Intended for
Energinet.dk

Document type
Report

Date
July 2023

ENERGY ISLAND BORNHOLM

TECHNICAL REPORT – MODELLING AND ASSESSMENT OF UNDERWATER NOISE AND VIBRATIONS

Bright ideas. Sustainable change.

ENERGY ISLAND BORNHOLM
TECHNICAL REPORT – MODELLING AND ASSESSMENT OF UNDERWATER NOISE AND VIBRATIONS

Project name	**Energy Island Bornholm**
Project no.	**1100048531**
Recipient	**Energinet.dk**
Document type	**Report**
Version	**1.0**
Date	**05.07.2023**
Prepared by	**CRIM**
Checked by	**ADREN**
Approved by	**JAKK**
Approved by Client	**BES**
Description	**Modelling and assessment of underwater noise and vibrations**

Ramboll
Hannemanns Allé 53
DK-2300 Copenhagen S
Denmark

T +45 5161 1000
F +45 5161 1001
https://ramboll.com

ENOE_RAM_WPK_TE001_1.docx

Doc ID REH2021N00237-RAM-RP-00027

Rambøll Danmark A/S
DK reg.no. 35128417

Member of FRI

CONTENTS

Terms and abbreviations

Units:

μm/s - micrometer per second
μPa - micropascal
dB – decibel
deg – degrees (angle)
dia - diameter
Hz - hertz
kHz - kilohertz
km - kilometer
m - meter
min - minute
mm - millimeter
MW - megawatt
Pa - pascal
s - second

Metrics:

TL - transmission loss
SPL,pk - zero-to-peak sound pressure level
SEL - single strike sound exposure level
SELcum - cumulative sound exposure level
SPL - continuous sound pressure level
T - averaging time
Z - acoustic characteristic impedance
c - sound velocity
f - frequency
n - count

Abbreviations:

DBBC - double big bubble curtain
DEA – Danish Energy Agency
EIA – environmental impact assessment
EMODnet - European Marine Observation and Data Network
HSD - hydro sound damper, hydro sound damper
NMS - noise mitigation system
OWF - offshore wind farm
PTS - permanent threshold shift
PCW - phocid carnivores in water, seals weighted sound level
SEA – strategic environmental assessment
TTS - temporary threshold shift
VHF – very high frequency
WTG - wind turbine generator

1. SUMMARY

This report describes the work carried out in relation to the modelling and assessment of the underwater noise as input to the Strategic Environmental Assessment (SEA) for Energy Island Bornholm. This study is an underwater noise propagation modelling for the construction of the proposed offshore windfarm (OWF) and addresses monopile piling with and without mitigation measures. Modelling scenarios were defined to reflect the actual project as well as possible, with the objective to determine expected noise levels, allowing for accurate impact assessment. The modelling included both cumulative and single strike sound exposure levels as well as zero-to-peak sound pressure levels. A comparison with various criteria from the literature leads to the following tables as a summary of worst-case impact ranges for harbour porpoises, seals and fish for monopile impact pile driving.

A summary of the results (maximum impact threshold distances) is provided here in Tables 1-1, 1-2 and 1-3 to give a general overview of the potential impacts with applied noise mitigation measures (NMS). As can been seen in the results, the impact threshold limit distances for permanent and mortal injury (PTS, mortal injury) are quite small for marine mammals with the noise mitigation measures combined with soft-start ramp up piling schedules and including a flee factor for the various animal species. However, behavior impact disturbance distances for marine mammals and temporary impacts for fish are substantial.

Table 1-1 Construction activity modelling results/radial distance to threshold limits Harbour Porpoises, maximum corrected.

Activity	PTS	TTS	Behaviour
Monopile piling (NMS*) 18 m dia.	0 meters	0 meters	7306 meters

*NMS, Noise Mitigation system and Double Big Bubble Curtain (DBBC), Hydro Sound Damper (HSD) and Acoustic Deterrent Device (ADD).

Table 1-2 Construction activity modelling results/radial distance to threshold limits for Seals, maximum corrected.

Seals			
Activity	**PTS**	**TTS**	**Behaviour**
Monopile piling (NMS*) 18 m dia.	0 meters	0 meters	6487 meters

*NMS, Noise mitigation system and Double Bubble Curtain (DBBC), Hydro Sound Damper (HSD) and Acoustic Deterrent Device (ADD).

Table 1-3 Construction activity modelling results/radial distance to threshold limits for Fish, maximum corrected.

Fish				
Activity	**Species**	**Mortal injury**	**Recoverable injury**	**TTS**
Monopile piling (NMS*) 18 m dia.	Herring	10 meters	10 meters	2500 meters
Monopile piling (NMS*) 18 m dia.	Cod (juvenile)	10 meters	10 meters	6000 meters
Monopile piling (NMS*) 18 m dia.	Cod (adult)	10 meters	10 meters	3000 meters
Monopile piling (NMS*) 18 m dia.	Larvae	500 meters	n/a	n/a

*NMS, Noise mitigation system and Double Big Bubble Curtain (DBBC) and Hydro Sound Damper (HSD).

2. INTRODUCTION

With the Climate Agreement for Energy and Industry of the 22nd of June 2020, the majority of the Danish Parliament decided that Denmark will become the first country in the world to develop two energy islands. One of these islands will be the island of Bornholm located in the Baltic Sea ("Energioe Bornholm"), with wind farms south-west of Bornholm with an installed capacity of up to 3.8 GW. The designated wind farm areas consist of Bornholm I South (118 km^2), Bornholm I North (123 km^2) and Bornholm II (410 km^2). The wind farms areas will contain wind turbines with a maximum height of 330 m, maximum 7 transformer platforms, as well as subsea cables. The island of Bornholm will house the High Voltage Station and serve to distribute the produced energy.

As a consequence of these political decisions a series of biological and scientific investigations has to be carried out for a well-defined pre investigation area as part of the baseline mapping of this part of the Baltic Sea. This also includes an investigation of the expected noise propagation from the construction and operation of the wind farms.

The construction of an offshore wind farm involves activities that can produce underwater noise where pile driving has the potential to disturb or harm marine mammals and fish in the area.

The purpose of this study is to provide the potential worst case underwater noise levels associated with impact pile driven monopiles. However the concession owner will be able to choose another methods for wind turbine foundations with less underwater noise impacts. The study of underwater noise propagation are based on the following setups:

- Construction
    - Monopile pile driving without noise mitigation
    - Monopile pile driving with noise mitigation

The modelling will be performed in accordance with Environmental Impact Assessments (EIA) of similar OWFs and DEA guidelines on underwater noise assessment for monopile-driving: Guidelines for underwater noise, Prognosis for EIA and SEA assessments, Danish Energy Agency (Energistyrelsen) May 2022 and Guideline for underwater noise - Installation of impact or vibratory driven piles May 2022, DEA. These guidelines form the basis for calculation and assessment of underwater noise.

For each wind turbine design option of the project, significant "worst-case" noise sources will be identified, and based on this, representative modelling positions will be chosen. The modelling is based on the design for the actual project to the extend concrete technical data is available, while a "worst-case" assumption will be applied for currently unspecified inputs. The modelling includes the determination of impact ranges (distances) from the various activities where potential impact can occur.

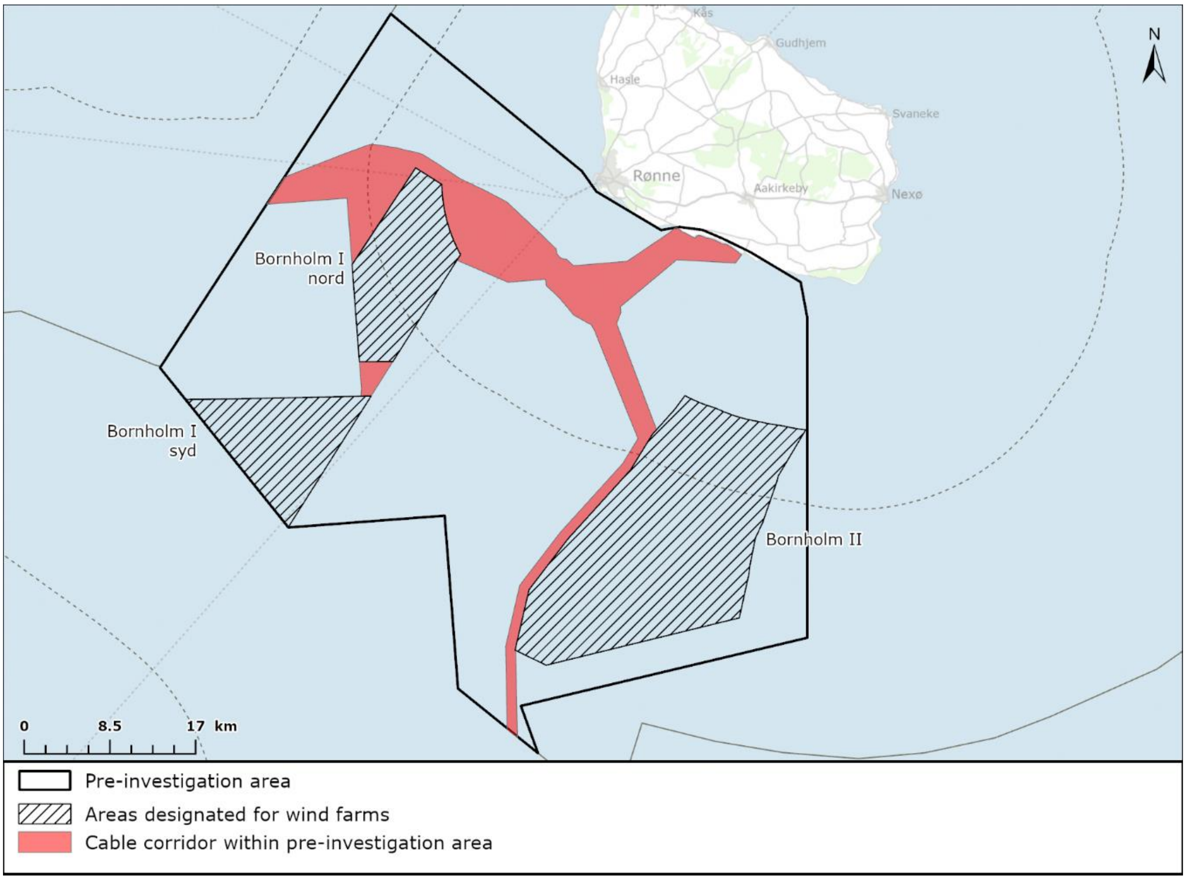

Figure 2-1 Planning areas for the offshore wind farm and subsea cables near Bornholm.

3. NOISE MODELLING POSITIONS

Ramboll together with Energinet chose 4 representative positions within each of the two wind farm areas (see Figure 3-1). At each position underwater noise from monopile pile driving with and without noise mitigation will be modelled.

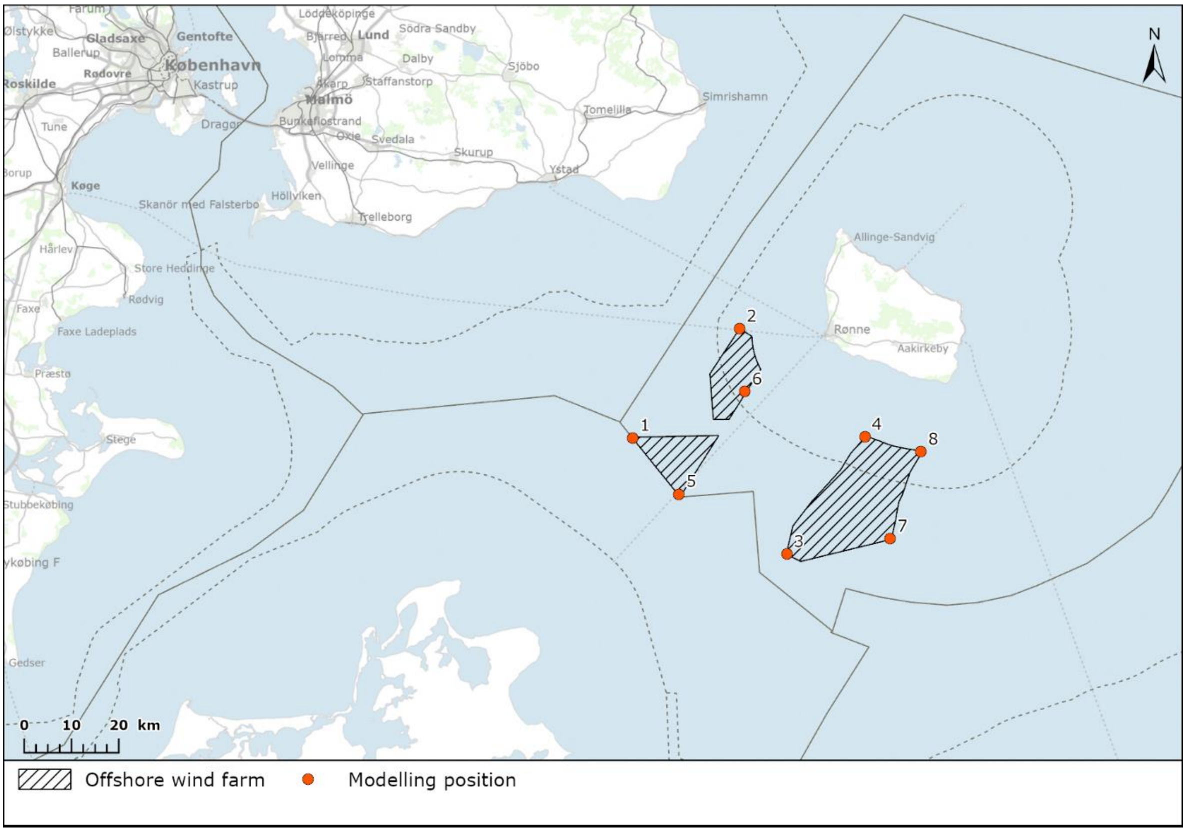

Figure 3-1 Modelling positions.

4. UNDERWATER SOUND

Underwater sound, like sound in the air, is disturbances from a source in a medium – here water – travelling in a 3-dimensional manner as the disturbances propagate with the speed of sound.

Sound travels at different speeds in different medias. The speed of sound is determined by the density and compressibility of the medium. Density is the mass of the material in a given volume, and compressibility is a measure of how much a substance could be compressed for a given pressure. The denser and the more compressible the media is, the slower the sound waves will travel. Water is much denser than air, but since it is nearly incompressible the speed of sound is about four times faster in water than in air. The speed of sound can also be affected by temperature. Sound waves tend to travel faster at higher temperatures.

Underwater sound can be measured as a change in pressure and can be measured with a pressure sensitive device (hydrophone).

Because of the large range pressure amplitudes of sound, it is convenient to use a decibel (dB) logarithmic scale to quantify pressure levels. The underwater sound pressure level in decibels (dB) is defined in the following equation:

Sound Pressure Level (SPL) = $20\log_{10}(P/P_0)$

P is the pressure and P_0 is the reference pressure. The reference pressure is 1 micropascal (μPa) for underwater sound which is different from sound pressure levels in the air. For this reason, sound pressure levels in the water and air cannot be directly compared.

Underwater sound levels vary with the sound source's time signature and acoustic environmental conditions. Therefore, noise levels are defined in terms of exposure, average and/or maximum levels. The following acoustic parameters are commonly used to assess the noise impact from underwater noise sources for the identified local marine life.

4.1 Applicable acoustic parameters

Metrics definitions are given in ISO 18406 and the following key terms are used in this document:

Sound Pressure Level (SPL) – this quantifies the magnitude of a sound at a given point, i.e., how loud it is, and is measured in decibels (dB). As a relative unit, dB is quoted relative to 1 micropascal in underwater studies (so, dB re 1 μPa).

$$SPL = 10\,Log_{10}\left[\frac{\hat{P}^2}{P_0^2}\right] = 20\,Log_{10}\left[\frac{\hat{P}}{P_0}\right]$$

Sound Exposure Level (SEL) – this is a decibel measure for describing how much sound energy a receptor (e.g., a marine animal) has received from an event and is normalized to an interval of one second (quoted in dB re. 1 μPa^2s). It can be thought of as a logarithmic measure of Sound Exposure and hence a 3 dB increase in SEL equates to a doubling of sound energy; dB re. 1 μPa^2s.

$$SEL = 10\,\log_{10}\left[\frac{E}{E_0}\right]$$

The single-strike sound exposure level (abbreviation: SELss) is defined in ISO 18406 for a specific acoustic pulse, or event. The reference value is 1 μPa²s.

Cumulative Sound Exposure (SEL (cum)) – this is the time integral of the squared pressures over the duration of a sound or series of sounds. It enables sounds of differing duration and level to be characterized in terms of total sound energy normalized to an interval of one second (quoted in dB re. Pa²s). SELcum is the cumulated SEL over a noise-causing activity (e.g., pile driving).

Peak pressure level (PEAK) – the zero-to-peak sound pressure at a given point in time.

$$L_{peak} = 20\ \log_{10}\left[\frac{p_{peak}}{p_0}\right]$$

Root mean square (RMS) – the sound pressure averaged over a given time; The RMS SPL is commonly used to evaluate the effects of continuous noise sources. The RMS sound pressure level or SPL is the mean square pressure level. This is the Root Mean Square (RMS) of the sound pressure taken over a time interval T=t2-t1 [s]. The related level in dB is often referred to as "equivalent continuous sound pressure level", (symbol: LeqT) over time interval T. The sound pressure level is abbreviated as SPL. The RMS sound pressure level (abbreviated as SPL, symbol: Lp,rms) in dB. The reference value for underwater sound pressure is p0=1 μPa. For the purpose of evaluating behavioural reactions to the noise, the RMS-sound pressure level calculated over a time interval corresponding to the average integration time of the mammalian ear (125 ms) is used.

Pulsed/impulsive sound – a discontinuous sound source comprising one or more instantaneous sounds as during munitions clearance.

Continuous sound – sound source, like a vessel engine, or humming as in drilling operation.

4.2 Underwater sound source levels

Based on existing underwater sound measurements, we will estimate the sound source levels and frequency spectrum for the identified significant sound sources for potential underwater noise impacts. Where applicable, to obtain an equivalent source level at 1 m from the source, for the purpose of acoustic propagation modelling, we will back-propagate the pressure field according to cylindrical spreading loss, or 15·log(r). The purpose of the back-propagation step is to determine the effective source level at 1 m that will be used in the acoustic propagation model.

5. UNDERWATER SOUND PROPAGATION MODEL

The underwater sound propagation model calculates estimates of the sound field generated from underwater sound sources. The results of the modelling are used to determine the potential impact distances (noise maps/contour plots) from the identified significant underwater noise sources for the various identified marine life in the area. Based on source location and underwater source sound level, the acoustic field at any range from the source is estimated using dBSea's acoustic propagation model (Parabolic equation method (≤315 Hz), Jensen 2011 and ray tracing (>315 Hz)). The sound propagation modelling uses acoustic parameters appropriate for the specific geographic region of interest, including the expected water column sound speed profile, the bathymetry, and the bottom geo-acoustic properties. This is done to produce site-specific estimates of the radiated noise field as a function of range and depth. The acoustic model is used to predict the directional transmission loss from source locations corresponding to receiver locations. The received level at any 3-dimensional location away from the source is calculated by combining the source level and transmission loss, both of which are direction dependent. Underwater acoustic transmission loss and received underwater sound levels are a function of depth, range, bearing, and environmental properties. The output values can be used to compute or estimate specific noise metrics relevant to safety criteria filtering for frequency-dependent marine mammal hearing capabilities.

Underwater sound source levels are used as input for the underwater sound propagation program, which computes the sound field as a function of range, depth, and bearing relative to the location of the source.

The model assumes that outgoing energy dominates over scattered energy and computes the solution for the outgoing wave equation. An approximation is used to provide two-dimensional transmission loss values in range and depth, i.e., computation of the transmission loss as a function of range and depth within a given radial plane is carried out independently of neighbouring radials (reflecting the assumption that sound propagation is predominantly away from the source).

The received underwater sound levels are computed from the 1/3-octave band frequency sound source levels by subtracting the numerically modelled transmission loss at each 1/3-octave band centre frequency and then summing across all frequencies to obtain an overall value. For this study, transmission loss and received levels were modelled for 1/3-octave frequency bands between 12.5 and 80000 Hz. Because the source of underwater noise considered in this study are predominantly low-frequency sources, this frequency range is sufficient to capture essentially all of the energy outputs. The received levels will be converted to all the applicable underwater acoustic parameters.

Bathymetry data will be provided from EMODNET (The European Marine Observation and Data Network).

Water column data (salinity, temperature, speed of underwater sound/depth) are provided from ICES (International Council for the Exploration of the Sea) HELCOM specific measurement stations positioned close to the selected modelling positions.

Seabed conditions for areas close to the modelling positions are provided by geological surveys conducted by Energinet.

Predictions have been performed for both winter (worst month) and summer water column conditions which have different underwater sound propagation characteristics and will show the maximum underwater noise level of the whole sea depth.

The sound propagation model will run with the source levels, activity time and environmental parameterization and generate noise maps. The levels depicted in the noise maps will be the maximum predicted level for that location at any depth down to the bottom and will include the following acoustic parameters for each of the identified sound sources (ISO18405 and ISO18406):

- SELss, Sound Exposure Level (linear, VHF and PCW weighted), dB re. 1μPa^{2}s
- SELcum, Cumulative Sound Exposure Level (Linear, VHF and PCW weighted), dB re. 1μPa^{2}s
- SPL, RMS 125 ms. levels (linear), dB re. 1μPa
- SPL, Peak (linear), dB re. 1μPa

The results of the acoustic modelling (noise maps and impact distances) will be reported in terms of the underwater sound levels of each specific acoustic metric for distances up to 50 km. As well, a vertical sound propagation profile plot for the dominant sound source frequency bands will be generated to show the variation in underwater sound propagation in regard to sea depth. A calculation grid x 200, y 200, z 20; 24 radial slices 200 range points was selected to provide adequate resolution for impact distances.

6. BASELINE FOR THE IMPACT ASSESSMENT OF UNDERWATER NOISE

The pressure levels of the sound source and the associated impact zones can be viewed as indicative precautionary ranges. It is important to note that it is highly unlikely that any marine mammal would stay at a stationary location or within a fixed radius of any other noise source. The behaviour of receivers (animals) will be included in a model of exposure. A worst-case assumption of a stationary animal can be made, but this is likely to overestimate the extent of especially the impact threshold zones considerably and therefore included is a simple model for animal escape, including a threshold for reaction followed by movement radially away from the sound source during the whole duration of the pile driving.

Marine mammal movement will be modelled as a movement with a speed of 1.5 m/s.

Fish are assumed to flee differently (Anderson 2017) from the noise source. Fish fleeing will be modelled in calculating the sound exposure level. For Herring, 1.04 m/s and for Cod 0.38 m/s (juvenile) and 0.9 m/s (adult) have been use for this study.

The fleeing of the animal will be affected by the overall sound exposure for the whole piling period and is included in the calculations as described in the Guidelines for underwater noise, Prognosis for EIA and SEA, Danish Energy Agency (DEA) May 2022.

6.1 Marine mammals

Generally, the effect of noise on marine mammals can be divided into four broad categories that largely depend on the individual's proximity to the sound source:

- Detection
- Masking
- Behavioural changes
- Physical damages

The limits of each zone of impact are not sharp, and there is a large overlap between the zones. The four categories are described below, based on Southall et al. (2007).

Detection ranges depend on background noise levels as well as hearing thresholds for the animals in question.

Masking occurs when noise interferes with an animal's ability to perceive (detect, interpret, and/or discriminate) a sound. There are still many uncertainties regarding how masking affects marine mammals.

The occurrence and significance of a **behavioural change** varies by individual, species, and circumstances. Some sounds may not cause any response, while others may result in minor to significant changes in a variety of behaviours, such as diving, surfacing, feeding, vocalizing and/or mating.

Physical damage to marine mammals relates to damage to the hearing apparatus. Physical damages to the hearing apparatus may lead to permanent changes in the animals' detection threshold (permanent threshold shift, PTS). This can be caused by the destruction of sensory cells in the inner ear, or by metabolic exhaustion of sensory cells, support cells or even auditory nerve cells. Hearing loss is usually only temporary (temporary threshold shift, TTS) and the animal will regain its original detection abilities after a recovery period. For PTS and TTS, the sound intensity is an important factor for the degree of hearing loss, as is the frequency, the exposure duration, and the length of the recovery time.

The proposed criteria for PTS, TTS and behavioural response in this report are based on results presented in scientific literature and/or commonly and currently used in environmental impact assessments of underwater sound. The behaviour of receivers (animals) is essential to include in a model of exposure.

6.1.1 Marine mammal auditory weighting function

The ability to hear sounds varies across a species' hearing range. Most mammal audiograms have a typical "U-shape," with frequencies at the bottom of the "U" being those to which the animal is more sensitive, in terms of hearing. Auditory weighting functions best reflect an animal's ability to hear a sound (and do not necessarily reflect how an animal will perceive and behaviourally react to that sound). To reflect higher hearing sensitivity at particular frequencies, sounds are often weighted. Auditory weighting functions have been proposed for marine mammals, specifically associated with PTS/TTS acoustic thresholds expressed in the SELcum metric, which take into account what is known about marine mammal hearing (Southall, 2019) and is in line with the DEA guidelines (DEA, 2022). Very High Frequency (VHF) weighted impact threshold limits are applicable to Harbour Porpoises. Phocid Carnivores in Water (PCW) weighted threshold limits are applicable to Seals.

6.1.2 Noise source characteristics

When analysing the auditory effects of noise exposure, it is often helpful to broadly categorize noise as either impulse noise — noise with high peak sound pressure, short duration, fast rise-time, and broad frequency content — or non-impulsive (i.e., steady state) noise. When considering auditory effects, sonars, other coherent active sources, and vibratory pile driving are considered to be non-impulsive sources, while explosives, impact pile driving, and air guns are treated as impulsive sources. Note that the terms non-impulsive or steady-state do not necessarily imply long duration signals, only that the acoustic signal has sufficient duration to overcome starting transients and reach a steady-state condition. For harmonic signals, sounds with duration greater than approximately 5 to 10 cycles are generally considered to be steady-state.

6.1.3 Harbour porpoise criteria

Table 6-1 and 6-2 summarizes criteria for assessing impacts for marine mammal (Harbour Porpoise). The criteria are associated with different impacts and limits. The proposed criteria for PTS, TTS and behavioural response in this report are based on the guideline from the Danish Energy Agency (DEA, 2022), which is based on results presented in scientific literature and/or commonly and currently used in environmental impact assessments of underwater sound. The behaviour of receivers (animals) is essential to include in a model of exposure.

Table 6-1 Harbour porpoise noise exposure criteria for hearing loss.

Species	Functional hearing group	Noise effect	Threshold (Impulsive noise)	Threshold (Non-impulsive noise)	Reference
Harbour porpoise	Very High-frequency cetaceans VHF	PTS	155 dB re 1μPa²s SELcum (weighted)	173 dB re 1μPa²s SELcum (weighted)	*Southall et al. 2019*
		TTS	140 dB re 1μPa²s SEL cum(weighted)	153 dB re 1μPa²s SELcum (weighted)	*Southall et al. 2019*

Table 6-2 Harbour porpoise noise exposure criteria for behavioural displacement.

Species	Noise type	Threshold	Reference
Harbour porpoise	Impact piledriving	103 dB re 1μPa rms, 125 ms, (VHF weighted)	*DEA 2022*

6.1.4 Seals criteria

Table 6-3 summarizes criteria for assessing impacts for marine mammal (Seals). The criteria are associated with different impacts and limits. The proposed criteria for PTS, TTS and behavioural response in this report are based on the guideline from the Danish Energy Agency (DEA, 2022), which is based on results presented in scientific literature and/or commonly and currently used in environmental impact assessments of underwater sound. The behaviour of receivers (animals) is essential to include in a model of exposure. Detection distances were not determined in this study for seals as they are less sensitive to underwater noise than Harbour porpoises.

Table 6-3 Seal noise exposure criteria for hearing loss.

Species	Impact type (Reference)	Fleeing speed [m/s]	Impulsive noise criteria [dB] SEL, SELcum	Continuous noise criteria [dB] SEL
Seal	PTS (DEA 2022, Southall 2019)	1.5	185 PCW (SELcum)	201 PCW (cum)
Seal	TTS (DEA 2022, Southall 2019)	1.5	170 PCW (SELcum)	181 PCW (cum)
Seal	Behaviour (Russel 2016)	-	151 (single strike, SEL)	n/a

6.1.5 Offshore pile driving noise limits (Germany)

Germany's Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) has created guidelines for how to protect the marine mammals from harmful effects during the construction of offshore wind farms in the German exclusive economic zone in the North Sea. The underwater noise generated by pile driving operations at offshore wind farms can have significant adverse effects on marine mammals, both on the individual and the population level. The guidelines recommend utilizing the best available technology to minimize noise exposure and other adverse effects on the marine environment. The German Federal Maritime and Hydrographic

Agency (BSH) has established a dual threshold for permissible noise levels, which must not be exceeded at 750 meters away from the source, of SEL 160 dB re 1 μPa^{2}s or SPL(peak) 190 dB re 1 μPa and are shown in Table 6-4.

These limits have often been adopted for Swedish offshore projects and are calculated in this study to show how the underwater noise levels compare to these limits. As well, the VHF, PCW weighted levels at 750 meters, are calculated. However, this study will consider excluding the German unweighted limits, but are kept at the moment and saved for further investigation if relevant. The problem with the German limits, is that they underestimate the effect of the bubble curtain mitigation.

Table 6-4 German underwater noise limits (maximum allowable at 750 meters from the noise source).

Species	Max. SEL @ 750 meters dB re. 1μPa^{2}s	Max. Peak @750 meters dB re. 1μPa
Marine mammals	160 dB	190 dB

6.2 Fish

Sound, at higher intensities, may have a diverse range of effects on fish. These may include death, hearing impairment, damage to anatomical structures, and changes in physiology, neural function, behaviour, and development.

6.2.1 Fish criteria

Table 6-5 summarizes criteria for assessing impacts for fish. The criteria are associated with different impacts and limits. These threshold values for impact have been determined by an assessment of available values from the most recent scientific literature and accepted limits. (Popper 2014, Andersson et al. 2017).

Definition of Effects:

- *Mortality and mortal injury:* immediate or delayed death.
- *Recoverable injury*: injuries, including hair cell damage, minor internal or external hematoma, etc. None of these injuries are likely to result in mortality.
- *TTS:* short- or long-term changes in hearing sensitivity that may or may not reduce fitness.

Exposure distances for herring and cod including escape rates. For herring this study will use 1.04 m/s and for cod this study have used 0.38 m/s (juvenile) and 0.9 m/s (adult).

Table 6-5 Threshold criteria level and impact distances for fish.

Species	Impact type (Ref.)	Fleeing speed [m/s]	Impulsive noise criteria [dB] Peak	Impulsiv noise criteria [dB] SELcum	Continuous noise criteria [dB]SELcum
Fish	Mortal injury (Popper 2014)	0.9 Herring 0.38 Cod (juvenile) 1.04 Cod (adult)	207	207 (SELcum)	-
Fish	Recoverable injury (Popper 2014)	0.9 Herring 0.38 Cod (juvenile) 1.04 Cod (adult)	207	203 (SELcum)	222 (SELcum) 48 hours,170 rms

Species	Impact type (Ref.)	Fleeing speed [m/s]	Impulsive noise criteria [dB] Peak	Impulsiv noise criteria [dB] SELcum	Continuous noise criteria [dB]SELcum
Fish	TTS (Popper 2014)	0.9 Herring 0.38 Cod (juvenile) 1.04 Cod (adult)	-	186 (SELcum)	204 (SELcum) 12 hours, 158 rms
Larvae	Mortal injury (Popper 2014)	0	207	210 (SELcum)	

7. UNDERWATER SOUND SOURCE MODEL INPUTS

The noise sources (pile driving with, without mitigation and operation) of the project will be identified and give their respective sound source levels, characteristics and frequency spectrum. These parameters will be determined based on available measurement data and adjusted to meet the OWF proposed design concepts and will be used as input to the underwater sound propagation model.

7.1 Pile driving source levels

This study uses the 1/3-octave spectrum from Bellmann et al. (2020) as that represents the most up-to-date and comprehensive collection of spectra. dBSea source levels (without mitigation) are adjusted to meet levels for a design worst case diameter monopile at 750 meters as shown Figure 7-1.

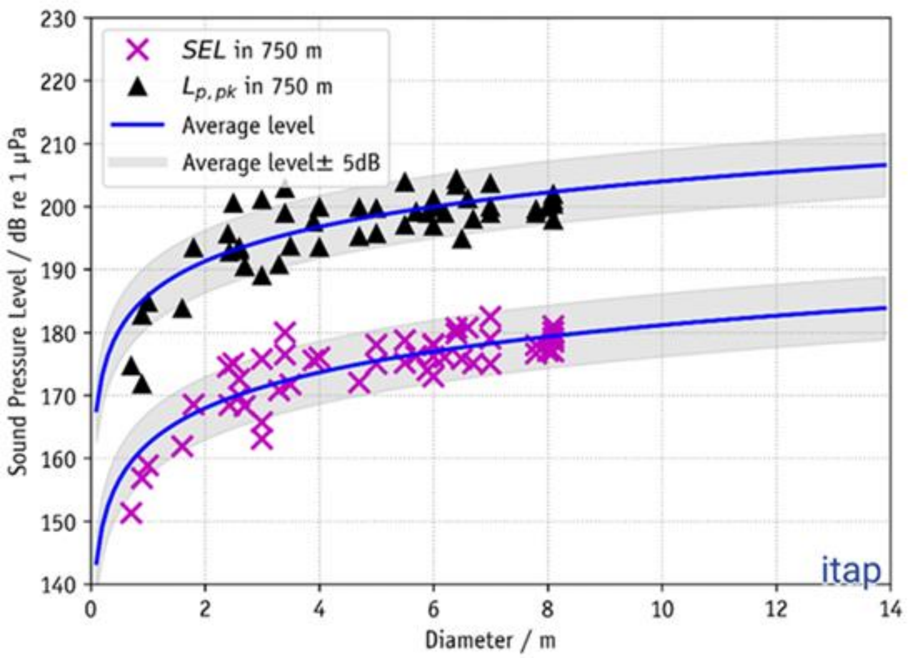

Figure 7-1 Measured data for pile driving (Bellmann et al. 2020).

The pile driving source levels are based on measured values for the sound exposure level (SEL) and for the zero-to-peak sound pressure level ($L_{p,pk}$) of previous projects. The emitted sound level depends on many different factors, such as e. g. wall thickness, blow energy, diameter and soil composition (soil resistance) and water depth. Since all parameters mentioned might interact with each other, it is not possible to make exact statements on the impact of a single parameter, therefore only one parameter, the pile diameter, is used a basis for the sound source level. The following figure shows sound levels measured during pile-driving construction works at a number of windfarms plotted over the input parameter "pile diameter". The bigger the sound-emitting surface in the water, the bigger the sound entry. This means, the evaluation-relevant level values increase with increasing pile surface, thus the diameter of the pile. It should also be noted that the relationship is not linear.

The source level uncertainty is ± 5 dB, just taking into account the input parameter „pile diameter", and is based on the scatter of the actual existing measured results that is probably due to further influencing factors, such as e. g. blow energy and reflecting pile skin surface.
The following comparison between the predicted values and the measured level values was covered adequately in any case by the specified model uncertainty (± 5 dB). In most cases, the model slightly overestimated the level value in 750 m distance (not published data). Therefore, an application in the present case is possible from a practical point of view. The source levels are likely to be conservative.

The sound frequency spectrum shown below in Figure 7-2 (without mitigation) is used in the model.

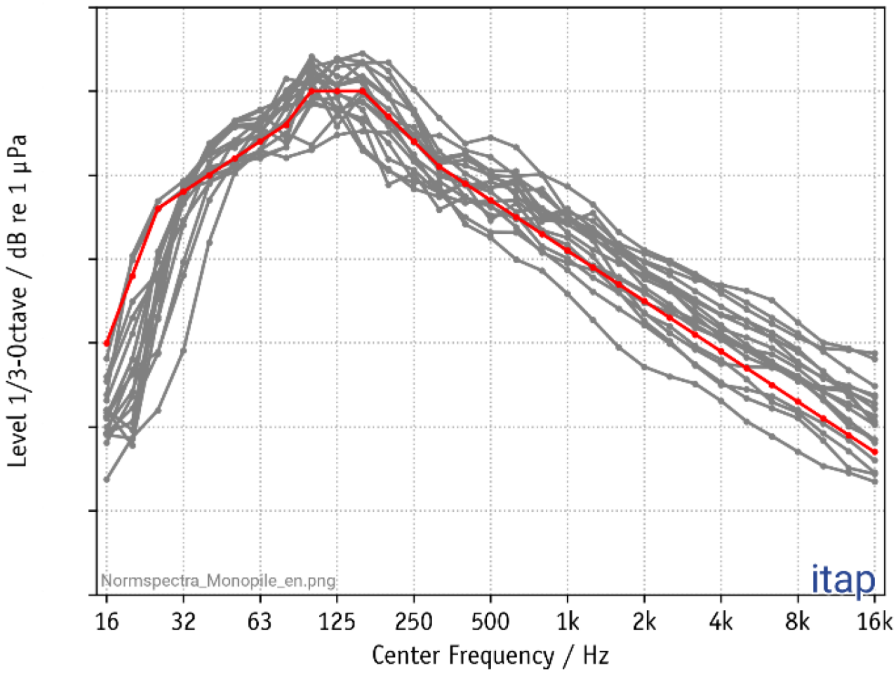

Figure 7-2 Spectrum data. Grey lines are measured red line is theorectical average (Bellmann et al. 2020).

We are using the 1/3-octaveband frequency spectrum from Bellmann et al. (2020) as that represents the most up-to-date and comprehensive collection of spectra. The dBSea overall source levels used (12.5-80KHz, without mitigation) was adjusted to meet levels for an 18 meter diameter monopile are shown below in Table 7-1 and the corresponding 1/3 octaveband frequency spectrum levels are shown in Table 7-2. This monopile diameter of 18 meters has been provided by Energinet.dk.

Table 7-1 Sound source levels.

Source	Information	Source Level, Peak, re. 1µPa @ 1 meter, peak.	Source Level, rms, re. 1µPa @ 1 meter,	Source Level, SEL(1sec), re. 1µPa^{2}s @ 1 meter, single strike, Max.
Monopile Impact Piling (unmitigated)	Impulsive. 18-meter diameter monopile	255 dB	238 dB	231 dB

Table 7-2 Source levels - Frequency spectra (dB re. 1 microPascal).

Freq. 1/3 octave band (Hz)	16	20	25	32	40	50	63	80	100	125	160	200	250	315	400	500	630	800	1 kHz
Spectra (non-linear dist. Correction), dB	205	206	217	212	216	219	220	221	225	224	223	219	216	211	209	206	200	200	199
Freq. 1/3 octave band (kHz)	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0	12.5	16.0	20.0	25.0	32.0	40	50	64	
Spectra (non-linear dist. Correction), dB	197	196	195	193	189	189	187	185	183	181	180	178	177	175	174	172	171	169	

7.1.1 Pile driving schedule

Energinet has provided a representative piling profile schedule with estimated number of strikes, soft start program with hammer energy. This pile driving schedule is used for the SELcum calculations and is shown in Table 7-3.

Table 7-3 Pile driving schedule.

Foundation			Monopile
Number of piles			1
Impact hammer			IHC S-4000 (6000kJ)
Pile Diameter			18 m
Total number of strikes pr. pile			7000
Pile driving procedure			
Name	**Number of strikes**	**% of maximum hammer energy**	**Time interval between strikes [s]**
Soft-start	300	10	4
Ramp-up	400	20-80	4
Full power	6300	100	2

7.2 Noise mitigation

Noise mitigation systems are expected to be used for the impact piling if monopiles will be used. A description of the potential, feasible noise mitigation systems is described in the following sections.

7.2.1 Acoustic Deterrent Device

In the context of offshore piling, an Acoustic Deterrent Device (ADD) serves as a marine mammal mitigation technique. Ideally, it deters animals from potential injury zones.
The use of an ADD is mandatory during the construction sequence of any single foundation, except for relatively low-noise scenarios where the impact distance for PTS<200 m.

The ADD shall be activated at least 15 minutes before pile installation start-up. If the pile installation is inactive for more than 2.5 hours, the ADD shall have been active for another 15 minutes before installation may start again

This modelling is using a practical worst-case scenario of the piling operation and assumes the piling to be performed with and without ADD characterising the piling situation with simultaneous failure of both noise mitigation means and ADD.

7.2.2 Noise mitigation systems

Based on available published data the noise mitigation systems *Double Big Bubble Curtain* (DBBC) and *Hydro Sound Damper* are well approved techniques under actual offshore applications.

The mitigation (HSD+DBBC) transmission loss data for pile driving is shown as a red line in Figure 7-3.

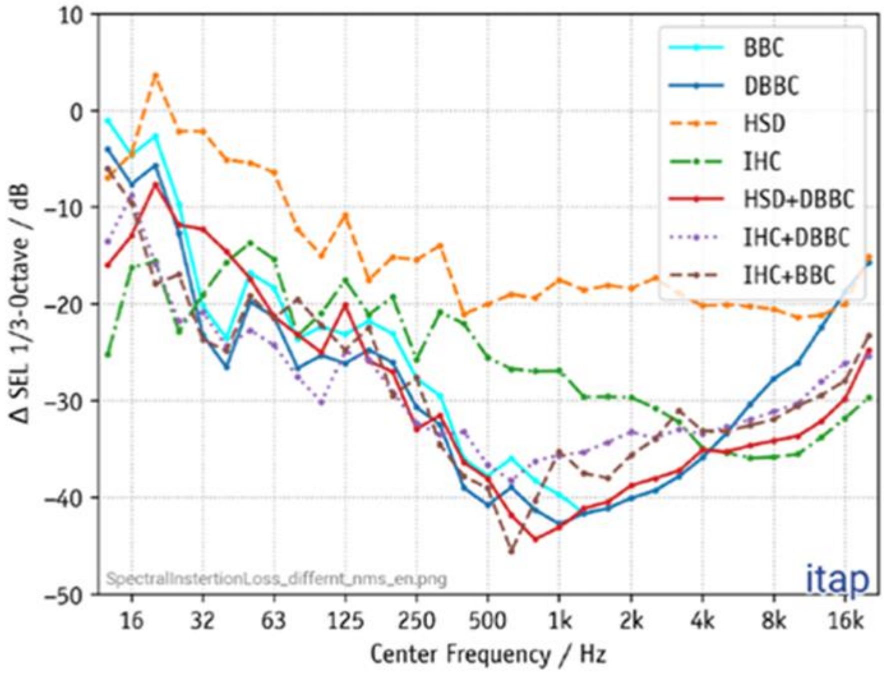

Figure 7-3 Noise mitigation reduction spectrum (Bellmann et al. 2020).

7.2.3 Double Big Bubble Curtain (DBBC)

The Double Big Bubble Curtain (DBBC) is one of the most practicable and most frequently used (>600 applications) noise mitigation systems. Additionally, two funded R&D projects were conducted to understand the main influencing factors of a Double Big Bubble Curtain on the overall noise reduction (Nehls & Bellmann, 2015; Bellmann et al., 2018).

At the moment, noise reductions for the sound exposure level (SEL) of up to 18 dB (maximum measured noise reduction, un-weighted) are possible by using a Double Big Bubble Curtain (DBBC) in the North Sea at water depths till 40 m. The average overall un-weighted noise reduction of an optimized DBBC mostly ranged between 15 dB and 16 dB (Bellmann, 2014; Bellmann et al., 2018 and Bellmann et al., 2015; Bellmann et al., 2020).

The noise reduction of Big Bubble Curtains depends on many factors like water depth, current, used hole configuration in the applied nozzle hoses on the seabed and compressed air supply. It is important to enhance the Big Bubble Curtain system configuration to the local project-specific conditions (Bellmann et al., 2018). Decisive for a successful application are:

- a sufficient amount of compressed air and
- a complete wrapping of the pile by the Big Bubble Curtain.

The required air volume depends on the water depth due to the static pressure of the surrounding water. In the North Sea (where the most BBC applications took place), an applied air volume of $\geq 0.5\ m^3/(min*m)$ is currently state-of-the-art for water depths up to 40 m. In order to enable a complete wrapping of the pile, a sufficient distance of the Big Bubble Curtain nozzle hoses to the pile is required. This distance depends on the local current and the water depth (drifting effects). Means by setting up the BBC system configuration, the water depth and the current, but also the type of installation vessel (DP), anchor moored floating vessel of jack-up barge) shall be considered by designing the overall length of the applied nozzle hoses and the layout shape used. Typically, a current of up to 1 knot is no problem for applying an optimized BBC system with respect to the drifting effects.

Furthermore, the sound reduction of each noise mitigation system is highly frequency-dependent and thus, the resulting (single-number) sound reduction depends on the spectral composition of the piling noise, without the application of a noise abatement measure.

7.2.4 Hydro Sound Damper (HSD)

The Hydro Sound Damper is a near-to-pile noise abatement system, which often is applied in combination with a single or a Double Big Bubble Curtain (DBBC). The HSD-system consists of a net with HSD-elements and a lowering and lifting device. The HSD-elements consist of different foam elements in different sizes. Each HSD-element is adjusted to different frequencies and water depths, so that the HSD-system must be adjusted to each individual offshore project.
The whole system (lowering and lifting device, nets and HSD-elements) can be telescoped via winch systems for the transport as well as for the mobilization and demobilization. Until now, this noise abatement system was used as standard in monopile installations with pile diameters up to 8 m and a water depth to approx. 40 m and showed a constant noise reduction of 10 dB in the North Sea at water depths of up to 40 m.

7.2.5 Combination of near-to-pile and far-from-pile Noise Abatement Systems

The following combinations of technical Noise Abatement Systems for the installation of monopiles in serial use have been used in the construction of the foundation structures using the impact pile-driving procedure in construction projects:

- HSD + Double Big Bubble Curtain (DBBC)

In this report we used feasible noise mitigation using a HSD + DBBC to reduce noise from piling activities to show the benefits of the noise reduction. With this combination, noise reductions of 22 dB (un-weighted) and more could be achieved (Bellmann et al., 2020). A reduction of 22 dB (un-weighted) was used in the noise modelling. The amount of additional reduction with multiple mitigation measures is limited because the remaining noise after the reduction is in the lower frequencies, which is more difficult to reduce.

However, the aim of this report is not to pinpoint one method, but rather to show the impact of installing monopiles with, and without mitigation measures. The conclusion will come in the appropriate technical reports.

Tables 7-4 and 7-5 show the overall source levels and respective frequency spectra.

Table 7-4 Construction sound source levels with mitigation.

Source	Information	Source Level, Peak, re. 1µPa @ 1 meter, peak.	Source Level, rms, re. 1µPa @ 1 meter,	Source Level, SEL(1sec), re. 1µPa²s @ 1 meter, single strike, Max.
Monopile Impact Piling (with mitigation: HSD and DBBC)	Impulsive. 18-meter diameter	233 dB	219 dB	209 dB

Table 7-5 Source levels with mitigation - Frequency spectra (dB re. 1 microPascal).

Freq. 1/3 octave band (Hz)	16	20	25	32	40	50	63	80	100	125	160	200	250	315	400	500	630	800	1 kHz
Spectra (non-linear dist. Correction), dB	180	193	198	200	199	199	196	196	199	204	198	194	187	184	177	173	167	164	163
Freq. 1/3 octave band (kHz)	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10.0	12.5	16.0	20.0	25.0	32.0	40	50	64	
Spectra (non-linear dist. Correction), dB	162	161	160	160	158	158	156	154	153	152	151	151	149	148	146	145	143	142	

8. GEOACOUSTIC MODELLING INPUTS

8.1.1 Bathymetry

The relief of the sea floor is an important parameter affecting the propagation of underwater sound, and detailed bathymetric data are therefore essential to accurate modelling. A base-level-resolution bathymetric dataset for the entire study area will be obtained from public EMODNET (The European Marine Observation and Data Network).

8.1.2 Geoacoustic properties

Seabed layer information was gathered from the available Geological survey data for areas close to the modelling positions and used in the modelling. The layers used in the modelling and the main parameters are depicted in Table 8-1 (Anderson 2017). These seabed conditions are used for the whole modelling area and an average of the whole site because limited data and could be adjusted to have individual seabed layer properties in the next version.

Table 8-1 Overview of seabed geoacoustic profile used for the modelling for positions, (Cp = compressed wave speed, α = compressional attenuation).

Seabed layer (m)	Material	Geoacoustic property
0 – 20	Sand	C_p = 1650 m/s α = 0.8 dB/λ
>20	Bedrock	C_p = 5250 m/s α = 0.1 dB/λ

8.1.3 Sound speed profiles/salinity

Water column data (salinity, temperature/depth) has been provided from ICES (International Council for the Exploration of the Sea) HELCOM specific measurement stations positioned close to the selected modelling positions. This data is used to calculate the sound speed profile for the modelling positions and used as input in the underwater sound propagation model. The salinity was set at 8 PSU (summer - winter) to calculate the underwater sound absorption coefficient (Ainslie and McColm, 1998).

Predictions have been performed for both winter (worst month) and summer water column conditions which have different underwater sound propagation characteristics and are shown in Table 8-2.

Table 8-2 Speed of sound profile data at the modelling positions.

Depth (m)	Winter Speed of sound m/s	Summer Speed of sound m/s
0	1418	1485
10	1418	1482
20	1418	1464
30	1420	1440
40	1420	1432
50	1420	1428

9. UNDERWATER NOISE MODELLING RESULTS

The sound propagation model was run with the source levels, source spectrum and environmental parameterization described in previous sections. The distances predicted to the various threshold limits are the maximum at any depth down to the bottom. The results of the acoustic modelling are given in terms of the maximum average radial distances from the investigation activities to the applicable assessment underwater noise threshold levels specified. The results of this study provide the expected potential underwater noise levels and exposure levels needed for assessments of potential impact on the harbour porpoise population, seals and fish and provide relevant documentation as part of the environmental permitting process.

Due to the relatively even sea floor bathymetry, the underwater sound does propagate relatively equal in all directions. For a better representation of the range of the radial distance from the activities to the impact threshold limits, the average of maximum distances of all positions are given. Figure 9-1 and Figure 9-2 are examples showing the propagation in horizontal and vertical plot to show 3-dimensional character of the underwater sound propagation.

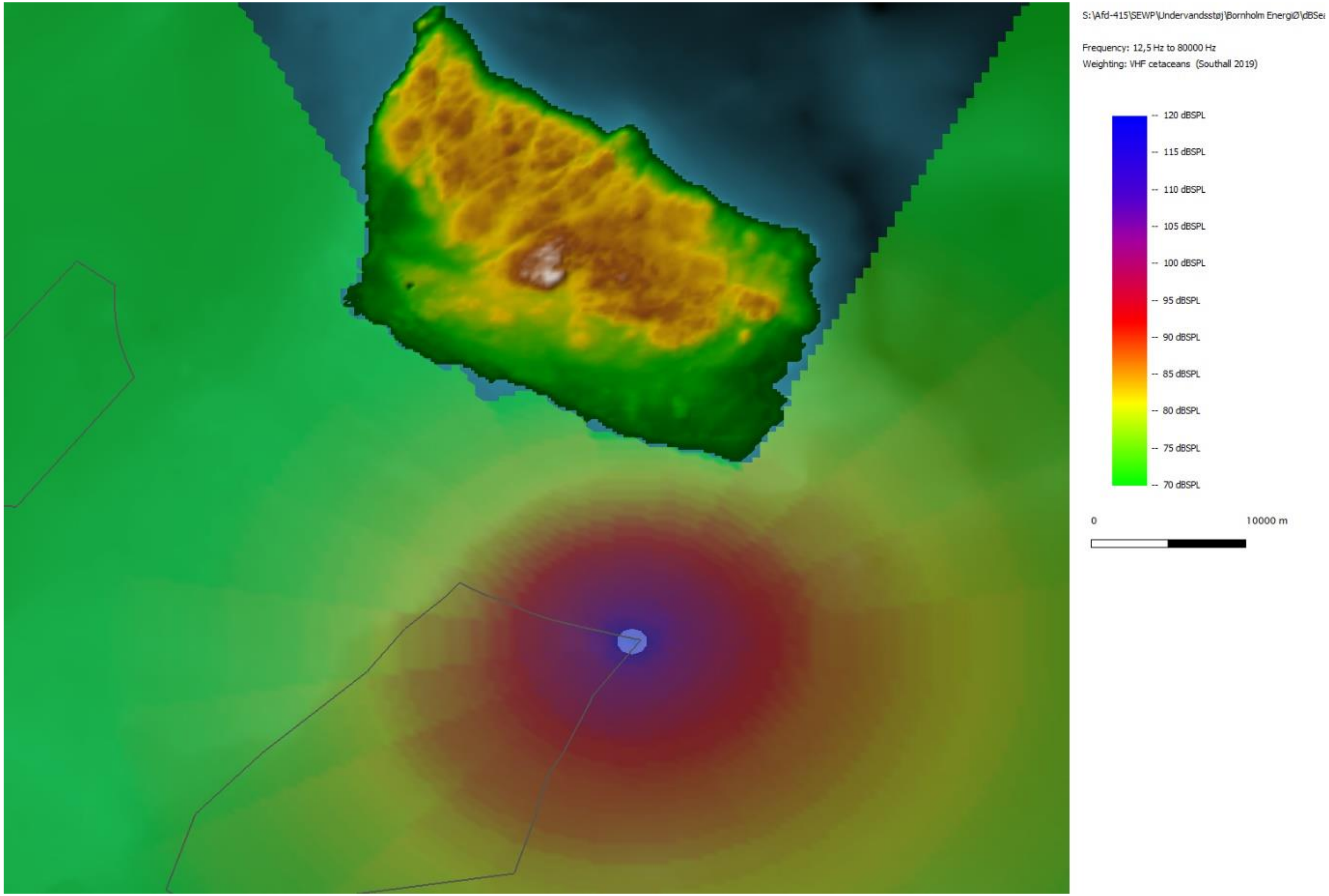

Figure 9-1 Example of horizontal underwater propagation (weighted VHF) vs. distance for Monopile pile driving.

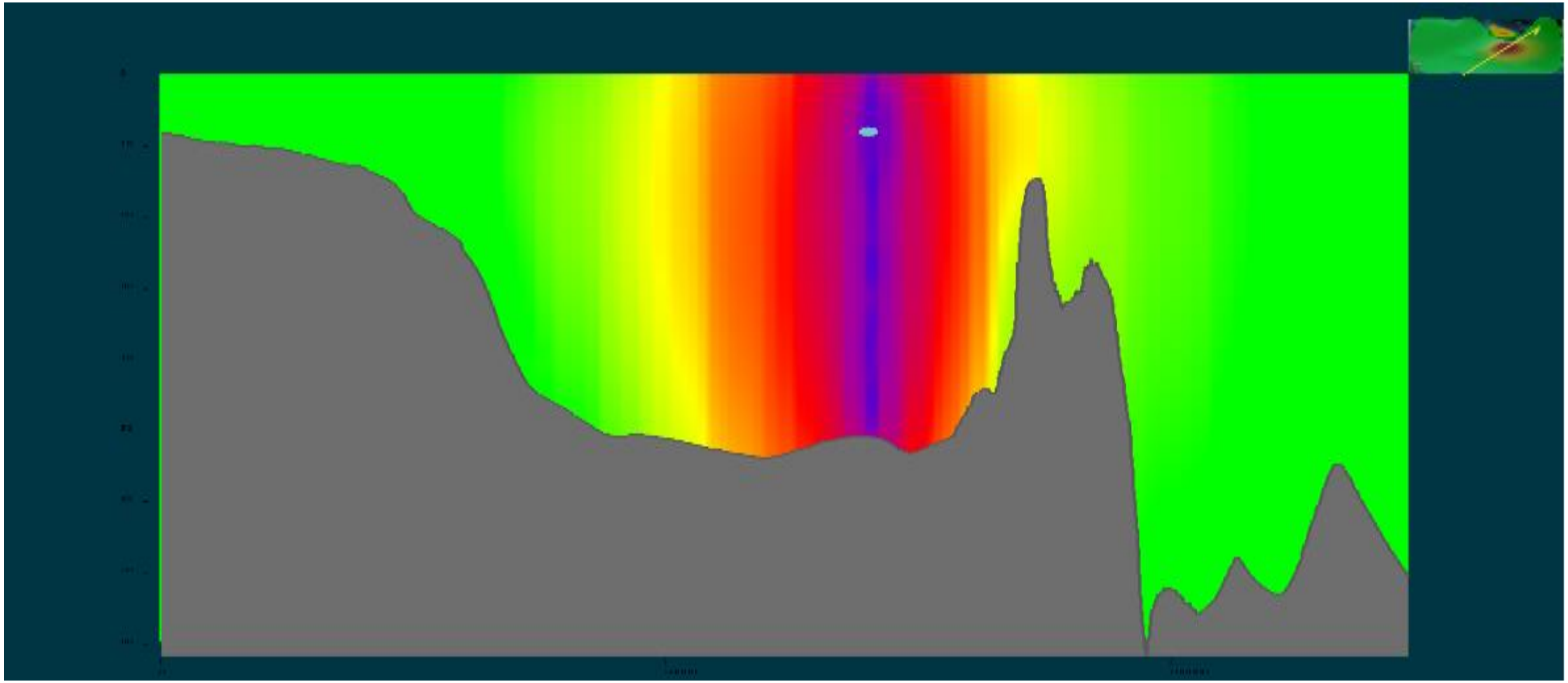

Figure 9-2 Example of vertical plot of underwater noise propagation (Unweighted) vs. depth and distance for Monopile pile driving.

The following sections summarize the results of the acoustic modelling in terms of the average maximum radial distances from the activities to the applicable assessment underwater noise threshold levels specified in Chapter 7.

9.1 Harbour Porpoise - distances to applicable assessment threshold level limits

For activities that have a potential to cause a PTS impact on harbour porpoise the effect of soft-start time is included in the cumulative noise exposure (SELcum) calculation. With a soft-start, the harbour porpoise will start to swim from the source of noise far enough from the source of noise before a risk of PTS. It is common practice in many seismic regulations and pile driving to ask for a gradual increase of sound emissions when beginning or after a stop in transmissions for whatever reason (technical, navigational, or due to a shutdown because of a marine mammal sighting). The rationale behind a soft-start is to provide a gradually increasing sound level, alerting any nearby marine mammals, and giving them opportunity to move to safe distances before the array starts transmitting at full power and in this way protect them from developing PTS or sustaining other injuries.

Impact pile driving of monopiles are calculated and have a soft start included in the modelling.

In the event that there could be two piling activities operating close to each other (800 meters apart), the detection and behaviour distances from each individual piling would be the same because the source is an impulse source, and the impacts are not synchronized to hit at the exact same time and the behaviour/detection thresholds are based on single strike levels. The piling of 2 piles would need to be synchronized within to 125 milliseconds (very unlikely, if not impossible) to potentially increase a combined behaviour response. The behaviour response distance should be considered the same.

The minimum noise reduction required for the proposed piling scenario (size, schedule and soft-start) to meet the PTS and TTS threshold limits, including the effect of an Acoustic Deterrent Device (ADD) is shown in Table 9-1. The use of an ADD is mandatory during the construction sequence of any single foundation and serves as a marine mammal mitigation technique of 200 meters deterrence

Table 9-1 The minimum noise reduction required for the unmitigated piling scenario to meet the VHF PTS and TTS threshold limits.

Activity	Unweighted	VHF weighted
Monopile piling, 18 m diameter	20 dB	36 dB

Table 9-2 shows the impact threshold distances from the pile driving modelling scenarios.

Table 9-2 Construction activity modelling results/radial distance from the activity/bubble curtain to threshold limits, average/maximum,

Modelling positions	Activity	Impulsive PTS*	Impulsive TTS*	Behaviour*
Harbour Porpoise (Winter)				
1-4	Monopile piling, 18 m diameter (no mitigation)	500 meters	25 kilometres	41.3/45.3 kilometres 32.9/51.2 kilometres 38.9/53.3 kilometres 34.3/51.9 kilometres
5-8	Monopile piling, 18 m diameter (no mitigation)	500 meters	25 kilometres	40.8/49.8 kilometres 38.5/51.2 kilometres 40.5/55.2 kilometres 38.0/54.8 kilometres
1-4	Monopile piling, 18 m diameter (with HSD, double BBC, and ADD)	0 meters (from BBC)	0 meters (from BBC)	7.2/7.3 kilometres 7.1/7.3 kilometres 5.6/6.5 kilometres 4.5/5.4 kilometres
5-8	Monopile piling, 18 m diameter (with HSD, double BBC, and ADD)	0 meters (from BBC)	0 meters (from BBC)	5.4/6.5 kilometres 6.1/7.0 kilometres 7.2/7.2 kilometres 7.1/7.3 kilometres
Harbour Porpoise (Summer)				
1-4	Monopile piling, 18 m diameter (no mitigation)	100 meters	18 meters	30.7/37.5 kilometres 23.3/34.8 kilometres 18.5/30.1 kilometres 13.4/17.3 kilometres
5-8	Monopile piling, 18 m diameter (no mitigation)	100 meters	18000 meters	14.3/18.8 kilometres 22.9/33.3 kilometres 22.5/35.2 kilometres 22.9/38.1 kilometres
1-4	Monopile piling, 18 m diameter (with HSD, double BBC, and ADD)	0 meters (from BBC)	0 meters (from BBC)	7.2/7.3 kilometres 7.1/7.3 kilometres 5.5/6.5 kilometres 3.9/4.8 kilometres
5-8	Monopile piling, 18 m diameter (with HSD, double BBC, and ADD)	0 meters (from BBC)	0 meters (from BBC)	5.3/5.7 kilometres 6.1/6.9 kilometres 7.0/7.7 kilometres 6.9/7.3 kilometres

* ENS guidelines, 2022. PTS, TTS Includes animal fleeing at 1.5 m/s.

9.2 Seals – distances to applicable assessment thresholds

For activities that have a potential to cause a PTS impact on seals the effect of soft-start time is included in the cumulative noise exposure (SELcum) calculation. With a soft-start, the seal will start to swim from the source of noise far enough from the source of noise before a risk of PTS. It is common practice in many seismic regulations and pile driving to ask for a gradual increase of sound emissions when beginning or after a stop in transmissions for whatever reason (technical, navigational, or due to a shutdown because of a marine mammal sighting). The rationale behind a soft-start is to provide a gradually increasing sound level, alerting any nearby marine mammals, and giving them opportunity to move to safe distances before the array starts transmitting at full power and in this way protect them from developing PTS or sustaining other injuries.

Impact pile driving of monopiles are calculated and have a soft start included in the modelling.

The minimum noise reduction required for the proposed piling scenario (size, schedule and soft-start) to meet the PTS and TTS threshold limits, including the effect of an Acoustic Deterrent Device (ADD) is shown in Table 9-3. The use of an ADD is mandatory during the construction sequence of any single foundation and serves as a marine mammal mitigation technique of 200 meters deterrence

Table 9-3 The minimum noise reduction required for the unmitigated piling scenario to meet the PWC PTS and TTS threshold limits.

Activity	Unweighted	VHF weighted
Monopile piling, 18 m diameter	22 dB	38 dB

Table 9-4 shows the impact threshold distances from the pile driving modelling scenarios.

Table 9-4 Construction activity modelling results/radial distance from the activity/bubble curtain to threshold limits, average/maximum.

Modelling positions	Activity	Impulsive PTS**	Impulsive TTS**	Behaviour*
Seals (Winter)				
1-4	Monopile piling, 18 m diameter (no mitigation)	1000 meters	40 kilometres	34.0/38.4 kilometres 28.0/38.1 kilometres 29.3/37.3 kilometres 27.1/38.4 kilometres
5-8	Monopile piling, 18 m diameter (no mitigation)	1000 meters	40 kilometres	32.2/38.4 kilometres 30.2/38.4 kilometres 32.5/44.9 kilometres 29.5/39.8 kilometres
1-4	Monopile piling, 18 m diameter (with HSD, double BBC, and ADD)	0 meters (from BBC)	0 meters (from BBC)	4.3/4.8 kilometres 4.5/4.9 kilometres 4.4/4.9 kilometres 3.8/4.9 kilometres
5-8	Monopile piling, 18 m diameter (with HSD, double BBC, ADD)	0 meters (from BBC)	0 meters (from BBC)	3.1/3.5 kilometres 3.6/4.1 kilometres 5.0/4.9 kilometres 6.3/6.5 kilometres
Seals (Summer)				
1-4	Monopile piling, 18 m diameter (no mitigation)	1000 meters	40 kilometres	29.9/38.9 kilometres 20.9/31.2 kilometres 14.9/28.4 kilometres 11.8/22.5 kilometres
5-8	Monopile piling, 18 m diameter (no mitigation)	1000 meters	40 kilometres	12.9/23.7 kilometres 20.1/31.6 kilometres 23.1/35.9 kilometres 21.8/34.1 kilometres
1-4	Monopile piling, 18 m diameter (with HSD and double BBC, and ADD)	0 meters (from BBC)	0 meters (from BBC)	4.3/4.8 kilometres 3.8/4.2 kilometres 3.9/4.6 kilometres 3.2/4.2 kilometres
5-8	Monopile piling, 18 m diameter (with HSD, double BBC, and ADD)	0 meters (from BBC)	0 meters (from BBC)	3.8/4.6 kilometres 3.9/4.2 kilometres 4.1/4.3 kilometres 5.0/5.5 kilometres

* Russel 2016

** ENS Guidelines (2022), Includes animal fleeing at 1.5 m/s.

9.3 Marine mammals – weighted (VHF, PCW) noise levels at 750 meters distance

Table 9-5 show the predicted underwater noise levels (SELss) for the mitigated (DDBC and HSD) monopile pile driving.

Table 9-5 Construction act1ivity modelling noise levels weighted values (VHF and PCW) maximum at 750 meters.

Activity	@ 750 meter, VHF SEL, dB re 1µPa²s	@ 750 meter, PCW SEL, dB re 1µPa²s
Monopile piling, 18 m diameter (with HSD and double BBC)	112 dB (VHF)	145 dB (PCW)

9.4 Fish

Impact threshold exposure distances for herring and cod including escape rates. For herring this study will use 1.04 m/s and for cod his study have used 0.38 m/s (juvenile) and 0.9 m/s (adult) and are shown in Table 9-6.

Table 9-6 Construction activity modelling results/radial distance from the activity/bubble curtain to threshold limits, average maximum (with double big bubble curtain and HSD).

Receptor	Impact type (Reference)	Fleeing speed [m/s]	Impulsive noise criteria [dB] Peak	Impulsive noise criteria [dB] SEL	Monopile piling, 18 m diameter (with HSD and double BBC)
Fish	Mortal injury (Popper 2104)	Herring 1.04 Cod(j) 0.38 Cod 0.9	207	207 (cum)	10 meters (peak) 10 meters (peak) 10 meters (peak)
Fish	Recoverable injury (Popper 2014)	Herring 1.04 Cod(j) 0.38 Cod 0.9	207	203 (cum)	10 meters (peak) 10 meters (peak) 10 meters (peak)
Fish	TTS (Popper 2014)	Herring 1.04 Cod(j) 0.38 Cod 0.9	-	186 (cum)	2500 meters 6000 meters 3000 meters
Larvae	Mortal injury (Popper 2014)	0	207	210 (cum)	500 meters (cum)

10. CONCLUSIONS

This study is an underwater noise propagation modelling for the construction (pile driving) of the proposed OWF. The purpose of this study is to provide the expected potential underwater noise levels and exposure levels needed for assessments of potential impact on the Harbour Porpoise population, seals and fish and provide relevant documentation as part of the environmental permitting process.

The modelled potential underwater noise levels and exposure levels were compared to relevant impact threshold limits for harbour porpoise, seals and fish. The following overall conclusions can be drawn from the results.

As can been seen in the results, the impacts permanent and mortal injury (PTS, mortal injury) are quite small for marine mammals with the noise mitigation measures combined with soft-start ramp up piling schedules and including a flee factor for the various animal species. However, behaviour impact disturbances for marine mammals and temporary impacts for fish are substantial.

10.1 Harbour Porpoise

1) Because of the mitigation measures proposed for the pile driving, the modelling results show that there is no risk of permanent hearing injury (PTS) for Harbour Porpoises for construction activities.

2) Modelled behaviour winter threshold maximum distances are up to 7.3 km (VHF weighted noise levels) from the monopile pile driving (with HSD and DBBC).

10.2 Seals

1) Because of the mitigation measures used for the pile driving, the modelling results show that there is no risk of permanent hearing injury (PTS) for Seals.

2) Modelled behaviour winter threshold distances are 6.5 km (unweighted noise levels) from the monopile pile driving (with HSD and DBBC).

10.3 Fish

1) With the mitigation measures used for the pile driving, the modelling results show that there is a risk of mortal injury for fish that are within 10 meters and 800 meters for recoverable injury and approximately 6 km TTS for monopile piling.

2) With the mitigation measures used for the pile driving, the modelling results show that there is a risk of mortal injury for larvae within 500 meters for monopile piling.

11. REFERENCES

Anderson *et al*., 2017, A framework for regulating underwater noise during pile driving, Swedish Defence Research Agency (FOI). Swedish Environmental Protection Agency 2017.

Ainslie M. A., McColm J. G., 1998 "A simplified formula for viscous and chemical absorption in sea water", Journal of the Acoustical Society of America, 103(3), 1671-1672.

Andersson *et al*., 2016, Andersson MH, Andersson S, Ahlsén J, Andersson BL, Hammar J, Persson LKG, Pihl J, Sigray P & Wikström A: Underlag för reglering av undervattensljud vid pålning. Vindval rapport 6723, August 2016.

Bellmann M. A., Brinkmann J., May A., Wendt T., Gerlach S. & Remmers P.,2020, Underwater noise during the impulse pile-driving procedure: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values. Supported by the *Federal Ministry for the Environment, Nature Conservation and Nuclear Safety* (*Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit* (BMU)), FKZ UM16 881500. Commissioned and managed by the *Federal Maritime and Hydrographic Agency* (*Bundesamt für Seeschifffahrt und Hydrographie* (BSH)), Order No. 10036866. Edited by the *itap GmbH*.

Bellmann, 2014, Overview of existing Noise Mitigation Systems for reducing Pile-Driving Noise. Proceeding on the Internoise 2014, Melbourne Australien.

Bellmann *et al*., 2015, Bellmann MA., Schuckenbrock J., Gündert S., Müller M., Holst H. & Remmers P.: Is there a State-of-the-Art to reduce Pile-Driving Noise, proceeding book: Wind Energy and Wildlife Interaction (Presentations from the CWW2015 Conference, Editor Johann Köppel, ISBN978-3-319-51270-9, Springer Verlag, 2015.

Danish Energy Agency (DEA), 2022, Guidelines for underwater noise, Prognosis for EIA and SEA assessments, Energistyrelsen.

Danish Energy Agency (DEA), 2022, Guideline for underwater noise, Installation of impact or vibratory driven piles, Energistyrelsen.

International Organization for Standardization. ISO 18406:2017 Underwater acoustics – Measurement of radiated underwater noise from percussive pile driving. Geneva (Switzerland): ISO; 2017

International Organization for Standardization. ISO 18405:2017 Underwater acoustics – terminology. Geneva (Switzerland): ISO; 2017.

Jensen, F.B., Kuperman, W.A., Porter, M., B., Schmidt, H., 2011, Computational Ocean Acoustics, Second Edition Springer, New York, Dordrecht, Heidelberg, London.

Matuschek, Rainer, 2009, Measurements of Construction Noise During Pile Driving of Offshore research Patforms and Wind Farms, NAG/DAGA.

Maxon, Skellerup, Tougaard, Working Group, 2015, Marine mammals and underwater noise in relation to pile driving, Energinet.dk Underwater noise and marine mammals Rev2 – 4, Energinet.dk.

Nedwell and Edwards, 2004, A review of measurements of underwater man-made noise carried out by Subacoustech Ltd, 1993 – 2003. Subacoustech Report ref: 534R0109.

NOAA, NMFS, 2018, Revisions to: Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0).

Popper, 2014, Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by, ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI Registered with ANSI on 20 April 2014.

Russell, D.J.F., G.D. Hastie, D. Thompson, V.M. Janik, P.S. Hammond, L.A.S. Scott-Hayward, J. Matthiopoulos, E.L. Jones, and B.J. McConnell., 2016, Avoidance of wind farms by harbour seals is limited to pile driving activities. J. Appl. Ecol.:1-11.

Southall, B.L., Bowles, A.E., Ellison, W.T., Finneran, J.J., Gentry, R.L., Greene, C.R.J., Kastak, D., Ketten, D.R., Miller, J.H., Nachtigall, P.E., Richardson, W.J., Thomas, J.A., Tyack, P., 2007, Marine mammal noise exposure criteria: initial scientific recommendations. Aquatic Mammals 33, 411-521.

Southall, 2019, Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing. *Aquatic Mammals* 2019, *45*(2), 125-232, DOI 10.1578/AM.45.2.2019.125 2019

Tougaard, J., 2016, Input to revision of guidelines regarding underwater noise from oil and gas activities - effects on marine mammals and mitigation measures, DCE – Danish Centre for Environment and Energy.

Tougaard, J., Carstensen, J., Teilmann, J., Skov, H., and Rasmussen, P., 2009, Pile driving zone of responsiveness extends beyond 20 km for harbour porpoises (Phocoena phocoena, (L.)). J.Acoust.Soc.Am. 126, 11-14.

Tougaard, J., Wright, A.J., and Madsen, P.T., 2015, Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises. Marine Pollution Bulletin, 90(1-2): p. 196-208.

Tougaard and Dahne, 2017, JASA Express Letters, Why is auditory frequency weighting so important in regulation of underwater noise?

Tougaard, Hermannsen, and Madsen, 2020, How loud is the underwater noise from operating offshore windturbines? JASA article, 24 November.