of turbines and nominal capacity installed (solid and broken lines, respectively).

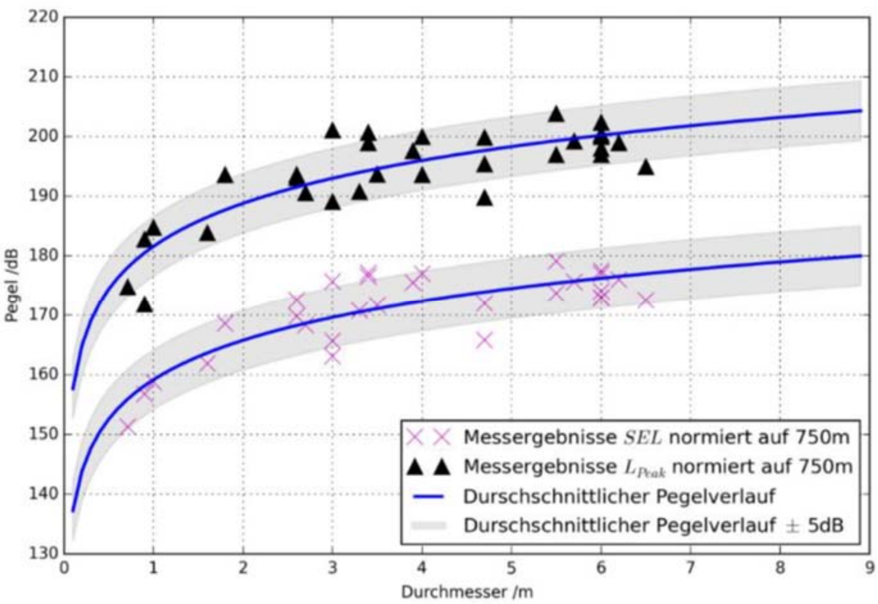
Underwater noise has been a key issue from the beginning. In particular the installation of monopile foundations (and later tripods and jacket types) by means of percussive piling has attracted considerable attention, but also the noise from operating wind farms (both the turbines themselves and the service vessels) was raised early on as a concern.

The key species investigated in European context is the harbour porpoise – by far the most common cetacean in the North Sea and adjacent shelf waters. There are many similarities between harbour porpoises and Taiwanese white dolphins, so many of the conclusions from the European studies are likely applicable to Taiwanese white dolphins as well, but there are also important differences between the two species. See further in section 7.1.

6.1 Pile driving

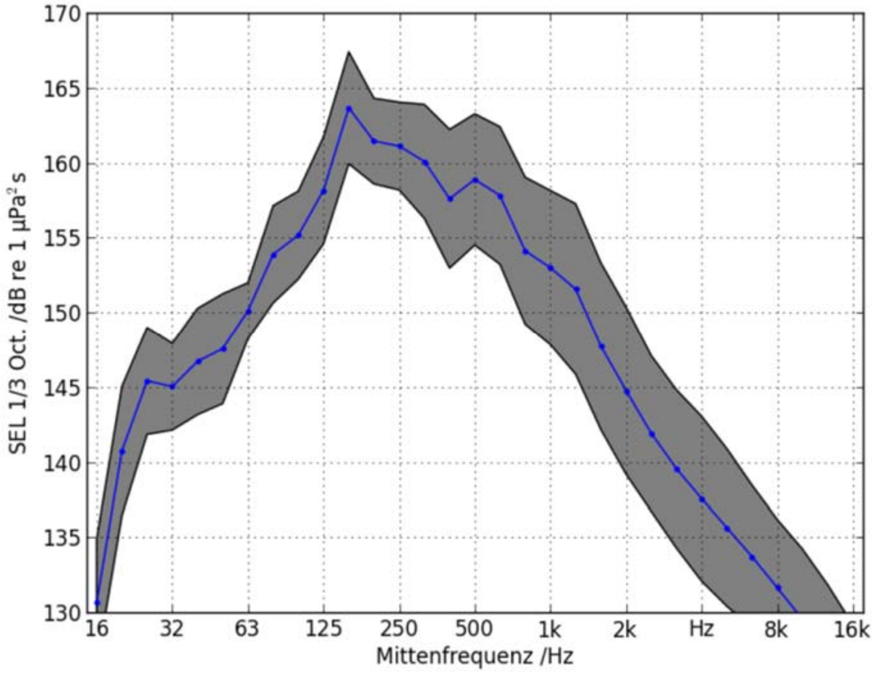
Several types of foundations are used for offshore wind turbines. The most common types are monopiles, tripods and jacket foundations. All of these types of foundations are piled into the seabed by means of hydraulic hammers. Unless mitigated, such pile driving can generate very loud sound pressures, related primarily to the size of the pile (figure 6.4).

Figure 6.3. Measured peak sound pressure (triangles, in dB re. 1 μPa) and single strike SEL, unweighted, measured from a range of different pile diameters (crosses, in dB re. 1 μPa²s). Lines indicate average relationships (± 5 dB in grey). From Nehls and Bellmann (2016)



Piling of one pile, whether a large diameter monopile or one of the three to four smaller piles used for a tripod or jacket foundation, requires typically several thousand strikes by the hammer, to be driven sufficiently deep into the seabed. Impact rate is typically one stroke per 1-2 seconds and the resulting noise is thus a long sequence of pulses. Each pulse is roughly 0.1 s long and with most energy at low frequencies, typically a few hundred Hz, but with energy distributed also at higher frequencies. See figure 6.5 for a typical example of the frequency spectrum of pile driving noise.

Figure 6.4. Median third-octave band spectrum of pile driving noise measured 750 m from piles without bubble curtains in operation. X-axis indicate centre-frequencies of third-octave bands and y-axis single strike sound exposure level (SEL_{SS}). Grey area indicates the variation among individual pulses. From Nehls and Bellmann (2016)



The reaction of porpoises to pile driving has been studied during construction of several wind farms. Initially all pilings were performed unmitigated, i.e. without any attenuating air bubble curtains. Irrespective of the size of the monopiles, the results showed displacement and / or disturbance of the behaviour of porpoises out to distances of at least 20 km from the piling site (Tougaard et al. 2009a, Brandt et al. 2011, Dähne et al. 2013, Haelters et al. 2015). A single example, from the German wind farm Alpha Ventus, is shown in figure 6.5.

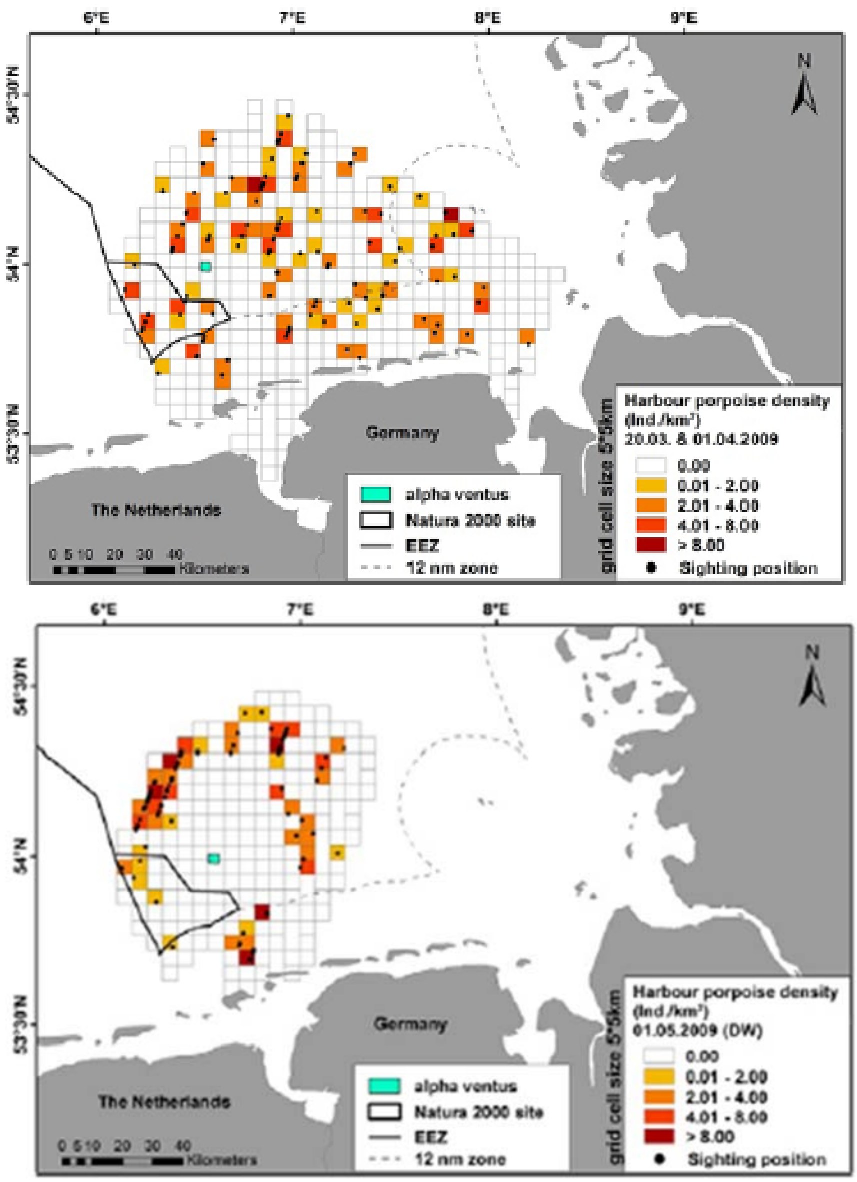
6.1.1 Mitigation

Due to the wide-ranging effects of pile driving on porpoises an extensive development work was initiated with the aim of developing methods to mitigate the effects of pile driving on especially harbour porpoises.

Two different types of mitigation can be used during pile driving operations, to reduce impact on porpoises. The first type is aimed at mitigating injury (hearing damage) to animals and can consist of visual observers controlling a no-go zone for the animals around the foundation, often combined with an active deterrence of animals prior to start of the pile driving. This deterrence can be attained by use of loud warning sounds (seal scarers), together with a gradual ramp-up of hammer energy and strike rate (soft start). Seal scarers emit powerful deterrence sounds, typically between 10 kHz and 20 kHz and are capable of deterring porpoises out to distances of several kilometres (e.g. Brandt et al. 2012, Brandt et al. 2013, Dähne et al. 2017, Mikkelsen et al. 2017).

The second type of mitigation aims both at reducing risk of injury and reducing impact on the behaviour of animals. This is done by attenuating the radiated noise from the pile driving. Such attenuation can be achieved in various ways. See Caltrans (2009) for a comprehensive review.

Figure 6.5. Porpoises observed from aerial survey before (top) and during (bottom) pile driving at the German offshore wind farm Alpha Ventus. Blue square indicate position of pile driving operation. From Dähne et al. (2013).



The most promising way to attenuate pile driving noise is by means of air bubble curtains, used first in connection to harbour and bridge work in Hong Kong harbour (Würsig et al. 2000) and San Francisco Bay (Caltrans 2009), but in recent years developed into large-scale systems capable of operating in connection to large pile driving operations in water depths exceeding 30 m. An example of a deployed double bubble curtain is shown in figure 6.6.

One of the key beneficial features of the bubble curtain, compared to for example seals scares as mitigation tool, is that whereas the seal scarers are effective in protecting porpoises against damage to their hearing, by keeping animals out of the zone of injury, the bubble curtain actually reduces the size of the zone of injury. This has the additional effect of also reducing the size of the zone where the behaviour of animals is affected. A secondary beneficial feature of the bubble curtain is that it is independent of visual observer and thus can be applied to piling during both day and night time hours.

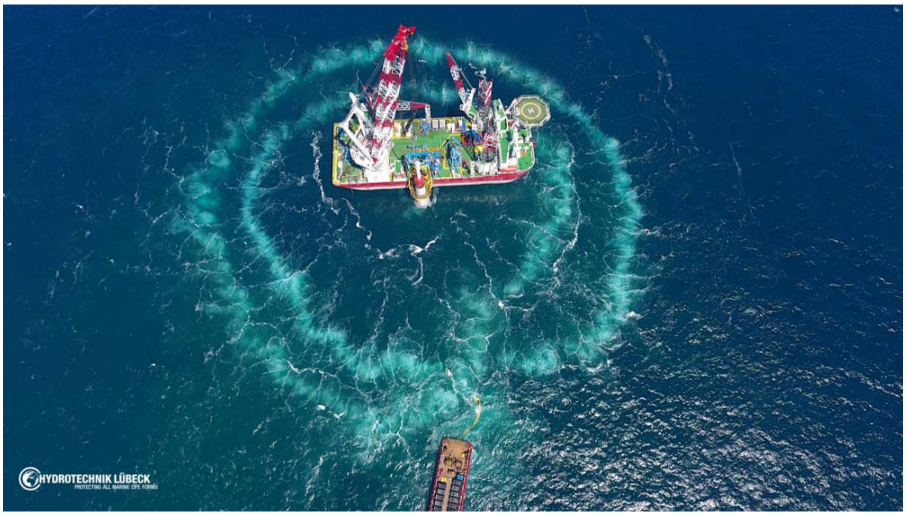


Figure 6.6. Double bubble curtain (so-called Big Bubble Curtain), deployed around a barge with monopile and hydraulic hammer. The ship in the bottom of the photo carries the large array of air compressors needed to feed the array. Source: Hydrotechnik Lübeck

Several studies have thus indicated that reaction distances for porpoises to pile driving noise with bubble curtains are reduced significantly (Nehls and Bellmann 2016, Dähne et al. 2017), as is the time before animals return to the construction area after end of pile driving.

Bubble curtains, such as the one shown on figure 6.6, has made it possible to comply with the rather restrictive German guidelines for underwater noise (see further below) for construction of offshore wind farms in recent years in German waters.

6.2 Operation

A few studies have looked at the effect of offshore wind farms on the abundance of porpoises inside the wind farm, compared to baseline measurements before construction began.

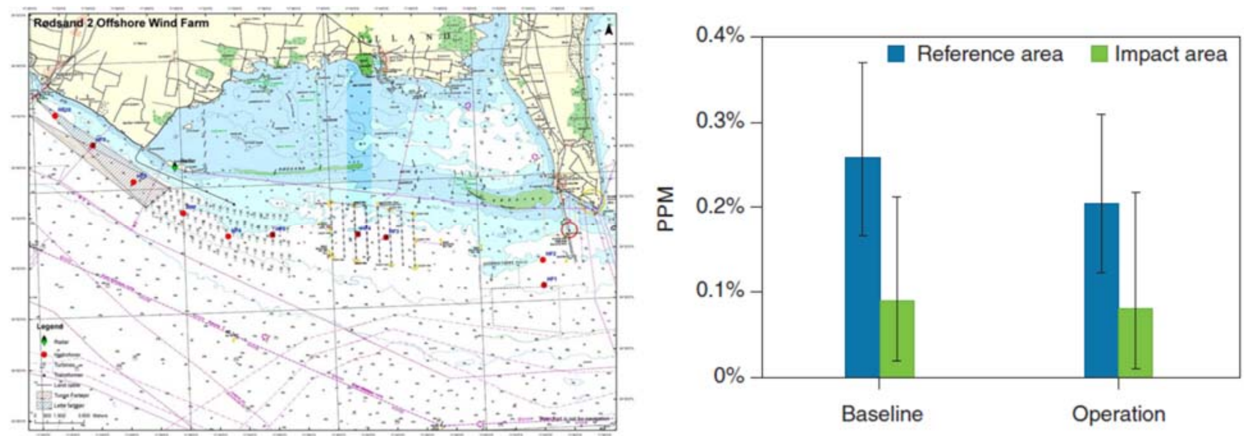
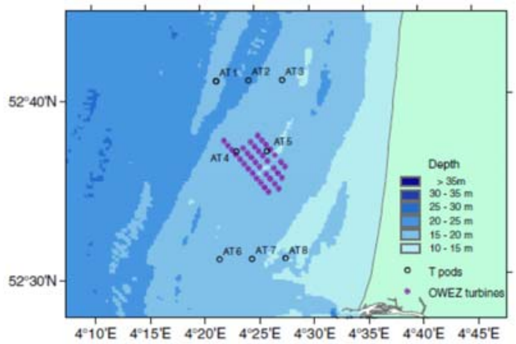


Figure 6.7. Harbour porpoise acoustic detections before and after construction of Nysted II offshore wind farm. Porpoises were monitored acoustically inside the wind farm (five stations indicated with red dots in the western part of the map left and compared to two reference stations located to the east in the map. Two additional stations were located inside an older wind farm (Nysted), in centre of map. Right panel shows porpoise presence, quantified as average percent porpoise positive minutes before and after construction and inside the wind farm and at the reference stations. From Teilmann et al. (2012).

One example is shown in figure 6.7, which is from the Rødsand 2 offshore wind farm located in the Western Baltic Sea. Abundance of harbour porpoises were assessed by passive acoustic monitoring, where dataloggers (C-PODs), recorded the presence of porpoises through detection of their echolocation clicks (Teilmann et al. 2012). Porpoise abundance was quantified as percent porpoise positive minutes, which expresses the fraction of a 24 h day where porpoise echolocation clicks could be detected, assessed minute by minute.

The results from Rødsand 2 (Teilmann et al. 2012) showed that in general there were more porpoises in the reference area than in the wind farm area, but that the ratio between the two areas was unaffected by the presence of the wind farm, i.e. the relative abundance of porpoises inside the wind farm area was unaffected by the presence of the turbines.



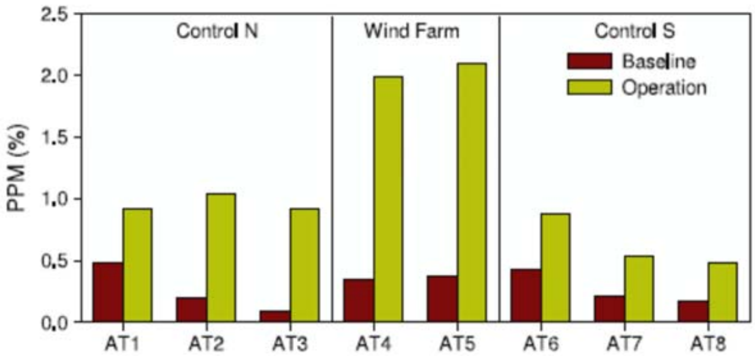


Figure 6.8. Another study of the effect of an offshore wind farm, Egmond aan Zee in the Dutch North Sea. Abundance inside the wind farm area (purple symbols in map, left) was compared to the abundance in two reference areas, north and south of the wind farm, respectively. Porpoise abundance before and after construction and separated out into each recording station, is shown to the right. From Scheidat et al. (2011) .

A later study in the Egmond aan Zee offshore wind farm off the Dutch North Sea coast (figure 6.8) showed a general and substantial increase in porpoise abundance from baseline before construction to operational period. This increase is consistent with other observations, supporting a long-term increase in porpoise abundance in the Dutch North Sea (Camphuysen et al. 2008) and is as such unrelated to the wind farm. However, the relative increase in porpoise abundance inside the wind farm area was larger than in the reference areas, indicating that there were also more porpoises inside the wind farm relative to the outside, after the wind farm was put into operation.

It could not be determined why porpoises apparently were attracted to the wind farm, but at least two possibilities have been suggested (Scheidat et al. 2011). One is that increased food abundance connected to the artificial reefs created around the turbine foundations could have attracted porpoises. The other suggested explanation is that as this part of the North Sea is very heavily trafficked by cargo ships and intense beam trawler fishery, the presence of the wind farm, closed to trawling and shipping, has created a refuge with less disturbance than the outside (Scheidat et al. 2011).

6.2.1 Artificial reefs

As mentioned for the Egmond aan Zee offshore wind farm, it is very likely that the hard substrate of turbine foundations and scour protection (large boulders placed around the foundation) will play a role as artificial reefs, with an associated increase in biodiversity and production. The latter through the increased access to the topmost meters of the water column, where there is plenty of light for primary production. This artificial reef effect and the possible beneficial role it may have for larger animals, such as marine mammals, has not been well studied. One example, however, indicates that at least some individuals of harbour seals are able to exploit the resource of the artificial reefs. Figure 6.9 shows how one seal equipped with a satellite transmitter actively seeked the turbine foundations and the Fino 1 platform, presumably in order to access a profitable food resource on the hard substrate reefs.

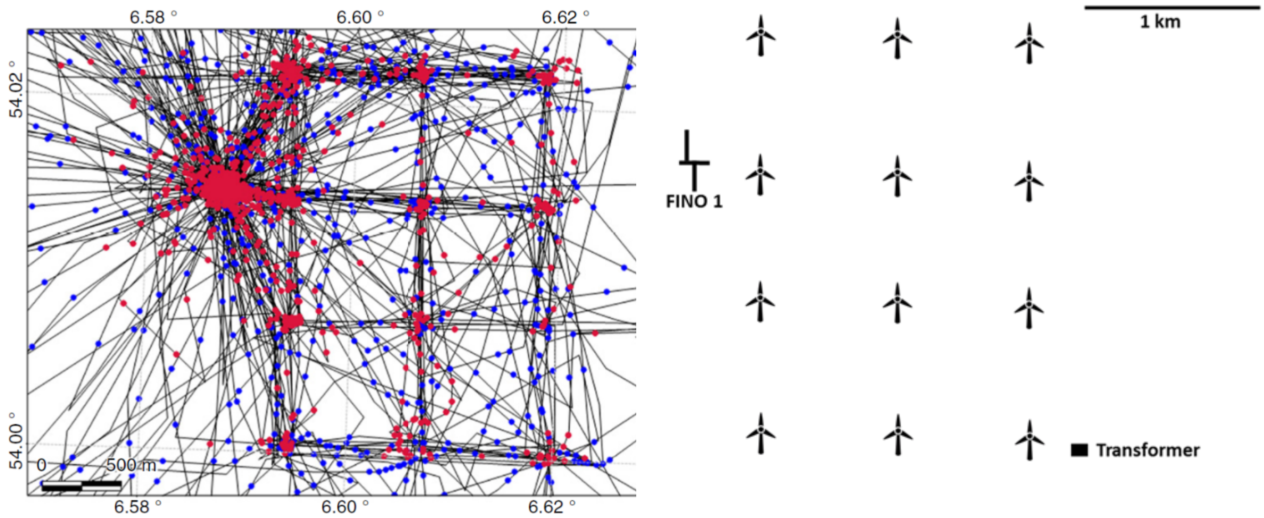


Figure 6.9. Tracks of a single harbour seal, tracked by GPS/satellite transmitter while swimming in and around the German offshore wind farm Alpha Ventus (outline shown on the right). It is evident that the seal actively seeks the turbine foundations, as well as the foundation of the research platform Fino 1 to the west of the wind farm. Partly redrawn from Russell et al. (2014).

6.3 Summary of European experiences

Summing up from the above it is concluded that construction of offshore wind farms, in particular pile driving in connection to installing the foundations, constitute a large and significant impact on harbour porpoises, but also that this impact can be reduced to acceptable levels by application of bubble curtains during pile driving.

Experience with effects of wind farms in operation is more limited, but the data available suggest that there are no negative effects of the operational wind farm and that the wind farm in some cases may be a positive addition to the local environment.

7 Pile driving and Taiwanese white dolphins

There is little doubt that installation of jacket foundations in near-shore waters on the Taiwanese west coast will result in considerable noise emissions and this likely constitutes the single most important issue when discussing potential negative impact on Taiwanese white dolphins during the construction phase. Having realised this early on, the developer CIP has committed to attenuate the radiated noise, and by this restrict the single strike SEL to no more than 160 dB re. 1μPa²s, unweighted, at a distance of 750 m from the pile. This will bring emissions in accordance with current regulation in Germany, aimed at protecting harbour porpoises (German Federal Ministry for the Environment and Nuclear Safety 2013) and will likely be achieved by means of bubble curtains (see 0 above). However, as it is not given that regulation aimed at protecting harbour porpoises in the North and Baltic Seas from damage to their hearing is pertinent to white dolphins in the Strait of Taiwan, and the predicted maximum noise levels are therefore compared below to requirements of other regulatory frameworks. These are the guidance provided by NOAA / NMFS and the Danish Energy Agency. The background of both regulations are given above in section 5, including discussion of inadequacies in the three regulatory frameworks.

7.1 Similarities and differences between the regulatory situation in Europe and Taiwan

As the majority of studies on effects of construction and operation of offshore wind farms has been conducted in European waters and with harbour porpoises as target species, it is relevant to address to what degree harbour porpoises are useful as model animals for white dolphins in the Taiwan Strait. Some of the parameters of importance in assessments and regulation are listed for the two species in table 7.1.

Table 7.1. Comparison between harbour porpoises and white dolphins on a number of parameters relevant for regulation of underwater noise from offshore wind farm construction and operation.

Factor	Harbour porpoise	Taiwanese white dolphin
Shallow-water habitat	Yes	Yes
Deeper waters (>20 m)	Yes	No
Habitat range	Large	Very small
Calving interval	1-2 years	>4 years
Species group	High-frequency cetacean	Mid-frequency cetacean
Susceptible to masking below 20 kHz	Probably limited	Yes
Subject to bycatch	Yes	Yes
Reaction to pile driving noise	Strong	Likely strong
Resilience	High (North Sea)	Critically low
Population status	Least concern (except Baltic Sea)	Critically endangered

When discussing susceptibility of individuals to injury and disturbance from underwater noise there are probably few differences between the two species. In terms of sensitivity to hearing damage and behavioural disturbance, it is generally considered that porpoises are among the most sensitive species of odontocetes and it will thus be a precautionary measure to use them as a model for white dolphins. Only when it comes to possible masking of communication sounds does the white dolphin appear as significantly more sensitive than porpoises, as the dolphins use the frequency band below 20 kHz for communication whistles, whereas porpoises exclusively rely on frequencies above 100 kHz also for communication.

7.2 Hearing loss (TTS/PTS) caused by pile driving

Noise mitigation measures, likely in the form of air bubble curtains, will be used to reduce the pile driving noise radiated from the pile driving. CIP commits to reducing single strike SEL to no more than 160 dB re. 1 µPa²s, unweighted in a distance of 750 m from the pile. This brings the emissions in accordance with current regulation in Germany, aimed at protecting harbour porpoises. Other countries and authors have used other methods to assess hearing loss. Below is an evaluation of exposures calculated by these different methods and judged against their own thresholds, all under the assumption that the single strike SEL does not exceed 160 dB re. 1 µPa²s, unweighted in a distance of 750 m from the pile. The technology of bubble curtains has undergone a rapid development in recent years (e.g. Nehls and Bellmann 2016) and is now a mature technology used routinely in German waters. Among the many examples is the recent installation of foundations in the Veja Mate offshore wind farm (402MW nominal capacity) in German waters.

7.2.1 Danish Energy Authority guidelines

These guidelines (Skjellerup et al. 2015, Skjellerup and Tougaard 2016) are tailored to pile driving noise and harbour porpoises. The most important difference is the incorporation of movement of the animals away from the noise source, coupled with calculation of the cumulative exposure over a single pile driving (i.e. one pile). If a worst-case situation is considered, where a dolphin is located 750 m from the pile at the start of pile driving and it immediately starts to move away at a moderate pace of 1.5 m / s (Williams et al. 2017), then the distance to the pile at the n'th pile strike will be given as:

$$r_n = 750 + (n-1) \cdot v/f \qquad \text{Equation 7.1}$$

Where v is the speed of the animal and f is the strike frequency (set to 1 per second). Maximum received level (SEL_{SS}) is 160 dB re. 1 µPa²s at 750 m and is assumed to decrease with distance according to a simple transmission loss model:

$$RL(r) = RL_{750} - 17\log_{10}(r/750) \qquad \text{Equation 7.2}$$

If it is assumed that 3000 pile strikes are needed per pile, then the cumulated exposure can be computed as:

$$SEL_{cum} = 10\log_{10}\left(\sum_{n=1}^{3000} 10^{RL(r)/10}\right) \qquad \text{Equation 7.3}$$

The development of the three parameters through a 50 minute long pile driving is illustrated in figure 7.1. It is evident that the first strikes contribute disproportionally much to the cumulated SEL, which increases rapidly over the first strikes and then levels off. The final SELcum under the above assumptions is 187 dB re. 1 µPa²s (unweighted). This should be compared to the TTS and PTS thresholds of (Skjellerup and Tougaard 2016), 175 and 190 dB re 1 µPa²s, respectively (table 5.1 above). Thus, in this worst-case scenario, where a dolphin is 750 m away at the first pile strike, it will be likely to acquire TTS, but not PTS from the exposure it receives during the piling.

Two important factors are not considered in this simplified approach, however. First, the actual exposure is likely to be less than 187 dB re. 1 µPa²s, as the assumption that single strike SEL is constant and equal to the maximally permitted level throughout the piling is unlikely to be true. A real piling is typically initiated with a gradual ramp up of hammer energy and strike frequency, as the pile is positioned correctly and sometimes sinks into the seabed by its own weight alone. The applied hammer energy is furthermore linked to the friction encountered in the seabed and thus very likely to increase gradually through the pile driving as the pile penetrates deeper and deeper.

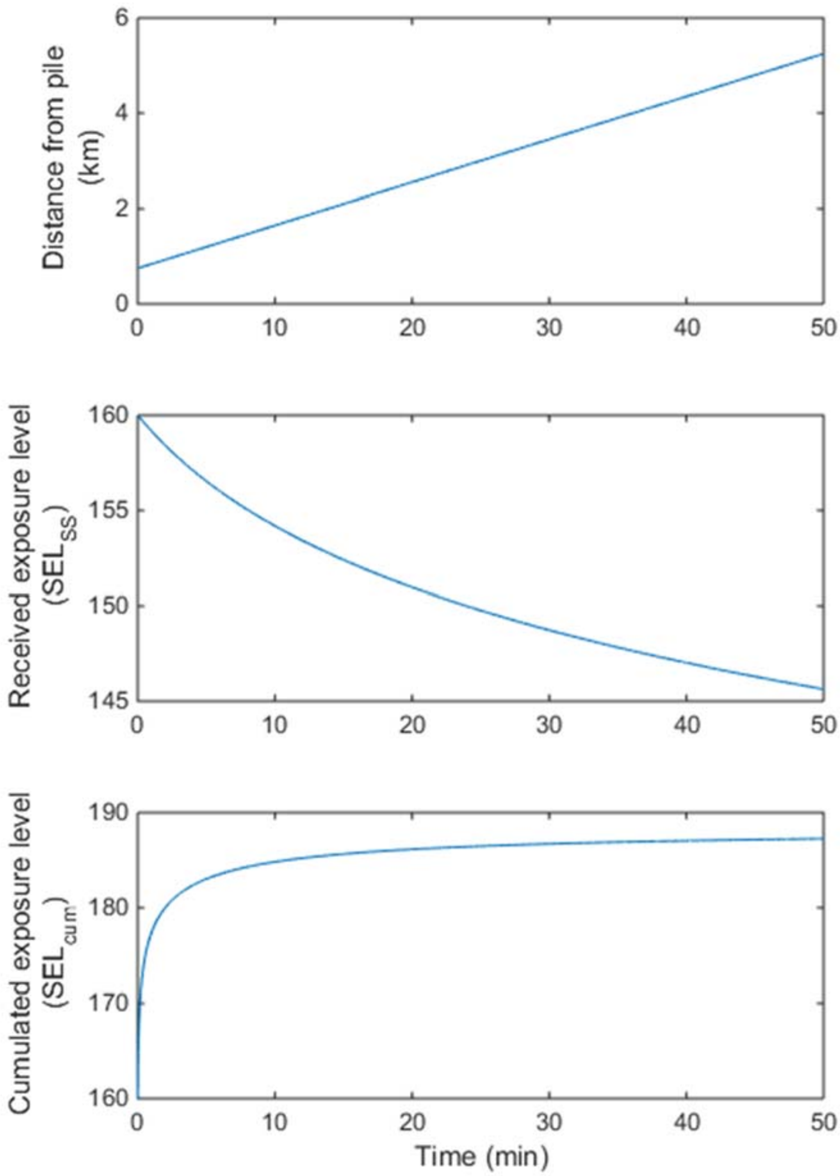


Figure 7.1. Development of the received level and the cumulated sound exposure level, as a dolphin swims away from a pile driving. See text for further explanation.

Second, the thresholds derived by Skjellerup and Tougaard (2016) were unweighted, even though the authors acknowledged the need for an appropriate weighting in order to generalize the results (see also section 5.1.3 above). The thresholds were derived on the basis of experimental studies with playback of pile driving noise (recorded without a bubble curtain) to a porpoise (Kastelein et al. 2015). This means that the frequency spectrum of the noise used to derive the threshold was essentially identical to the spectrum of a real pile driving noise (without bubble curtain). This means that it is not of particular importance which weighting function one selects, as the same weighting is performed on both the experimental results on which the threshold is based, and the estimated exposure one is comparing against the threshold. Adding a bubble curtain changes this, however, as the bubble curtain affects the higher frequencies disproportionally more than the lower frequencies, which again means that the part of the frequency spectrum where dolphins have their best hearing is more affected by the bubble curtain than the lower frequencies. This means that the higher frequencies, more likely to be responsible for inducing TTS and PTS (due to their higher audibility), will be strongly attenuated with a bubble curtain. The thresholds of Skjellerup and Tougaard (2016) are thus likely to overestimate the actual impact, when a bubble curtain is in place.

7.2.2 NOAA/NMFS guidance

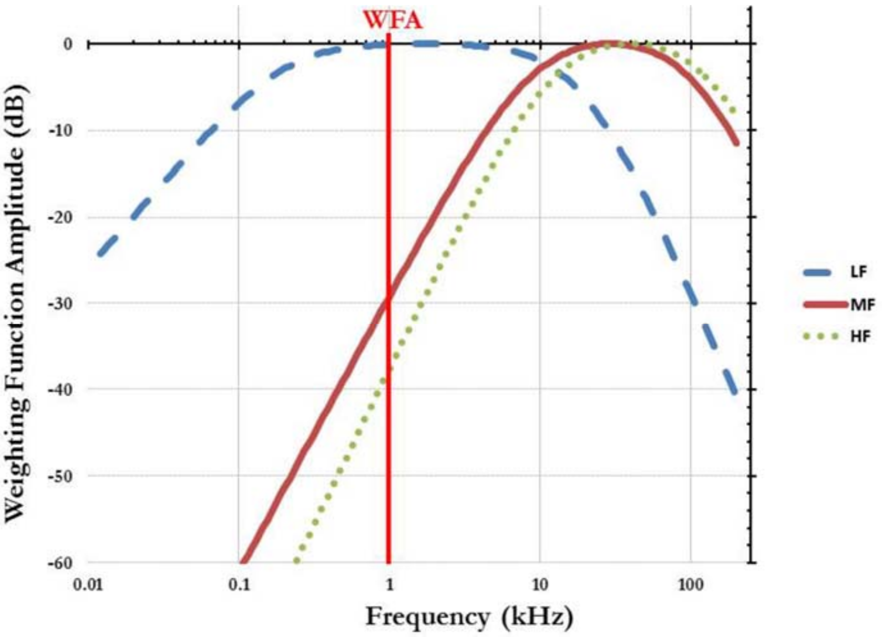
These guidelines require that cumulative sound exposure level (SELcum) is computed over 24 hours. If we assume that 3000 pile strikes are needed for installation of one pile and all four piles on one jacket can be installed within 24 hours, then the cumulated SEL can be found from the single strike SEL and the number of strikes, n (assuming all are identical):

$$SEL_{cum} = SEL_{SS} + 10\log_{10} n$$

Thus, if the maximum SEL_{SS} is assumed to be 160 dB re 1 µPa^{2}s in 750 meters distance, then unweighted SELcum equals 160 + 10log$_{10}$(12000) = 201 dB re. 1 µPa^{2}s.

The NOAA / NMFS guidance specifies a frequency weighting to be applied to the signals before comparing them to the thresholds. This frequency weighting is frequency specific (figure 7.2) and thus difficult to apply without knowing the exact frequency spectrum of the pile driving noise. This is important, as the air bubble curtain is likely to modify the frequency spectrum of the pulses considerably, by a disproportionally larger attenuation of the higher frequencies (see figure 5.4). In the presence of a bubble curtain there is very little energy in the pile driving noise above 1 kHz and it thus seems a reasonable precautionary approach to use the weighing coefficient at 1 kHz, as most of the energy would be well below and thus in reality should be weighted with an even smaller coefficient. The weighing coefficient for mid-frequency cetaceans at 1 kHz is 29 dB, i.e. the maximum weighted SELcum-24h is equal to 172 dB re. 1 µPa^{2}s in the flat part of the weighting curve (figure 7.2) This is the SELcum that a dolphin would be exposed to if it lingered around the pile driving site for 24 hours in a distance of 750 m from the pile. Comparing this to the TTS and PTS thresholds of the guidelines (table 5.1), of 170 and 185 dB re. 1 µPa^{2}s in the flat part of the weighting function it is concluded that according to these guidelines, the dolphins would not be at risk of acquiring hearing damage. This is concluded even though the SELcum is above the threshold, but this is under the admittedly unrealistic assumption that the dolphin should choose to remain within 750 m from the foundations for 24 hours, during active pile driving. If the dolphin moves away, for whatever reason, the result will be that the resulting SELcum drops below the threshold.

Figure 7.2. Auditory frequency weighting functions for low-frequency (LF), mid-frequency (MF), and high-frequency (HF) cetaceans. Red line indicate the weighting coefficients at 1 kHz. From National Marine Fisheries Service (2016).



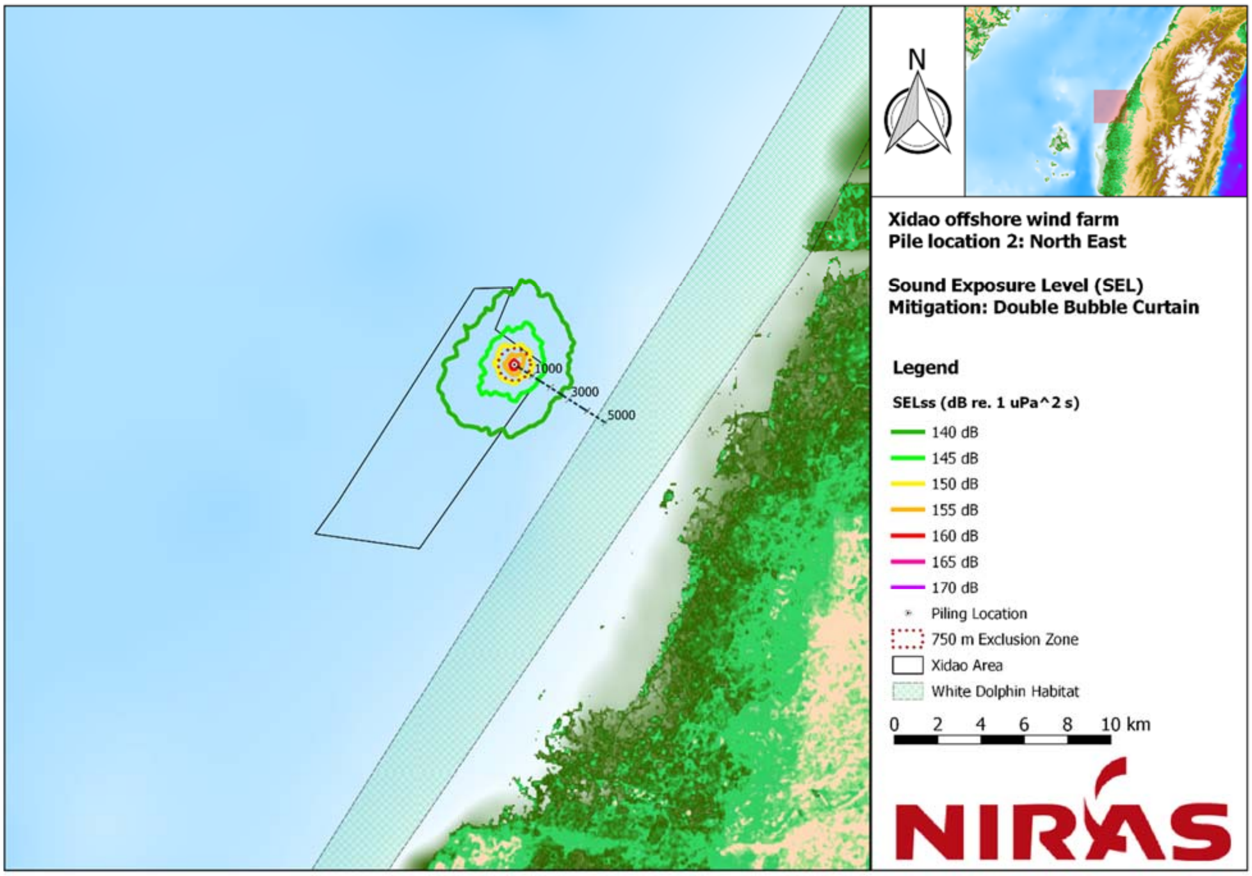
7.3 Behavioural reactions

Temporary and permanent hearing loss is only one form of impact, another important factor is behavioural effects (such as deterrence, resulting in temporary habitat loss). Different sources also supply different guidance with respect to how this is assessed. As described in section 5.2.1 above. The relevant parameter from these assessments is the expected maximum reaction distance, or impact range. Beyond these ranges the animals may still be able to hear the pile driving noise, but they are not expected to react to them.

German regulation

According to the German guidelines (German Federal Ministry for the Environment and Nuclear Safety 2013) a behavioural reaction can be expected in porpoises when the single strike SEL exceeds 140 dB re. 1 µPa^{2}s (unweighted). A realistic scenario of the extent of the 140 dB re. 1 µPa^{2}s iso-energy contour is shown in figure 8.3. Underwater sound propagation modelling was carried out for a number of worst case pile installations in the three areas of Changfang, Fufang and Xidao (only the two closest to the coast, in Xidao are shown in figure 7.3). A 3D environmental acoustic model was built in the software dBSea 2.1.2 (Pedersen and Keane 2016), based on best available environmental data. Bathymetry was extracted from Ryan et al. (2009), while sediment profiles were implemented as multi-point multi-layer profiles based on Chen et al. (1988), EGS (Taiwan) Limited (2013) and Wood Thilsted Partners (2017). Temperature, salinity and sound speed profiles were made available by CIP (EGS (Taiwan) Limited 2013).

Each sound propagation modelling was based on a source level of 210 dB SELss @ 1m re. 1 µPa^{2}s, and reported source frequency spectrum, inspired by Ainslie et al. (2012). Sound propagation modelling was carried out using a combination of Parabolic Equation and Ray theory algorithms. CIP has committed to assure that underwater noise levels are continuously kept below 160dB re.1µPa^{2}s at 750 m distance for the pile installation based on experiences from the Veja Mate project in German Water. CIP foresees that the use a double bubble curtain noise mitigation system, with an estimated broadband noise attenuation effect of ΔSEL=15 dB re.1µPa^{2}s, will be the implemented mitigation method.



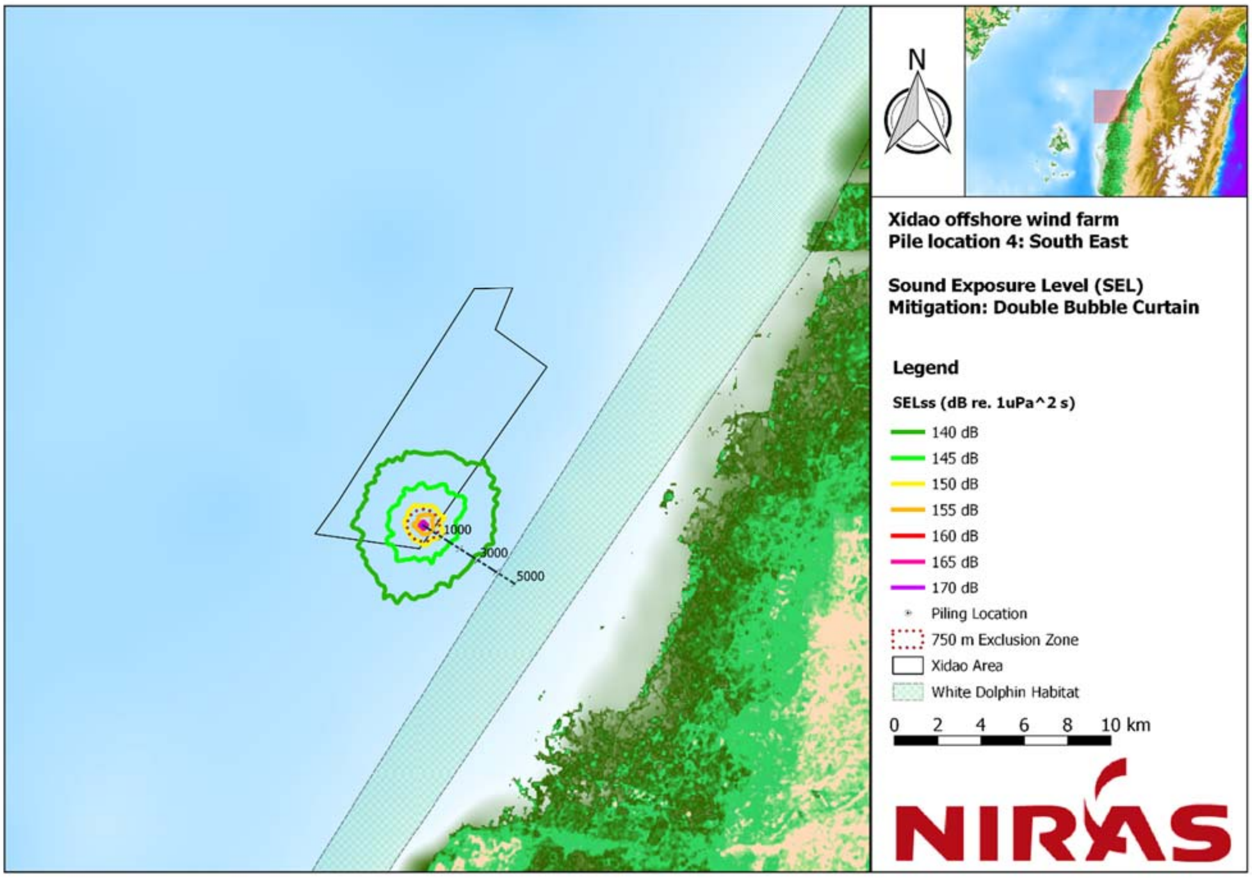


Figure 7.3. Iso-energy contours (SEL_{SS}) around two simulated pile driving in the Xidao area. The 140 dB re. 1 μPa^2s contour, equal to the behavioural response threshold of the German regulation. Blue-green band along the coast indicate the white dolphin core habitat.

A summary of sound propagation results for the three consent zones (Chanfang, Fufang and Xidao) with regard to the expected noise threshold of SELss≤140 dB re.1μPa²s inside the white dolphin habitat, is given in Table 7.2.

Table 7.2. Sound propagation results for Changfang, Fufang and Xidao areas, with respect to compliance with 140 dB SEL threshold. The table shows the modelled minimum distance from the piling site towards the white dolphin habitat, at which a received level of 140 dB SEL can occur for any full hammer energy hammer strike (with bubble curtains). In no cases does the 140 dB SEL contour extend into the white dolphin core habitat.

Location	Distance to 140 dB SEL in direction of the white dolphin habitat (km)	Minimum distance from 140 dB SEL contour to the white dolphin core habitat (km)
Changfang NW	4.2	10.4
Changfang NE	2.6	5.9
Changfang SW	4.4	10.3
Changfang SE	3.5	5.1
Fufang NW	4.5	10.0
Fufang NE	3.5	5.2
Fufang SE	3.2	6.5
Xidao NW	2.6	5.0
Xidao NE	2.7	1.9
Xidao SW	3.3	4.5
Xidao SE	3.4	0.7

It is concluded that all pile installations will be in compliance with the 140 dB SEL threshold with the use of a $\Delta SEL = 15\ dB$ noise mitigation system. The technical reports for each area are available in Appendix A.

NOAA/NMFS guidance

NOAA/NMFS is not very specific when it comes to guidance on thresholds for behavioural reactions. As described above in section 5.2.1, they offer only an unspecific interim guidance level of 160 dB re 1 μPa (L_{eq}) as threshold for behavioural disruption for impulsive noise. The duration over which the L_{eq} shall be computed is not given, but for pile driving noise it makes sense to use the duration of the pulse, i.e. a few hundred milliseconds. The relationship between L_{eq} and SEL_{SS} is given by:

$$SEL_{SS} = L_{eq} + 10\log_{10} d \iff L_{eq} = SEL_{SS} - 10\log_{10} d \qquad \text{Equation 7.4}$$

Where d is the duration.

The maximum range where reactions are expected can be found by application of a transmission loss model as above, and sticking to the maximum SEL_{SS} of 160 dB re. 1 μPa²s 750 m from the pile. The received level at distance r is thus given as:

$$RL(r) = SEL_{SS}(750m) - 10\log_{10} d - 17\log_{10}(\frac{r}{750}) \qquad \text{Equation 7.5}$$

If pulse duration is set to 100 ms, the equation can be solved for r, such that RL(r) equals the response threshold (160 dB re. 1 μPa):

$$SEL_{SS} - 10\log_{10} d - 17\log_{10} r = 160 \iff$$

$$r = 750 \cdot 10^{(SEL_{SS} - 10\log_{10} d - 160)/17} \qquad \text{Equation 7.6}$$

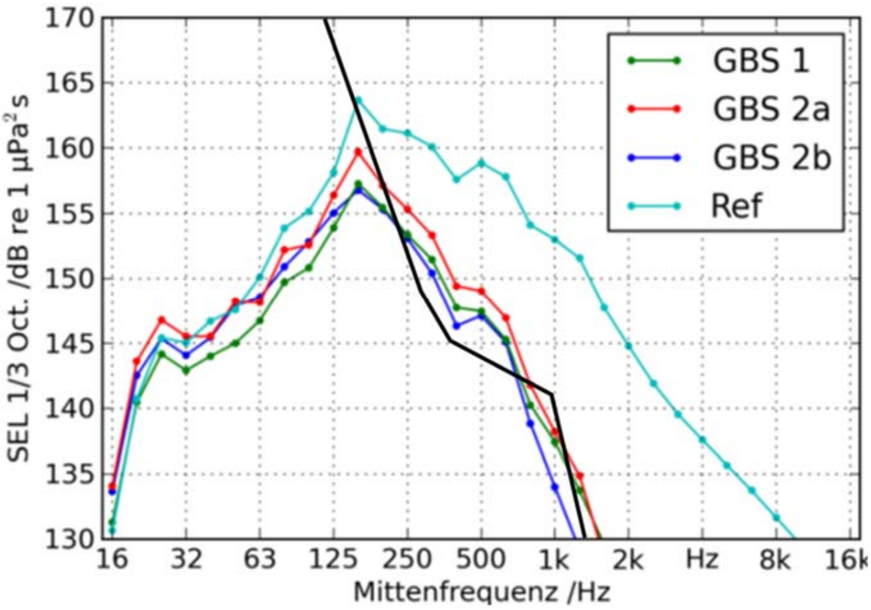
If d is set to 100 ms, this means that received L_{eq} of a single pulse will be 160 dB re. 1 µPa in a distance of 2.8 km from the pile. This distance should be compared to the minimum distance from foundation to the white dolphin habitat, found in table 8.2 as 4.1 km (Xidao SE). In other words, the NOAA / NMFS guidance level is not exceeded inside the white dolphin habitat.

Danish guidance

No guidelines have been adopted by Danish Agencies yet, but recommendations can be found in Tougaard et al. (2015), as also described in section 5.2.1 above. Threshold for behavioural response (fleeing) in porpoises is estimated to be 45 dB above the hearing threshold. It is unclear how such a criterion can be applied in a quantitative way to broadband pulses, but one approach is shown in figure 7.8. Here the third-octave spectrum of piling noise 750 m from the pile is plotted together with the audiogram of a bottlenose dolphin, offset 45 dB on the y-axis. The offset hearing threshold, now a proxy for the behavioural response threshold, follows the pile driving noise spectrum (with bubble curtains) above 150 Hz very closely (by coincidence). This can be interpreted such that the pile driving noise is just around the threshold for behavioural reaction (displacement) and is in stark contrast to the case for the pile driving noise without bubble curtains. The third-octave levels at higher frequencies are 10-20 dB above the offset audiogram and dolphins are thus predicted to react to the unmitigated pile driving.

Given that the assumptions are valid, this analysis predicts only weak responses to the noise at 750 meters distance. There is one unknown in this line of arguments, however, and this is the pile driving noise above 2 kHz. This noise is not visible on the figure from Nehls and Bellmann (2016) and it thus remains a possibility that there are high-frequency components above 2 kHz in the noise, which extend further above the offset audiogram. However, the very strong attenuation of frequencies above 1-2 kHz is in line with other measurements (e.g. Dähne et al. 2017).

Figure 7.4. Third-octave noise spectra from a pile driving (Nehls and Bellmann 2016); same as figure 5.4), overlaid with the audiogram of a bottlenose dolphin (Johnson 1968), offset 45 dB on the y-axis (black line).



7.4 Masking

Very little can be said about possible masking by the pile driving noise, due to lack of experimental results to support such statements. Judging from the spectrum of the mitigated pile driving noise (such as figure 7.5), it is noted that very low levels of energy is present at frequencies above 1-2 kHz. This means that the frequency band 3-15 kHz used by the white dolphins for whistle communication (Wang et al. 2016c, Hoffman et al. 2017) is not disturbed by the pile driving noise and therefore the potential for masking of communication is low, even close to the pile driving operation. Masking of echolocation sounds is even more unlikely, as they have peak energy above 100 kHz and hardly any energy at all below 20 kHz (Fang et al. 2015).

8 Noise from operational wind farms

Offshore wind turbines generate noise as the wings, gears and generator rotates. The moving gears in the gearbox is the primary source of the noise transmitted as vibrations down the turbine tower and radiated into the surrounding waters. Thus, the power density spectra of the underwater noise very commonly shows that most of the energy is located at single frequencies, corresponding to the engagement frequency (and possibly harmonics) of the moving teeth on the gears (figure 8.1).

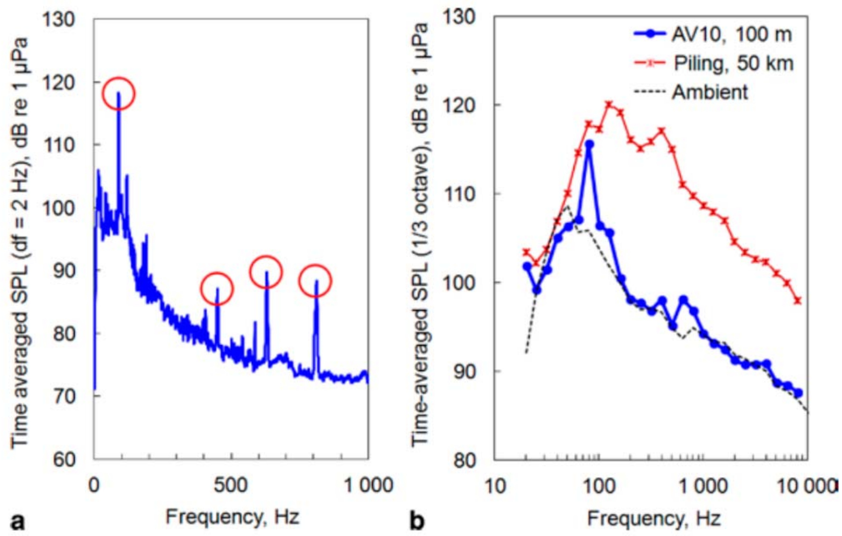


Figure 8.1. Operational noise measured 100 m from a 5 MW turbine at Alpha Ventus offshore wind farm. The turbine was operating at maximal power output. A) shows power density spectrum of the noise. Note the powerful component at 90 Hz and the harmonic overtones at 450 Hz, 630 Hz and 810 Hz. B) Third-octave spectrum of the same noise (blue), together with ambient noise (broken line), recorded at the same location and same wind speed, but before installation of the turbines, and noise from a distant pile driving (red). From Betke (2014)

Numerous recordings of underwater noise from operating turbines exists. A recent is shown in figure 8.1 and some of the earlier measurements are shown in figure 8.2. These recordings span a large range of turbine sizes, from 500 kW nominal power (Vindeby, figure 8.2), to 5 MW (Alpha Ventus, figure 8.1), but do not reveal any strong relationship between size and noise level. There is thus nothing in the available data that suggests that larger turbines are more (or less) noisy than smaller turbines, when it comes to underwater noise.

The type of foundation could quite possibly affect the noise levels too, but the data in figure 8.1 and 8.2 are both from turbines with concrete foundations and monopile foundations. The only turbine that really stands out is the small turbine at Utgrunden, Sweden (square symbols in figure 8.2). The noise measured from this turbine was significantly louder than other turbines, especially at the higher frequencies. One possible explanation for this could be its placement on subsea bedrock, whereas all the other turbines are placed on soft bottom (Madsen et al. 2006).

Two factors are important when assessing the possible impact of turbine underwater noise on dolphins. The first factor is the absolute level of the noise, compared to the hearing ability of the dolphins (the audiogram). The second factor is the level of the noise in relation to the ambient (background) noise. Only if the turbine noise is above both the hearing threshold and the ambient noise, is the noise audible to the dolphin. Figure 8.3 shows the peaks in the noise spectrum from Alpha Ventus (figure 8.1a) plotted together with audiograms from a white dolphin (Li et al. 2012) and bottlenose dolphin (Johnson 1968). The white dolphin audiogram was obtained from an animal in a pool in a marine park, which means that the thresholds could likely be masked by low frequency noise from the surroundings and sensitivity thus underestimated. The bottlenose dolphin audiogram is therefore included as a possible lower estimate of the sensitivity, as this audiogram was obtained under very quiet conditions in a research tank. In addition, the bottlenose dolphin audiogram was also measured to lower frequencies than the white dolphin audiogram. Included in figure 8.3 is also an example of background noise measured at position A5 in the Xidao area (Ocean Sound Taiwan 2017). The figure shows that the noise from Alpha Ventus in a distance of 100 m is at least 10 dB below the bottlenose dolphin audiogram and hence completely inaudible. It is also seen that only the fundamental tone at 90 Hz is significantly above the ambient noise.

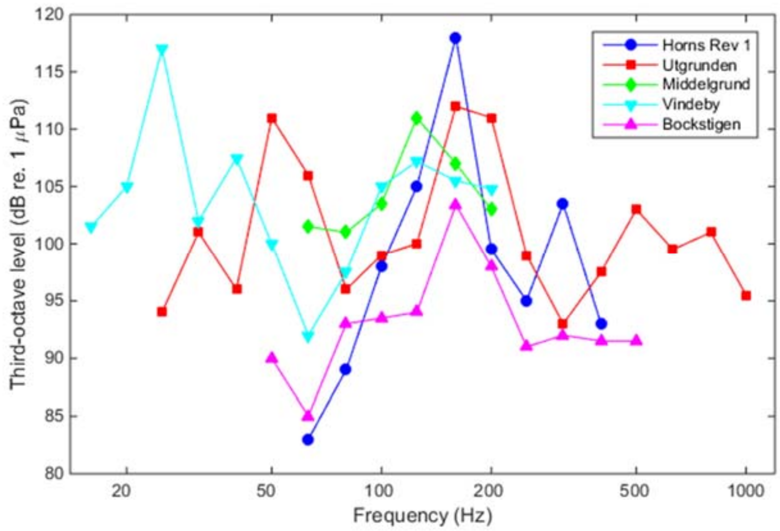


Figure 8.2. Underwater noise recorded from five different turbines, expressed as third-octave levels (and thus directly comparable to figure 1b) and levels normalized to a recording distance of 100 m. Sources: Ingemansson Technology AB (2003), Betke (2006), and Tougaard et al. (2009b)

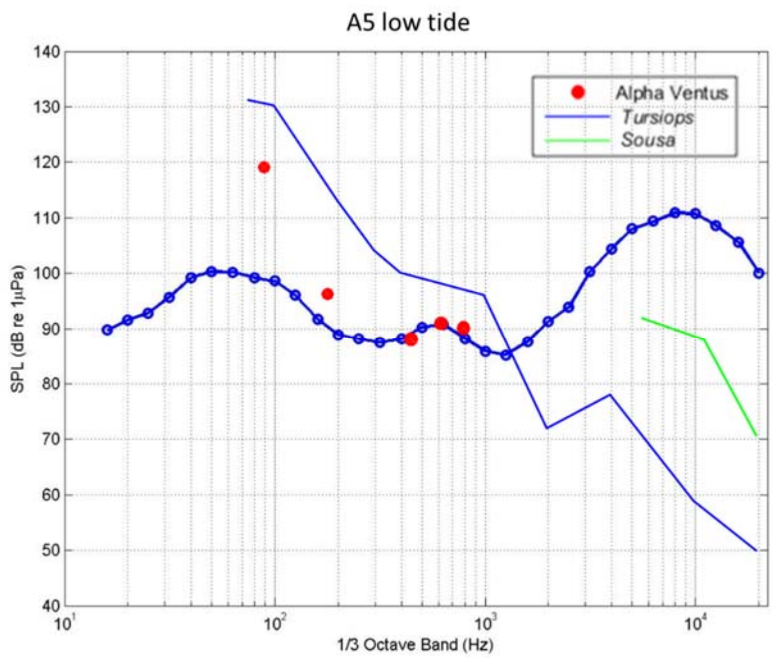


Figure 8.3. Tonal components of the noise 100 m from a 5 MW turbine at Alpha Ventus (from figure 8.1a), together with a 1 hour average third-octave spectrum of ambient noise from the proposed turbine site in the Xidao area. Lines are audiograms from white dolphin and bottlenose dolphin.

Assuming that turbines are comparable to the turbines in the Alpha Ventus wind farm is thus seems unlikely that dolphins will be able to hear the turbine noise at a distance of 100 m or more. Closer to the foundation the noise will be louder and at some point it will likely become audible to the dolphins.

8.1 Cumulative noise from several turbines

Concern has been raised over cumulative impact from several turbines in the same area. If two turbines produce noise at the same frequency and at the same sound pressure level, the two sounds can add and thus result in an increased sound pressure level. Figure 8.4 shows an idealized example of this. The noise from two identical turbines combine as:

$$L_{eq-combined} = 10\log_{10}\left(10^{L_{eq1}/10} + 10^{L_{eq2}/10}\right) \qquad \text{Equation 8.1}$$

Where L_{eq1} and L_{eq2} are the received sound pressure levels of the two turbines, respectively.

Only in the region roughly half-way between the turbines does the sum significantly exceed the sound pressure level of the closest turbine. Closer to one or the other turbine the contribution of the distant turbine to the sum is virtually zero. At most, the sum of the noise from the two turbines can be 3 dB more than the noise form the individual turbines (exactly half way between them). Adding more turbines does not change much. If four identical turbines are considered, the combined noise level at the exact centre between them would be 6 dB higher than the noise level of any of the individual turbines and as one moves away from the centre, the noise will be increasingly determined by the closest turbine. To achieve an additional 3 dB increase in noise level, one would have to be at the exact centre between 8 identical turbines, at which point the geometry is no longer consistent with the normal layout of wind farms. It is thus not possible, even under idealized conditions, to raise the combined noise level above the hearing thresholds. A dolphin will never be able to hear more than one turbine and only so when it is considerably closer to the turbine than 100 m.

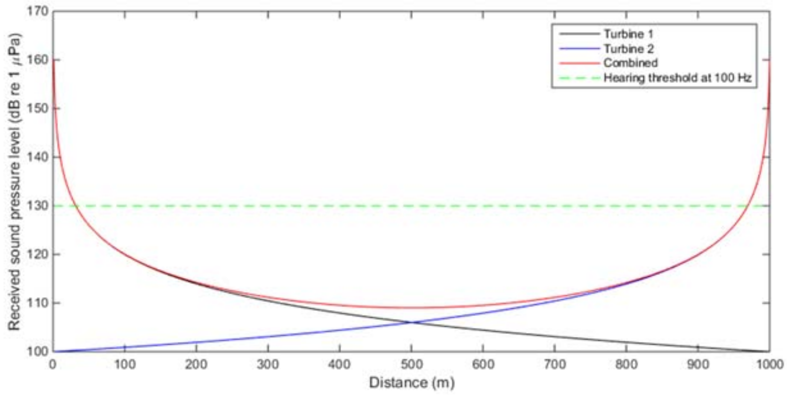


Figure 8.4. Idealized model of summation of noise from two identical turbines placed 1000 m apart. Each turbine is modelled as a point source with a spherical transmission loss (20 log r) and the combined noise level is found from equation 8.1. Included is also the hearing threshold for a bottlenose dolphin at 100 Hz.

9 Secondary (knock-on) effects

It is central to point out the possibility of secondary effects of offshore wind farms not covered in the previous. The Taiwanese white dolphin is critically endangered (Reeves et al. 2008), with a population size below 100 individuals (Wang et al. 2012). Furthermore, the combined effect of existing anthropogenic pressures: bycatch, habitat degradation and fragmentation, reduced freshwater run-off, and pollution with both sewage and chemicals, means that the population trend is negative (Wang et al. 2007, Dungan et al. 2011, Huang et al. 2014, Wang et al. 2016a, Karczmarski et al. 2017).

Bycatch in the local gill and trammel fishery is probably one of the most significant pressures on the population (Ross 2015). Thus, Slooten et al. (2013) showed than more than 30% of the population has visible marks after entanglement in nets. Demographic modelling of the population development calls for immediate action, as most of the modelled scenarios lead to extinction of the Taiwanese white dolphin within a few generations (Araújo et al. 2014). Maximum sustainable bycatch rate was estimated by Slooten et al. (2013) to be less than 1 animal every 7 years, i.e. essentially zero bycatch.

It is thus not sufficient for the long-term survival of the Taiwanese white dolphin that offshore wind development is done in a way that does not directly impact the dolphins. If nothing else is done to reduce the existing pressures, the dolphins will go extinct. This also means that the possible interactions between the offshore wind farms and the existing pressures becomes central to assess. The presence of the wind farms will inevitably change the ways the coastal area can be used for other activities, with possible implications for the dolphins. Such changes could for example be:

- Changes to shipping routes. The shipping lanes parallel to the coast becomes confined to a corridor between the deep-water wind farms and the coastal wind farms.

- Bottom trawling will not be allowed inside the wind farms for safety reasons. This will likely be beneficial to the seabed inside the wind farms, but could be offset by increased fishing pressure in other areas, outside the wind farms.

- There will likely be restrictions to other types of fishery inside the wind farms. Changes in the gill net and trammel net fishery could have a major impact on the white dolphins, positive or negative, strongly depending on whether the fishing effort in the dolphin habitat increases or decreases as a result of these changes.

There are likely several other knock-on effects, but a full assessment of these is beyond the scope of this report.

10 Conclusion

From the above it is evident that the proposed development of offshore wind along the Taiwanese west coast raises several issues with respect to the endemic and critically endangered Taiwanese white dolphin. Unmitigated pile driving during construction is likely to constitute a significant source of disturbance and possible injury (in the form of temporary or permanent hearing damage) to the dolphins. However, as exemplified by one of the nearshore projects: Xidao, an installation protocol involving the use of for example a double bubble curtain and commitment to compliance with the current German regulation (single pulse SEL 750 meter from the foundation lower than 160 dB re. 1 μPa^2s, unweighted), will reduce the impact to a degree where dolphins inside the core dolphin habitat are unlikely to be exposed to noise levels capable of inflicting hearing loss (TTS) or affecting behaviour.

Once the turbines are in operation, the noise from the turbines is expected to be considerably below levels that can have an impact on dolphins inside the core habitat. In fact the noise is not expected to be audible to dolphins, unless they are within about hundred meters or closer to the turbines.

The direct impact on white dolphins from construction and operation of offshore wind farms in the Taiwan Strait is thus considered to be manageable by appropriate mitigation measures. The direct impact is considered to be within limits that do not further endanger the already small and threatened population. However, the possible knock-on effects from anticipated and unanticipated changes especially to the local fishery and thus dolphin bycatch rates, have not been included in the assessment. These effects, as well as possible mitigations to reduce bycatch, are critical to assess. Not only that, but assessments must be followed by implementation of appropriate regulation and mitigation of the other pressures, in order to secure the long-time survival of the Taiwanese white dolphin.

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TAIWANESE WHITE DOLPHINS AND OFFSHORE WIND FARMS

Taiwan has proposed development of offshore wind energy in the Eastern Taiwan Strait, which is home to the endemic and critically endangered Taiwanese white dolphin *(Sousa chinensis taiwanensis)*. The most significant source of disturbance from offshore wind is noise from percussive piling on turbine foundations. The direct impact on Taiwanese white dolphins from construction and operation of offshore wind farms in the Taiwan Strait is considered to be manageable by appropriate mitigation measures (most importantly by application of air bubble curtains during percussive piling of turbine foundations) and within limits, that will not further endanger the population of dolphins. However, considering and handling possible knock-on effects from changes in use of the areas, including consequences for bycatch rates in fisheries, is critical in order to secure the long-time survival of the Taiwanese white dolphin.

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