ENERGINET

MARINE ENVIRONMENTAL STUDIES – NORTH SEA I

TECHNICAL REPORT FOR UNDERWATER NOISE AND VIBRATIONS

10 JUNE 2024

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PROJECT NAME: MARINE ENVIRONMENTAL STUDIES – NORTH SEA I
PROJECT NO.: 22003230
DATE: 10-06-2024
VERSION: 3.0
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DESCRIPTION: UNDERWATER NOISE AND VIBRATIONS

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CONTENTS

Metics	
SEL_{05}	5 % exceedance of the Sound Exposure Level
SEL_{cum}	*Cumulative sound exposure*
SEL_{ss}	*Single strike sound exposure Level*
SPL	*Root mean square sound pressure level*
TL	Transmission Loss
A	Absorption coefficient
f_g	Cut off frequency
k	Propagation term

Units	
°C	*Degree Celsius*
‰	*Parts per thousand*
dB	*Decibel*
g/cm^3	*Gram per cubic centimeter*
Hz	*Hertz*
kHz	*Kilohertz*
kJ	*Kilojoule*
m	*Meter*
m/s	*Meter per second*
mm	*Millimeter*
MW	*Megawatt*

Abbreviations	
ADD	*Acoustic deterrence devices*
BfN	*Federal Agency for Nature Conservation*
DBBC	*Double Big Bubble Curtain*
GfUN	*Guideline for underwater noise*
GIS	*Geographic information system*
HF	*High-frequency*
HSD	*Hydro Sound Damper*
LAT	*Lowest Astronomical Tide*
LF	*Low-frequency, low-frequency*
NAS	*Noise Abatement System*
NSI.1	North Sea I, area 1. The name of area including all three OWF areas (A1, A2 and A3) and the shipping corridors in between the three sub-areas
OWF	*Offshore Windfarm*
PCW	*Phocid pinnipeds*
PTS	*Permanent threshold shift*
RAM	*Range-dependent Acoustic Model according to Collins (1995)*
TTS	*Temporary threshold shift*
VHF	*Very-high-frequency*
WTG	*Wind Turbine Generator*

1 SUMMARY

BACKGROUND

In order to accelerate the expansion of Danish offshore wind production, it was decided with the agreement on the Finance Act for 2022 to offer an additional 2 GW of offshore wind for establishment before the end of 2030. In addition, the parties behind the Climate Agreement on Green Power and Heat 2022 of 25 June 2022 (hereinafter Climate Agreement 2022) decided), that areas that can accommodate an additional 4 GW of offshore wind must be offered for establishment before the end of 2030. Most recently, a political agreement was concluded on 30 May 2023, which establishes the framework for the Climate Agreement 2022 with the development of 9 GW of offshore wind, which potentially can be increased to 14 GW or more if the concession winners – i.e. the tenderers who will set up the offshore wind turbines – use the freedom included in the agreement to establish capacity in addition to the tendered minimum capacity of 1 GW per tendered area.

In order to enable the realization of the political agreements on significantly more energy production from offshore wind before the end of 2030, the Danish Energy Agency has drawn up a plan for the establishment of offshore wind farms in three areas in the North Sea, the Kattegat and the Baltic Sea, respectively.

The North Sea I, area 1 (from now on NSI.1) has a total area of 1.400 km^2 which is divided into three sub-areas (From now on OWF-A1, A2 and A3) planned for offshore wind farms (see Figure 1-1). The NSI.1 is located 20-80 km off the coast of West Jutland and from each of the three sub-areas there will be corridors for export cables connecting the offshore wind farms to the onshore grid.

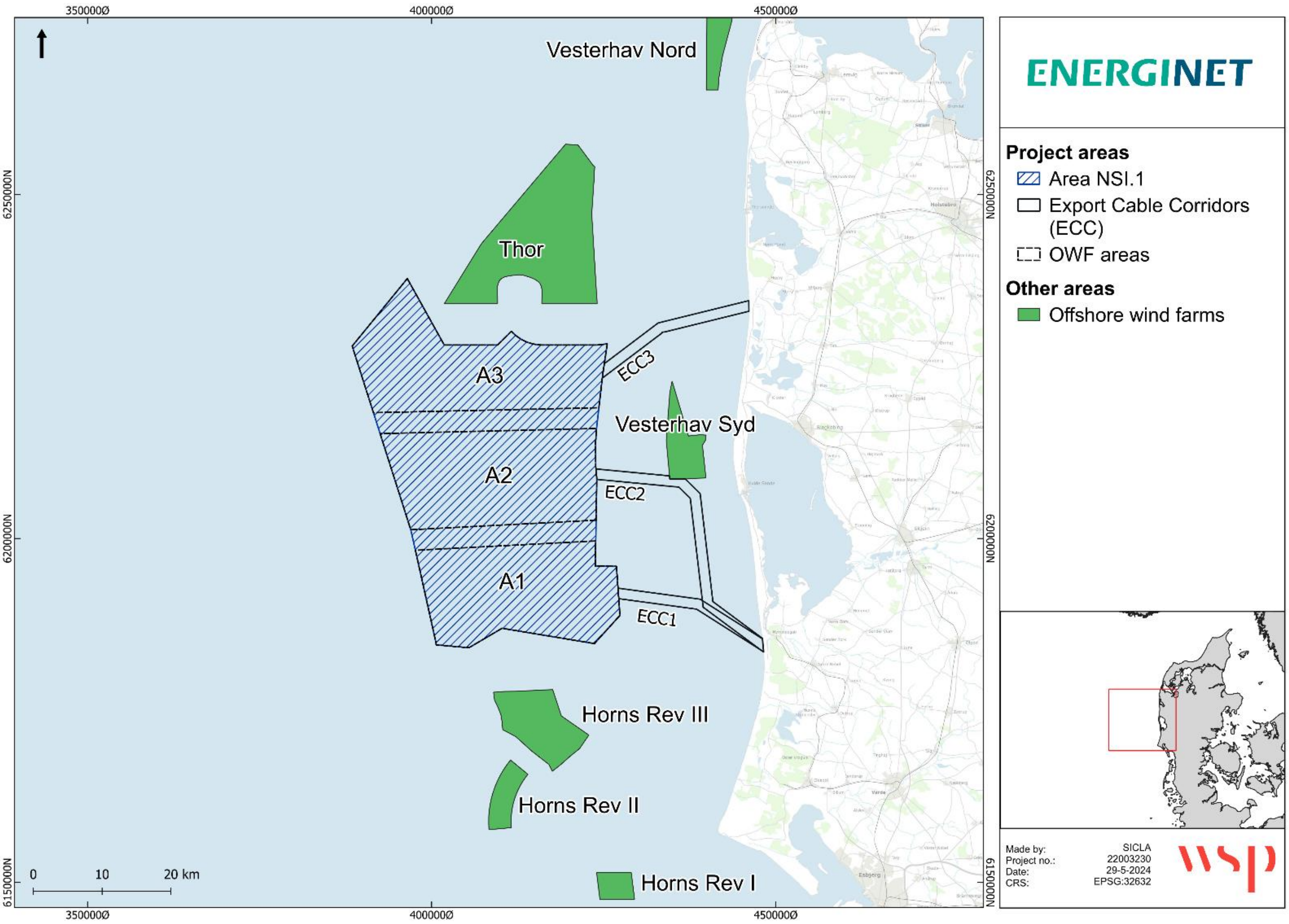

Figure 1-1. Overview of the three planned offshore wind farms (A1, A2 and A3) within North Sea I, area 1. The map also illustrates other offshore windfarms in the area (existing and approved).

OBJECTIVE

This report describes the work carried out as part of the pre-investigation for the NSI.1 OWF areas. This study is an underwater noise propagation modelling for the construction of the offshore wind turbines in the NSI.1 OWF areas and addresses monopile piling with and without mitigation measures. Modelling scenarios were defined to reflect the planned project, 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. Table 1-1 shows the maximum radial impact ranges for very-high-frequency cetaceans (VHF) (e. g. harbour porpoise, *Phocena phocena*), high-frequency cetaceans (HF) (e. g. White beaked dolphin, *Lagenorhynchus albirostris*), low-frequency cetaceans (LF) (e. g. Minke whale, *Balaenoptera acutorostrata*) and phocid pinnipeds (PCW) (e. g. harbour seal, *Phoca vitulina*) for monopile piling.

METHODOLOGY

The underwater noise model is carried out on two scenarios, in order to reflect the likely range of the future offshore wind farms, with regard to both size of monopiles and layout of turbines. Size and layout of the turbines will be determined by the future OFW developer(s). One of the modelling scenarios in this report is a wind farm layout with a total amount of 201 15 MW wind turbine generators (WTG), (67 per sub-area), which are to be installed in the NSI.1 area on monopile foundations with a diameter of 13 m. The other scenario is that 111 27 MW WTGs (37 per sub-area) will be installed on monopile foundations with a diameter of 18 m. The forecast modelling was done for a single exemplary location within each sub-area and OWF layout, which represent "worst case" scenario for that sub-area. For all locations, two piling sequences are considered: one with 4,000 kJ max blow energy and one with 6,000 kJ max blow energy.

Depending on how the development of new WTGs progresses, a scenario with 111 27 MW WTGs will also be considered in this forecast. The modelling was done for a single exemplary location within each sub-area and OWF layout, which represent a "worst case" scenario for each sub-area. For all locations, two piling sequences are considered: one with 4,000 kJ max blow energy and one with 6,000 kJ max blow energy.

The expected single Strike Sound Exposure Level values (SEL_{ss}) are calculated for a distance of 750 m based on an empirical model. The results are fitted to a numerical estimated transmission loss model, which was set up for each location in 24 different directions. With the transmission loss model, the cumulative Sound Exposure Level (SEL_{cum}) for a start distance of 200 m, with different frequency weightings according to Southall et al. (2019), were calculated as well as impact ranges for the threshold criteria according to Energistyrelsen ." Guidelines for underwater noise, Prognosis for EIA and SEA assessments" (2022) (GfUN)

CONCLUSION

According to GfUN (Energistyrelsen 2022), piling is allowed without the use of an ADD if the PTS impact distances are below 200 m, which is aimed for this project.

Depending on the species considered, the impact ranges for the unmitigated cases differ significantly. Due to the low-frequency sound input during piling, LF cetaceans have the largest PTS ranges, followed by VHF cetaceans, which hardly perceive low-frequency sound, but for which more sensitive threshold criteria were defined. The same noise mitigation concepts are applied in the modelling for each of the sub-areas. To avoid the risk of suffering PTS in the range of < 200 m, a DBBC is sufficient for all species except the LF-Cetaceans. They require a combination of HSD+DBBC. A summary of the results (maximum impact threshold distances) with a combination of HSD+DBBC is provided here in Table 1-1.

Table 1-1. Maximum radial impact ranges for the 4,000 and 6,000 kJ hammer with NAS* for all four marine mammal hearing groups. *NAS, Noise abatement system including Double Big Bubble Curtain (DBBC) and Hydro Sound Damper (HSD)

Activity	Hearing group	PTS [m]	TTS [m]	Behavior [km]
4,000 kJ (NAS*)	LF	120	11,299	-
	HF	6	11	-
	VHF	12	27	4.619
	PCW	39	99	-
6,000 kJ (NAS*)	LF	120	12,594	-
	HF	6	11	-
	VHF	12	27	5.600
	PCW	39	99	-

2 INTRODUCTION

2.1 BACKGROUND

In order to accelerate the expansion of Danish offshore wind production, it was decided with the agreement on the Finance Act for 2022 to offer an additional 2 GW of offshore wind for establishment before the end of 2030. In addition, the parties behind the Climate Agreement on Green Power and Heat 2022 of 25 June 2022 (hereinafter Climate Agreement 2022) decided), that areas that can accommodate an additional 4 GW of offshore wind must be offered for establishment before the end of 2030. Most recently, a political agreement was concluded on 30 May 2023, which establishes the framework for the Climate Agreement 2022 with the development of 9 GW of offshore wind, which potentially can be increased to 14 GW or more if the concession winners – i.e. the tenderers who will set up the offshore wind turbines – use the freedom included in the agreement to establish capacity in addition to the tendered minimum capacity of 1 GW per tendered area.
In order to enable the realization of the political agreements on significantly more energy production from offshore wind before the end of 2030, the Danish Energy Agency has drawn up a plan for the establishment of offshore wind farms in three areas in the North Sea, the Kattegat and the Baltic Sea, respectively.

The North Sea I area 1 has a total area of 1.400 km^2 which is divided into three sub-areas planned for offshore wind farms. The North Sea I area 1 is located 20-80 km off the coast of West Jutland and from each of the three sub-areas there will be corridors for export cables connecting the offshore wind farms to the onshore grid.

The purpose of this background report is to calculate the expected impact ranges of underwater noise on marine mammals according to the current planning status of three OWFs within the area NSI.1.
The geographical location of the NSI.1 area is illustrated in Figure 1-1.

2.2 OBJECTIVE

This is a baseline study for the NSI.1 OWF with the purpose of calculating the expected underwater noise input according to the current planning status and comparing it with the official requirements according to the GfUN (Energistyrelsen 2022). Based on the unmitigated results, different noise mitigation measures are taken into account with realistic best-case examples to show their potential and to verify which noise mitigation measures are suitable to fulfill the noise criteria according to the GfUN (Energistyrelsen 2022).

The focus is currently on two different layouts, one with a 15 MW wind turbine generator (WTG) and one with a 27 MW WTG, although WTG of this size are not yet available on the market.
Based on the current pile driving analysis, two piling sequences were defined with two different maximum pile driving energies, one for the currently largest available pile hammer with 4,000 kJ, and a one in which a 6,000 kJ hammer is considered.
From the two possible layouts, one location from each sub-area is selected from which the highest noise input is expected.
Due to identical assumptions, which are considered as input data for each foundation, site-specific differences are only to be expected due to the water depth profile and the associated transmission loss.

3 METHODOLOGY

3.1 AREA AND SUB-AREAS

The Project Area of the NSI.1 OWF is located approximately 20 km west of the Ringkøbing Fjord, within the Danish EEZ in the North Sea, and is divided into three sub-areas with shipping corridors between them. The water depths in the project area ranges between 11 m and 35 m (LAT) (See Figure 3-1 and Figure 3-2).

According to the current planning status, the final layout has not yet been decided. For the purpose of this underwater noise study two scenarios have been established; one with a total of 201 15 MW wind turbine generators (WTG), 67 per sub-area, which are to be installed on monopile foundations with a diameter of 13 m, and a scenario with a total of 111 27 MW WTGs installed on monopile foundations with a diameter of 18 m. Possible layouts of both scenarios are shown in the following figures. For the model, one exemplary location in each sub-area was chosen. Since there are no differences in pile diameter and blow energy between the respective foundations, the locations were selected in such a way, that the greatest possible differences in the location-specific transmission loss can be expected.

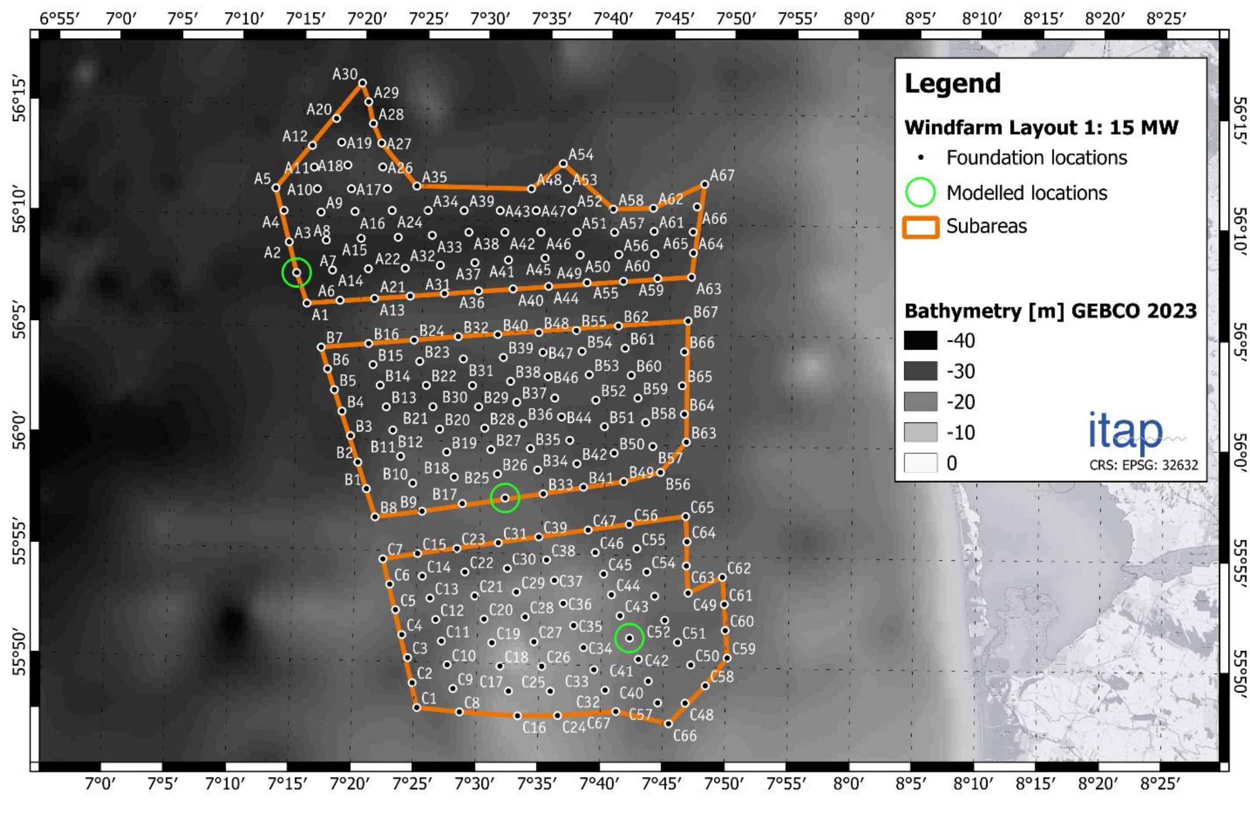

Figure 3-1. Wind Farm Example Layout of NSI.1 OWF for the 15 MW WTG scenario and the three sub-areas as of the strategic environmental assessment. The locations A2, B25 and C42 considered for use in the underwater noise modeling in each sub-area, are marked with green circles.

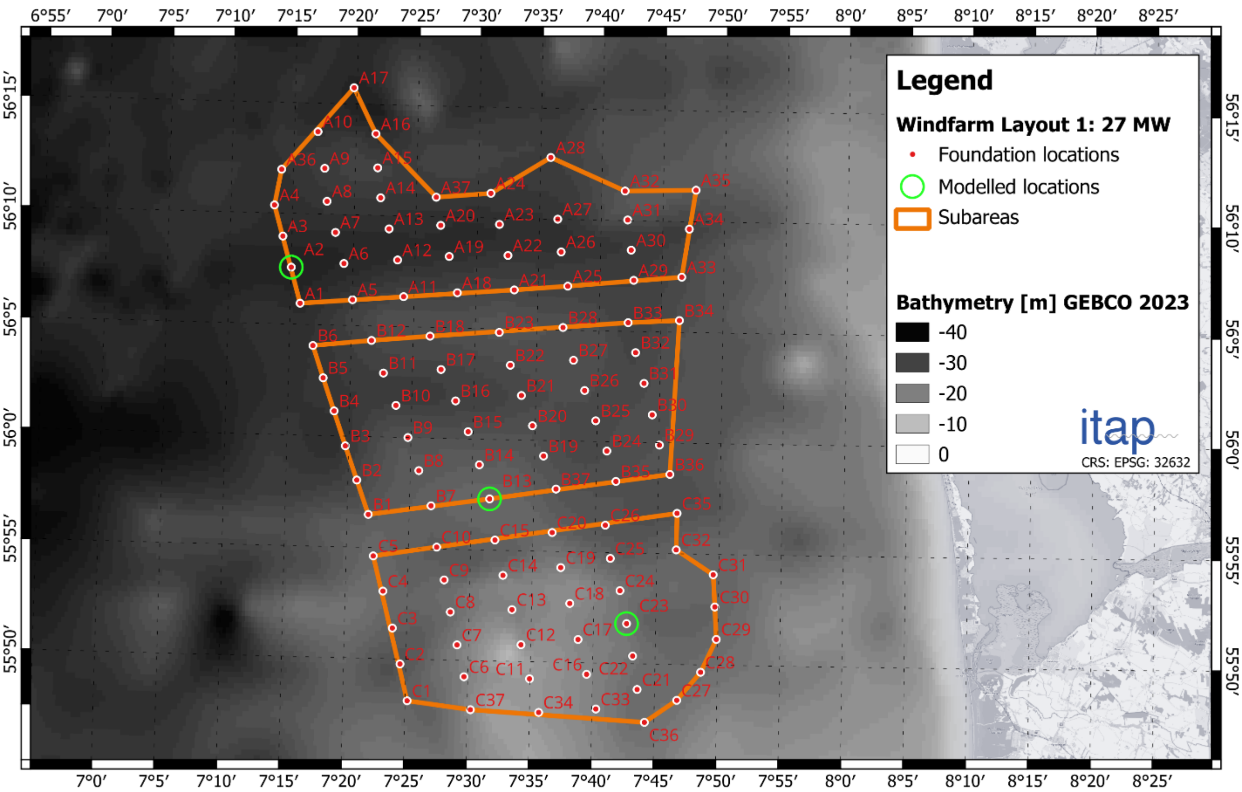

Figure 3-2. Wind Farm Example Layout of NSI.1 OWF for the 27 MW WTG scenario and the three sub-areas as of the strategic environmental assessment. The locations A2, B13 and C23 considered for use in the underwater noise modeling in each sub-area, are marked with green circles.

3.2 SOUND PROPAGATION IN SHALLOW WATERS

3.2.1 IMPACT OVER DISTANCE

For approximate calculations, it can be assumed, that the sound pressure decreases with the distance according to a basic power law. The level in dB is reduced about:

$$TL = k \cdot \log_{10}\left(\frac{r_1}{r_2}\right) \quad [\text{dB}]$$

Equation 1

with

r_1 and r_2 - Distances to the sound source. By convention, the distance to the sound source increases from r_1 to r_2 ,

k - absolute term (in shallow waters, an often-used value is k = 15, for spherical propagation, k = 20).

TL - Transmission Loss.

Often, the transmission loss is indicated for the distance r_1 = 1 m (fictitious distance to an assumed point source). This is used to calculate the sound power of the pile-driving at a distance of 1 m; often, this is called source level. When r_1 = 1 m, Equation 1 reduces to $TL = k \log_{10}(r)$. It must be considered, that the equation above is only valid for the far field of an acoustic signal, meaning in some frequency-dependent distance from the source. Considering piling noise, this is true for distances above 50 m.

Additionally, the absorption in water becomes more apparent in distances of several kilometers and leads to a further reduction of the sound pressure. This is taken into account with a constant proportional to the distance. Equation 1 expands to:

$$TL = k \log_{10}(r) + \alpha\, r \, [\text{dB}]$$

Equation 2

3.2.2 *IMPACT OF WATER DEPTH*

Sound propagation in the ocean is influenced by water depth. Below a certain cut-off frequency (f_g), a continuous sound propagation is impossible. The shallower the water, the higher this cut-off frequency is. The cut-off frequency (f_g) also depends on the type of sediment. An example of the lower cut-off for predominantly arenaceous soil as a function of water depth, is depicted in Figure 3-3. Moreover, the band widths of the lower cut-off frequency (f_g) at different soil layers, e. g. clay and chalk (till or moraine), are illustrated in grey (Jensen, et al. 2011). Sound around the cut-off frequency (f_g) is reduced or damped to a larger extent with an increasing distance to the sound source.

In this forecast, however, the sound propagation is calculated using a numerical model. This already considers the influence of water depth. The function shown in Figure 3-3 according to Jensen et al. (2011) serves only as an example illustration.

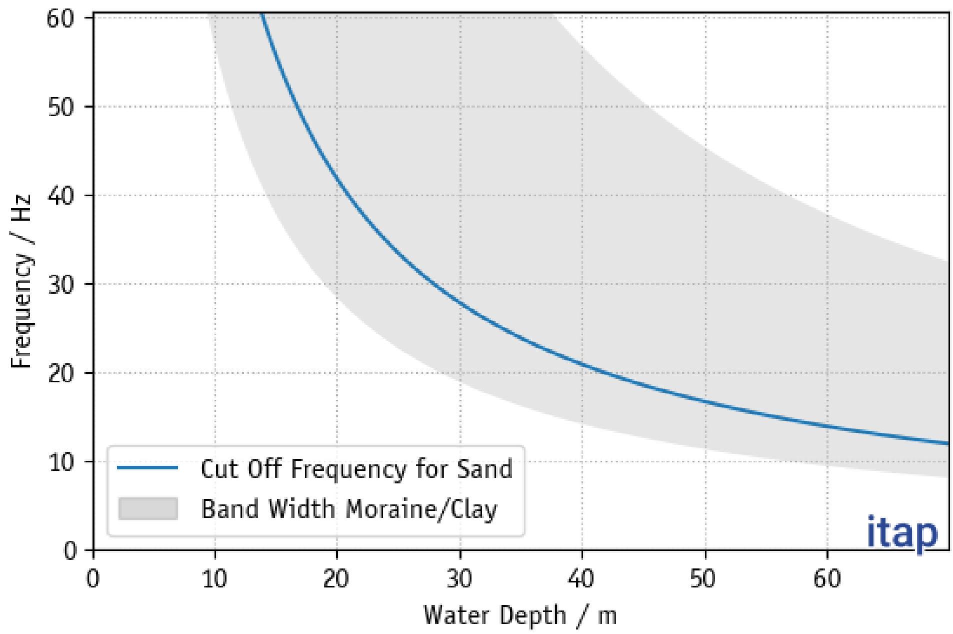

Figure 3-3. Theoretical lower (limit) frequency (f_g) for an undisturbed sound propagation in water as a function of the water depth for different soil stratifications (example adapted from Urick (1983); Jensen et al., (2011); the example shows the possible range caused by different soil, the presented soil types does not necessarily correspond to the soil in the project area).

3.3 THRESHOLD LEVEL

The emission of underwater noise during piling is a human intervention in the marine environment, which can have negative effects on the marine fauna. High sound pressure has the potential to harm marine mammals potentially leading to behavioral disturbance and permanent PTS (Permanent Threshold Shift) or temporary hearing damage TTS (Temporary Threshold Shift).

Table 3-1. Noise modeling threshold criteria and considered fleeing speeds for different animals according to GfUN by Energistyrelsen (2022). PTS: Permanent Threshold Shift, TTS: Temporary Threshold Shift.

Receptor	Impact type	metric	Fleeing speed [m/s]	Criteria [dB]
VHF	PTS	$SEL_{\text{cum, VHF}}$	1.5	155
VHF	TTS	$SEL_{\text{cum, VHF}}$	1.5	140
VHF	Avoidance	SPL_{VHF}	0	103
PCW	PTS	$SEL_{\text{cum, PCW}}$	1.5	185
PCW	PTS	$SEL_{\text{cum, PCW}}$	1.5	170
HF	PTS	$SEL_{\text{cum, HF}}$	1.5	185
HF	TTS	$SEL_{\text{cum, HF}}$	1.5	170
LF	PTS	$SEL_{\text{cum, LF}}$	1.5	185
LF	TTS	$SEL_{\text{cum, LF}}$	1.5	170

In order to assess the impact of noise on marine mammals, relevant threshold levels for impulsive sounds from various studies (Southall, et al. 2019) (Tougaard, Wright und Madsen 2015) were summarized in the GfUN (Energistyrelsen 2022) and used to determine impact ranges for different species of marine mammals. The guideline refers to the following metrics whose terminology conforms to ISO 18406 (2017) and is also used in this report:

- Root-mean-square sound pressure level (SPL)
- Single-strike sound exposure Level (SEL_{ss})
- Cumulative sound exposure (SEL_{cum})

Any noise mitigation measures should be adjusted so that the probability of marine mammals being present within the impact areas for PTS is very low. According to GfUN (Energistyrelsen 2022), this is the case if the PTS areas are < 200 m. If this is not possible, acoustic deterrence devices (ADD) can be used. This option requires separate calculation of the PTS ranges for harbor porpoises.

Pertaining to threshold levels for auditory injury of marine mammals, frequency weighted threshold levels are modelled. The frequency weighting functions are based on the audiograms for generalized hearing groups according to the recommendations by Southall et al. (2019). By means of hearing group specific weighting functions, frequencies outside the optimal hearing range are given less weight than frequencies within the hearing range. Figure 3-4 shows the weighting functions provided by Southall et al. (2019) for very-high-frequency cetaceans (VHF) (e. g. harbour porpoise, *Phocena phocena*), high-frequency cetaceans (HF) (e. g. White beaked dolphin, *Lagenorhynchus albirostris*), low-frequency cetaceans (LF) (e. g. Minke whale, *Balaenoptera acutorostrata*) and phocid pinnipeds (PCW) (e. g. harbour seal, *Phoca vitulina*). For modeling of cumulative Sound Exposure Levels (SEL_{cum}), an accumulation period of 24 hours, as recommend by the Southall et al. (2019), is applied in line with GfUN (Energistyrelsen 2022).

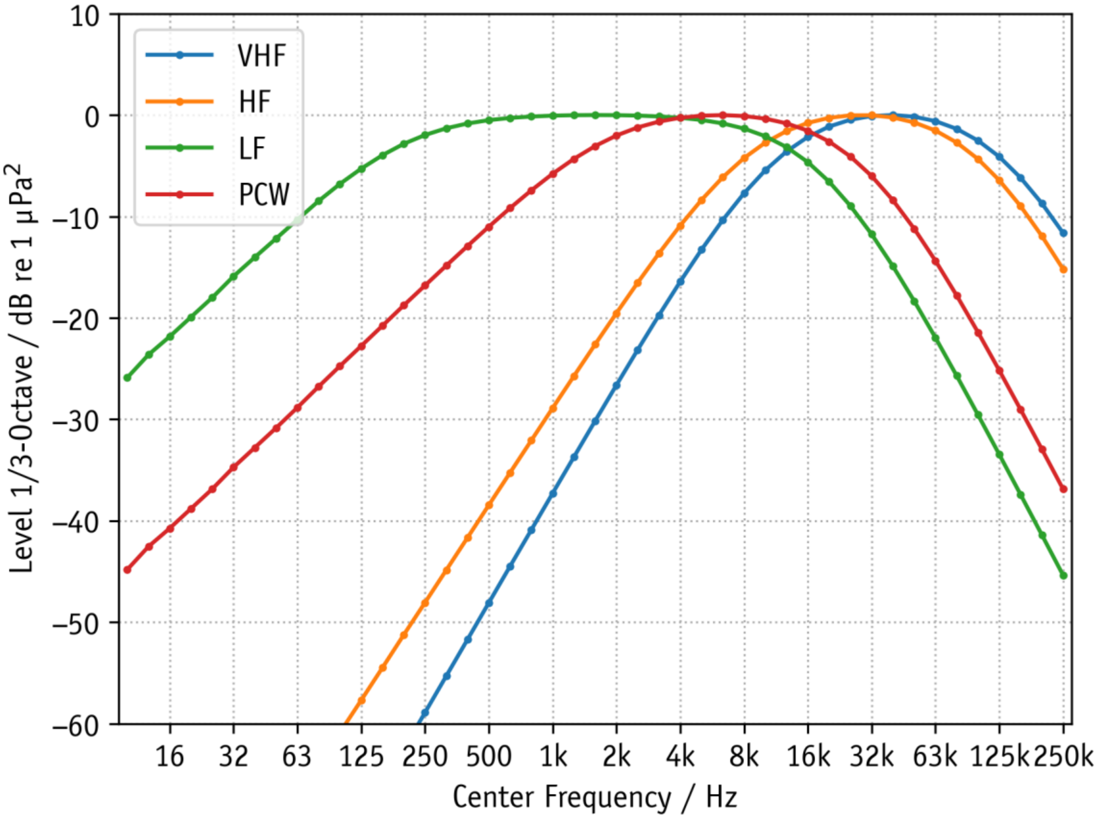

Figure 3-4. Weighting functions for very high-frequency cetaceans (VHF), high-frequency cetaceans (HF), low-frequency cetaceans (LF) and phocid seals (PCW) according to Southall et al. (2019).

3.4 MODEL DESCRIPTION

The model is based on an empirical database with measurements of unmitigated pile driving in 750 m distance. With that the expected single Strike Sound Exposure Level values SEL_{ss} are calculated as a function of the pile diameter, see Figure 3-5. The model uncertainty is ± 5 dB, when just accounting for the input parameter „pile diameter". Further impact parameters, like the blow energy and adjustments based on the soil conditions and water depth, are considered as described below in chapter 3.5.
For the prognosis, it is assumed that the ratio of the introduced blow energy that is converted into sound, is constant. Different ground conditions require different levels of blow energy and are therefore covered by this parameter. By considering the blow energy as a second input parameter, the overall prediction uncertainty can be reduced to ± 2 dB (Gündert 2014). Special soil conditions can result in higher sound radiation. For the modelling work there is no information about special soil conditions in the area considered for the modelling. However, if such special soil conditions existing in the area, such risks are covered with safety margins.

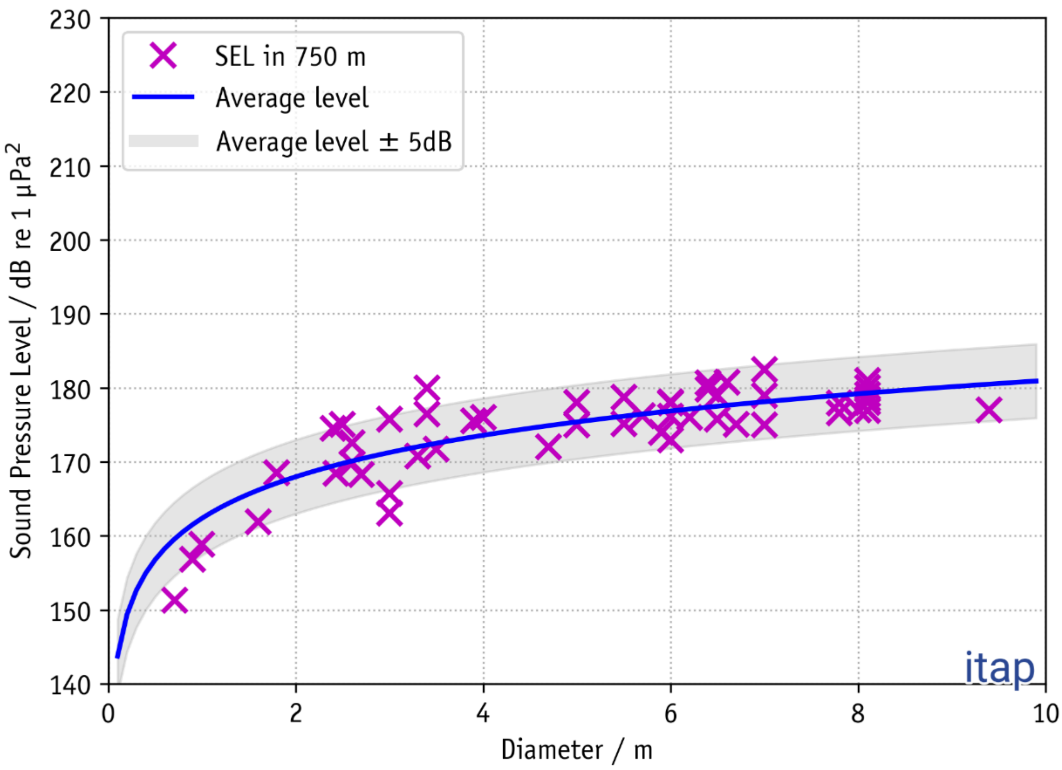

Figure 3-5. Measured broadband 5 % exceedance Sound Exposure Levels (SEL_{05}) at pile driving construction works as function of the pile diameter at a number of offshore wind farms (OWFs) (measurement data from itap database).

3.5 DETERMINATION OF THE SOURCE AND PROPAGATION LEVEL

The single strike Sound Exposure Level (SEL_{SS}) varies during the course of pile driving and depends on, as mentioned before, several parameters (e. g. pile diameter, reflecting pile skin surface, blow energy, soil conditions, wall thickness, etc.). The applied model only considers the pile diameter as influencing parameter in a first step. To get a statistically valid result of the loudest expected blows, the empirical model is based on the 5 % exceedance of the Sound Exposure Level (SEL_{05}).

3.5.1 BLOW ENERGY

Blow energy in the context of underwater noise refers, in this? project, to the energy generated during pile driving. A doubling in of the blow energy, meaning that the impact force on the pile becomes more intense, is considered with an increase of 2.5 dB (Gündert 2014). In order to take this influence into account in the model, a corresponding reference energy was determined based on empirical data.

3.5.2 HYDRO HAMMER

Currently, the influence of different hydraulic hammer types is not considered, since too many influencing paramet ers and factors exist, e. g. anvil design, contact area between hammer and pile, pile-gripper, or pile-guiding frame. Theoretical studies point out, that the influence of different hammer types could be in a range of 0 dB to 3 dB. No valid empirical data regarding different hammer types currently exist. Therefore, the *itap* model is focusing on the worst case (loudest possible) scenario. In case new and statistically valid results for the influencing factor hammer type becomes available within the project duration, these findings will be considered.

3.5.3 GROUND COUPLINGS

For the model, a constant ratio between blow energy and emitted sound energy during piling is assumed. That means that an increasing soil resistance (SRD-value) requires higher blow energies, which are already considered. But there are also circumstances in which this linear relationship does not apply. With a chalk layer, for example, there is the possibility that the hammer will cause the entire layer to vibrate, and it will become louder shortly before the hammer penetrates it. Higher sound pressure levels can also occur briefly in boulder clay. If such layers occur in the construction area, they will be taken into account accordingly with safety margins. However, such bottom structures are not expected in the North Sea.

3.5.4 SPECTRUM OF PILING NOISE

The estimations of the broad-band Sound Exposure Level (SEL_{ss}) shown in chapter 3.4, are based on the broad-band measuring data of different studies (Figure 3-5). However, the impact of noise abatement systems is highly frequency dependent. For this reason, estimations of the frequency composition of the respective source levels must be made for the calculations.

Figure 3-6 shows the spectral distribution in 1/3-Octave / dB re 1 µPa^2 of 113 different pile-driving measurements at different locations in different offshore windfarms. The range of different frequencies is shown by the gray area and the median of all 113 measurements as the blue line (unpublished measurement from itap). The spectra determined at different distances as well as at different blow energies and pile diameters run similarly. The frequency spectrum shows a maximum within the range 60-250 Hz. At frequencies above approximately 250 Hz, the level decrease gradually, while for frequencies lower than approximately 60 Hz a steep decrease in levels is observed. The cutoff frequency at low frequencies depends on water depth. The deeper the water, the lower the cutoff frequency. The maximal water depth in the NSI.1 project area is about 35 m. This results in cut-off frequencies < 50 Hz.

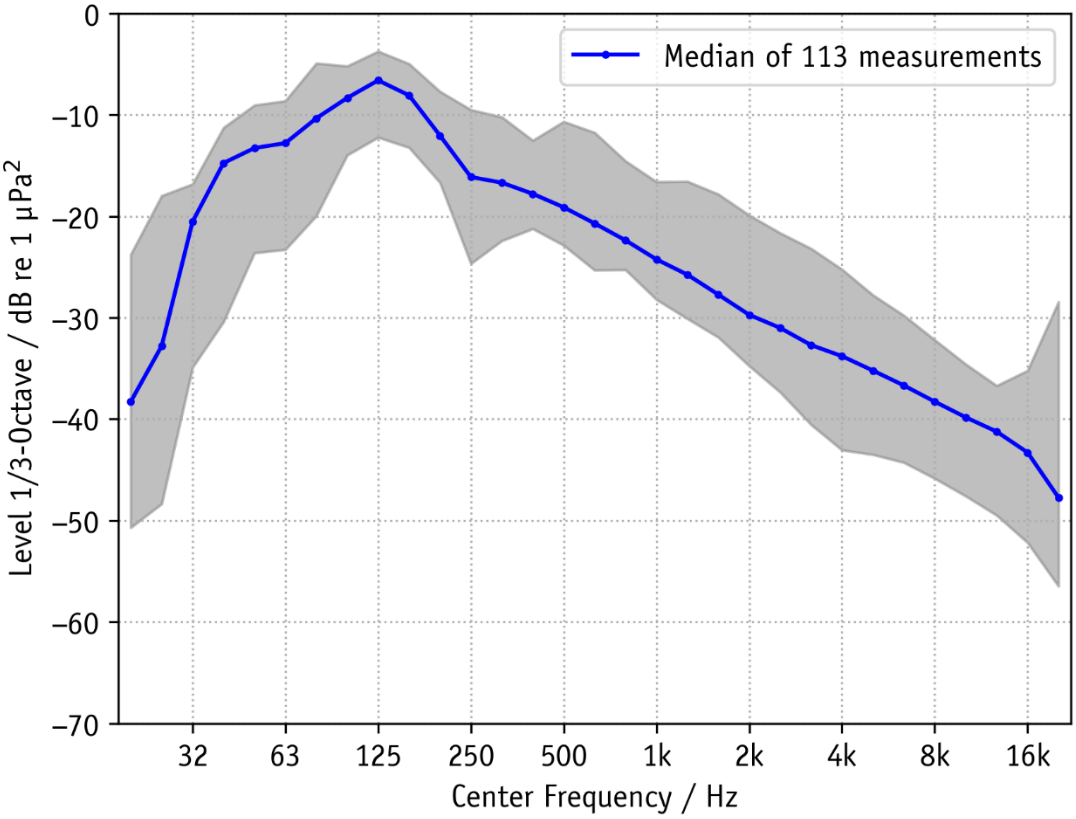

Figure 3-6. Median Sound Exposure Level (SEL_{SS}) and min/max ranges used for modeling (unpublished measurements from itap).

From measurements collected over the last two years (2021-2023), it has become apparent, that the hydraulic hammer type as well as the pile diameter, can have an influence on the piling noise spectrum generated during piling. The trend shows that the local maximum shifts to lower frequencies in the case of larger pile hammer types and larger pile diameters. At present, however, these influencing factors cannot be estimated with statistical validity and are therefore not accounted for in this forecast.

In detail, the spectral course of a piling noise event is not exactly predictable according to the present state of knowledge. Thus, for the modeling, an idealized model spectrum for the Sound Exposure Level will be extracted from the measured data of comparable construction projects. Figure 3-6 shows the shape of this idealized 1/3-octave-spectrum in blue color. The frequency-dependent amplitudes are normalized in a way so that the sum level of this spectrum, in 750 m distance, corresponds to the broadband source levels calculated before.

3.5.5 WATER DEPTH

The water depth influences sound propagation in the sea. Below a certain cut-off frequency, however, a continuous sound propagation is not possible. The shallower the water, the higher this frequency is. Figure 3-3 in chapter 3.2.2 shows the cut-off frequencies for an undisturbed sound propagation. For the modeling, all frequencies below this cut-off frequency will decrease with 12 dB/octave. The maximal water depth in the NSI.1 project area is about 35 m. This results in cut-off frequencies of < 50 Hz.

3.5.6 TRANSMISSION LOSS

For the modelling of the transmission loss, $TL = k\ \log_{10}(r) + \ \alpha\, r$ [dB] (Equation 2) is considered. To adapt the propagation term and the absorption coefficient to the local conditions, the transmission loss for frequencies was estimated for 24 transects in 15°-steps from the source using numerical model approaches and the bathymetry of the first 15 km from GEBCO 2023 of a 40 km x 40 km grid quantized in 2 m steps. A frequency range between 20 Hz and 125 kHz was considered. Below 50 Hz and beyond 40 kHz the propagation coefficients are so high, that these frequencies were neglected for distances below the reference distance of 750 m due to the high attenuation. Otherwise, unrealistically high values would result for this distance range; a high attenuation for distances above the reference distance of 750, lead to a high increase for distances below the reference distance. For frequencies below 5 kHz the Range-dependent Acoustic Model (RAM) according to Micheal D Collins (1995) and above 5 kHz the BELLHOP Beam tracing approach (Porter 2011) were used. For this, a constant receiver depth of 5 m was considered.
From the numerical results, the propagation term and the absorption coefficient are estimated using the ordinary least squared curve fitting. The resulting propagation terms and the absorption coefficients are listed for each third octave band and direction (marked with a "T" followed by the spatial direction in degrees) in the enclosed document: NS1_MES_WSP_WPD_TLC (**Fejl! Henvisningskilde ikke fundet.** 1).

3.5.7 MODELING REQUIREMNETS

The validated empirical pile-driving model fulfills the national guidelines from regulator GfUN (Energistyrelsen 2022) for impact pile-driving predictions, including the required outputs.

3.6 CALCULATION PROCEDURE

3.6.1 STEP 1. BROAD-BAND SOUND EXPOSURE LEVEL AT 750 M

The *itap* model predicts the Sound Exposure Level (SEL) based on the empirical data base in a specified distance of 750 m to the source in accordance to the requirements of the German measurement guidance (BSH 2011) and the international standard (ISO 18406 2017). The model results depend on the following parameter:

(i) the pile diameter,

(ii) the blow energy.

3.6.2 STEP 2: FREQUENCY DEPENDENCY OF THE SOURCE LEVEL AND TRANSMISSION LOSS

Similar to the broad band level, the spectral shape of the mitigated and unmitigated single strike Sound Exposure Level is based on the empirical database. All available 1/3-octave-spectra with the same noise mitigation measure were normalized to the same broadband level. These include 113 different measurements from unmitigated monopile pile installations (in the from North Sea and the Baltic Sea), 249 measurements from monopile installations using a double Big Bubble Curtain (DBBC), 49 using a Hydrosound Damper (HSD) and 684 using a combination of Hydrosound Damper and double Big Bubble Curtain (HSD+DBBC). From these measurements, the median is used as reference spectrum in 750 m distance and adjusted to the expected broad band level. As the measurement data used as a base generally only covers a frequency range up to 22 kHz, the resulting spectra are extrapolated to high frequencies up to 250 kHz. Figure 3-6 shows the spectral shape for the unmitigated SEL_{ss} in 750 m distance and the complete range of all available datasets. The resulting reference spectrum in 750 m distance is added to the transmission loss table, described in chapter 3.5.6.

3.6.3 STEP 3: CUMULATIVE SOUND EXPOSURE LEVEL

The cumulative Sound Exposure Level (SEL_{cum}) is the energetic sum of all impulses, a fleeing marine mammal is receiving during a piling installation, assuming that one monopile is installed within 24 hours. Therefore, a piling sequence needs to be defined, which was done by the client based on actual pile driving analyses.

The distance at which a fleeing marine mammal is located at a defined start distance for each individual pile-driving impulse is then determined. A constant fleeing speed of 1.5 m/s according to GfUN (Energistyrelsen 2022) is assumed for all of the marine mammals considered in this report. The single strike Sound Exposure Level SEL_{ss} is determined for each of the calculated distances.

3.6.4 STEP 4: IMPACT RANGES

The estimation of impact ranges is an iterative process. The cumulative SEL as described above is determined for 1 m start distance. If the resulting SELcum is above the respective threshold criteria, the calculation is repeated with increasing start distances as long as the result is above the criteria. The first iterated start distance, where the SELcum is below the respective criteria, gives the resulting impact range for the respective criteria and directions.

3.6.5 STEP 5: NOISE MAPS

The noise maps show the calculated impact ranges in all directions for each threshold criteria at each location within a Geographic Information System (GIS).

3.7 POSSIBLE SOURCES OF ERROR

The use of an empirical model for level estimation always brings a certain amount of variance and therefore also a certain amount of uncertainty. Measurements from completed construction projects (Bellmann, et al. 2020) with monopiles shows, that the measured SEL at the end of the pile driving sequence stays constant or decreases by up to 25 % despite an increase of the blow energy, i. e., it does not increase.

1. One possible explanation for this is the high penetration depth of the piles and the resulting elevated stiffness of the pile to be driven. There were also cases in which the Sound Exposure Levels steadily increased until the maximum penetration depth was reached (at simultaneous increase of the blow energy). The measurement data used for calculation at the reference distance of 750 m shows a scattering of +/- 5 dB in relation to the pile diameter (Figure 3-5). By considering the impact of "blow energy" the uncertainty is reduced.

2. The comparison of the model predictions with real measured data from 2012 until now, shows an uncertainty of ± 2 dB (not published data from different projects) for the SEL in a distance of 750 m to the piling event, with the tendency, that the *itap* model results with the input data "pile diameter" and "blow energy" mostly overestimates the metric SEL_{ss} in a distance of 750 m slightly.

3. It should be noted that this uncertainty only relates to single strike values. The entire piling sequence is determined by a pile driving analysis, which is also subject to an uncertainty that adds up to the prediction uncertainty. This means that significantly greater uncertainties apply to the SEL_{cum}.

4. The primary factor contributing to model uncertainty is transmission loss (TL) largely due to its sensitivity to weather conditions such as wind and waves. This can lead to uncertainties of over 2 dB in level predictions over distances greater than 10 km (Wang, et al. 2014). Typically, both semi-empirical and theoretical methods for estimating transmission loss underestimate propagation loss, resulting in an overestimation of levels over long distances.

4 NOISE MITIGATION

In general, noise mitigation can be achieved by applying:

- Noise Mitigation Systems, means to reduce the sound source level, like new hammer technologies,
- Noise Abatement Systems (NAS), means to reduce/damp the pile-driving noise in the water.

A general overview of Noise Mitigation Systems, technical Noise Abatement Systems and possible alternative low-noise foundation structures and -procedures, was published on behalf of the Federal Agency for Nature Conservation (BfN) for the first time in 2011 (Koschinski and Lüdemann 2011). In the following years, this study was updated (Koschinski and Lüdemann 2013). In Verfuss, Sinclair and Sparling (2019) a general overview of technical NAS is also given on behalf of the Scottish Natural Heritage. In this study, the effectiveness of each single Noise Abatement System and the expected costs of application are assessed by questionnaires. In Bellmann et al. (2020), an overview of the achieved overall noise reductions with Noise Mitigation Systems and Noise Abatement Systems within German waters were summarized.
In the following, the Noise Abatement Systems as well as the Noise Mitigation System will be described.

4.1 NOISE MITIGATION SYSTEMS

4.1.1 NOISE-OPTIMIZED PILING PROCEDURE

A possibility for underwater noise reductions is, as already mentioned, the reduction of the applied blow energy. Empirically, the acoustic parameters decrease approximately 2.5 dB, when the blow energy is halved (Gündert 2014). By applying "noise-optimized" pile-driving procedures with high blow rates and blow counts as well as low energy, the lower blow energy can almost be compensated by an increase of the blow frequency. The application of a noise-optimized pile-driving procedure depends significantly on the soil resistance value, which is highly depending on the penetration depth; the higher the penetration depth, the higher blow energy is usually needed. The sound reduction potential of "noise-optimized" pile-driving procedures is currently estimated to 1-3 dB. It depends on the soil properties and was measured in previous projects in the North Sea (unpublished data of itap GmbH).
When applying a noise-optimized pile-driving procedure, a real-time underwater noise monitoring in a distance of 750 m in accordance with the (ISO 18406 2017) is highly advised.

4.1.2 NEW HAMMER TECHNOLOGIES MNRU OR PULSE

New impact hammer techniques are currently under development such as the Menck Noise Reduction Unit (MNRU) or the PULSE system from IQIP b.v.. These new hammer techniques try to reduce the peak amplitude of the force transmission between hammer and pile and to prolong the duration of each single strike. Currently, these new hammer technologies are still under development. The damping effect can be adjusted by using different volumes of liquid levels inside the PULSE-unit ranging from 0 mm to 700 mm (reflecting 0 % to 100 %). Based on experiences, the minimum liquid level is 100 mm (P_{min}), 400 mm (P_{med}) and 700 mm (P_{max}). It was observed during the PULSE offshore-tests, that the transferred energy into the monopile was reduced due to the application of the PULSE-unit because this device is operating as a spring-damper system. Based on a conducted pile monitoring, the energy loss by application of the PULSE-unit ranged between 3 % for P_{zero} (means 0 mm liquid), 15 % for P_{med} and 30 % for P_{max}. This means that 30 % of the hammer energy might be reduced by the P_{max}.
First measurements show an overall noise reduction between 2 dB to 6 dB on the Sound Exposure Level; slightly higher overall noise reductions are achieved for the peak Sound Pressure Level. For the PULSE-setting P_{med} an overall noise reduction of 2 dB to 5 dB was measured.

However, based on the Blue-Piling offshore test, it is expected, that the unmitigated pile-driving spectrum will be shifted slightly towards low frequencies, resulting in a decrease in spectrum towards high frequencies. This means that the overall spectral shape will be flatter. The first offshore results where the PULSE unit is applied under real offshore conditions, also indicate a shift of the noise entry into water towards lower frequencies (unpublished data from itap GmbH).

Typically, the maximum noise entry into water by pile driving of unmitigated monopiles will be between 80 Hz to 160 Hz. By application of the new hammer technologies (PULSE, MNRU) the maximum noise entry into the water might range between 32 Hz to 200 Hz. This might have an influence of the achievable noise mitigation by applying noise abatement systems, but the effect is currently not statistically valid.

For the *MNRU* no measurements with or without the *MNRU* system under real offshore conditions are available, so a reliable evaluation regarding the achievable overall noise reduction cannot be given now. Therefore, an overall noise reduction of 4 dB broadband can be assumed.

4.2 NOISE ABATEMENT SYSTEMS

4.2.1 DOUBLE BIG BUBBLE CURTAIN (DBBC)

One of the most frequently applied noise abatement systems is the single and the double Big Bubble Curtain (BBC; DBBC). The Big Bubble Curtain is the only far-from-pile noise abatement system, that has been used in series production and is suitable for offshore use. The Big Bubble Curtain is used for the installation of monopiles as well as jacket structures, that are anchored to the seabed using the impulse pile-driving method.

However, the noise reduction of Big Bubble Curtains depends on many factors. Based on current knowledge, subsequent system configurations for a single or a double Big Bubble Curtain are necessary to achieve double-digit decibel-values for the noise reductions. By complying with the minimum requirements listed below, noise reductions significantly below 10 dB_{SEL} were observed.

System configurations for an optimized single/double Big Bubble Curtain:	
Hole size (diameter) and hole spacing:	1 - 2 mm all approximately 20 - 30 cm
Amount of air used:	≥ 0,5 m^3/(min*m) *[DBBC]*
Distance between the nozzle hoses:	≥ a water depth for a double BBC (flow-dependent)
Total length of both nozzle hoses:	≤ 1.800 m
Regular maintenance of the nozzle hoses applied.	
No turbulence-generating obstacles in the nozzle hoses.	

It is known from practical experience, that the difference between a single and an optimized Double Big Bubble Curtain with approximately comparable system configurations is 3 dB on average. Experience has shown that noise reductions of 15 dB to 16 dB are possible with a DBBC at water depths around 40 m.

The exact adaptation of the bubble curtain to the local conditions is not part of this prognosis. Due to the high variances caused by different system configurations, it is also not possible to make precise statements about the expected noise reduction.

Enhanced Big Bubble Curtain (eBBC)

An enhanced Big Bubble Curtain (eBBC) uses a nozzle hose with a diameter of 152 mm instead of the standard diameter of 102 mm. This enhancement results in a higher possible air volume of up to 1.1 $m^3/(min*m)$, instead of 0,5 $m^3/(min*m)$. First offshore tests have shown that a noise reduction equal to those of a Double Big Bubble Curtain can be reached. By changing the inner hose set of a Double Big Bubble Curtain (DBBC) to an enhanced Big Bubble Curtain (eBBC), an additional noise reduction up to 2 dB can be reached (unpublished measurement data of itap).

4.2.2 HYDRO SOUND DAMPER (HSD)

If the noise reduction of the DBBC is not sufficient, it would be possible to additionally use a Hydro Sound Damper (HSD). The Hydro Sound Damper consists of a fishing net with HSD-elements and a circular ballast ring. The HSD-elements consist of different foam material elements in different sizes. Each HSD-element is tuned to different frequencies and water depths, and the HSD-system must thus be adapted to the specific offshore wind project.

The whole system (ballast rings, grids and HSD-elements) can be driven into one another like a telescope for transport, as well as for the mobilization and demobilization via winch systems. It should be mentioned that, at present, the ballast box incl. lifting tools are always constructed for each single installation vessel (project-specific enhancement) and is not a state-of-the-art device. So far, the HSD system has mostly been applied for monopile installations and has shown sound reductions in the lower two-digit decibel range (10 dB to 12 dB) at water depths of up to 40 m in the North Sea, and at currents up to 1 knot (Bellmann, et al. 2020).

4.2.3 COMBINATION OF NEAR-TO-PILE AND FAR-FROM-PILE NOISE ABATEMENT SYSTEMS

At this point, it should be noted, that the noise reductions of each individual (separately) applied noise abatement system do not add up in a linear fashion, but are spectrally summed up, i. e. two noise abatement systems of 13 dB noise reduction each, do not result in a total of 26 dB noise reduction when applied simultaneously, but in a significantly lower total noise reduction.

From the logistic and acoustic perspective, the two noise mitigation systems, bubble curtains and hydro sound damper, are well combinable since the bubble curtains (BBC or DBBC) are operated from a separate vessel in some distance to the pile-driving position (generally at least 70 m) whereas the HSD system is directly operated from the installation vessel.

One advantage of using a HSD system in combination with a DBBC system is the ability to make optimizations during ongoing operation between the respective installations. In the case of the HSD, the HSD-elements could be tuned and optimized to certain frequencies in advance. The number of HSD-elements can be increased at any time by the complete exchange of a net, if needed. With a combination of optimized HSD and optimized DBBC, noise reductions of up to 19 to 20 dB_{SEL} (averaged) were achieved in the North Sea at 40 m water depth and 1 knot current (Bellmann, et al. 2020).

5 MODELING SCENARIOS

5.1 EXISTING CONDITIONS

The sound level at a location depends on the source strength and the transmission loss in water. As described in Chapter 3.5, the source strength of the individual blows depends primarily on the pile diameter and the blow energy. The pile diameter is the same for all foundations. Two cases are considered for the blow energy: one with 4,000 kJ max blow energy and one with 6,000 kJ max blow energy. The piling sequences defined for these cases are shown in Table 5-1 and Table 5-2.

Table 5-1. Considered piling sequence for the 4,000 kJ case including a soft start and a ramp-up procedure.

Number of blows	Blow energy [kJ]	Blow rate [blows/min]
225	400	15
75	1,000	15
75	2,000	15
75	3,000	15
10,050	4,000	15

Table 5-2. Considered piling sequence for the 6,000 kJ case including a soft start and a ramp-up procedure.

Number of blows	Blow energy [kJ]	Blow rate [blows/min]
225	400	15
75	1,000	15
75	2,000	15
75	3,000	15
75	4,000	15
75	5,000	15
6,400	6,000	30

The transmission loss in water depends on the composition of the water, the spatial extent (water depth) and the attenuation at the boundary layer to the sediment. These are accounted for in the model as follows:

Table 5-3. Input parameter for transmission loss model.

Parameter	Value
Water depth:	According to Annex 2
Water temperature:	10°C
Salinity	32 ‰
Sound speed in water	1,485 m/s
Sound Speed in seabed	1,650 m/s
Seabed density	1.6 g/cm^3
Seabed Attenuation	0.8 dB

The water temperature and the salinity were used to calculate the sound speed in water. The temperature is only shown here for completeness, the impact of temperature is negligible for the transmission loss in the frequency range under consideration. The model does not consider any background level. It will be assumed that the signal-to-noise-ratio between the pile-driving noise and the background noise will always be ≥ 10 dB. All relevant input parameters are summarized below for each sub-area.

5.2 ACOUSTICALLY RELEVANT INPUT DATA

5.2.1 NSI.1-A3

The following input data will be considered for the model:

Input data for the foundations	
- Foundation:	A02 for 15 MW WTG and A02 for 27 MW WTG (Figure 3-1 and Figure 3-2)
- Foundation types:	Monopiles
- Pile diameter:	13 m for 15 MW WTG and 18 m for 27 MW WTG
- Water depth:	35 m
- Blow energy:	Two sequences with max blow energies of 4,000 kJ and 6,000 kJ
- Noise Abatement Systems:	DBBC, HSD, HSD+DBBC

Model assumption to calculate the source level:	
- Input parameter #1:	pile diameter
- Input parameter #2:	blow energy: initial value (model internal parameter); 2.5 dB addition or deduction per duplication or halving of blow energy,
- Soil conditions:	no additions
- Broad band shifts and safety margins:	for ground couplings: 0 dB for penetration depth: 0 dB

5.2.2 NSI.1-A2

The following input data will be considered for the model:

Input data for the foundations	
- Foundation:	B25 for 15 MW WTG and B13 for 27 MW WTG (Figure 3-1 and Figure 3-2)
- Foundation types:	Monopiles
- Pile diameter:	13 m for 15 MW WTG and 18 m for 27 MW WTG
- Water depth:	24 m
- Blow energy:	Two sequences with max blow energies of 4,000 kJ and 6,000 kJ
- Noise Abatement Systems:	DBBC, HSD, HSD+DBBC

Model assumption to calculate the source level:	
- Input parameter #1:	pile diameter
- Input parameter #2:	blow energy: initial value (model internal parameter); 2.5 dB addition or deduction per duplication or halving of blow energy,
- Soil conditions:	no additions
- Broad band shifts and safety margins:	for ground couplings: 0 dB for penetration depth: 0 dB

5.2.3 NSI.1-A1

The following input data will be considered for the model:

Input data for the foundations	
- Foundation:	C42 for 15 MW WTG and C23 for 27 MW WTG (Figure 3-1 and Figure 3-2)
- Foundation types:	Monopiles
- Pile diameter:	13 m for 15 MW WTG and 18 m for 27 MW WTG
- Water depth:	21 m (C42), 22 m (C23)
- Blow energy:	Two sequences with max blow energies of 4,000 kJ and 6,000 kJ
- Noise Abatement Systems:	DBBC, HSD, HSD+DBBC

Model assumption to calculate the source level:	
- Input parameter #1:	pile diameter
- Input parameter #2:	blow energy: initial value (model internal parameter); 2.5 dB addition or deduction per duplication or halving of blow energy,
- Soil conditions:	no additions
- Broad band shifts and safety margins:	for ground couplings: 0 dB for penetration depth: 0 dB

6 MODELING RESULTS

6.1 UNMITIGATED PILE DRIVING

6.1.1 CALCULATED LEVEL VALUES

Considering the model approaches in chapter 5 and the piling sequences described in chapter 5.2, the following single Strike (Figure 6-1 and Figure 6-2) and cumulative Sound Exposure (Figure 6-3 and Figure 6-4) are expected without noise mitigation measures. To make the number of calculated variants clearer, the results for all six considered foundations (two monopile diameter sizes and two energy blow levels at 1 positions in each of the three sub-areas) as broadband level and frequency weighted level are summarized in the following Barplots (Figure 6-1 and Figure 6-2). The level difference between both maximum blow energies is 1.5 dB. The directional differences for each location and distance of the 24 calculated directions are shown as black Error lines (from min to max) for each bar. Since 750 m is the reference distance, there are no directional level changes for this distance. A detailed result presentation of all single strike and cumulative metrics as well as the impact ranges for each direction can be found in the enclosed table NS1_MES_WSP_WPD_MOR (**Fejl! Henvisningskilde ikke fundet.** 2).

6.1.2 SINGLE STRIKE SOUND EXPOSURE LEVEL (SEL)

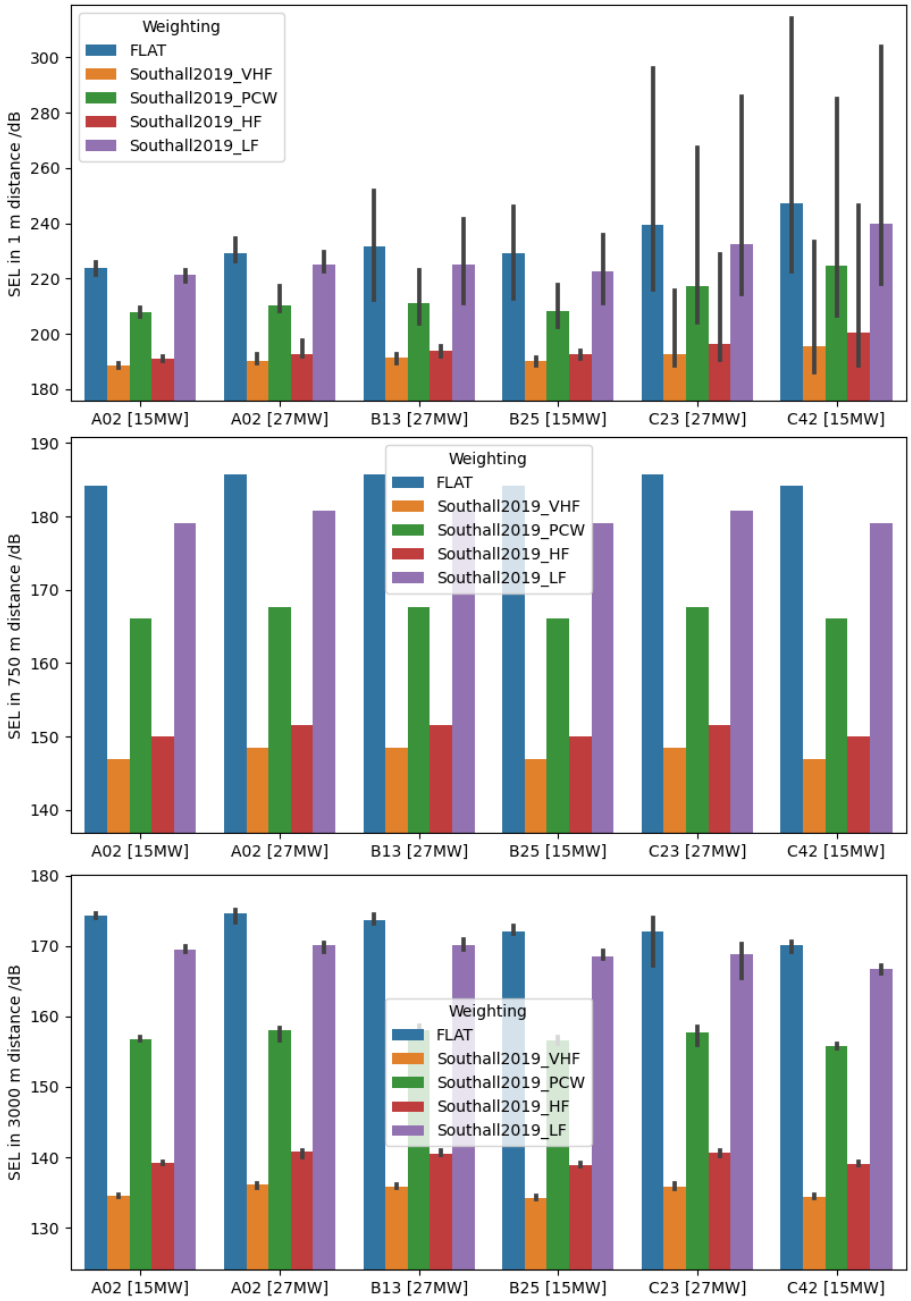

Figure 6-1. Calculated broadband Sound Exposure Level (SEL) for different frequency weightings according to Southall et al. (2019) and in different distances for each location considering a maximum blow energy of 4,000 kJ (unmitigated). The blue FLAT-bare represent unweighted values see GfUN .

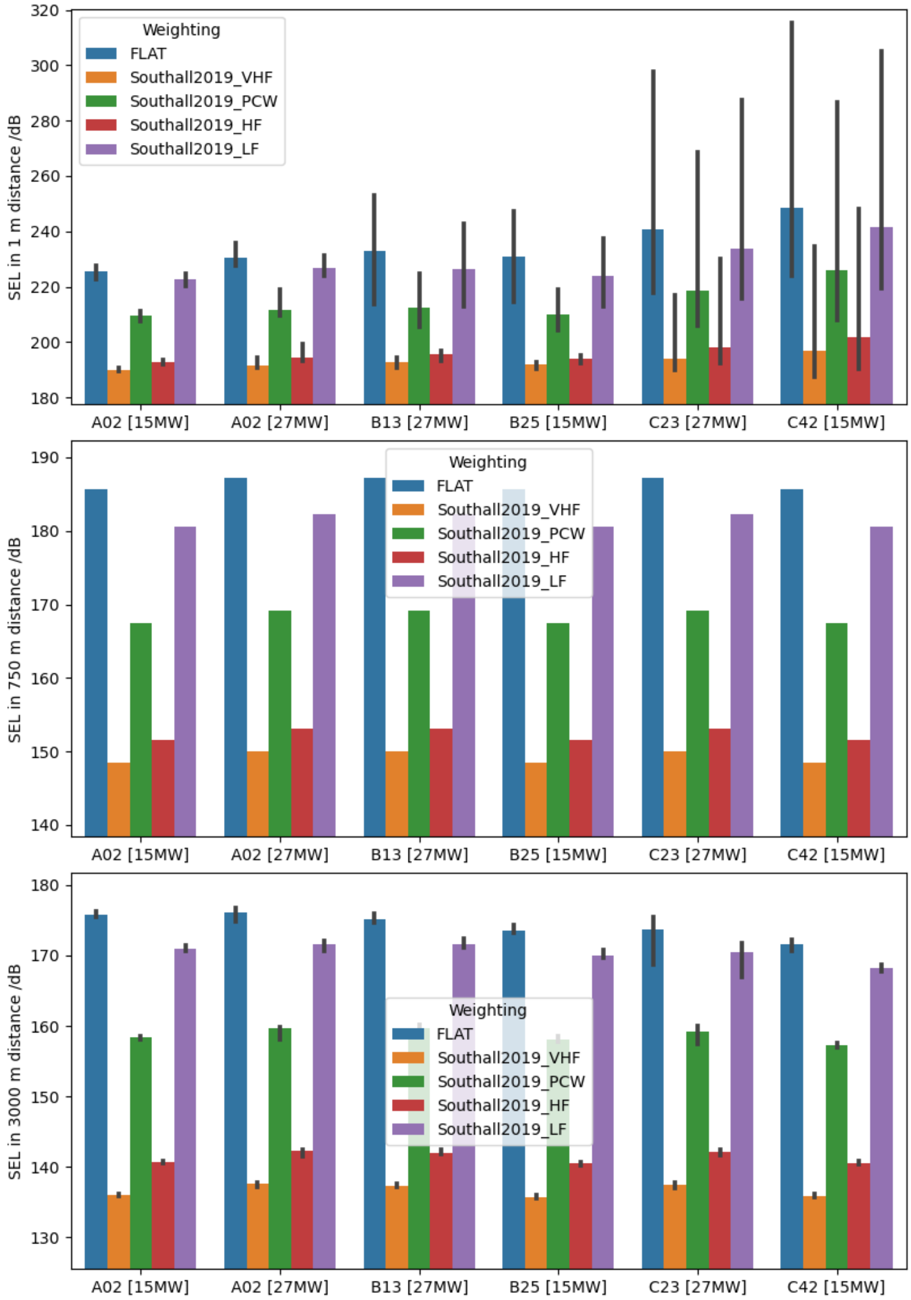

Figure 6-2. Calculated broadband Sound Exposure Level (SEL) for different frequency weightings according to Southall et al. (2019) and in different distances for each location considering a maximum blow energy of 6,000 kJ (unmitigated) The blue FLAT-bare represent unweighted values see GfUN .

6.1.3 CUMULATIVE SOUND EXPOSURE LEVEL (SEL_{CUM})

Cumulative impacts depend on the number of blows, which in turn depends on the soil properties. Based on the available pile driving analyses, it can be assumed that site-specific differences lead to a reduction in total number of blows.

Due to the fleeing of the respective species, the received SEL_{ss} decreases with increasing distance to the installation. For the SEL_{cum} this has the consequence, that it is saturated and hardly increases with increasing number of blows. This is approximately the case when the SEL_{ss} is at least 20 dB lower than the loudest SEL_{ss}. A 20 dB lower SEL means that 99% less sound energy is contained in the impulse. If the source level remains constant over the piling sequence, this is the case from ten times the starting distance. Figure 6-3 and Figure 6-4 summarizes the expected SEL_{cum} for 200 m scaring distance as barplots.

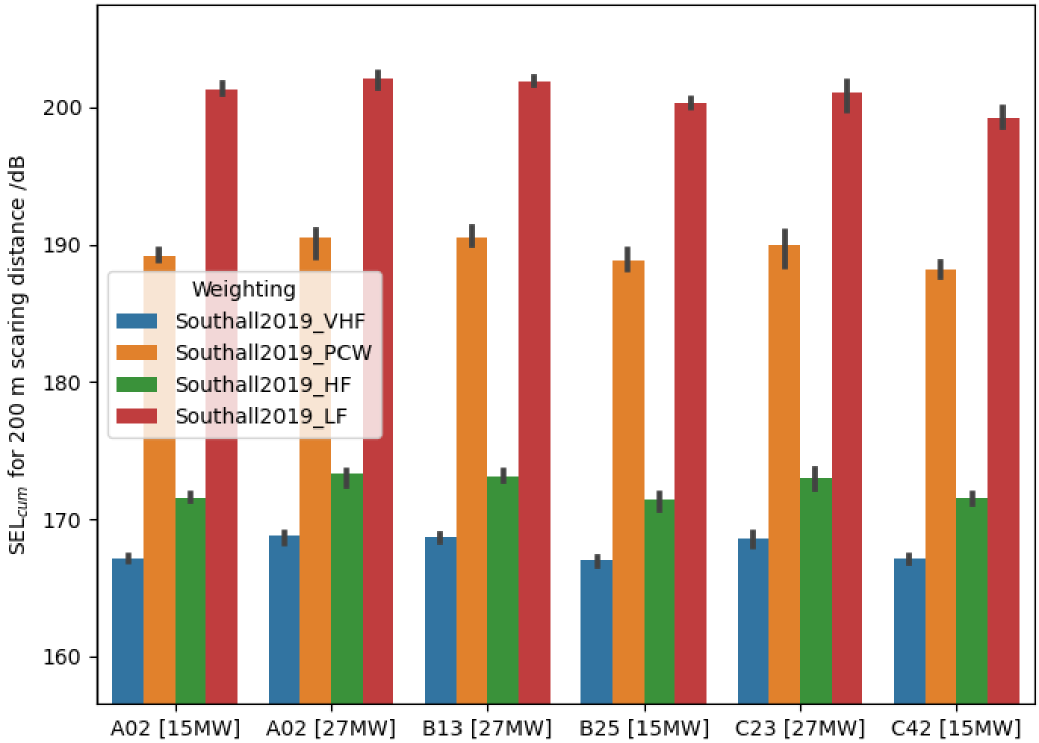

Figure 6-3. Cumulative Sound Exposure Level (SEL$_{cum}$) for 200 m scaring distance for each piling position (unmitigated) considering different frequency weightings according to Southall et al. (2019) and a piling sequence with a maximum blow energy of 4,000 kJ.

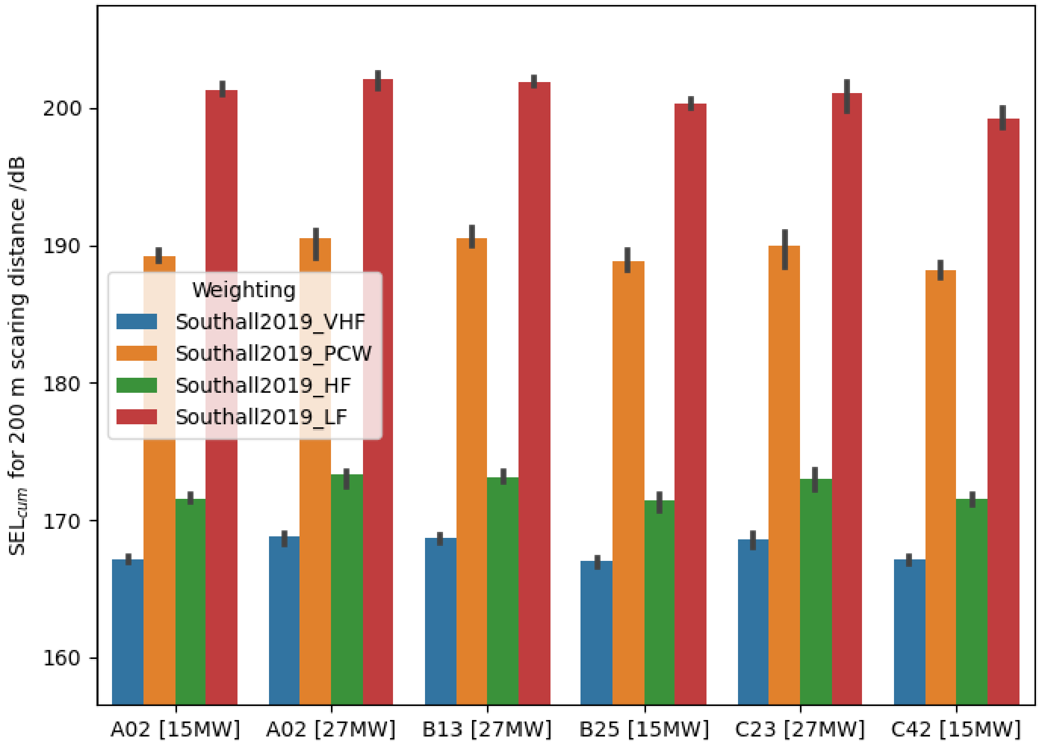

Figure 6-4. Cumulative Sound Exposure Level (SEL$_{cum}$) for 200 m scaring distance for each piling position (unmitigated) considering different frequency weightings according to Southall et al. (2019) and a piling sequence with a maximum blow energy of 6,000 kJ.

6.1.4 DISTANCES TO THRESHOLD LEVEL

The following tables (6-1 to 6-4) show the distances at which the impact distances fall below the threshold criteria from Chapter 3.3. These distances indicate how far a marine mammals must be away from the construction site at the start of piling, so that it is unlikely to suffer permanent (PTS) or temporary hearing damage (TTS) or to show an escape reaction. The detailed values can be found in the enclosed table NS1_MES_WSP_WPD_MOR (**Fejl! Henvisningskilde ikke fundet.** 2)

The impact distances for each unmitigated scenario are shown below as a bar plot in Figure 6-5 for the 4,000 kJ case and in Figure 6-6 for the 6,000 kJ case. The error bars show the variance in different directions. As an example, the impact distances in all modeled spatial directions for the 13 m scenario with 4000 kJ at location C42, are shown as a noise map in Figure 6-7.

Table 6-1. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 13 m monopiles and 4,000 kJ blow energy sequence (unmitigated).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B25 [km]	Distance at C42 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	3,236	3,319	1,893
VHF	PTS	$SEL_{cum,VHF}$	155	9,906	9,791	11,107
HF	PTS	$SEL_{cum,HF}$	185	0,001	0,002	0,014
LF	PTS	$SEL_{cum,LF}$	185	24,992	18,575	13,045
PCW	TTS	$SEL_{cum,PCW}$	170	57,553	49,993	38,215
VHF	TTS	$SEL_{cum,VHF}$	140	80,012	64,598	65,232
HF	TTS	$SEL_{cum,HF}$	170	0,572	0,564	0,575
LF	TTS	$SEL_{cum,LF}$	170	> 100	> 100	46,451
VHF	Avoidance	SEL_{VHF}	103	> 100	> 100	> 100

Table 6-2. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 13 m monopiles and 6,000 kJ blow energy sequence (unmitigated).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B25 [km]	Distance at C42 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	4,032	4,113	2,462
VHF	PTS	$SEL_{cum,VHF}$	155	11,045	10,921	12,354
HF	PTS	$SEL_{cum,HF}$	185	0,001	0,002	0,014
LF	PTS	$SEL_{cum,LF}$	185	26,537	20,056	14,409
PCW	TTS	$SEL_{cum,PCW}$	170	58,513	49,993	38,215
VHF	TTS	$SEL_{cum,VHF}$	140	80,634	65,891	66,347
HF	TTS	$SEL_{cum,HF}$	170	0,752	0,747	0,770
LF	TTS	$SEL_{cum,LF}$	170	> 100	> 100	48,224
VHF	Avoidance	SEL_{VHF}	103	> 100	> 100	> 100

Table 6-3. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 18 m monopiles and 4,000 kJ blow energy sequence (unmitigated).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B13 [km]	Distance at C23 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	4,854	6,598	4,974
VHF	PTS	$SEL_{cum,VHF}$	155	14,206	15,54	15,02
HF	PTS	$SEL_{cum,HF}$	185	0,003	0,002	0,008
LF	PTS	$SEL_{cum,LF}$	185	18,325	32,891	19,578
PCW	TTS	$SEL_{cum,PCW}$	170	53,199	> 100	85,024
VHF	TTS	$SEL_{cum,VHF}$	140	96,887	> 100	> 100
HF	TTS	$SEL_{cum,HF}$	170	1,522	1,555	1,561
LF	TTS	$SEL_{cum,LF}$	170	74,015	> 100	> 100
VHF	Avoidance	SEL_{VHF}	103	> 100	> 100	> 100

Table 6-4. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 18 m monopiles and 6,000 kJ blow energy sequence (unmitigated).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B13 [km]	Distance at C23 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	5.833	7.714	5.972
VHF	PTS	$SEL_{cum,VHF}$	155	15.617	16.874	16.366
HF	PTS	$SEL_{cum,HF}$	185	0.003	0.002	0.008
LF	PTS	$SEL_{cum,LF}$	185	19.763	34.015	21.110
PCW	TTS	$SEL_{cum,PCW}$	170	54.522	> 100	84.721
VHF	TTS	$SEL_{cum,VHF}$	140	97.4	> 100	> 100
HF	TTS	$SEL_{cum,HF}$	170	1.942	1.966	1.986
LF	TTS	$SEL_{cum,LF}$	170	75.361	> 100	> 100
VHF	Avoidance	SEL_{VHF}	103	> 100	> 100	> 100

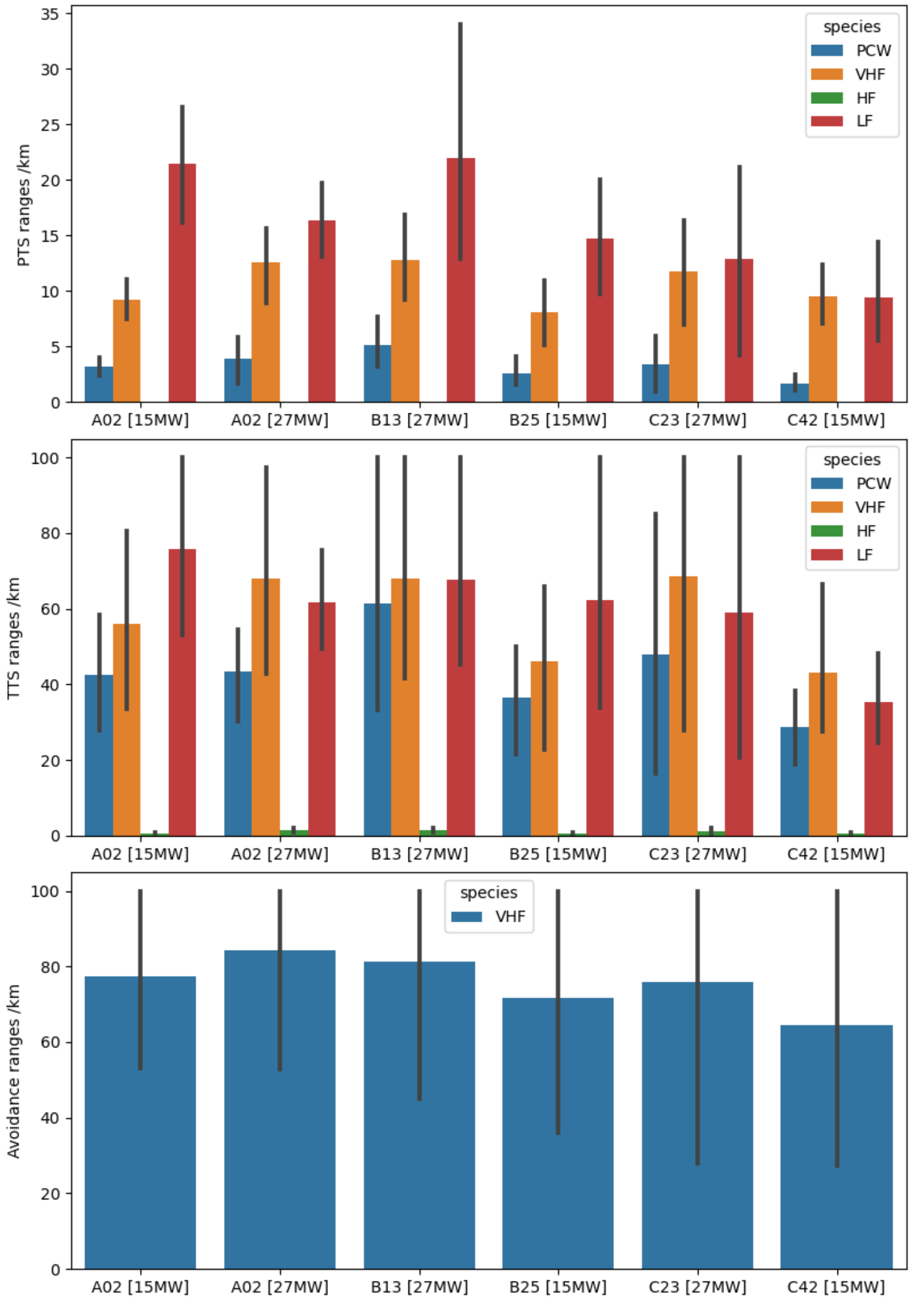

Figure 6-5. Impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for each location considering a piling sequence with a maximum blow energy of 4,000 kJ (unmitigated).

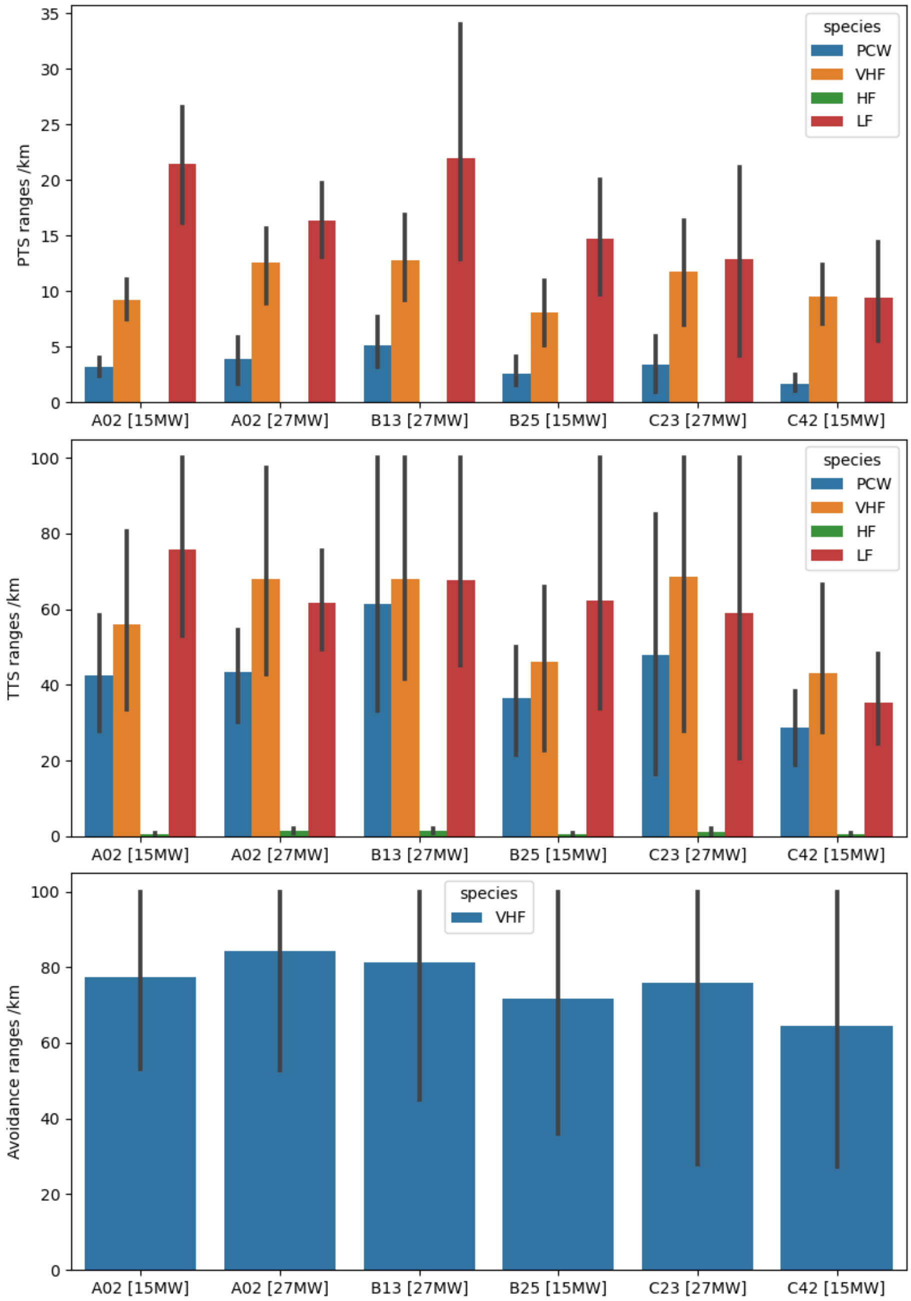

Figure 6-6. Impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for each location considering a piling sequence with a maximum blow energy of 6,000 kJ (unmitigated).

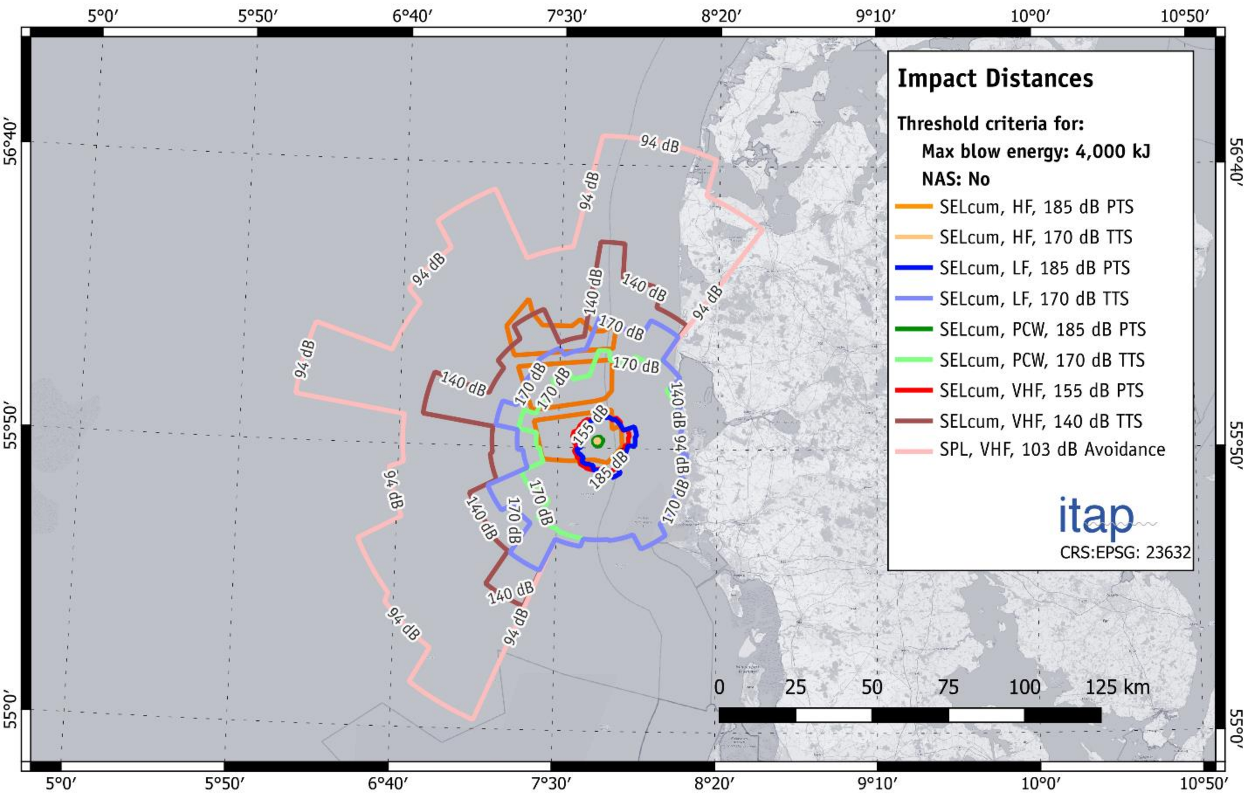

Figure 6-7. Impact ranges for the threshold criteria according to GfUN (Energistyrelsen 2022) for location C42 with 13 m pile diameter and the 4,000 kJ piling sequence (unmitigated).

6.2 MITIGATED PILE DRIVING: DOUBLE BIG BUBBLE CURTAIN (DBBC)

6.2.1 CALCULATED LEVEL VALUES

The following figures show the expected noise input when applying a DBBC. Apart from the DBBC, the same input data was assumed as for the unmitigated case. An example scenario was defined for the DBBC with a broadband noise reduction of 15 dB (Bellmann, et al. 2020). The 1/3 octave spectrum assumed for this, is based on measurement results at 750 m from the foundation of 249 previous measurements and is compared with the unmitigated spectrum in Figure 6-8.

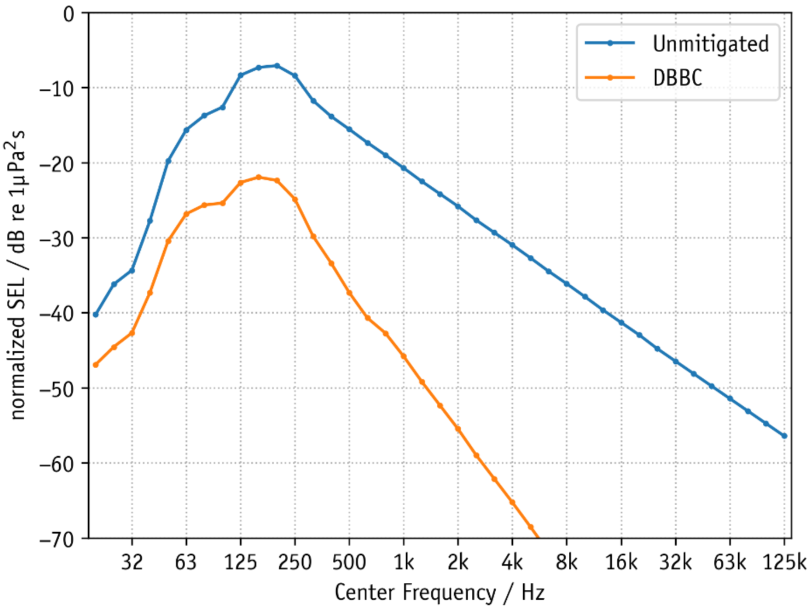

Figure 6-8. Normalized spectrum of a single strike Sound Exposure Level (SEL_{ss}) in 1/3 octaves for the unmitigated case and by using a DBBC with 15 dB total noise reduction.

To make the number of calculated variants clearer, the results for all six considered foundations (two monopile diameter sizes and two energy blow levels at 1 position in each of the three sub-areas) as broadband level and frequency weighted level are summarized in the following barplots (Figure 6-9 and Figure 6-10) in the same way as in the unmitigated case. The directional differences for each location and distance of the 24 calculated direction are shown as black error lines (from min to max) for each bar. A detailed result presentation of all single strike and cumulative metrics as well as the impact ranges for each direction can be found in the enclosed table NS1_MES_WSP_WPD_MOR (**Fejl! Henvisningskilde ikke fundet.** 2).

6.2.2 SINGLE STRIKE SOUND EXPOSURE LEVEL (SEL)

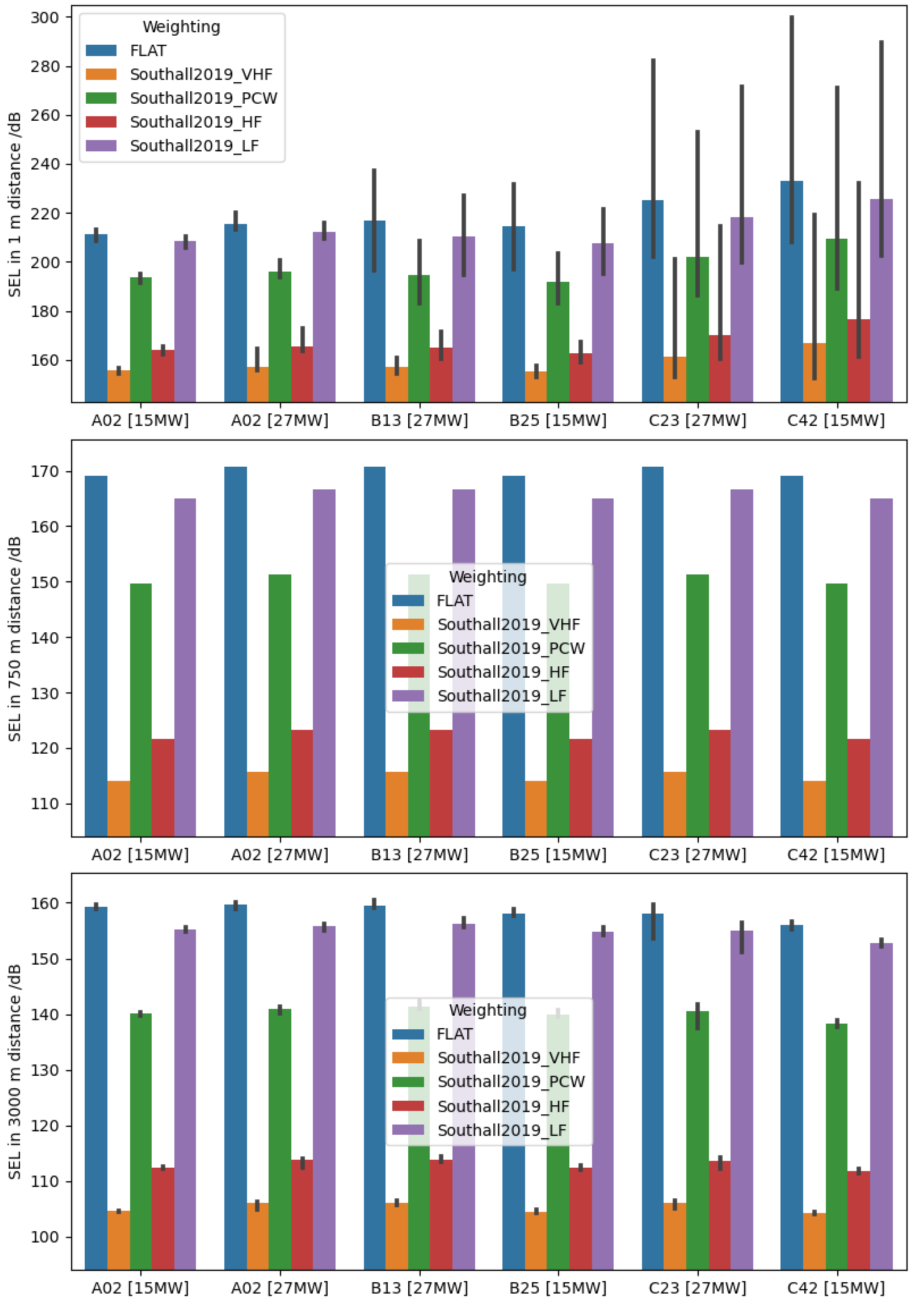

Figure 6-9. Calculated broadband Sound Exposure Level (SEL) for different frequency weightings according to Southall et al. (2019) and in different distances for each location considering a DBBC (15 dB noise reduction) and a maximum blow energy of 4,000 kJ.

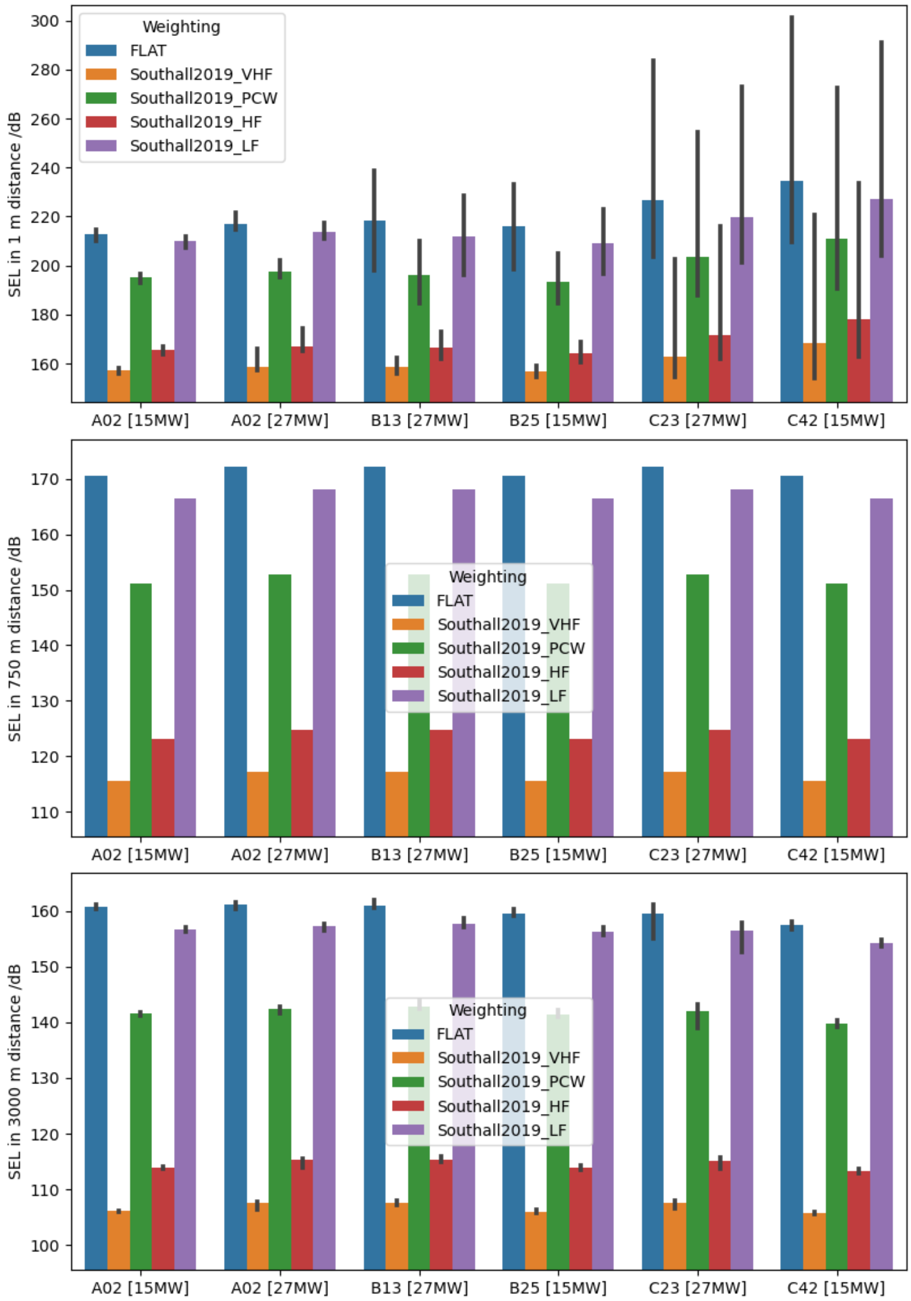

Figure 6-10. Calculated broadband Sound Exposure Level (SEL) for different frequency weightings according to Southall et al. (2019) and in different distances for each location considering a DBBC (15 dB noise reduction) and a maximum blow energy of 6,000 kJ.

6.2.3 CUMULATIVE SOUND EXPOSURE LEVEL (SEL_{CUM})

Figure 6-11 and Figure 6-12 summarizes the expected SEL_{cum} by using a DBBC for 200 m scaring distance as barplots.

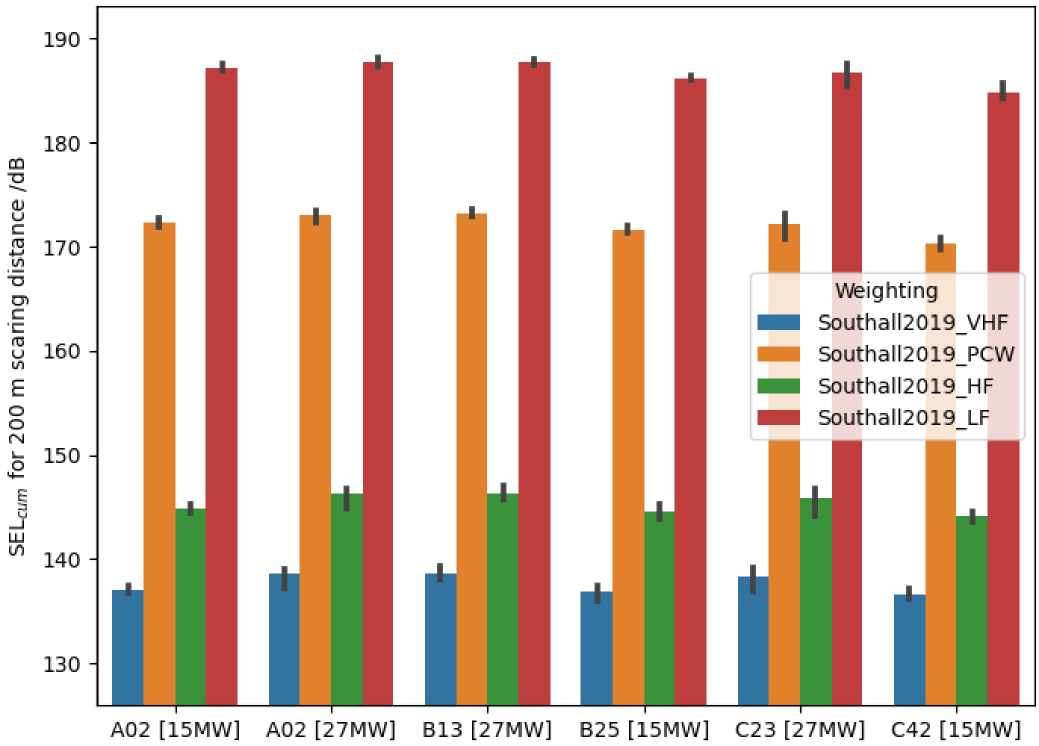

Figure 6-11. Cumulative Sound Exposure Level (SEL$_{cum}$) for 200 m scaring distance for each location considering a DBBC (15 dB noise reduction), different frequency weightings according to Southall et al. (2019) and a piling sequence with a maximum blow energy of 4,000 kJ.

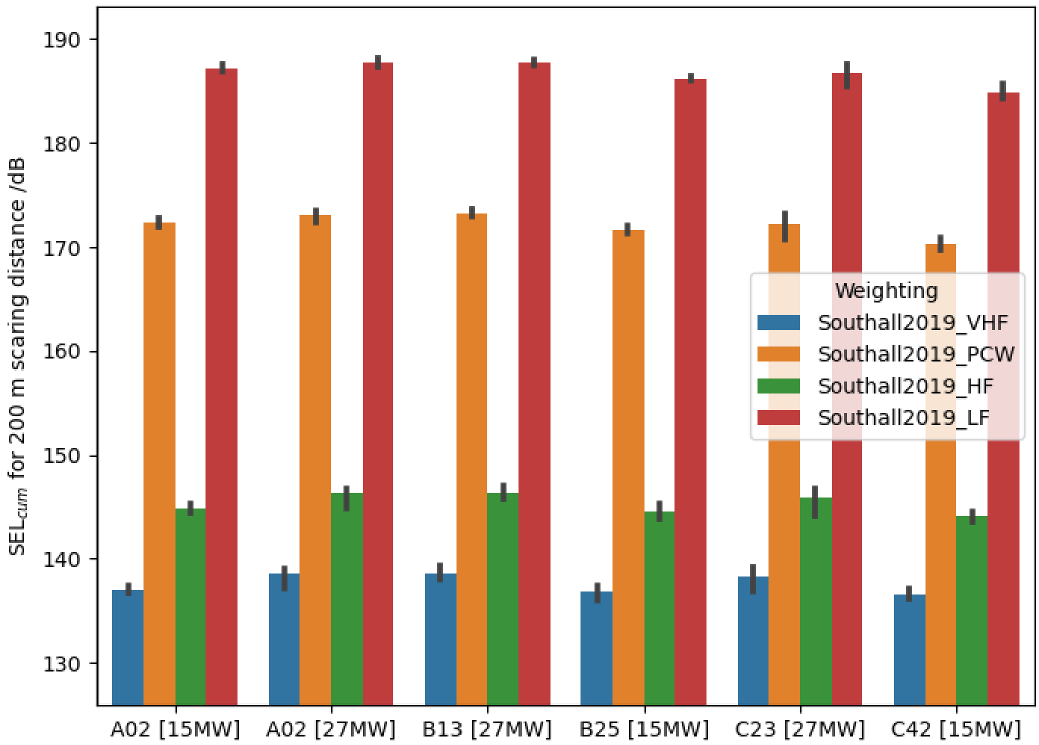

Figure 6-12. Cumulative Sound Exposure Level (SEL$_{cum}$) for 200 m scaring distance for each location considering a DBBC (15 dB noise reduction), different frequency weightings according to Southall et al. (2019) and a piling sequence with a maximum blow energy of 6,000 kJ.

6.2.4 DISTANCES TO THRESHOLD LEVEL

Table 6-5. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 13 m monopiles and 4,000 kJ blow energy sequence considering a DBBC (15 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B25 [km]	Distance at C42 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.002	0.003	0.05
VHF	PTS	$SEL_{cum,VHF}$	155	0.001	0.001	0.015
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.007
LF	PTS	$SEL_{cum,LF}$	185	1.036	0.547	0.227
PCW	TTS	$SEL_{cum,PCW}$	170	1.234	0.805	0.278
VHF	TTS	$SEL_{cum,VHF}$	140	0.016	0.017	0.044
HF	TTS	$SEL_{cum,HF}$	170	0.001	0.001	0.014
LF	TTS	$SEL_{cum,LF}$	170	26.817	15.217	9.486
VHF	Avoidance	SEL_{VHF}	103	12.19	12.185	11.533

Table 6-6. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 13 m monopiles and 6,000 kJ blow energy sequence considering a DBBC (15 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B25 [km]	Distance at C42 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.002	0.003	0.05
VHF	PTS	$SEL_{cum,VHF}$	155	0.001	0.001	0.015
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.007
LF	PTS	$SEL_{cum,LF}$	185	1.332	0.628	0.232
PCW	TTS	$SEL_{cum,PCW}$	170	1.637	1.000	0.322
VHF	TTS	$SEL_{cum,VHF}$	140	0.018	0.018	0.045
HF	TTS	$SEL_{cum,HF}$	170	0.001	0.001	0.014
LF	TTS	$SEL_{cum,LF}$	170	28.425	16.448	10.389
VHF	Avoidance	SEL_{VHF}	103	14.658	14.534	13.885

Table 6-7. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 18 m monopiles and 4,000 kJ blow energy sequence considering a DBBC (15 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B13 [km]	Distance at C23 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.004	0.005	0.036
VHF	PTS	$SEL_{cum,VHF}$	155	0.002	0.001	0.009
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.004
LF	PTS	$SEL_{cum,LF}$	185	1.017	1.048	0.868
PCW	TTS	$SEL_{cum,PCW}$	170	1.389	1.589	1.267
VHF	TTS	$SEL_{cum,VHF}$	140	0.049	0.053	0.05
HF	TTS	$SEL_{cum,HF}$	170	0.001	0.001	0.008
LF	TTS	$SEL_{cum,LF}$	170	14.868	19.957	13.063
VHF	Avoidance	SEL_{VHF}	103	14.834	16.216	15.128

Table 6-8. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 18 m monopiles and 6,000 kJ blow energy sequence considering a DBBC (15 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B13 [km]	Distance at C23 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.05	0.004	0.005
VHF	PTS	$SEL_{cum,VHF}$	155	0.015	0.002	0.001
HF	PTS	$SEL_{cum,HF}$	185	0.007	0.001	0.001
LF	PTS	$SEL_{cum,LF}$	185	0.232	1.228	1.16
PCW	TTS	$SEL_{cum,PCW}$	170	0.322	1.742	1.871
VHF	TTS	$SEL_{cum,VHF}$	140	0.045	0.069	0.08
HF	TTS	$SEL_{cum,HF}$	170	0.014	0.001	0.001
LF	TTS	$SEL_{cum,LF}$	170	10.389	16.027	21.275
VHF	Avoidance	SEL_{VHF}	103	13.885	17.579	19.872

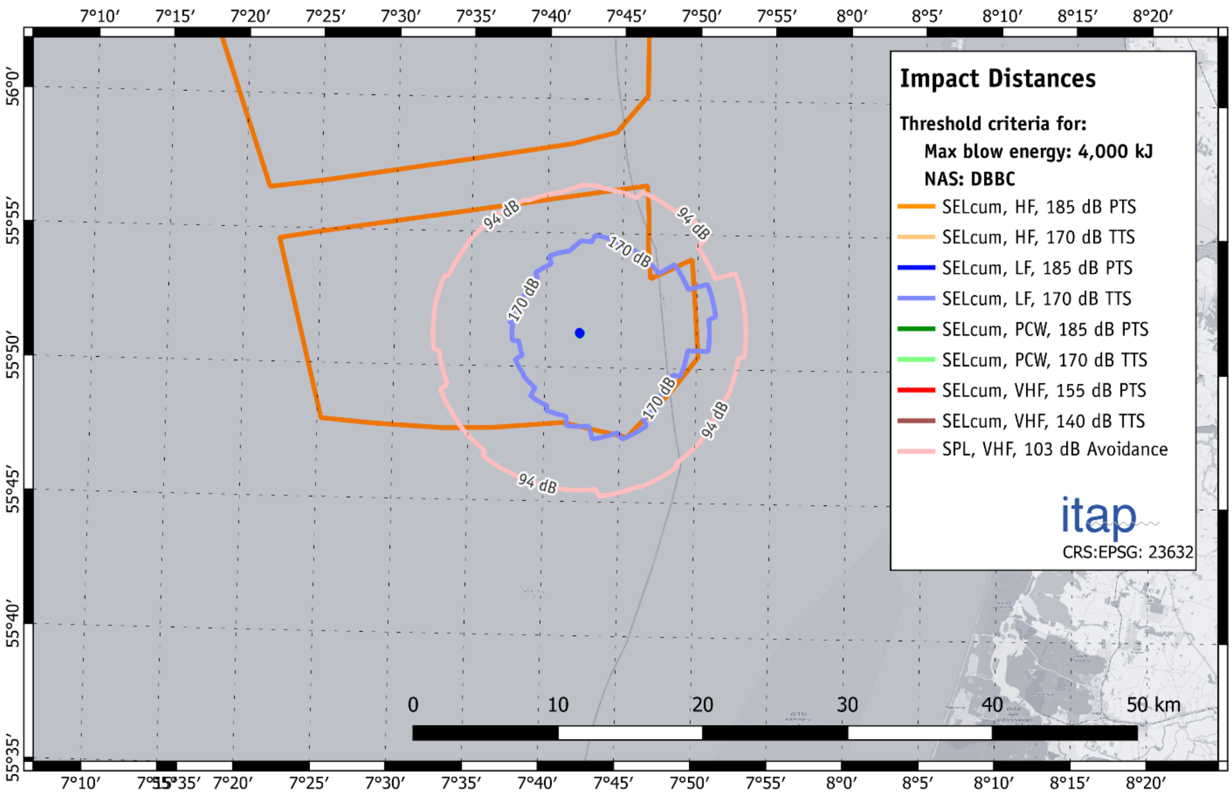

Figure 6-13. Impact ranges for the threshold criteria according to GfUN (Energistyrelsen 2022) for location C42 with 13 m pile diameter and the 4,000 kJ piling sequence considering a DBBC (15 dB noise reduction).

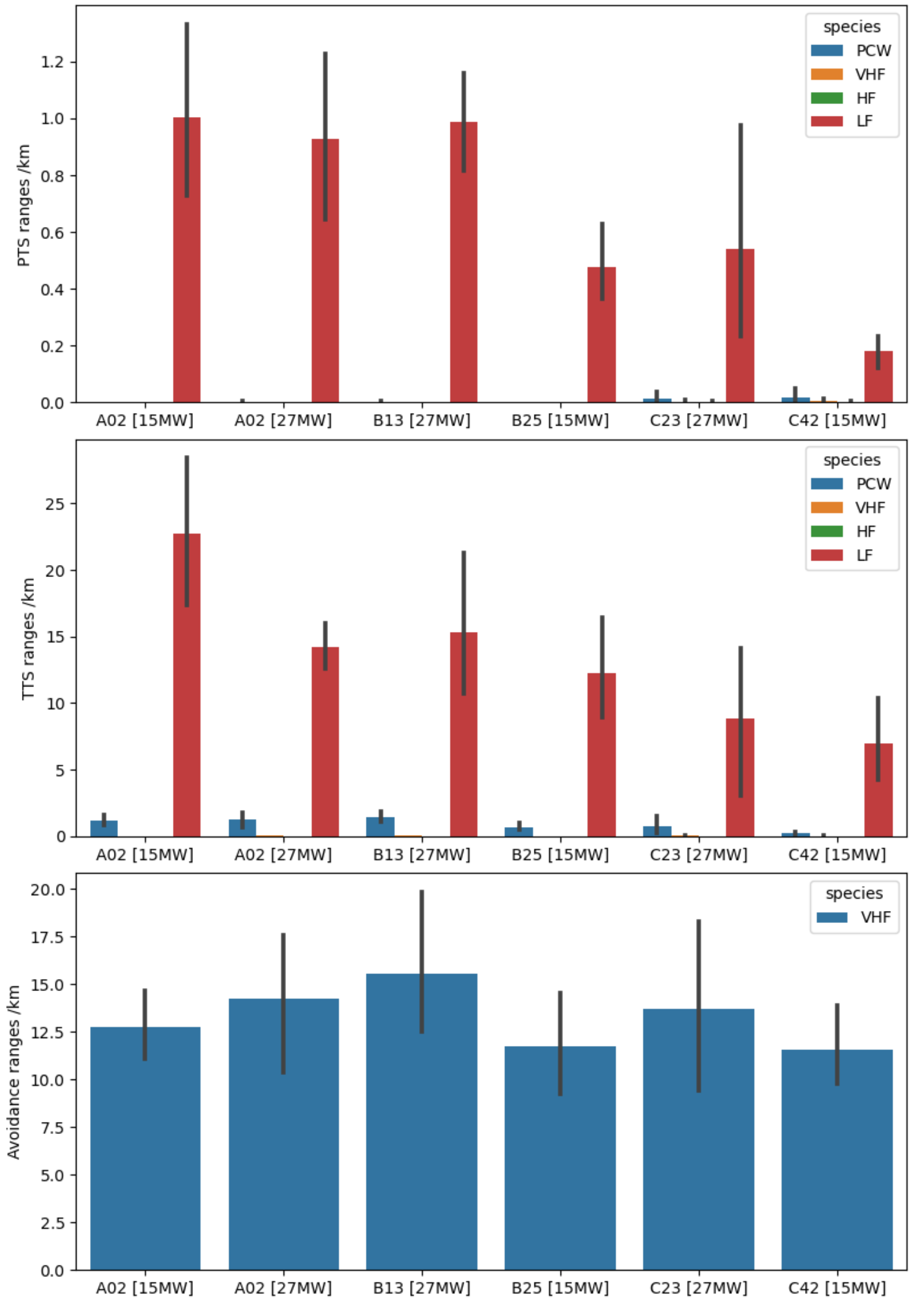

Figure 6-14. Impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for each location considering a piling sequence with a maximum blow energy of 4,000 kJ and a DBBC (15 dB noise reduction).

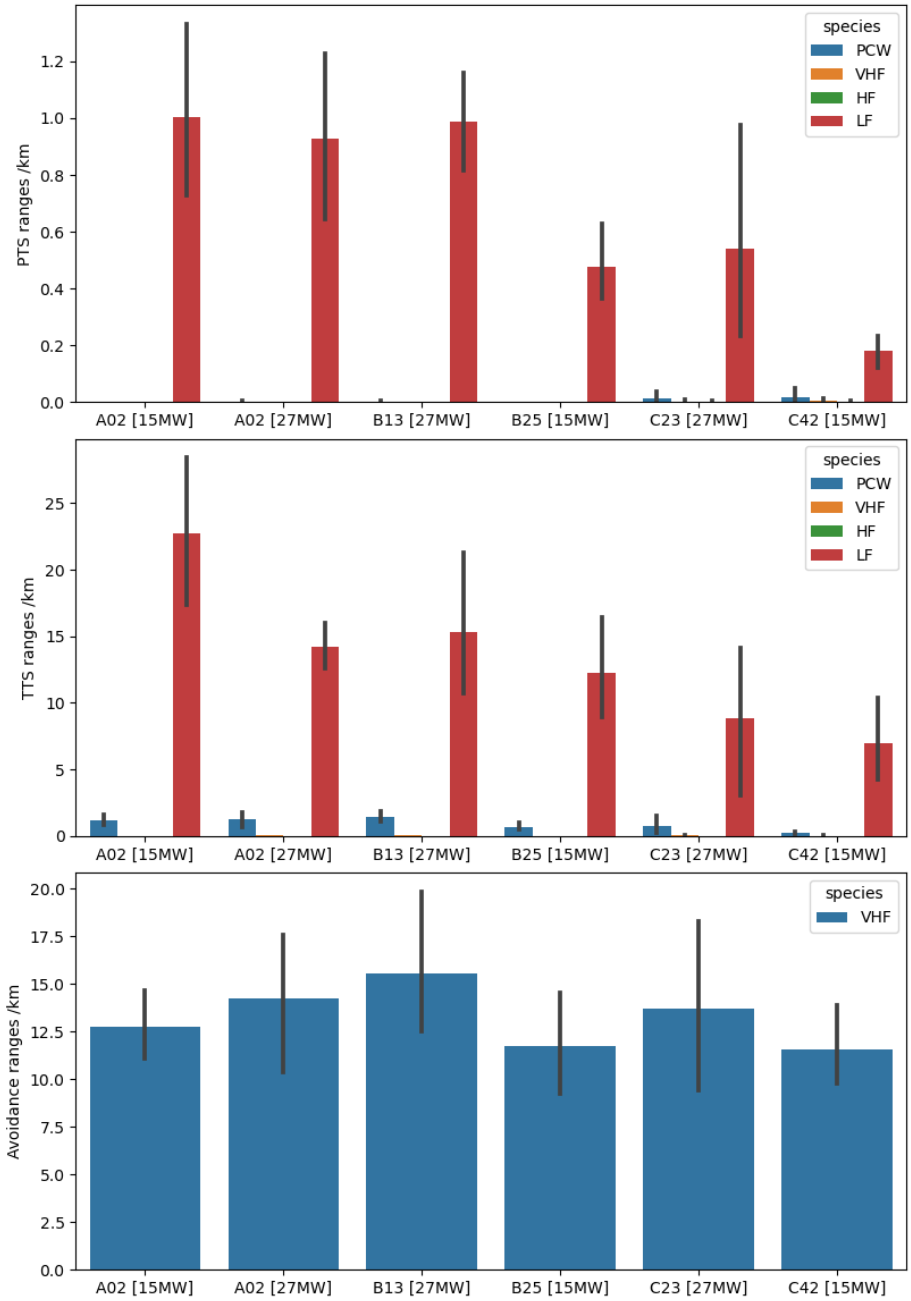

Figure 6-15. Impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for each location considering a piling sequence with a maximum blow energy of 6,000 kJ and a DBBC (15 dB noise reduction).

6.3 MITIGATED PILE DRIVING: HYDRO SOUND DAMPER (HSD)

6.3.1 CALCULATED LEVEL VALUES

The following figures show the expected noise input, when applying a HSD. Apart from the HSD, the same input data was assumed as for the unmitigated case. An example scenario was defined for the HSD with a broadband noise reduction of 12 dB (Bellmann, et al. 2020). The 1/3 octave spectrum assumed for this is based on measurement results at 750 m from the foundation of 249 previous measurements and is compared with the unmitigated spectrum in Figure 6-16.

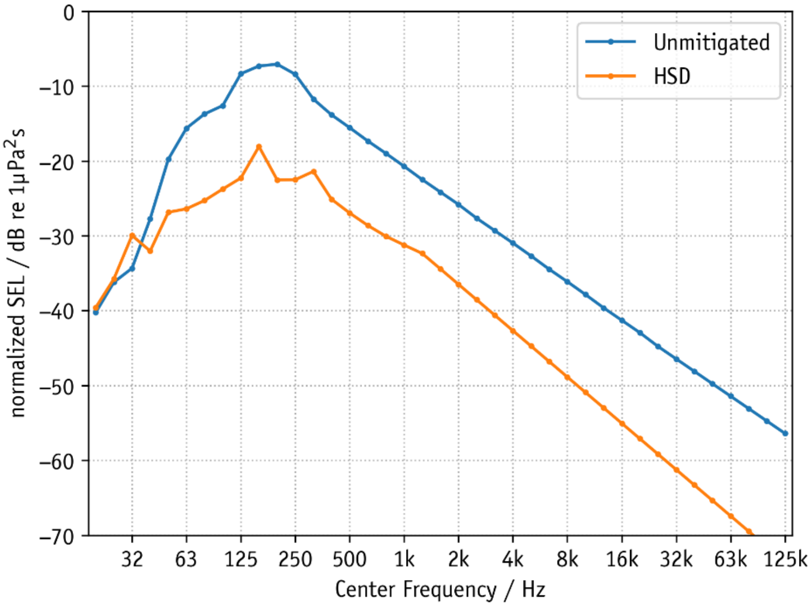

Figure 6-16. Normalized spectrum of a single strike Sound Exposure Level (SEL_{ss}) in 1/3-octaves for the unmitigated case and by using a HSD with 12 dB total noise reduction.

To make the number of calculated variants clearer, the results for all six considered foundations (two monopile diameter sizes and two energy blow levels at 1 position in each of the three sub-areas) as broadband level and frequency weighted level are summarized in the following barplots in the same way as in the unmitigated case. The directional differences for each location and distance of the 24 calculated direction are shown as black error lines (from min to max) for each bar. A detailed result presentation of all single strike and cumulative metrics as well as the impact ranges for each direction can be found in the enclosed table NS1_MES_WSP_WPD_MOR (**Fejl! Henvisningskilde ikke fundet.** 2).

6.3.2 SINGLE STRIKE SOUND EXPOSURE LEVEL (SEL)

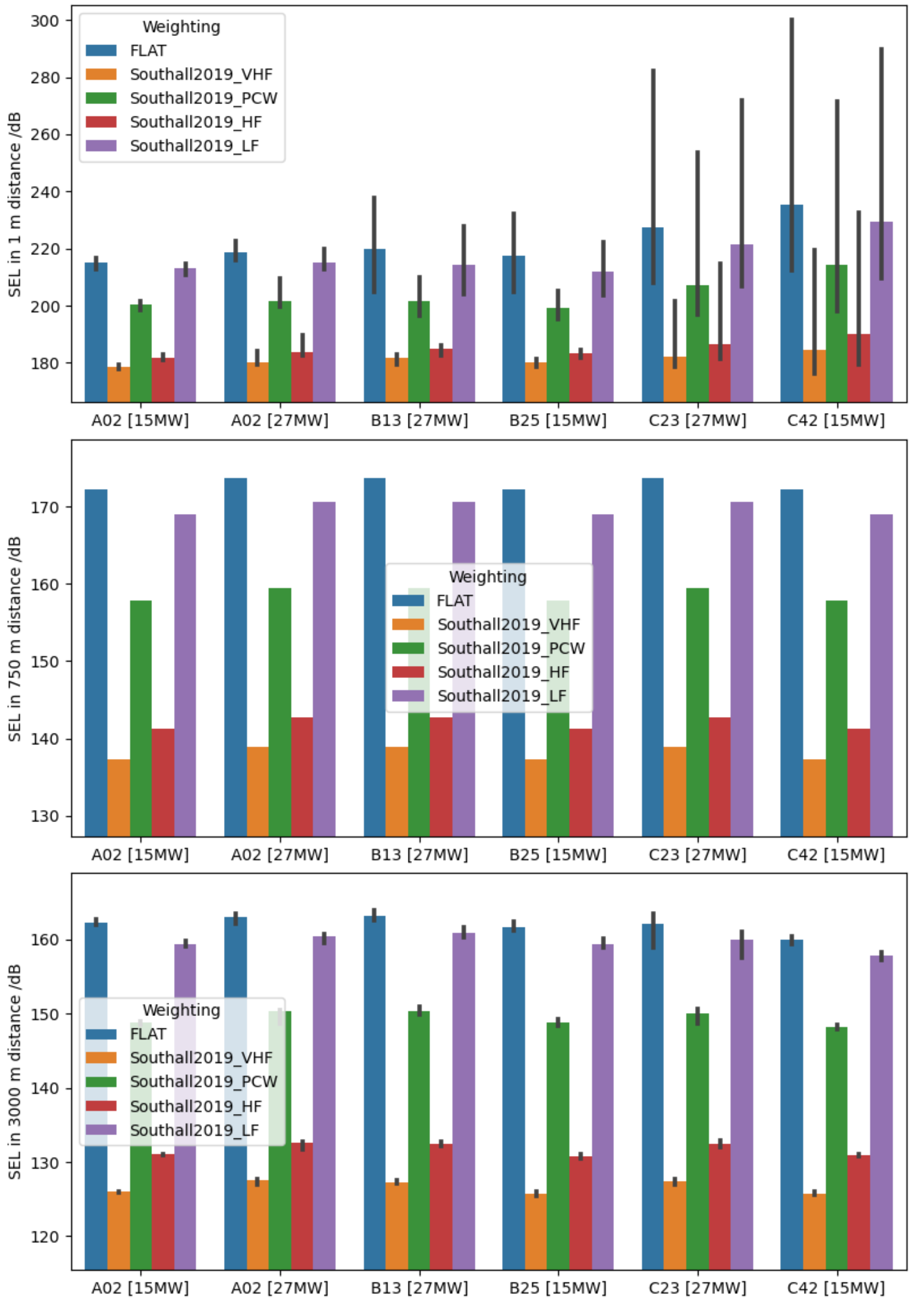

Figure 6-17. Calculated broadband Sound Exposure Level (SEL) for different frequency weightings according to Southall et al. (2019) and in different distances for each location considering a HSD (12 dB noise reduction) and a maximum blow energy of 4,000 kJ.

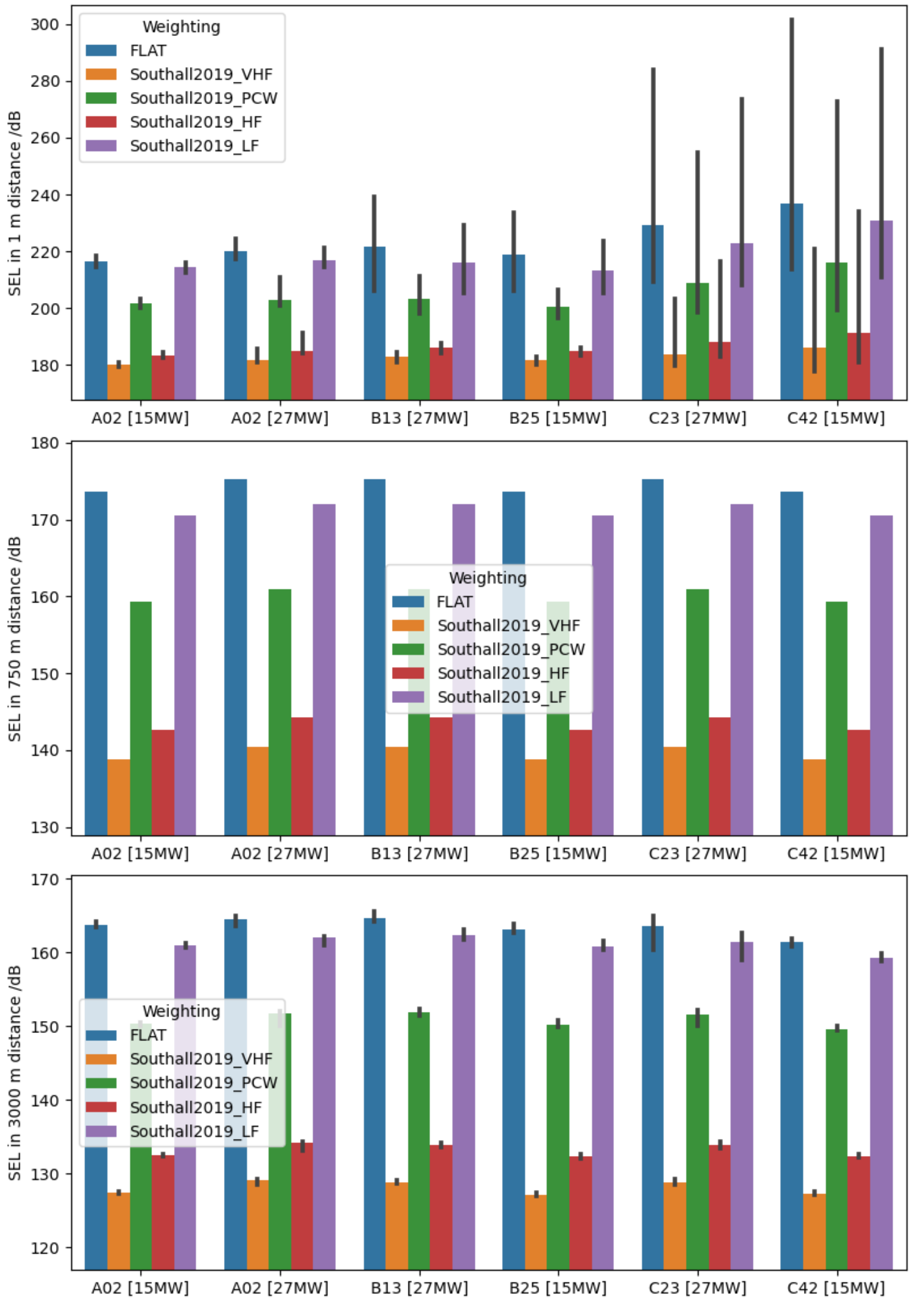

Figure 6-18. Calculated broadband Sound Exposure Level (SEL) for different frequency weightings according to Southall et al. (2019) and in different distances for each location considering a HSD (12 dB noise reduction) and a maximum blow energy of 6,000 kJ.

6.3.3 CUMULATIVE SOUND EXPOSURE LEVEL (SEL_{CUM})

Figure 6-19 and Figure 6-20 summarizes the expected SEL_{cum} by using a HSD for 200 m scaring distance as barplots.

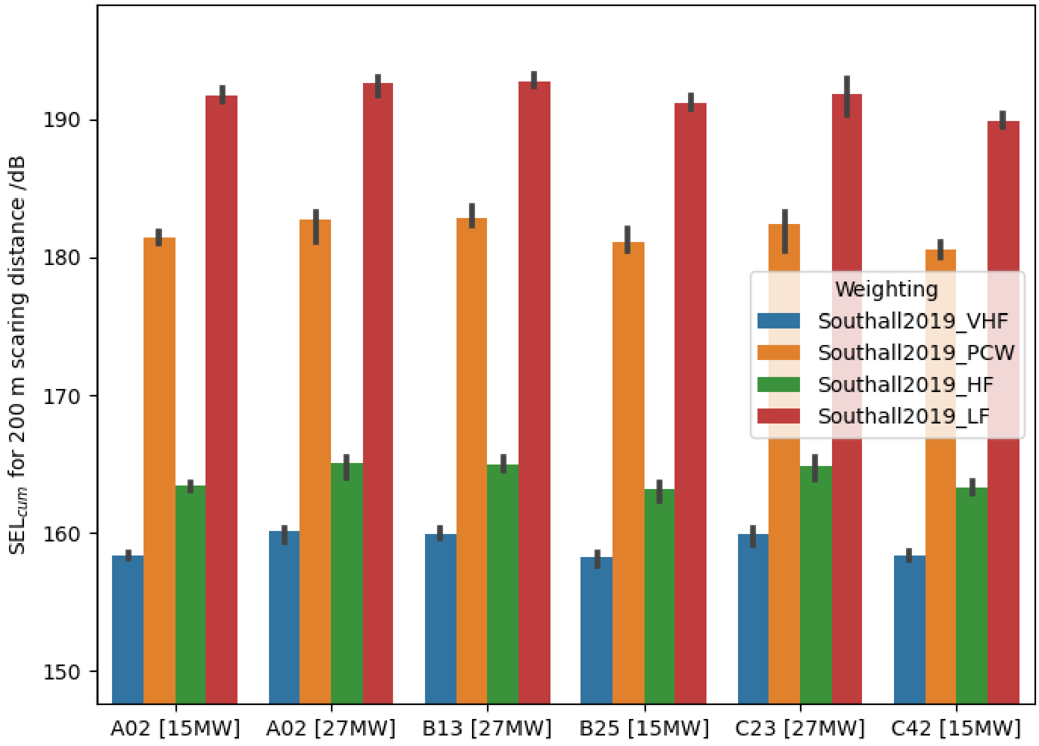

Figure 6-19. Cumulative Sound Exposure Level (SEL_{cum}) for 200 m scaring distance for each location considering a HSD (12 dB noise reduction), different frequency weightings according to Southall et al. (2019) and a piling sequence with a maximum blow energy of 4,000 kJ.

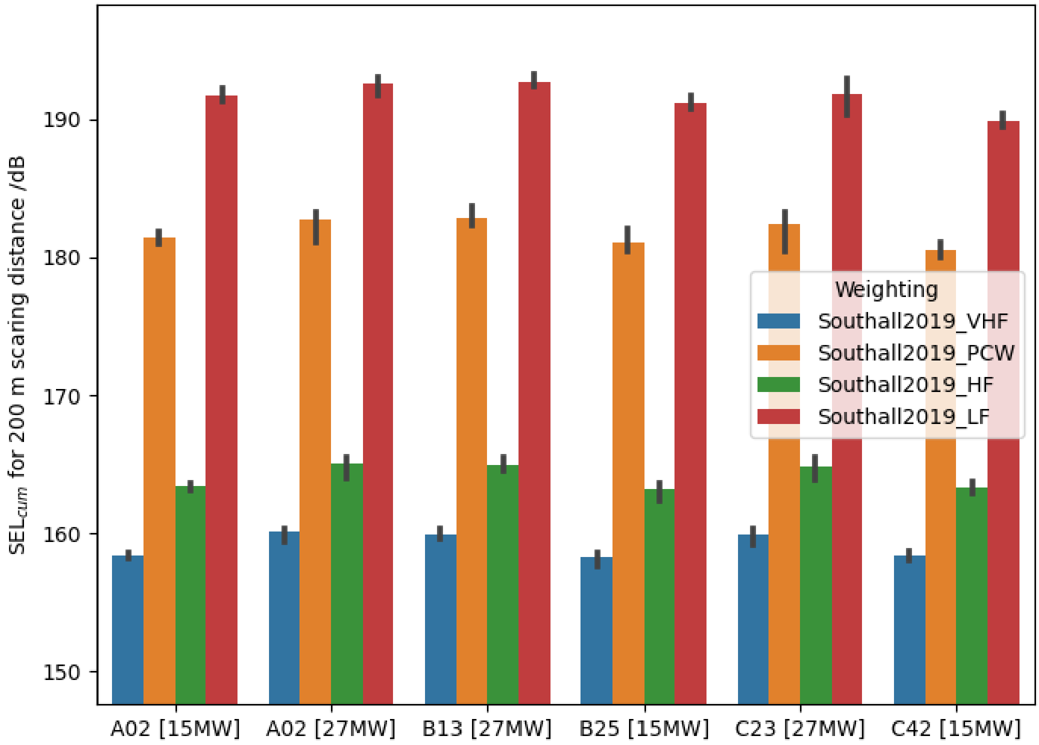

Figure 6-20. Cumulative Sound Exposure Level (SEL_{cum}) for 200 m scaring distance for each location considering HSD (12 dB noise reduction), different frequency weightings according to Southall et al. (2019) and a piling sequence with a maximum blow energy of 6,000 kJ.

6.3.4 DISTANCES TO THRESHOLD LEVEL

Table 6-9. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 13 m monopiles and 4,000 kJ blow energy sequence considering a HSD (12 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B25 [km]	Distance at C42 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.011	0.011	0.059
VHF	PTS	$SEL_{cum,VHF}$	155	1.266	1.224	1.304
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.007
LF	PTS	$SEL_{cum,LF}$	185	6.192	4.459	2.394
PCW	TTS	$SEL_{cum,PCW}$	170	21.246	22.618	19.181
VHF	TTS	$SEL_{cum,VHF}$	140	35.611	38.836	38.215
HF	TTS	$SEL_{cum,HF}$	170	0.004	0.005	0.017
LF	TTS	$SEL_{cum,LF}$	170	67.202	53.118	38.215
VHF	Avoidance	SEL_{VHF}	103	87.106	72.699	72.287

Table 6-10. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 13 m monopiles and 6,000 kJ blow energy sequence considering a HSD (12 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B25 [km]	Distance at C42 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.012	0.011	0.059
VHF	PTS	$SEL_{cum,VHF}$	155	1.565	1.521	1.647
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.007
LF	PTS	$SEL_{cum,LF}$	185	7.242	5.195	2.878
PCW	TTS	$SEL_{cum,PCW}$	170	22.789	24.137	20.657
VHF	TTS	$SEL_{cum,VHF}$	140	36.986	39.978	38.215
HF	TTS	$SEL_{cum,HF}$	170	0.004	0.005	0.017
LF	TTS	$SEL_{cum,LF}$	170	67.907	54.445	38.215
VHF	Avoidance	SEL_{VHF}	103	> 100	82.071	82.459

Table 6-11. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 18 m monopiles and 4,000 kJ blow energy sequence considering a HSD (12 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B13 [km]	Distance at C23 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.031	0.029	0.051
VHF	PTS	$SEL_{cum,VHF}$	155	2.557	2.56	2.604
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.004
LF	PTS	$SEL_{cum,LF}$	185	5.568	6.905	5.297
PCW	TTS	$SEL_{cum,PCW}$	170	22.631	41.458	29.723
VHF	TTS	$SEL_{cum,VHF}$	140	44.61	60.527	59.98
HF	TTS	$SEL_{cum,HF}$	170	0.012	0.009	0.012
LF	TTS	$SEL_{cum,LF}$	170	41.234	> 100	55.392
VHF	Avoidance	SEL_{VHF}	103	> 100	> 100	> 100

Table 6-12. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 18 m monopiles and 6,000 kJ blow energy sequence considering a HSD (12 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B13 [km]	Distance at C23 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.033	0.034	0.053
VHF	PTS	$SEL_{cum,VHF}$	155	3.102	3.087	3.154
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.004
LF	PTS	$SEL_{cum,LF}$	185	6.44	7.953	6.184
PCW	TTS	$SEL_{cum,PCW}$	170	24.298	42.341	31.083
VHF	TTS	$SEL_{cum,VHF}$	140	46.03	60.588	60.337
HF	TTS	$SEL_{cum,HF}$	170	0.012	0.01	0.013
LF	TTS	$SEL_{cum,LF}$	170	42.953	> 100	56.498
VHF	Avoidance	SEL_{VHF}	103	> 100	> 100	> 100

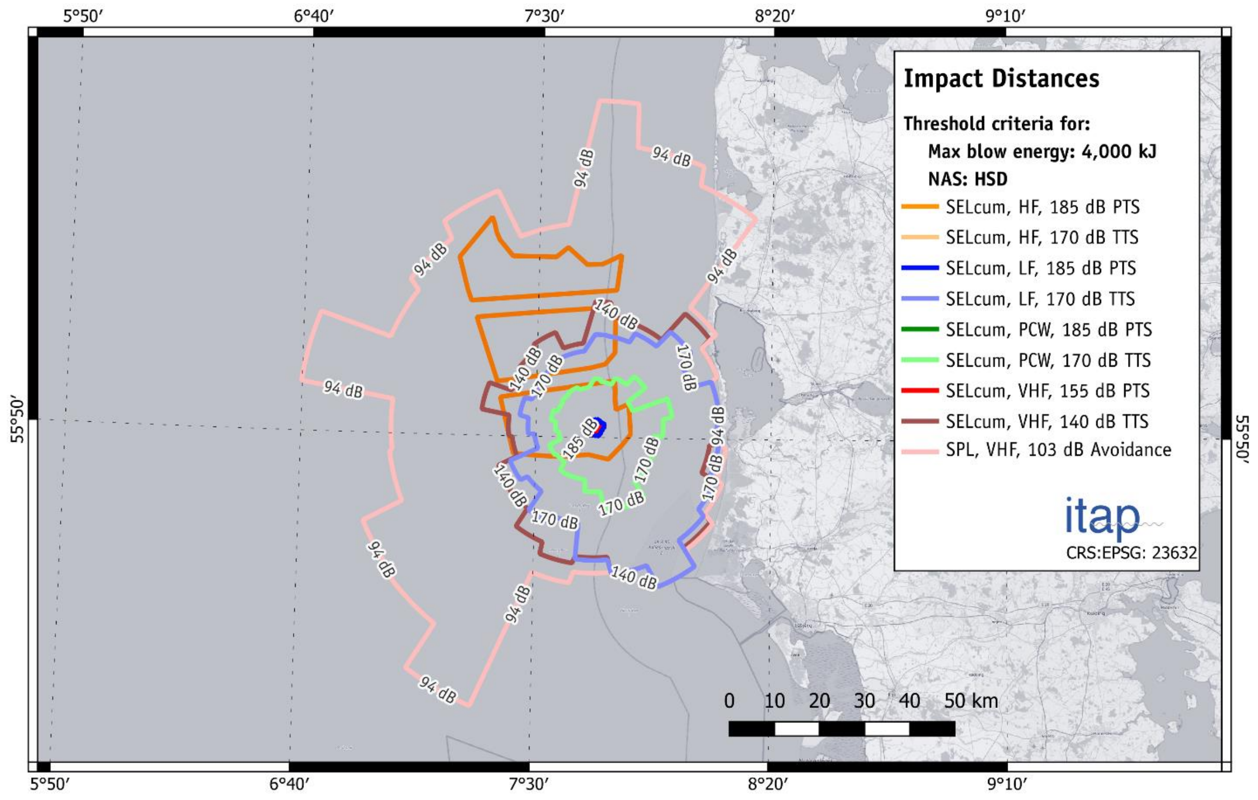

Figure 6-21. Impact ranges for the threshold criteria according to GfUN (Energistyrelsen 2022) for location C42 with 13 m pile diameter and the 4,000 kJ piling sequence considering a HSD (12 dB noise reduction).

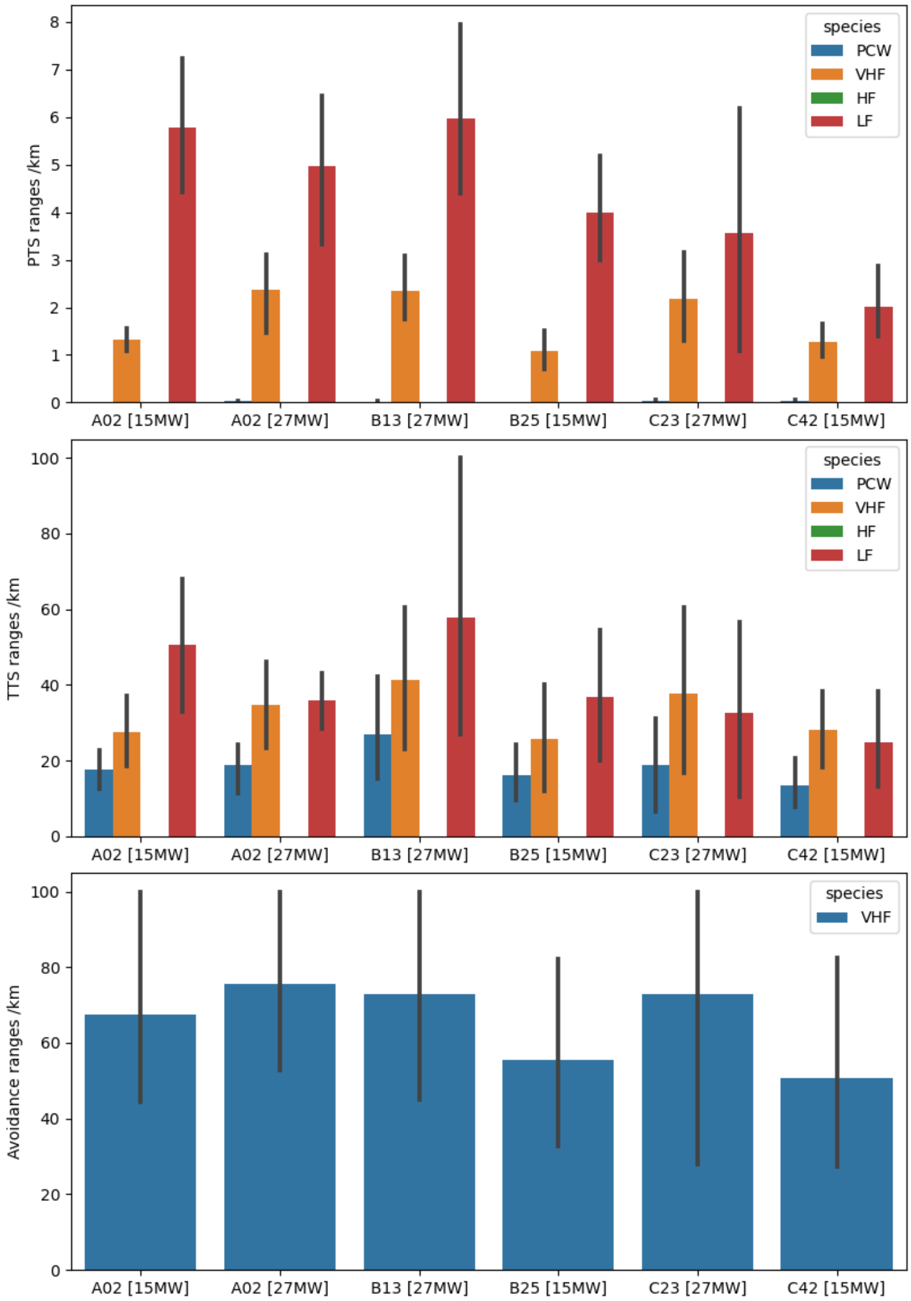

Figure 6-22. Impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for each location considering a piling sequence with a maximum blow energy of 4,000 kJ and a HSD (12 dB noise reduction).

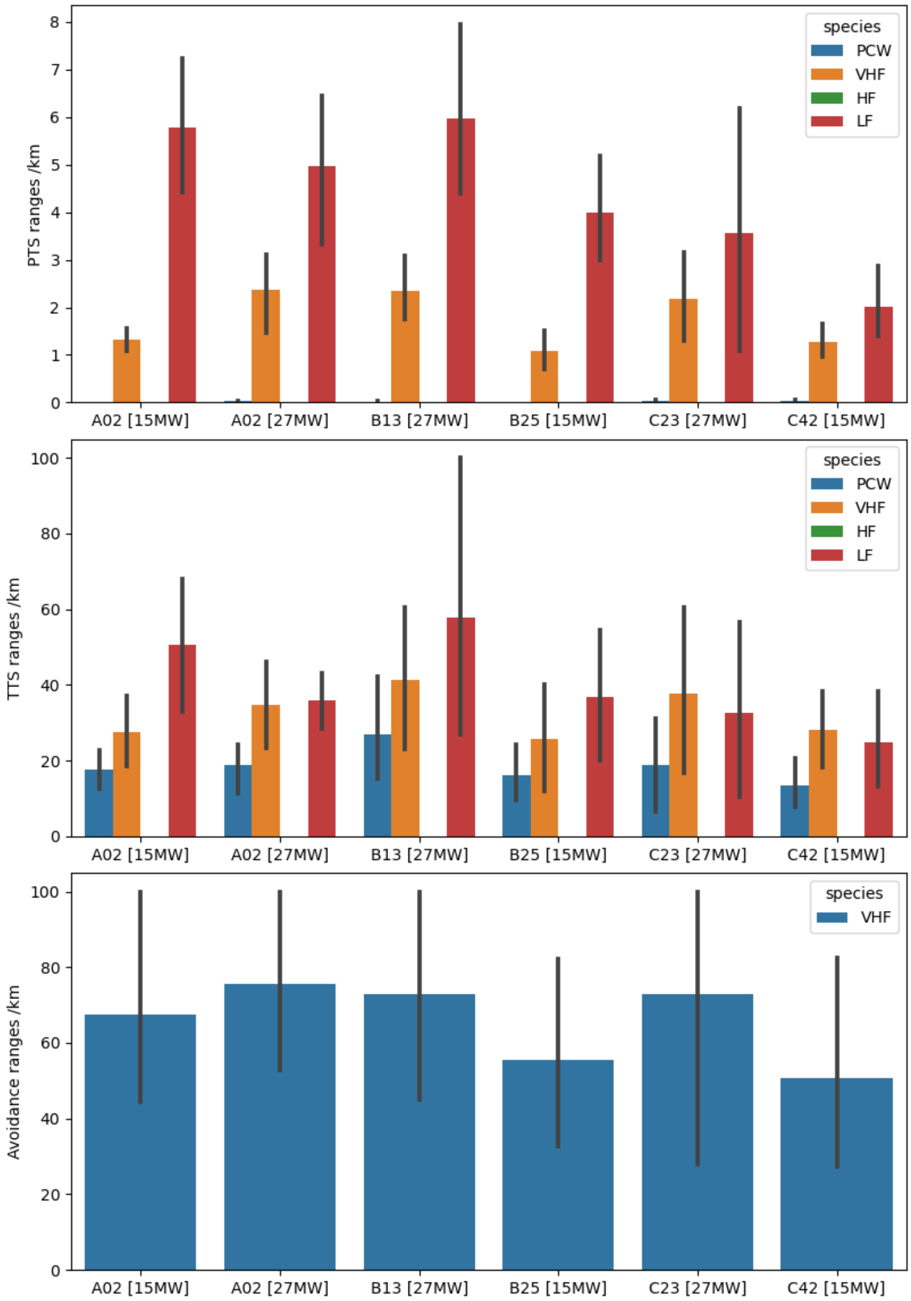

Figure 6-23. Impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for each location considering a piling sequence with a maximum blow energy of 6,000 kJ and a HSD (12 dB noise reduction).

6.4 MITIGATED PILE DRIVING: COMBINATION HSD+DBBC

6.4.1 CALCULATED LEVEL VALUES

The following figures show the expected noise input, when applying a combination of HSD+DBBC. Apart from the HSD+DBBC noise abatement combination, the same input data was assumed as for the unmitigated case. An example scenario was defined for the HSD with a broadband noise reduction of 12 dB (Bellmann, et al. 2020). The 1/3 octave spectrum assumed for this is based on measurement results at 750 m from the foundation of 249 previous measurements and is compared with the unmitigated spectrum in Figure 6-24.

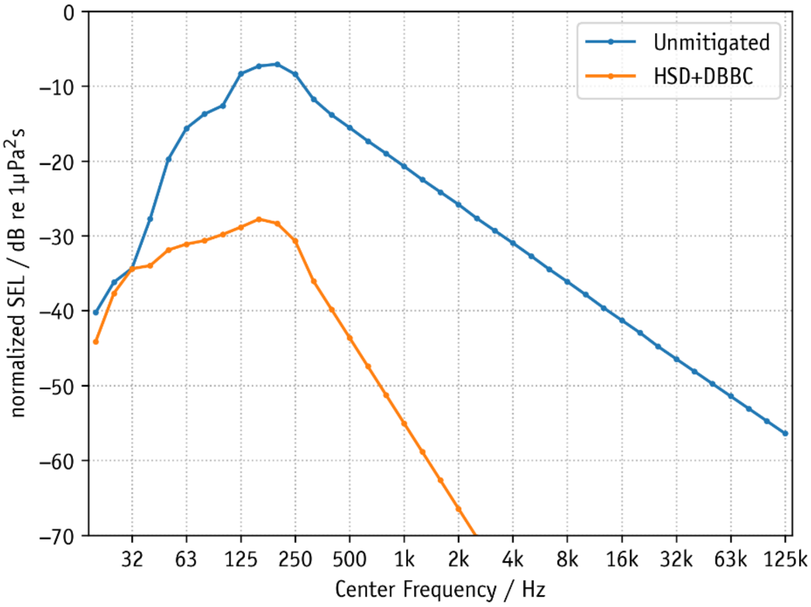

Figure 6-24. Normalized spectrum of a single strike Sound Exposure Level (SEL_{ss}) in 1/3-octaves for the unmitigated case and by using a combination of HSD+DBBC with 20 dB total noise reduction.

To make the number of calculated variants clearer, the results for all six considered foundations (two monopile diameter sizes and two energy blow levels at one position in each of the three sub-areas) as broadband level and frequency weighted level are summarized in the following barplots in the same way as in the unmitigated case. The directional differences for each location and distance of the 24 calculated direction are shown as black error lines (from min to max) for each bar.

A detailed result presentation of all single strike and cumulative metrics as well as the impact ranges for each direction can be found in the enclosed table NS1_MES_WSP_WPD_MOR (see supplementary data deliverables).

6.4.2 SINGLE STRIKE SOUND EXPOSURE LEVEL (SEL)

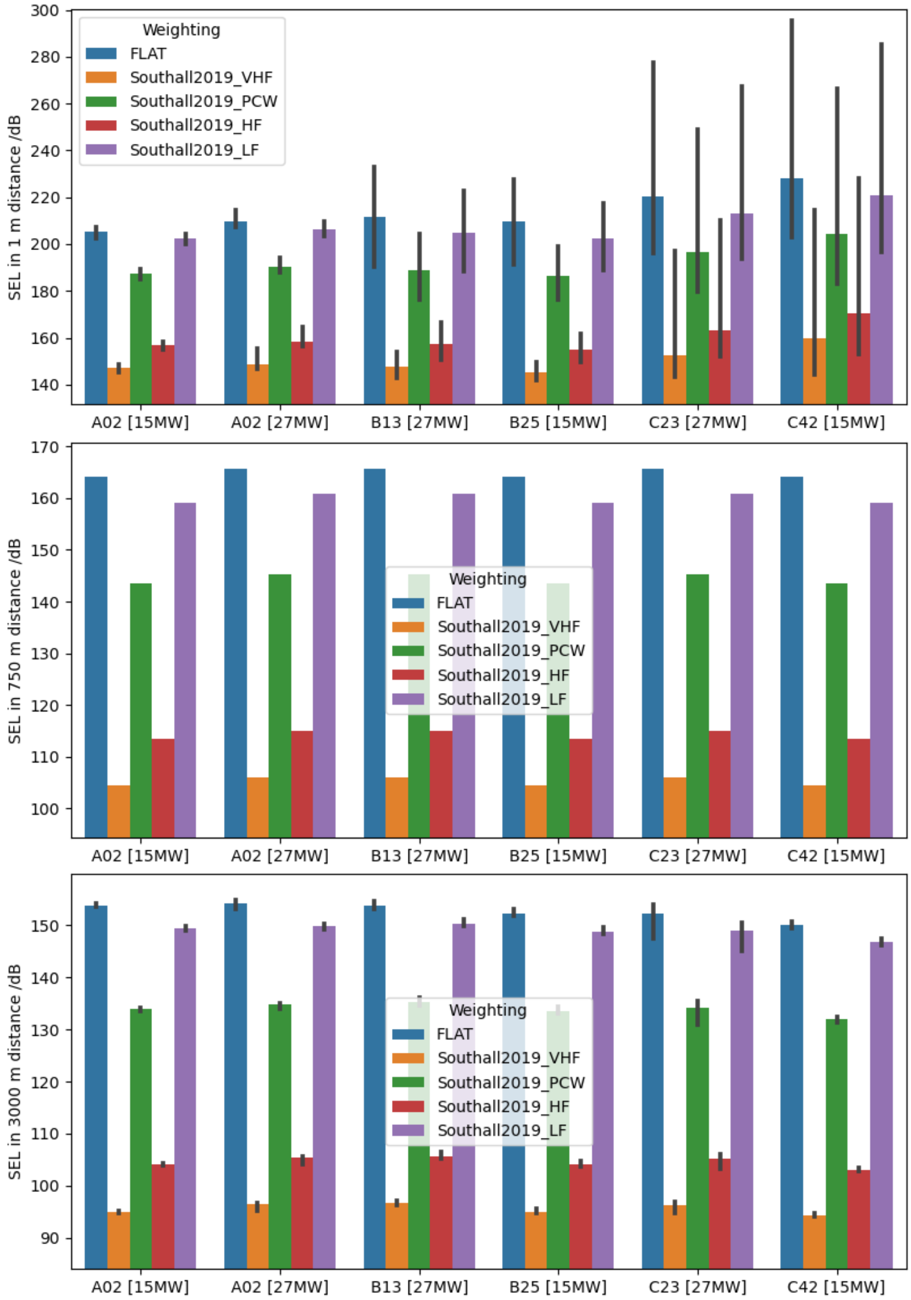

Figure 6-25. Calculated broadband Sound Exposure Level (SEL) for different frequency weightings according to Southall et al. (2019) and in different distances for each location considering a combination of HSD+DBBC (20 dB noise reduction) and a maximum blow energy of 4,000 kJ.

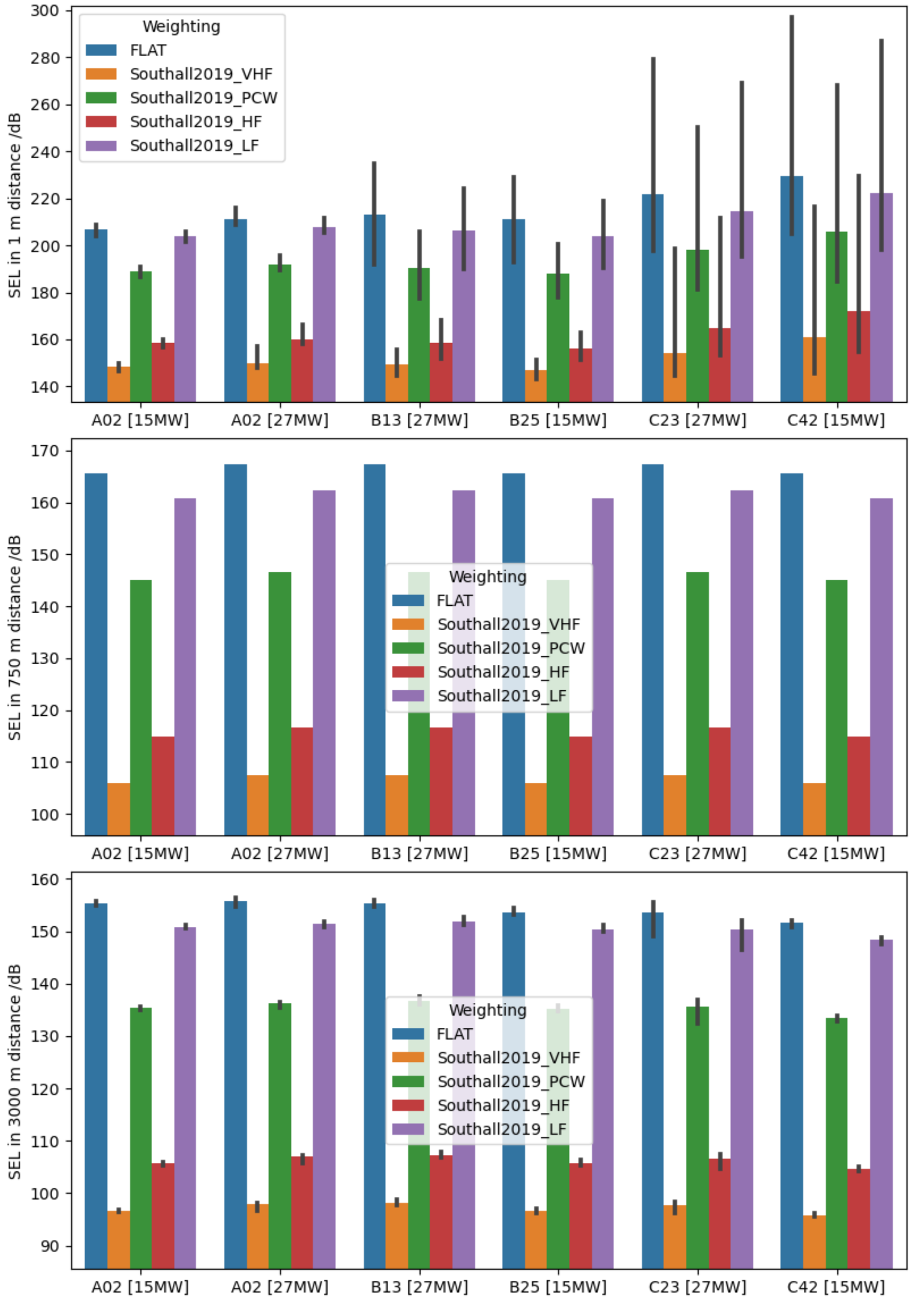

Figure 6-26. Calculated broadband Sound Exposure Level (SEL) for different frequency weightings according to Southall et al. (2019) and in different distances for each location considering a combination of HSD+DBBC (20 dB noise reduction) and a maximum blow energy of 6,000 kJ.

6.4.3 CUMULATIVE SOUND EXPOSURE LEVEL (SEL_{CUM})

Figure 6-27 and Figure 6-28 summarizes the expected SEL_{cum} by using a combination of DBBC and HSD for 200 m scaring distance as barplots.

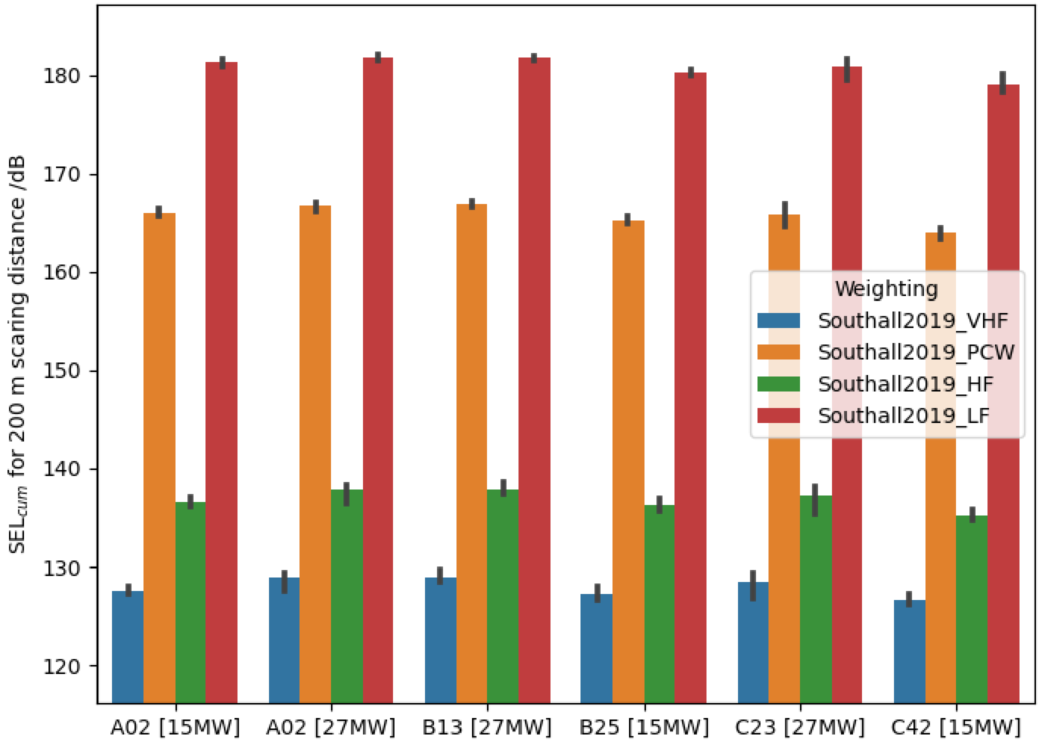

Figure 6-27. Cumulative Sound Exposure Level (SEL_{cum}) for 200 m scaring distance for each location considering a combination of HSD+DBBC (20 dB noise reduction), different frequency weightings according to Southall et al. (2019) and a piling sequence with a maximum blow energy of 4,000 kJ.

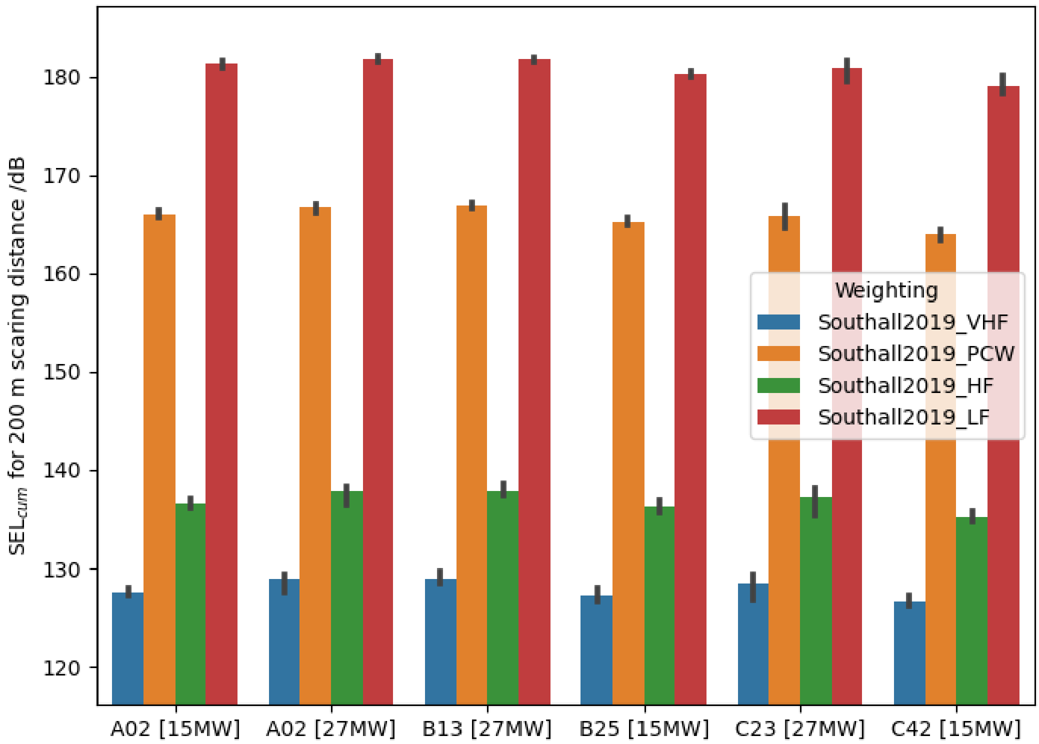

Figure 6-28. Cumulative Sound Exposure Level (SEL_{cum}) for 200 m scaring distance for each location considering a combination of HSD+DBBC (20 dB noise reduction), different frequency weightings according to Southall et al. (2019) and a piling sequence with a maximum blow energy of 6,000 kJ.

6.4.4 DISTANCES TO THRESHOLD LEVEL

Table 6-13. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 13 m monopiles and 4,000 kJ blow energy sequence considering a combination of HSD+DBBC (20 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B25 [km]	Distance at C42 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.001	0.002	0.039
VHF	PTS	$SEL_{cum,VHF}$	155	0.001	0.001	0.012
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.006
LF	PTS	$SEL_{cum,LF}$	185	0.017	0.024	0.12
PCW	TTS	$SEL_{cum,PCW}$	170	0.015	0.017	0.099
VHF	TTS	$SEL_{cum,VHF}$	140	0.002	0.002	0.027
HF	TTS	$SEL_{cum,HF}$	170	0.001	0.001	0.011
LF	TTS	$SEL_{cum,LF}$	170	11.299	6.166	3.559
VHF	Avoidance	SEL_{VHF}	103	3.601	3.744	3.281

Table 6-14. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 13 m monopiles and 6,000 kJ blow energy sequence considering a combination of HSD+DBBC (20 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B25 [km]	Distance at C42 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.001	0.002	0.039
VHF	PTS	$SEL_{cum,VHF}$	155	0.001	0.001	0.012
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.006
LF	PTS	$SEL_{cum,LF}$	185	0.019	0.024	0.12
PCW	TTS	$SEL_{cum,PCW}$	170	0.017	0.018	0.099
VHF	TTS	$SEL_{cum,VHF}$	140	0.002	0.002	0.027
HF	TTS	$SEL_{cum,HF}$	170	0.001	0.001	0.011
LF	TTS	$SEL_{cum,LF}$	170	12.594	6.865	3.93
VHF	Avoidance	SEL_{VHF}	103	4.444	4.561	3.917

Table 6-15. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 18 m monopiles and 4,000 kJ blow energy sequence considering a combination of HSD+DBBC (20 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B13 [km]	Distance at C23 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.002	0.003	0.026
VHF	PTS	$SEL_{cum,VHF}$	155	0.001	0.001	0.007
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.003
LF	PTS	$SEL_{cum,LF}$	185	0.043	0.043	0.109
PCW	TTS	$SEL_{cum,PCW}$	170	0.036	0.033	0.088
VHF	TTS	$SEL_{cum,VHF}$	140	0.004	0.003	0.018
HF	TTS	$SEL_{cum,HF}$	170	0.001	0.001	0.006
LF	TTS	$SEL_{cum,LF}$	170	7.445	7.735	6.129
VHF	Avoidance	SEL_{VHF}	103	4.390	4.619	4.491

Table 6-16. Maximum impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for the loudest direction in the scenario with 18 m monopiles and 6,000 kJ blow energy sequence considering a combination of HSD+DBBC (20 dB noise reduction).

hearing group	behavior	metric	Criteria [dB]	Distance at A02 [km]	Distance at B13 [km]	Distance at C23 [km]
PCW	PTS	$SEL_{cum,PCW}$	185	0.002	0.003	0.026
VHF	PTS	$SEL_{cum,VHF}$	155	0.001	0.001	0.007
HF	PTS	$SEL_{cum,HF}$	185	0.001	0.001	0.003
LF	PTS	$SEL_{cum,LF}$	185	0.044	0.045	0.109
PCW	TTS	$SEL_{cum,PCW}$	170	0.037	0.035	0.088
VHF	TTS	$SEL_{cum,VHF}$	140	0.004	0.003	0.018
HF	TTS	$SEL_{cum,HF}$	170	0.001	0.001	0.006
LF	TTS	$SEL_{cum,LF}$	170	8.205	8.543	6.736
VHF	Avoidance	SEL_{VHF}	103	5.368	5.600	5.448

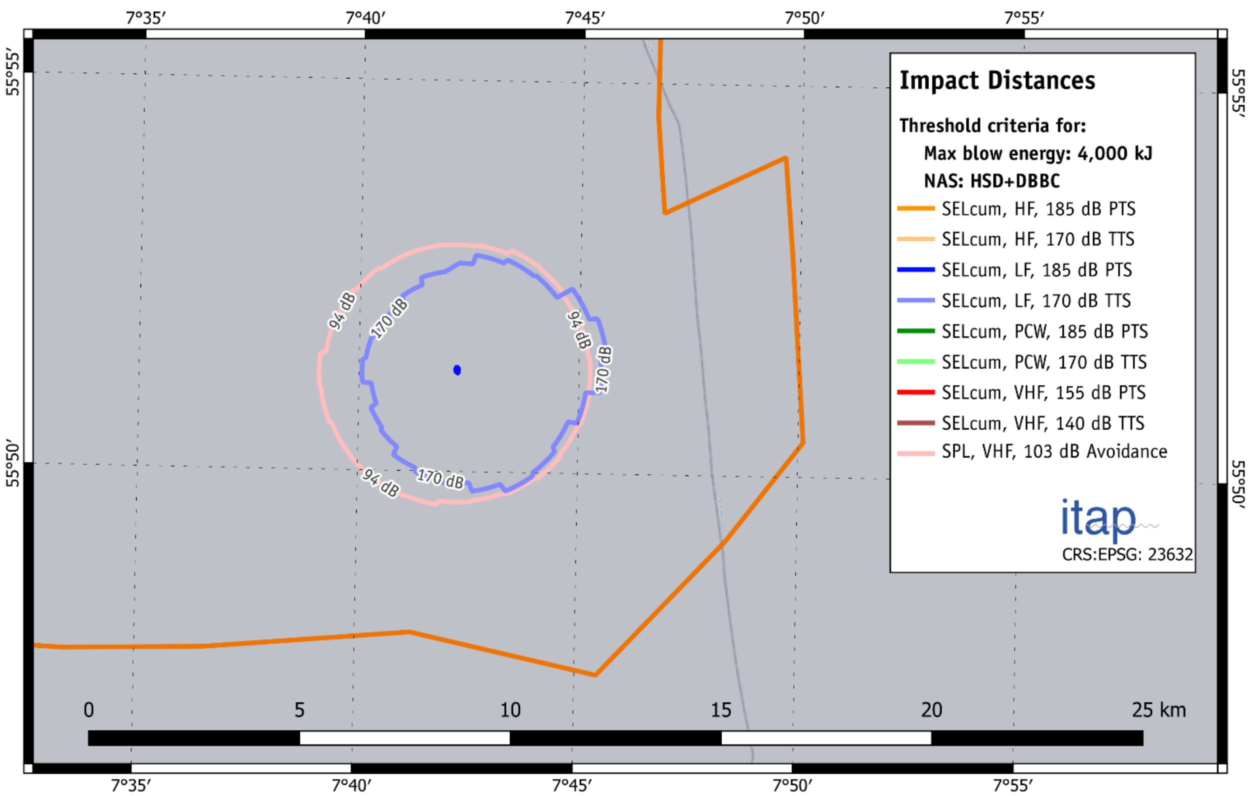

Figure 6-29 Impact ranges for the threshold criteria according to GfUN (Energistyrelsen 2022) for location C42 with 13 m pile diameter and the 4,000 kJ piling sequence considering a combination of HSD+DBBC (20 dB noise reduction).

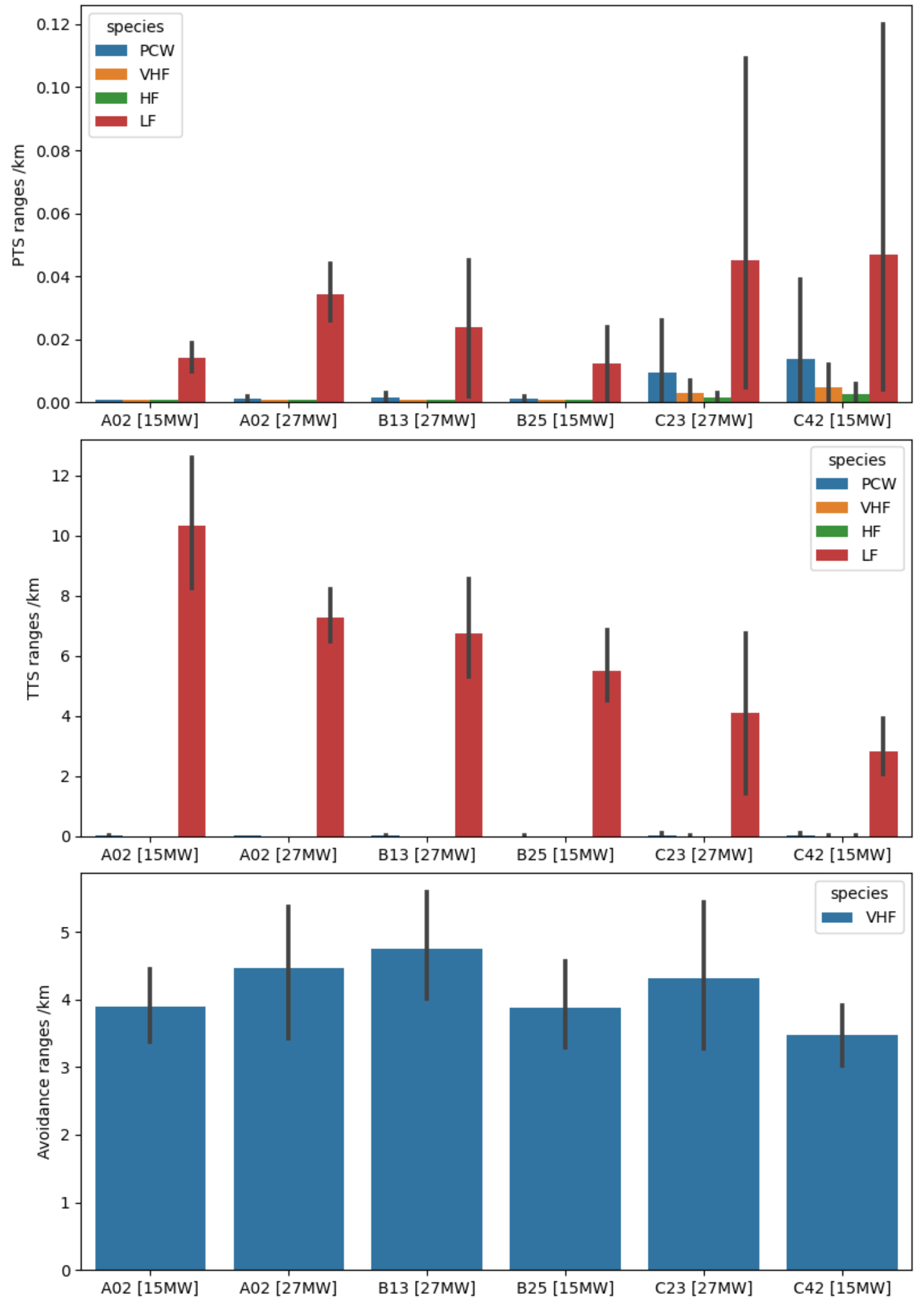

Figure 6-30. Impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for each location considering a piling sequence with a maximum blow energy of 4,000 kJ and a combination of HSD+DBBC (20 dB noise reduction).

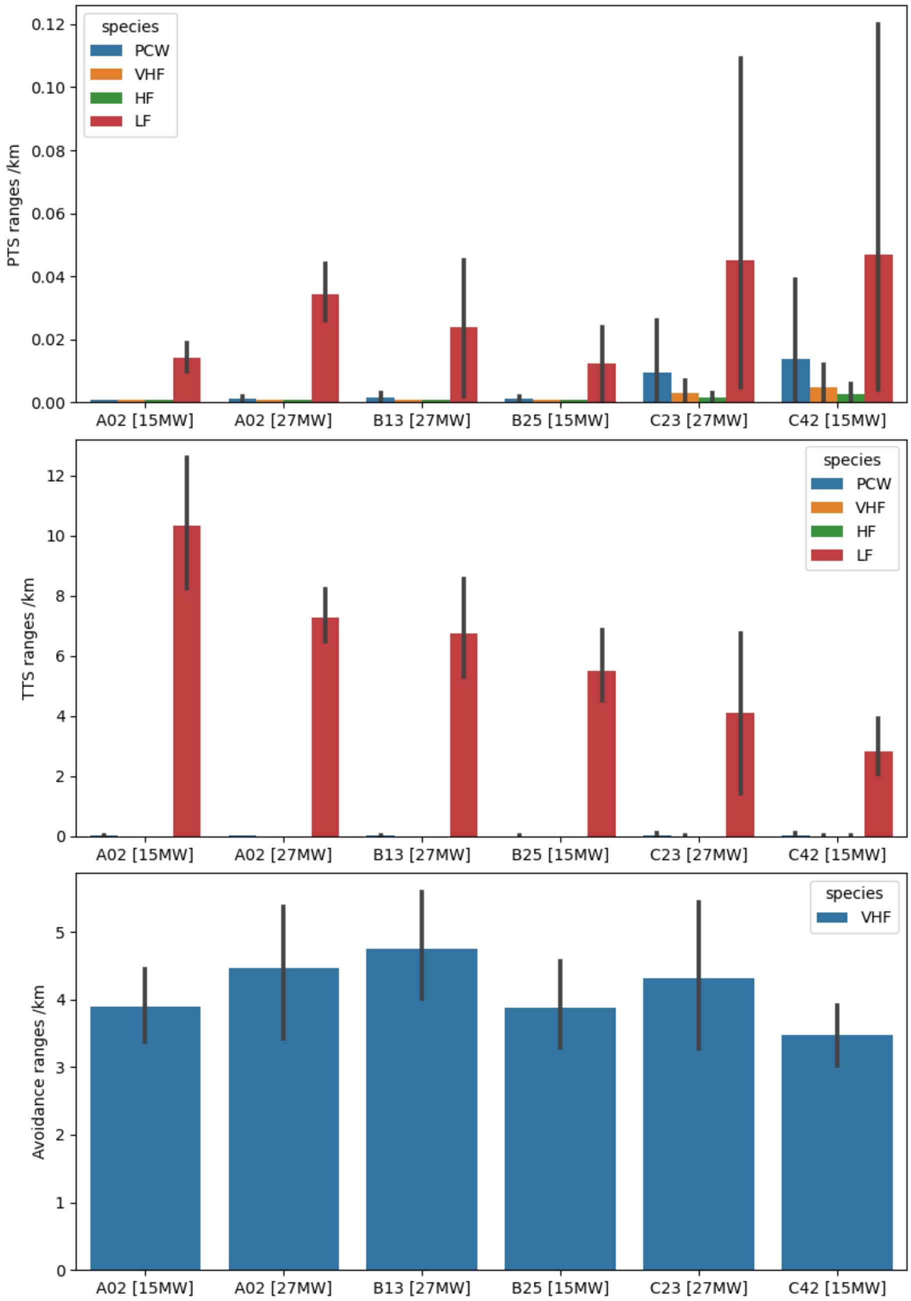

Figure 6-31. Impact distances for the threshold criteria according to GfUN (Energistyrelsen 2022) for each location considering a piling sequence with a maximum blow energy of 6,000 kJ and a combination of HSD+DBBC (20 dB noise reduction).

7 CONCLUSION

7.1 GENERAL

According to GfUN (Energistyrelsen 2022), piling is allowed without the use of an ADD if the PTS impact distances are below 200 m. The results of this study show that it is possible to ensure that a PTS impact does not occur outside 200 m distance with appropriate noise abatement systems.

Depending on the marine mammal species considered, the impact ranges for the unmitigated cases differ significantly. Due to the low-frequency sound resulting from impulse pile driving, LF cetaceans have the largest PTS ranges, followed by VHF cetaceans, which hardly perceive low-frequency sound, but for which more sensitive threshold criteria are defined.

In the following subsection the maximum expected impact ranges by using different noise mitigation concepts are presented for each sub-area. To avoid the risk of suffering PTS in the range of < 200 m, a DBBC is sufficient for all species except the LF-Cetaceans. They require a combination of HSD+DBBC.

7.2 NSI.1-A3

Table 7-1 to Table 7-4 show the maximum expected PTS distances for the three considered noise mitigation concepts (DBBC, HSD and HSD+DBBC). For the sake of clarity, the table is limited to the two most sensitive hearing groups, the LF and VHF cetaceans, for both pile diameter and piling sequences with 4,000 kJ and 6,000 kJ maximum blow energy.

For the example shown here, as well as for all other cases, the maximum PTS ranges for VHF cetaceans can be reduced to distances below 200 m by using a DBBC or by combining HSD+DBBC. For the PTS ranges of LF cetaceans, this can only be achieved by using a combination of HSD+DBBC.

Table 7-1. Maximum Impact distances expected at Location A02 with 13 m pile diameter and different noise mitigation concepts by using the hammer with 4,000 kJ maximum blow energy.

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	9.906
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	1.266
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	24.992
DBBC	LF	PTS	$SEL_{cum,LF}$	185	1.036
HSD	LF	PTS	$SEL_{cum,LF}$	185	6.192
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.017

Table 7-2. Maximum Impact distances expected at Location A02 with 13 m pile diameter and different noise mitigation concepts by using the hammer with 6,000 kJ maximum blow energy.

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	11.045
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	1.565
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	26.537
DBBC	LF	PTS	$SEL_{cum,LF}$	185	1.332
HSD	LF	PTS	$SEL_{cum,LF}$	185	7.242
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.019

Table 7-3. Maximum Impact distances expected at Location A02 with 18 m pile diameter and different noise mitigation concepts by using the hammer with 4,000 kJ maximum blow energy.

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	14.206
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.002
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	2.557
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	18.325
DBBC	LF	PTS	$SEL_{cum,LF}$	185	1.017
HSD	LF	PTS	$SEL_{cum,LF}$	185	5.568
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.043

Table 7-4. Maximum Impact distances expected at Location A02 with 18 m pile diameter and different noise mitigation concepts by using the hammer with 6,000 kJ maximum blow energy.

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	15.617
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.002
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	3.102
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	19.763
DBBC	LF	PTS	$SEL_{cum,LF}$	185	1.228
HSD	LF	PTS	$SEL_{cum,LF}$	185	6.440
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.044

7.3 NSI.1-A2

Table 7-5 to Table 7-8 shows the maximum expected PTS distances for the three considered noise mitigation concepts (DBBC, HSD and HSD+DBBC). For the sake of clarity, the table is limited to the two most sensitive hearing groups, the LF and VHF cetaceans, for both pile diameter and piling sequences with 4,000 kJ and 6,000 kJ maximum blow energy.

For the example shown here, as well as for all other cases, the maximum PTS ranges for VHF cetaceans can be reduced to distances below 200 m by using a DBBC or by combining HSD+DBBC. For the PTS ranges of LF cetaceans, this can only be achieved by using a combination of HSD+DBBC.

Table 7-5. Maximum Impact distances expected at Location B15 with 13 m pile diameter and different noise mitigation concepts by using the hammer with 4,000 kJ maximum blow energy

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	9.791
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	1.224
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	18.575
DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.547
HSD	LF	PTS	$SEL_{cum,LF}$	185	4.459
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.024

Table 7-6. Maximum Impact distances expected at Location B15 with 13 m pile diameter and different noise mitigation concepts by using the hammer with 6,000 kJ maximum blow energy.

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	10.921
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	1.521
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	20.056
DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.628
HSD	LF	PTS	$SEL_{cum,LF}$	185	5.195
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.024

Table 7-7. Maximum Impact distances expected at Location B13 with 18 m pile diameter and different noise mitigation concepts by using the hammer with 4,000 kJ maximum blow energy.

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	15.54
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	2.56
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	32.891
DBBC	LF	PTS	$SEL_{cum,LF}$	185	1.048
HSD	LF	PTS	$SEL_{cum,LF}$	185	6.905
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.043

Table 7-8. Maximum Impact distances expected at Location B13 with 18 m pile diameter and different noise mitigation concepts by using the hammer with 6,000 kJ maximum blow energy

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	16.874
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	3.087
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.001
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	34.015
DBBC	LF	PTS	$SEL_{cum,LF}$	185	1.16
HSD	LF	PTS	$SEL_{cum,LF}$	185	7.953
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.045

7.4 NSI.1-A1

Table 7-9 to Table 7-12 shows the maximum expected PTS distances for the three considered noise mitigation concepts (DBBC, HSD and HSD+DBBC). For the sake of clarity, the table is limited to the two most sensitive hearing groups, the LF and VHF cetaceans, for both pile diameter and piling sequences with 4,000 kJ and 6,000 kJ maximum blow energy.

For the example shown here, as well as for all other cases, the maximum PTS ranges for VHF cetaceans can be reduced to distances below 200 m by using a DBBC or by combining HSD+DBBC. For the PTS ranges of LF cetaceans, this can only be achieved by using a combination of HSD+DBBC.

Table 7-9. Maximum Impact distances expected at Location C42 with 13 m pile diameter and different noise mitigation concepts by using the hammer with 4,000 kJ maximum blow energy.

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	11.107
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.015
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	1.304
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.012
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	13.045
DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.227
HSD	LF	PTS	$SEL_{cum,LF}$	185	2.394
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.12

Table 7-10. Maximum Impact distances expected at Location C42 with 13 m pile diameter and different noise mitigation concepts by using the hammer with 6,000 kJ maximum blow energy

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	12.354
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.015
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	1.647
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.012
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	14.409
DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.232
HSD	LF	PTS	$SEL_{cum,LF}$	185	2.878
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.12

Table 7-11. Maximum Impact distances expected at Location C23 with 18 m pile diameter and different noise mitigation concepts by using the hammer with 4,000 kJ maximum blow energy.

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	15.02
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.009
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	2.604
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.007
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	19.578
DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.868
HSD	LF	PTS	$SEL_{cum,LF}$	185	5.297
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.109

Table 7-12. Maximum Impact distances expected at Location B13 with 18 m pile diameter and different noise mitigation concepts by using the hammer with 6,000 kJ maximum blow energy.

NAS	Hearing Group	Behavior	Metric	Criteria [dB]	Max distance [km]
Unmitigated	VHF	PTS	$SEL_{cum,VHF}$	155	16.366
DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.009
HSD	VHF	PTS	$SEL_{cum,VHF}$	155	3.154
HSD+DBBC	VHF	PTS	$SEL_{cum,VHF}$	155	0.007
Unmitigated	LF	PTS	$SEL_{cum,LF}$	185	21.11
DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.977
HSD	LF	PTS	$SEL_{cum,LF}$	185	6.184
HSD+DBBC	LF	PTS	$SEL_{cum,LF}$	185	0.109

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