Hesselø Offshore Wind Farm

Underwater noise
Technical report

ENERGINET ELTRANSMISSION A/S

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Contents

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Preface

This report was commissioned by Energinet to the consortium of NIRAS and Aarhus University and constitutes a description of the underwater noise in connection with the construction and operation of the proposed Hesselø OWF.

The report builds upon existing knowledge as well as new data and analysis collected and conducted during this project.

The report is divided in eight chapters and begin by a short introduction (chapter 1) and the aim of the report (chapter 2). Chapter 3 describes underwater noise basics and chapter 4 describes the baseline underwater soundscape. In chapter 5 underwater noise during construction is presented and chapter 6 provides the results of construction phase underwater noise emission. Chapter 7 describes noise during the operational phase and chapter 8 the conclusion.

The work within the consortium was divided so that DCE has been the main authors and responsible for Chapter 4 and 7 and NIRAS has been main author and responsible for the other chapters. All contributors have however consensus with regard to the underwater noise modelling and the main conclusions in the report.

Resumé (Dansk)

For at kunne vurdere påvirkningen af undervandsstøj i forbindelse med pælenedramning fra et projekt, som planen for Hesselø Havvindmøllepark giver mulighed for at realisere, er der udført en undervandsstøjmodellering, som viser undervandsstøjudbredelsen i og i nærheden af planområdet. I modellen er der inkluderet områdespecifikke informationer om dybdeforhold (bathymetri), saltholdighed (salinitet) samt temperatur og sedimentsammensætning. Støjmodelleringen er foretaget med udgangspunkt i konservative antagelser om den tid, det tager at nedramme pælene, hammerslagstyrke samt kildestyrke for undervandsstøjen. Derudover er det antaget at nedramning af pælene startes langsomt op med en soft-start/ramp-up procedure, hvor lydens intensitet øges langsomt for at give havpattedyrene mulighed for at svømme ud af nærområdet, inden der rammes ved fuld hammerslagkraft, og undervandsstøjen når sit maksimum.

De danske guidelines for undervandsstøjmodellering er under opdatering, og forventes at komme til at følge den nyeste viden og de seneste retningslinjer for pæleramning, hvor frekvensvægtning indgår i beregningerne af påvirkningsafstande for midlertidig og permanent høretab (hhv. TTS og PTS) samt undvigeadfærd hos de marine pattedyr. Disse tålegrænser er anvendt i beregningerne. Ved anvendelse af frekvensvægtning vægtes lyde efter hørbarhed for de enkelte arter.

Erfaringer fra andre projekter viser, at pælenedramning af store fundamenter uden brug af støjreducerende tiltag [Bellmann, et al., August 2020] kan medføre PTS hos havpattedyr, hvilket vil være en væsentlig påvirkning af havpattedyr. Derfor er der ikke udført undervandsstøjberegninger uden støjreducerende tiltag, men kun beregninger med støjreducerende tiltag, som tager udgangspunkt i den nyeste tilgængelige teknologi. Undervandsstøjudbredelsen fra pælenedramning er modelleret med anvendelse for et scenarie med en støjdæmpning svarende til, hvad der forventes ved anvendelse af et enkelt big boble gardin (BBC), samt et andet scenarie med anvendelse af en kraftigere støjdæmpning svarende til hvad der forventes ved anvendelse af ”double big bubble curtain” i kombination med en ”hydro sound damper” (HSD-DBBC).

Summary

For the planned offshore wind farm 'Hesselø', NIRAS has carried out underwater sound propagation modelling, for the installation of monopile foundations. Results of the modelling are intended for evaluation of the impact on marine mammals and fish. Underwater noise emission resulting from the operation of the wind farm is also evaluated.

Hesselø offshore wind farm (OWF) is located in Danish waters and must comply with Danish authority regulation for underwater noise emission from pile installation. Guidelines exist [Energistyrelsen, 2016], however they are currently under revision and project specific criteria has therefor been agreed with the Danish Energy Agency (Energistyrelsen) for the Hesselø OWF project. For marine mammals, frequency weighted $SELC_{24h}$ and $SPL_{RMS,fast}$ threshold levels must be used. For fish there are no guidelines, and evaluation of underwater noise impact on fish, is based on unweighted $SELC_{24h}$ threshold levels following available scientific literature.

Underwater noise emission modelling was calculated for three monopile foundation sizes (10 m, 13 m and 15 m diameter). Noise emission was calculated from four worst case source positions, expected to result in the largest noise emission in general, and towards nearby Natura 2000 areas.

A 3D acoustic model was created in dBSea 2.3.3, utilizing available knowledge about bathymetry, seabed sediment composition, water column salinity, temperature and sound speed in the specific area as well as a source model. Using advanced underwater sound propagation algorithms, the noise emission from each scenario was calculated in 180 directions (2° resolution) and with a grid resolution of 50 m x 1 m (Range step, depth).

From the underwater sound propagation model, mitigation requirements for the installation of each of the three different sizes of monopiles were determined, in order to comply with the agreed criteria for Hesselø OWF. The mitigation requirements are calculated by comparison of the $SEL_{c24h,weighting}$ to the harbour porpoise Permanent Threshold Shift (PTS) value of $SEL_{c24h,VHF}$ = 155 dB re 1 μPa²s, and the harbour seal PTS value of $SEL_{c24h,PW}$ = 185 dB re 1 μPa²s, provided a starting distance of 300 m from the installation and a fleeing behaviour of 1.5 m/s directly away from the pile. This results in mitigation requirements of $\Delta SEL_{VHF} = 8.6\ dB$ and $\Delta SEL_{PW} = 6.9\ dB$ for a 10 m monopile. Increasing the diameter to 13 m, the mitigation requirements increase by 2.3 dB both VHF- and PW-weighted. A further 1.2 dB of reduction is required if the monopile diameter is increased to 15 m. The calculated mitigation requirements can be seen in detail in Table 6.1. Additional sound propagation modelling is carried out using a Big Bubble Curtain (BBC) Noise Abatement Systems (NAS) equivalent, as well as a scenario where a Hydro Sound Damper together with a Double Big Bubble curtain (HSD-DBBC) NAS equivalent is used, which provides further mitigation.

Applying HSD-DDBC and BBC individually allows for determining the impact distances for the species of interest. This included species specific thresholds for avoidance behaviour, Temporary Threshold Shift (TTS) and PTS, as well as injury (for fish). Table 1.1 shows an overview of the worst case impact distances for cod, herring and marine mammals (harbour porpoise and seals). Results are provided in Table 6.3 and in Table 6.4 for fish and marine mammals respectively.

Table 1.1: Overview over impact distance for fish and marine mammals.

Species	Mitigation	Impact distance for fish and marine mammals									
		Injury			TTS			PTS	Behaviour		
		10m	13m	15m	10m	13m	15m	All	10m	13m	15m
Marine mam-mals	HSD-DBBC	-			<50m			<25m	6.8km	8.2km	9.1km
	BBC	-			60m	120m	180m	<25m	9.8km	11.4km	12.4km
Cod	HSD-DBBC	<25m			3.5km	5.5km	7.1km	-	-		
	BBC	<25m			4.4km	7.3km	9.5km	-	-		
Herring	HSD-DBBC	<25m			0.6km	2.0km	3.1km	-	-		
	BBC	<25m			1.2km	3.2km	4.9km	-	-		
Larvae and eggs	HSD-DBBC	375m	525m	625m	-			-	-		
	BBC	425m	575m	700m	-			-	-		
"-" Threshold is not obtained for this species.											

Abbreviations

Full name	Abbreviation
Offshore Wind Farm	OWF
Sound Exposure Level	SEL
Cumulative Sound Exposure Level	SEL_{C24h}
Sound Pressure Level	SPL
Permanent Threshold Shift	PTS
Temporary Threshold Shift	TTS
American National Oceanographic and Atmospheric Administration	NOAA
Noise Abatement System	NAS
Low-frequency	LF
High-frequency	HF
Very High-frequency	VHF
Big Bubble Curtain	BBC
Double Big Bubble Curtain	DBBC
Hydro Sound Damper	HSD
Noise Mitigation Screen	IHC-NMS
World Ocean Atlas	WOA18
Normal modes	NM
Parabolic Equation	PE

1 Introduction

With the Energy Agreement in June 2018 and the following 'Climate agreement for energy and industry, etc. 2020' in June 2020, the Danish parliament decided to tender for a new offshore wind farm of 800 – 1200 MW with grid connection in 2027. The offshore wind farm will be located in the central Kattegat approx. 30 km north of Gilbjerg Hoved on the north coast of Zealand. The wind farm is named Hesselø Offshore Wind Farm (Hesselø OWF) after the small uninhabited island of Hesselø, which is located southwest of the area. The Hesselø OWF will have an installed capacity of minimum 800 MW and maximum 1,200 MW.

The planning area for Hesselø OWF is shown in Figure 1.1.

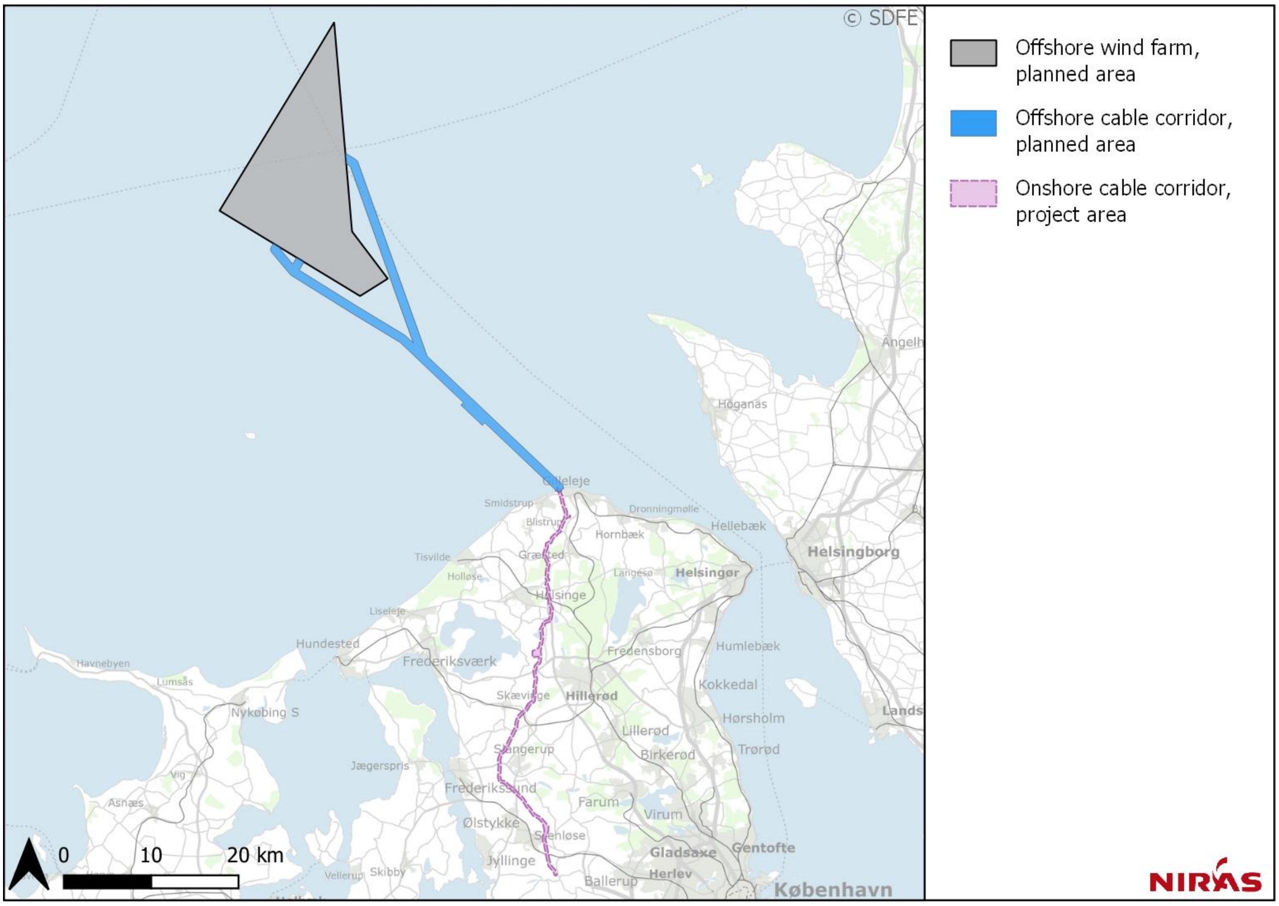


Figure 1.1 Planning area for Hesselø Offshore Wind Farm.

In order to ensure that Hesselø OWF will be supplying electricity by 2027, the Minister of Climate, Energy and Utilities has instructed Energinet to initiate the preliminary studies for the project – both offshore and on-shore. This includes strategic environmental assessment (SEA) of the plan for the overall project, completion of relevant environmental surveys etc., investigation of a grid connection from the coast to the connection point at Hovegaard High Voltage (HV) station and preparation of an environmental impact report (EIA) for the on-shore facilities.

The location of Hesselø OWF is based on a detailed screening of multiple areas for offshore wind farms in Danish waters carried out for the Danish Energy Agency and reported in spring 2020 [COWI, 2020].

This report documents the underwater sound propagation modelling for the installation of wind turbine foundations at Hesselø OWF. A literature study of the baseline underwater noise levels in the area as well as during operation of the OWF is provided.

One proposed foundation method is monopile foundations of 10 m, 13 m or 15 m diameter respectively. Other foundation methods may be used, however from an underwater noise emission perspective, only monopiles are considered relevant at this stage. The monopiles are proposed installed using impact pile driving, that potentially generate underwater noise levels that can cause injury, permanent and temporary threshold shift (PTS and TTS respectively) and behavioural response in marine mammals and fish.

2 Purpose

The purpose of this report is to model and describe underwater noise emission from construction and operation of the Hesselø OWF. A literature study on existing underwater noise levels in the area, underwater noise modelling from construction as well as a literature study and assessment of the underwater noise from operation of the wind farm is provided. For the construction phase, relevant impact distances for marine mammals and fish must be calculated, and for marine mammals in compliance with the criteria set by the Danish Energy Agency (Energistyrelsen).

3 Underwater noise basics

This chapter discusses general background knowledge for underwater noise, with definitions of used noise metrics, guideline requirements as well as threshold levels for quantifying the impact of noise. Furthermore, the methodology of underwater sound propagation is explained together with the relevant environmental parameters.

3.1 Sound level metrics

In the following, the reader is introduced to the acoustic metrics used throughout the report for quantifying the sound levels.

3.1.1 Sound Pressure Level ($\mathrm{SPL_{RMS}}$)

In underwater noise modelling, the Sound Pressure Level (SPL) is commonly used to quantify the noise level at a specific position, and in impact assessments, is used for assessing the behavioural response of marine mammals as a result of noisy activities. The definition given in [Erbe, 2011] is shown in Equation 1.

$$\mathrm{SPL_{RMS}} = 20 * \log_{10}\left(\sqrt{\left(\frac{1}{\mathrm{T}}\right)\int_{\mathrm{T}} \mathrm{p(t)}^2}\right) \ [\mathrm{dB\ re.\ 1\mu Pa}] \qquad \text{Equation 1}$$

Where p is the acoustic pressure of the noise signal during the time of interest, and T is the total time. $\mathrm{SPL_{RMS}}$ can be seen as the average unweighted SPL over a measured period of time. The time window must be specified for the metric. Often, a fixed time window of 125 ms, also called "fast", is used due to the integration time of the mammal ear [Tougaard & Beedholm, 2018]. The metric is then referred to as $\mathrm{SPL_{RMS-fast}}$.

3.1.2 Sound Exposure Level (SEL)

Another important metric is the Sound Exposure Level (SEL), which describes the total energy of a noise event [Jacobsen & Juhl, 2013]. A noise event can for instance be the installation of a monopile by impact pile driving, from the start to the end, or it can be a single noise event like an explosion.

The SEL is normalized to 1 second and is defined in [Martin, et al., 2019] through Equation 2.

$$\mathrm{SEL} = 10\log_{10}\left(\frac{1}{T_0 p_0^2}\int_0^T p^2(t)\right) \ [\mathrm{dB\ re.\,1\mu Pa^2 s}] \qquad \text{Equation 2}$$

Where T_0 is 1 second, 0 is the starting time and T is end time of the noise event, p is the pressure, and p_0 is the reference sound pressure which is $1\ \mu\mathrm{Pa}$. When SEL is used for reference to a single impulse, the term $\mathrm{SEL_{SS}}$ is sometimes used. When the SEL is used to describe the sum of noise from more than a single event (e.g. several pile driving pulses), the term Cumulative SEL, or $\mathrm{SEL_{C,<duration>}}$ is typically used.

Marine mammals can incur hearing loss, either temporarily or permanently as a result of exposure to high noise levels. The level of injury depends on both the intensity and duration of noise exposure, and the SEL is therefore a commonly used term to assess the risk of hearing impairment as a result of noisy activities. [Martin, et al., 2019].

The relationship between $\mathrm{SPL_{RMS}}$ in Equation 1 and SEL, in Equation 2, is given by Equation 3 [Erbe, 2011].

$$\mathrm{SEL} = \mathrm{SPL_{RMS}} + 10 * \log_{10}(T) \qquad \text{Equation 3}$$

3.1.3 Fleeing behaviour model

As mentioned in section 3.1.2, $\mathrm{SEL_{C,<duration>}}$ is useful for determining the combined noise impact from sound sources with a duration of more than a single pulse. In the assessment of TTS, PTS and injury caused by underwater noise on marine mammals and fish, $\mathrm{SEL_{C,<duration>}}$ is used to describe the noise dose received by the receptors. It is therefore important to include the fleeing behaviour of fish and marine mammals in the calculation of $\mathrm{SEL_{C,<duration>}}$.

For a stationary source, such as installation of a foundation, the installation procedure, as well as the fleeing speed for the receptor, must be included. A method for implementing such conditions in the calculation of $\mathrm{SEL_{C,<duration>}}$ has already been done by [Energistyrelsen, 2016], for the current Danish guidelines for pile driving activities, as given by Equation 4. Here, the duration is fixed to 24 hours to represent the daily $\mathrm{SEL_C}$. If multiple foundations are installed in the same 24 hour window, they all have to be included in the calculation.

$$\mathrm{SEL_{C24h}} = 10 * \log_{10}\left(\sum_{i=1}^{N} \frac{S_i}{100\%} * 10^{\left(\frac{\mathrm{SEL_{Max}} - X*\log_{10}(r_0 + v_f*\Delta t_i) - A*(r_0 + v_f*\Delta t_i)}{10}\right)}\right) \qquad \text{Equation 4}$$

Where:
- S_i is the percentage of full hammer energy of the i'th strike
- N is the total number of strikes for the pile installation
- $\mathrm{SEL_{Max}}$ is the source level at 1 m distance at 100% hammer energy
- X and A describe the sound propagation losses for the specific project site
- r_0 is the marine mammal distance to source at the onset of piling
- v_f is the fleeing speed of the marine mammal directly away from the source
- Δt_i is the time difference between onset of piling, and the i'th strike.

The parameters related to the source level, hammer energy, number of strikes and time between each strike must be based on realistic assumptions and can be achieved through a site specific drivability analysis. The relationship between hammer energy level and pile strike number is referred to as the hammer curve.

The sound propagation parameters (X and A) must be determined through an advanced sound propagation model, in which all relevant site specific environmental parameters are taken into account.

3.2 Underwater noise impact criteria

Guidance or threshold values for regulating underwater noise during construction of OWFs (pile driving) have been developed in several countries and by international organizations. There are different approaches in the different countries when it comes to estimating impacts from pile driving on marine mammals and fish.

Since the project is in Danish waters it must comply with current Danish authority guidelines on underwater noise emission from pile installation, however the Danish guidelines are currently under revision. In the absence of an official new guideline from the Danish Energy Agency, a specific methodology for underwater noise calculations and thresholds for Hesselø OWF has been developed by NIRAS. The methodology has been agreed with the DEA (see Appendix 4), and is presented below.

The area for the planned Hesselø OWF is located 8 km from the Danish-Swedish EEZ border, and it is therefore also relevant to consider the underwater noise emission into Swedish waters and thereby any Swedish regulation or guidelines for underwater noise. Sweden does not have specific guidelines for underwater noise emission, but handles the topic on a project by project basis. From recent applications for Swedish OWFs, such as "Skåne Havsvindpark" (Ørsted), "Stora Middelgrund" (Vattenfall), "Galatea-Galene" (OX2) and "Kattegat Syd" (Vattenfall), the approach to underwater noise emission is very similar to the methodology agreed with the Danish Energy Agency for the Hesselø OWF project and the results of the underwater noise modelling cover both Danish and Swedish praxis.

In the following subsections, the methodology for the modelling of underwater noise emission for the Hesselø OWF project is described in detail.

3.2.1 Methodology for underwater noise emission modelling

The agreed methodology for the assessment of underwater noise emission from the installation of monopiles in Hesselø OWF is described in the following.

For the assessment of underwater noise impact on fish, unweighted SEL_{C24h} threshold levels are used, see section 3.2.2. For marine mammals, frequency weighted SEL_{C24h} and $SPL_{RMS,fast}$ threshold levels are used, see section 3.2.3.

Underwater sound propagation modelling must include, to the extent necessary, noise mitigation, so that PTS does not occur for any marine mammals located more than 300 m from the pile location at the onset of piling. The calculation of any PTS and TTS must include animal fleeing behaviour. For marine mammals, this speed is set at 1.5 m/s, while for fish it is differentiated between species, and fish age. The 300 m (starting) distance for marine mammals is considered to be the likely clearance radius given the use of deterrent devices prior to piling, as well as the general noise emission from installation and support vessels near the pile installation.

When the mitigation requirement has been determined through underwater sound propagation modelling, a Noise Abatement Systems (NAS) with sufficient mitigation effect is selected, so that the mitigation requirement is met, and to ensure that other criteria for impact on fish and marine mammals is not exceeded. The use of a NAS, instead of a general mitigation effect, is chosen in order to provide a more realistic mitigation scenario. The selection of a NAS, will be based on best available knowledge into the achievable noise mitigation using commercially available and tested systems.

With the application of the NAS, revised calculations are performed for PTS, TTS and behaviour for marine mammals and for TTS and injury for fish, to act as input for the respective assessments.

Behaviour distances for harbour porpoises are documented and assessed exclusively for the mitigated scenario, as pile diving without mitigation is not considered a realistic scenario.

It must be noted, that the NAS proposed in this report, is based on worst case assumptions given the limited available information at this stage, and that a revised underwater noise assessment and choice of an actual

NAS must be carried out when the final foundation type and size, hammer, drivability analysis, detailed oceanographic and knowledge about the time of year the installation will take place, is known. Underwater sound propagation modelling must include at least the frequency range of: 16 Hz – 16 kHz, and must be carried out using appropriate sound propagation modelling software and algorithms (Ray, PE, NM). Calculations must cover at least a 20 km radius from any source position.

In the following, the specific threshold levels to be calculated for fish and marine mammals are provided.

3.2.2 Frequency unweighted threshold levels (fish)

Assessment of the noise impact on fish, is currently based on frequency unweighted threshold levels using the metric SEL_{C24h} thresholds for TTS and physical injury, as presented in Table 3.1.

Table 3.1: Unweighted threshold criteria for fish (Andersson et al., 2017), (Popper, et al., 2014), [Energistyrelsen, 2016], [Tougaard, 2016].

Species	Fleeing Speed [m/s]	Species specific unweighted thresholds (Impulsive) $SEL_{C24h,\mathrm{unweighted}}$	
		TTS [dB]	Injury [dB]
Cod, juvenile	0.38	185	204
Cod, adult	0.9	185	204
Herring	1.04	185	204
Larvae and eggs	0	-	207
"-" Thresholds is not obtained for this species			

3.2.3 Frequency weighted threshold levels (marine mammals)

For marine mammals, threshold levels for hearing impact are primarily based on a large study from the American National Oceanographic and Atmospheric Administration (NOAA), [NOAA, April 2018], where species specific frequency weighting is proposed, effectively taking the hearing sensitivity of each species into account when estimating the impact of a given noise source. Thresholds are divided into two groups of noise sources; impulsive and non-impulsive. Impulsive noise sources are sounds with a quick rise-time and short duration, and are considered more harmful to the hearing than non-impulsive sources which have a more continuous and stable acoustic nature. Examples of impulsive noises are those from impact pile driving, explosions and certain types of seismic exploration equipment such as airguns. Examples of non-impulsive sources are vessel noise, vibration pile driving and drilling.

In [NOAA, April 2018]; [Southall, et al., 2019] the marine mammal species, are divided into four hearing groups in regards to their frequency specific hearing sensitivities: 1) Low-frequency (**LF**) cetaceans, 2) High-frequency (**HF**) cetaceans, 3) Very High-frequency (**VHF**) cetaceans, 4) and Phocid pinnipeds (**PW**) (underwater). For this project, only the latter two hearing groups are relevant [NIRAS & DCE, 2021]. More details about the hearing groups and their frequency sensitivities are given in section 3.2.5. The hearing group weighted threshold criteria for all groups, can be seen in Table 3.2, with the irrelevant species for this project marked in grey.

Table 3.2: Species specific weighted threshold criteria for marine mammals. This is a revised version of Table AE-1 in [NOAA, April 2018] to highlight the important species in the project area [NOAA, April 2018]; [Southall, et al., 2019].

Hearing group	Representative species	Fleeing speed [m/s]	Species specific weighted thresholds (non-impulsive)		Species specific weighted thresholds (Impulsive)		
			SEL_{C24h}*		SEL_{C24h}*		$SPL_{RMS-fast}$*
			TTS [dB]	PTS [dB]	TTS [dB]	PTS [dB]	Behaviour [dB]
Low-Frequency Cetaceans	Minke whales	1.5	179	199	168	183	-
High-Frequency Cetaceans	White-beaked dolphin	1.5	178	198	170	185	-
Very High-Frequency Cetaceans	Harbour porpoise	1.5	153	173	140	155	100
Phocid Pinniped	Harbour seal	1.5	181	201	170	185	-
"-" Thresholds is not obtained for this hearing group. *: frequency weighted level							

In addition to the PTS and TTS thresholds, it is also proposed, in the technical report on marine mammals [NIRAS & DCE, 2021], to consider the behavioural impact on harbour porpoise, through the single pulse criteria $\mathrm{SPL}_{\mathrm{RMS-fast,VHF}} = 100\ dB\ re.1\mu Pa$ based on the recommendations by Tougaard et al. [2015]. No behavioural impact threshold for harbour seal is considered due to lack of knowledge.

3.2.4 Threshold distance representation

The unweighted and frequency weighted impact criteria, rely on determining the distances at which the various thresholds are likely to occur.

As such, threshold distances for injury, PTS and TTS describe the minimum distance from the source, a marine mammal or fish must at least be at, prior to onset of pile driving, in order to avoid the respective impact. Thus, it does not represent a specific measurable sound level, but rather a safe starting distance.

The threshold distance for behaviour, on the other hand, describes the specific distance, up to which, the behavioural response is likely to occur, when maximum hammer energy is applied to a pile strike.

It should be noted, that for impact pile driving, a significant portion of the installation time will not be carried out applying maximum hammer energy, however a steadily increasing amount of energy from soft start (10-15% of hammer energy) through ramp up (15%-99%) to full power (100%). Depending on the soil conditions, the hammer energy requirements through the ramp up and full power phases will vary from site to site, and even between individual pile locations within a project site.

3.2.5 Frequency weighting functions

As described in the previous section, the impact assessment for underwater noise includes frequency weighted threshold levels. In this section, a brief explanation of the frequency weighting method is given.

The different mammal species do not hear equally well at all frequencies. Humans for example are most sensitive to frequencies in the range of 2 kHz - 5 kHz and for frequencies outside this range, the sensitivity decreases. This frequency-dependent sensitivity correlates to a weighting function, for the human auditory system it is called A-weighting. For marine mammals the same principle applies through the weighting function, $\mathrm{W(f)}$, defined through Equation 5.

$$W(f) = C + 10 * \log_{10}\left(\frac{\left(\frac{f}{f_1}\right)^{2*a}}{\left[1+\left(\frac{f}{f_1}\right)^2\right]^a * \left[1+\left(\frac{f}{f_2}\right)^2\right]^b}\right) [dB] \qquad \text{Equation 5}$$

Where:

- a is describing how much the weighting function amplitude is decreasing for the lower frequencies.
- b is describing how much the weighting function amplitude is decreasing for the higher frequencies.
- f_1 is the frequency at which the weighting function amplitude begins to decrease at the lower frequencies [Hz]
- f_2 is the frequency at which the weighting function amplitude begins to decrease at the higher frequencies [Hz]
- C is the function gain [dB].

For an illustration of the parameters see Figure 3.1.

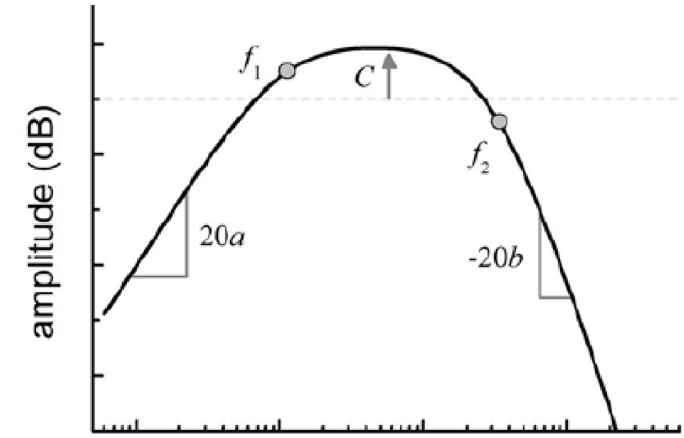


Figure 3.1: Illustration of the 5 parameters in the weighting function [NOAA, April 2018].

The parameters in Equation 5 are defined for the hearing groups of interest and the values are presented in Table 3.3.

Table 3.3: Parameters for the weighting function for the different hearing groups of relevance for the Hesselø OWF project [NOAA, April 2018].

Hearing Group	a	b	f_2 (kHz)	f_2(kHz)	C (dB)
Very High-frequency (VHF) cetaceans	1.8	2	12	140	1.36
Phocid pinnipeds (PW) (underwater)	1.0	2	1.9	30	0.75

By inserting the values from Table 3.3 into Equation 5, the spectra are obtained for the relevant hearing groups in Figure 3.2.

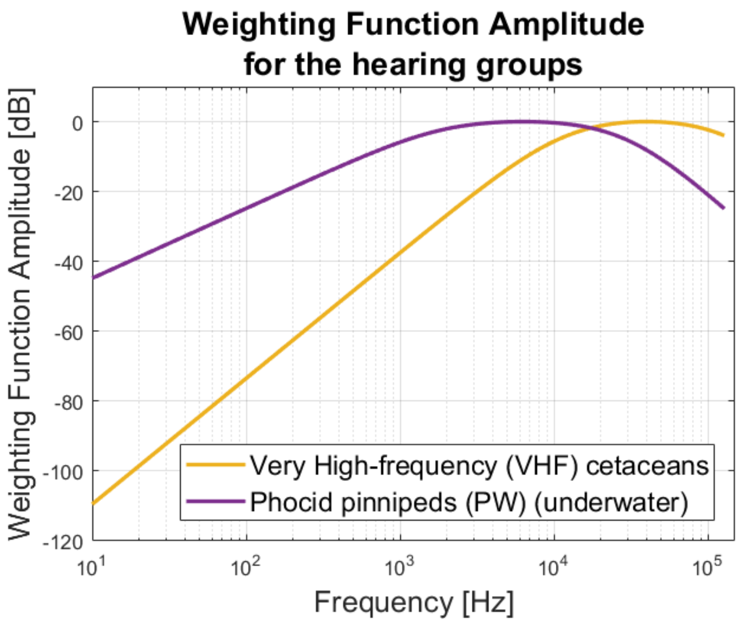


Figure 3.2: The weighting functions for the different hearing groups.

3.3 Underwater sound propagation modelling methodology

This section provides a brief overview of underwater sound propagation theory and the software program used for sound propagation modelling, followed by a general description of the environmental inputs.

3.3.1 Underwater sound propagation theory

This section is based on [Jensen, et al., 2011] chapter 1 and chapter 3 as well as [Porter, 2011], and seeks to provide a brief introduction to sound propagation in saltwater. For a more detailed and thorough explanation of underwater sound propagation theory see [Jensen, et al., 2011].

Sound pressure level generally decreases with increasing distance from the source. However, many parameters influence the propagation and makes it a complex process.

The speed of sound in the sea, and thus the sound propagation, is a function of both pressure, salinity and temperature, all of which are dependent on depth and the climate above the ocean and as such are very location dependent.

The theory behind the sound propagation is not the topic of this report, however it is worth mentioning one aspect of the sound speed profile importance, as stated by Snell's law, Equation 6.

$$\frac{\cos(\theta)}{c} = \text{constant} \qquad \text{Equation 6}$$

Where:
- θ is the ray angle [°]
- c is the speed of sound $\left[\frac{m}{s}\right]$.

This relationship implies that sound waves bend toward regions of low sound speed [Jensen, et al., 2011]. The implications for sound in water are, that sound that enters a low velocity layer in the water column can get trapped there. This results in sound travelling far with very low sound transmission loss (low sound energy loss).

When a low velocity layer occurs near the sea surface, with sound speeds increasing with depth, it is referred to, as an upward refraction. This causes the sound waves to be reflected by sea surface more than by the seabed. As the sea surface is often modelled as a calm water scenario (no waves), it causes reduced transmission loss, and thus a minimal loss of sound energy. This scenario will always be the worst case situation in terms of sound transmission loss. For some sound propagation models, this can introduce an overestimation of the sound propagation, if the surface roughness is not included.

When a high velocity layer occurs near the sea surface with the sound speed decreasing with depth, it is referred to, as a downward refraction. This causes the sound waves to be angled steeper towards the seabed rather than the sea surface, and it will thus be the nature of the seabed that determines the transmission loss. Depending on the composition of the seabed some of the sound energy will be absorbed by the seabed and some will be reflected. A seabed composed of a relatively thick layer of soft mud will absorb more of the sound energy compared to a seabed composed of hard rock, that will cause a relatively high reflection of the sound energy.

In any general scenario, the upward refraction scenario will cause the lowest sound transmission loss and thereby the largest sound emission.

In waters with strong currents, the relationship between temperature and salinity is relatively constant as the water is well-mixed throughout the year.

As an example, in the inner Danish and Swedish waters, as Kattegat, Skagerrak and the Baltic Sea, an estuary-like region with melted freshwater on top, and high saline water at the bottom, the waters are generally not well-mixed and great differences in the relation between temperature and salinity over depth can be observed. Furthermore, this relationship depends heavily on the time of year, where the winter months are usually characterized by upward refracting or iso-velocity sound speed profiles. In the opposite end of the scale, the summer months usually have downward refracting sound speed profiles. In between the two seasons, the sound speed profile gradually changes between upward and downward refracting.

The readings come from the NOAAs World Ocean Atlas database (WOA18), freely available from the "National Oceanic and Atmospheric Administration" (NOAA) at https://www.nodc.noaa.gov/OC5/woa18/, [NOAA, 2019] .

The physical properties of the sea surface and the seabed further affect the sound propagation by reflecting, absorbing and scattering the sound waves. Roughness, density and media sound speed are among the surface/seabed properties that define how the sound propagation is affected by the boundaries.

The sea surface state is affected mainly by the climate above the water. The bigger the waves, the rougher the sea surface, and in turn, the bigger the transmission loss from sound waves hitting the sea surface. In calm seas, the sea surface acts as a very reflective medium with very low sound absorption, causing the sound to travel relatively far. In rough seas states, the sound energy will to a higher degree be reflected backwards toward the source location, and thus result in an increased transmission loss. As previously mentioned, this is not always possible to include in sound propagation models, and the transmission loss can therefore be underestimated, leading to higher noise forecasts than what would actually occur.

Another parameter that has influence on especially the high frequency transmission loss over distance is the volume attenuation, defined as an absorption coefficient reliant on chemical conditions of the water column. This parameter has been approximated by Equation 7 [Jensen, et al., 2011]:

$$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 3.0 \times 10^{-4}f^2 \quad \left[\frac{\mathrm{dB}}{\mathrm{km}}\right] \qquad \text{Equation 7}$$

Where f is the frequency of the wave in kHz. This infers that increasing frequency also leads to increased absorption.

3.3.2 Sound propagation models

There are different algorithms for modelling the sound propagation in the sea, all building on different concepts of seabed interaction and sound propagation. The most commonly used for long distance modelling tasks are Ray tracing, Normal Modes (NM), and Parabolic Equation (PE).

Ray tracing has a good accuracy when working with frequencies above 200 Hz, however in very shallow waters, the minimum frequency would be higher, as the rays need space to properly propagate. Different techniques can be applied for ray tracing to improve and counteract certain of its inherent shortcomings [Jensen, et al., 2011]. Ray tracing furthermore, is the only algorithm that inherently supports directional sources, that is, sources that do not radiate sound equally in all directions.

The normal mode algorithm makes it possible to calculate the sound field at any position between the source and receiver. Since the modes grow linearly with frequency, the algorithm is usually used for low frequencies, because at high frequencies it is hard to find all the modes which contributed to the sound field [Wang, et al., 2014].

Last is the parabolic equation method, which is usually used for low frequencies, due to increasing computational requirements with frequency squared. This method is generally not used for frequencies higher than 1 kHz. The method is however more accepting of discontinuous sound speed profiles [Wang, et al., 2014].

In Table 3.4, an overview of the application range of the different sound propagation models is shown.

Table 3.4: An overview which indicates where the different sound propagation models are most optimal [Wang, et al., 2014]

Shallow water - low frequency	Shallow water - high frequency
Ray theory	Ray theory
Normal mode	Normal mode
Parabolic equation	Parabolic equation
Green – suitable; Amber – suitable with limitations; Red – not suitable or applicable	

3.3.3 Underwater sound modelling software

NIRAS uses the underwater noise modelling software: dBSea version 2.3.3 developed by Marshall Day Acoustics.

The software uses 3D bathymetry, sediment and sound speed models as input data to build a 3D acoustic model of the environment and allows for the use of either individual sound propagation algorithms or combinations of multiple algorithms, based on the scenario and need. For shallow water scenarios, a combination approach is usually preferred due to the individual algorithm limitations presented.

3.3.4 Environmental model

In this section, the environmental conditions are examined to determine the appropriate input parameters for the underwater noise model. The sound propagation depends primarily on the site bathymetry, sediment and sound speed conditions. In the following, the input parameters are described in greater detail.

3.3.4.1 Bathymetry

dBSea incorporates range-dependent bathymetry modelling and supports raster and vector bathymetry import.

Figure 3.3 shows the bathymetry map for Europa, where darker colours indicate deeper areas, and lighter colours indicate more shallow water. The resolution of the map is 115 x 115 metres. EMODnet has created the map using Satellite Derived Bathymetry data products, bathymetric survey data sets, and composite digital terrain models from a number of sources. Where no data is available EMODnet has interpolated the bathymetry by integrating the GEBCO Digital Bathymetry [EMODnet, 2021].

Figure 3.3: Bathymetry map over European waters from EMODnet [EMODnet, 2021].

3.3.4.2 *Sediment*

In dBSea, the sound interaction with the seabed is handled through specifying the thickness and acoustic properties of the seabed layers all the way to bedrock. It can often be difficult to build a sufficiently accurate seabed model as the seabed composition throughout a project area is rarely uniform. The thickness and acoustic properties of the layers, from seabed all the way to bedrock, is generally obtained thought literature research in combination with available site specific seismic survey findings.

For determining the top layer type, the seabed substrate map (Folk 7) from https://www.emodnet-geology.eu/ is generally used. This map is shown in Figure 3.4.

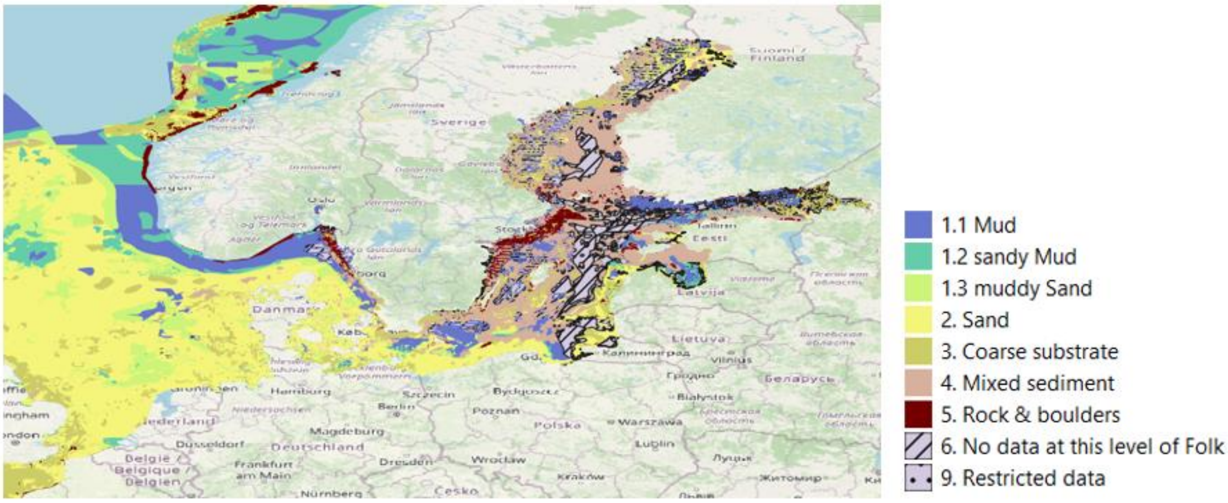


Figure 3.4: A section of the seabed substrate map, (Folk 7) [EMODnet, 2021].

3.3.4.3 *Sound speed profile, salinity and temperature*

The sound propagation depends not only on bathymetry and sediment but also on the season dependent sound speed profile. To create an accurate sound speed profile, the temperature and salinity must be known throughout the water column for the time of year where the activities take place.

NIRAS examined NOAAs WOA18, freely available from the "National Oceanic and Atmospheric Administration" (NOAA) at https://www.nodc.noaa.gov/OC5/woa18/, [NOAA, 2019] which contains temperature and salinity information at multiple depths throughout the water column.

For each of the sediment model positions, the nearest available sound speed profile, as well as average temperature and salinity will be extracted for the desired months.

4 Baseline underwater soundscape

Ambient underwater noise in Kattegat has been studied in the EU projects BIAS [Sigray, et al., 2016] and JOMOPANS (https://northsearegion.eu/jomopans/) and is covered by the Danish underwater noise monitoring program. As part of these projects, underwater noise has been recorded on several monitoring stations in Kattegat and based on these measurements the soundscape has been modelled. Measurement stations for BIAS, JOMOPANS and the Danish national monitoring program are located outside and with some distance to Hesselø OWF. The closest stations are located midway between Anholt and Læsø and south of Hjelm, and are therefore not immediately relevant for the wind farm planning area. An ongoing monitoring program, TANGO, which studies the effects of changing shipping lanes in Kattegat on the soundscape, had noise recorders deployed between 2019 and 2021 around the shipping lane running east of the planning area for Hesselø OWF . These data will become publicly available during 2022 and thus also relevant for future environmental impact assessments. The same is the case for the noise recordings presently ongoing in planning area for Hesselø OWF.

The baseline soundscape in the planning area is quantified by the most recent soundscape models from the JOMOPANS project, as illustrated in Figure 4.1.

4.1 Median noise levels

Figure 4.1 shows the absolute sound pressure levels in three decadal frequency bands and expressed as the monthly median. The lowest decade, 20-200 Hz is primarily relevant for fish, such as cod, that use low-frequency sounds for communication [Ladich, 2019]; the middle decade (200 Hz- 2 kHz) is relevant for seals, whose communication sounds are in this band [Sabinsky, et al., 2017]; and the upper decade (2-20 kHz) is of relevance to seals and harbour porpoises. Visible in all three bands are the two main shipping lanes through the Great Belt and the Sound and which pass along the western and eastern border of the wind farm, respectively. Note that the shipping lane through the Sound has been moved to a new location closer to the Swedish coast from July 2020 (https://www.dma.dk/SikkerhedTilSoes/Sejladsinformation/RuterKattegatSkagerrak/Sider/default.aspx). This means that the noise levels in the eastern part of the planning area for Hesselø OWF likely have decreased since the modelled maps shown in Figure 4.1 were created.

Median noise level per decade inside the planning area did not differ much between summer and winter (Figure 4.2) and was around 90 dB re. 1 µPa and 105 dB re. 1 µPa for the lower and middle decades, which are those relevant for assessment of noise from wind turbines (see section 7.1). These levels are comparable to levels seen in other parts of the Baltic, close to shipping lanes [Mustonen, et al., 2019].

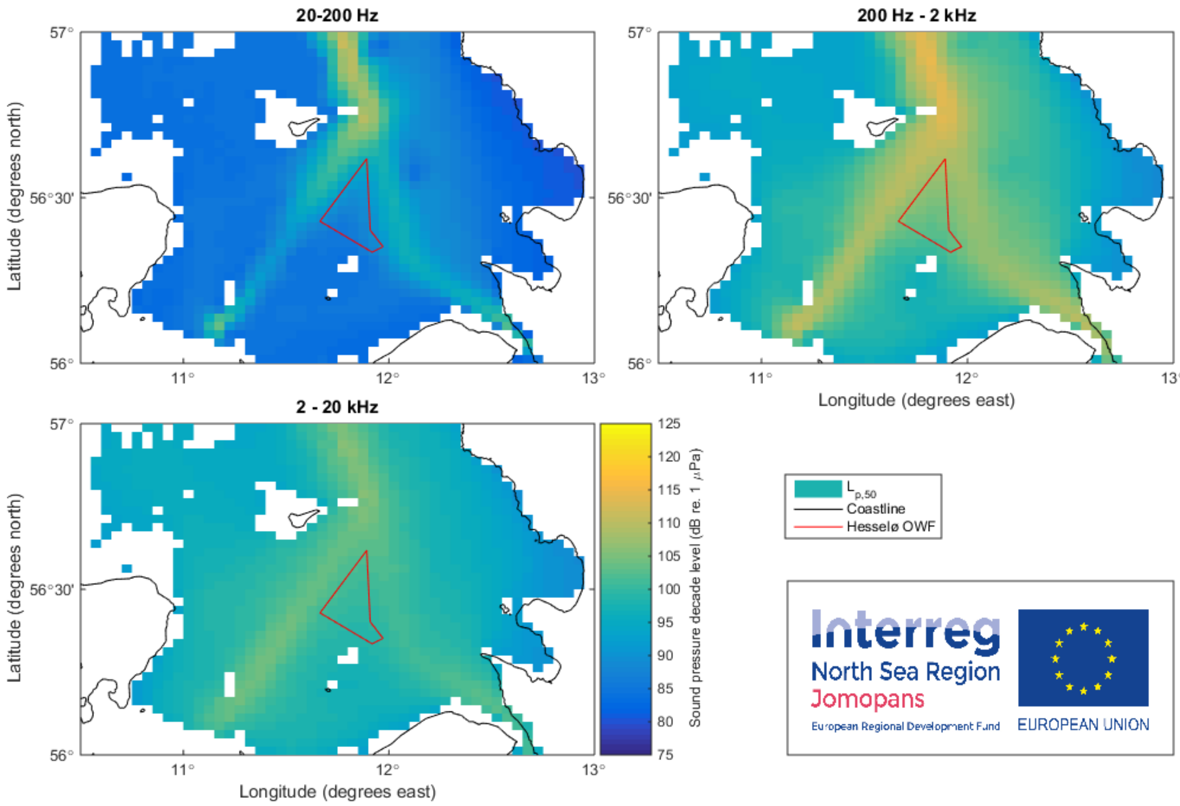


Figure 4.1: Median sound pressure levels modelled in three non-overlapping frequency bands, each one decade wide, and valid for June 2019. The noise was modelled as the sum of natural ambient noise, estimated from statistics of wind and waves, and the contribution from ships. Ship positions were taken from AIS data every 2 hours, propagated away from the ships' positions and added to the natural ambient noise. The maps thus represent the monthly median level of the levels in the several hundred 'snap-shots' calculated for each month. The spatial resolution of the model is approximately 400 x 400 m. The model is only considered valid for water depths greater than 5 m, hence the white cells indicating shallower waters are not included. Data courtesy of the JOMOPANS project.

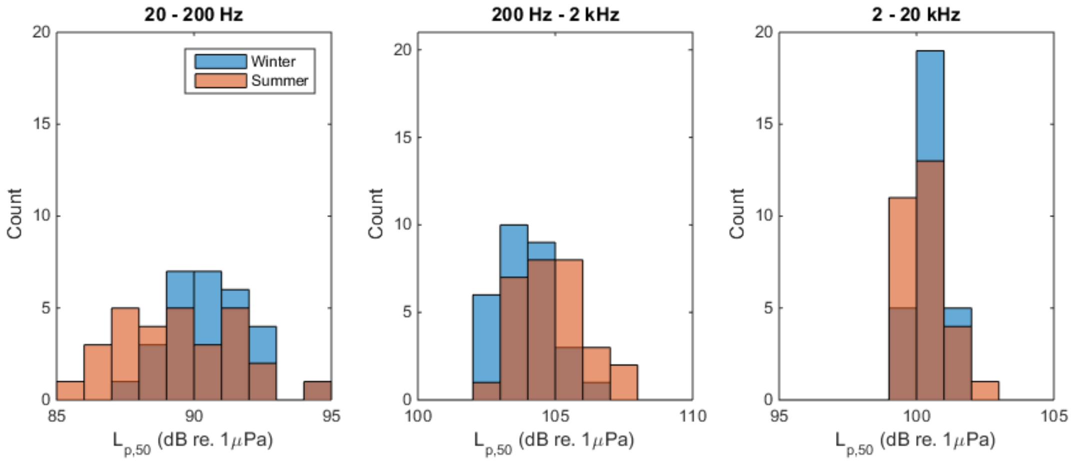


Figure 4.2: Distribution of median sound pressure levels modelled for winter (January) and summer (June) 2019 in three different frequency bands in the 29 grid cells inside the wind farm area. Note that the histograms represent the spatial variation in monthly medians. The instantaneous sound pressure levels can be both considerably higher and lower than the monthly median. Data courtesy of JOMOPANS.

4.2 Excess level – ship noise dominance

Another way of looking at the soundscape is by assessing the relative contribution of ship noise to the total noise level in the area. This can be done by the excess parameter, which expresses the amount (in dB) that the ambient noise level is elevated by the presence of ships. The spatial distribution of the excess level for the three frequency bands is shown in Figure 4.2. The highest excess levels are seen for the 20-200 Hz frequency band, where the shipping lane turns at the tip of the eastern reef of Anholt, whereas low levels were seen inside the wind farm area. This is likely related to the long wavelengths of the low frequency noise, which restricts efficient propagation from the deeper shipping lane into the shallower areas around the shipping lane. Highest median excess was found in the middle frequency band (see also Figure 4.4). It is noteworthy that the excess levels in the middle and upper bands are 3-4 dB higher in summer than in winter. This is a reflection of the fact that ship traffic is essentially constant throughout the year, whereas the wind-driven natural ambient noise is higher in winter. This means that the relative contribution of ship noise to the total noise is lower in winter, when wind noise is higher than in summer.

Concluding from Figure 4.2, the underwater soundscape in the planning area for Hesselø OWF is dominated by natural, wind-generated noise in the low decade band (20-200 Hz), but dominated by noise from the nearby shipping lanes in the two other bands. Note that the present day contribution of ship noise from the eastern shipping lane is likely to be lower than the modelling year 2019, due to the re-routing of the shipping lane into the Sound.

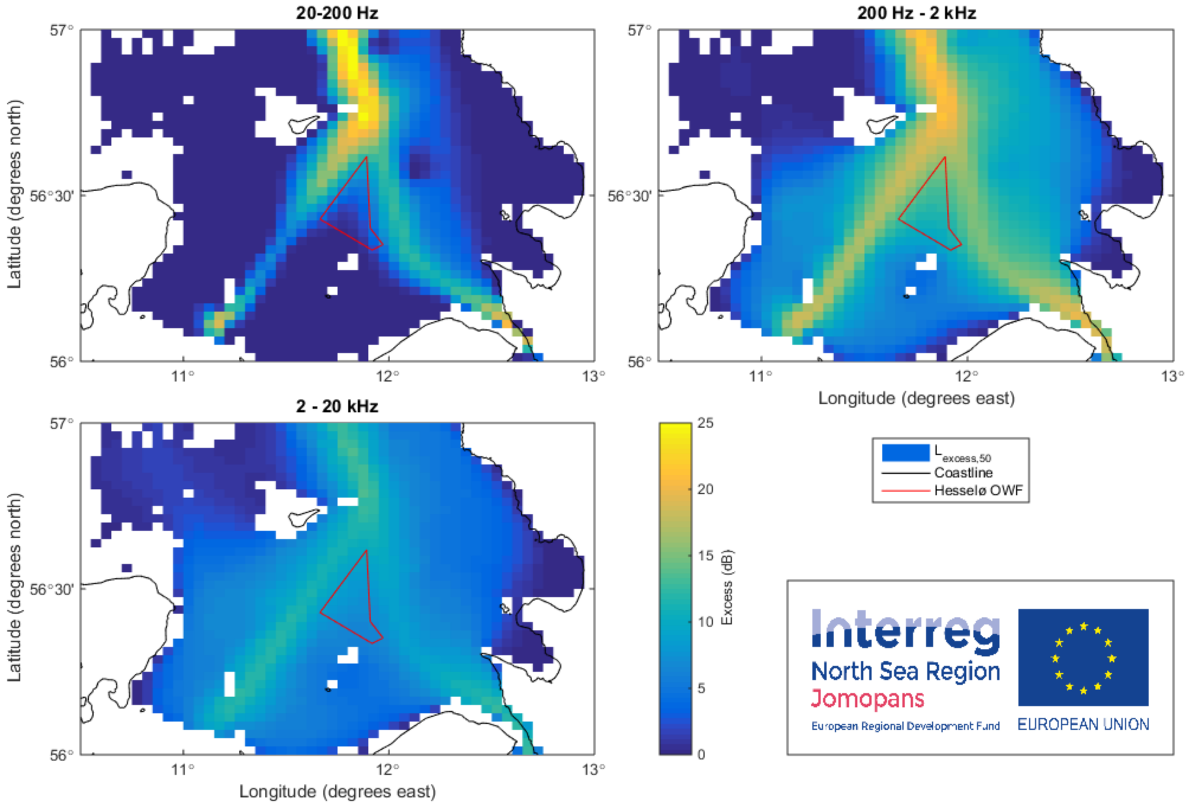


Figure 4.3: Median excess level, modelled for the month of June 2019 in three different frequency bands. The excess level expresses the difference between the total noise level (natural ambient + ship noise) and the natural ambient noise. By this definition a median excess level of 0 dB means that ship noise is not detectable for 50% of the time or more, whereas a median excess level of x dB indicates that the noise level is elevated because of ship noise by at least x dB above the natural ambient 50% of the time. Data courtesy of the JOMOPANS project.

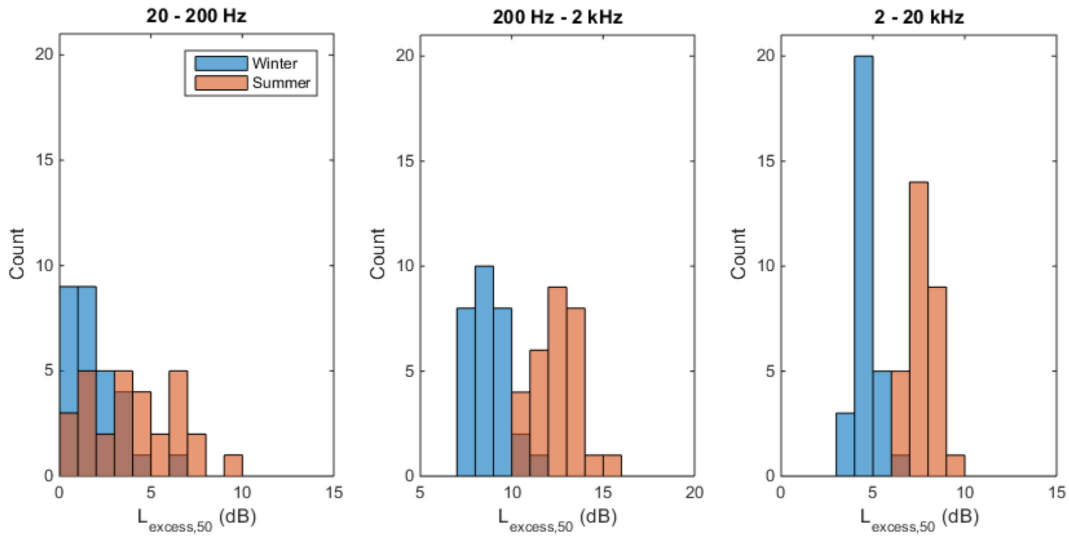


Figure 4.4: Distribution of median excess level, modelled for winter (January) and summer (June) 2019 in three different frequency bands. See text for explanation. Data courtesy of the JOMOPANS project.

5 Underwater noise during construction

As described in the introduction, monopile foundations are likely to be installed at Hesselø OWF with the sizes of either 10 m, 13 m or 15 m diameter. The installation is carried out using impact pile driving, which generates significant underwater noise levels, potentially harmful to the marine life. This chapter describes the sound propagation modelling carried out for this activity.

5.1 Source modelling methodology

To estimate the impact on marine mammals and fish, a source model is derived from project specific knowledge, as well as from available literature on pile driving source level and characteristics. This section includes discussion of the pile driving source level and frequency spectrum, as well as uncertainties related thereto. Methods for reducing pile driving noise levels are also examined.

5.1.1 Pile driving source level

The best available knowledge on the relationship between pile size and source sound level, comes from the newest published knowledge on measured sound levels from pile driving activities in [Bellmann, et al., August 2020], which provides a graphic summary of measured sound levels at 750 m distance as a function of pile size. This is shown in Figure 5.1. The measurements are all normalized to 750 m distance from the pile.

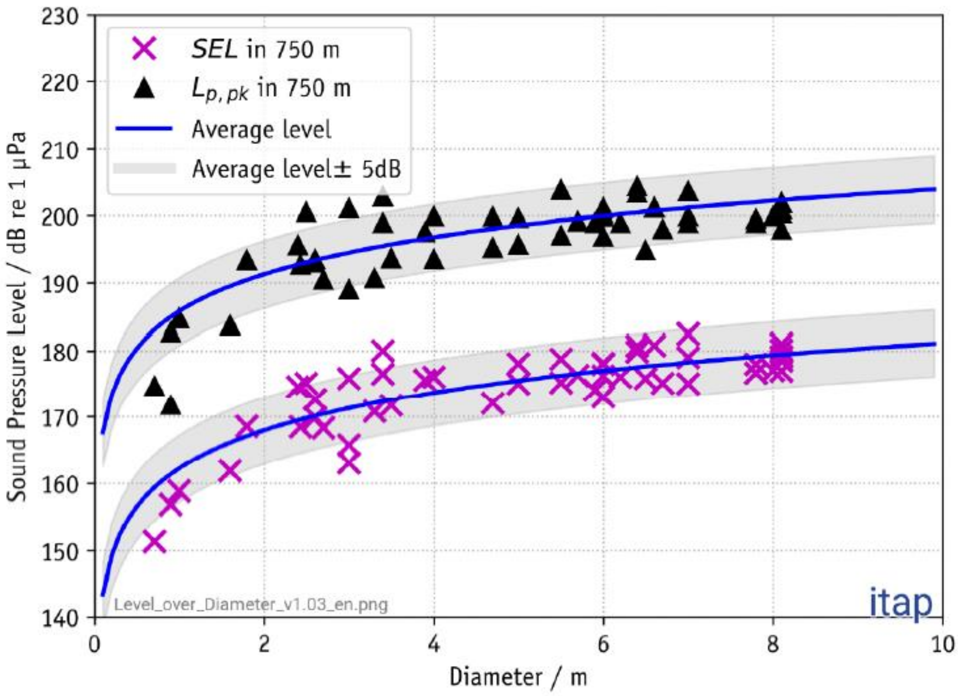


Figure 5.1: Relationship between measured SPL and SEL levels at 750 m distance, and pile size up to the largest pile diameter where data is available (Bellmann, et al., August 2020).

Examining Figure 5.1, the blue curve indicates the best fit of the measurement results. For the SEL results, this relationship between pile size and measured level is approximately $\Delta\mathrm{SEL} = 20 * \log 10\left(\frac{\mathrm{D2}}{\mathrm{D1}}\right)$ where D1 and D2 are the diameter of 2 piles, and $\Delta\mathrm{SEL}$ is the dB difference in sound level between the two. This relationship indicates that, when doubling the diameter, the SEL increases by 6 dB.

In order to use this data in an underwater sound propagation model, the source level in 1 m distance must however be known, and the 750 m value is therefore back-calculated to 1 m. This is done, using a combination of Thiele's equation for sound propagation [Thiele, 2002], as well as NIRAS own calibration model based on several measurements at real sites.

From Figure 5.1 it should be noted, that variations in measured sound levels for a specific pile size do occur, as indicated by the spread of datapoints, around the fitted (blue) lines. This spread gives a 95%-confidence interval of ±5 dB which is indicated by the grey shaded areas in Figure 5.1. This is considered to be a result of varying site conditions and hammer efficiency applied for the individual pile installations and projects. For any project, it should therefore be considered whether the site and project specific conditions call for a more cautious source level estimate, than that of the average fitted line. In the following section, the different parameters which give rise to uncertainties in regard to the source level, are examined.

5.1.2 Parameters influencing source level

In the following, a number of parameters influencing the actual source level for any specific installation is examined briefly.

5.1.2.1 Soil resistance

To install a monopile foundation, the pile has to be driven into the seabed. To be able to do this the predominant soil resistance has to be overcome. In general, the larger the soil resistance, the higher the hammer energy, which in turn increases the noise output [Bellmann, et al., August 2020]. For this reason, the harder, more compacted, and typically deeper, sediment layers require more force to penetrate, thus increasing hammer energy and noise output as the piling progresses.

5.1.2.2 Water depth

The water depth, in shallow water, can also influence the noise emission. When the water depth decreases, the cut-off frequency towards lower frequencies increases, which can be seen in Figure 5.2. Frequency content of the noise source, below the cut-off frequency, has difficulty propagating through the water column, and will be attenuated at an increased rate, compared to frequency content above the cut-off [Bellmann, et al., August 2020].

The cut-off frequency towards lower frequencies is dependent on, not only the water depth, but also the upper sediment type of the seabed.

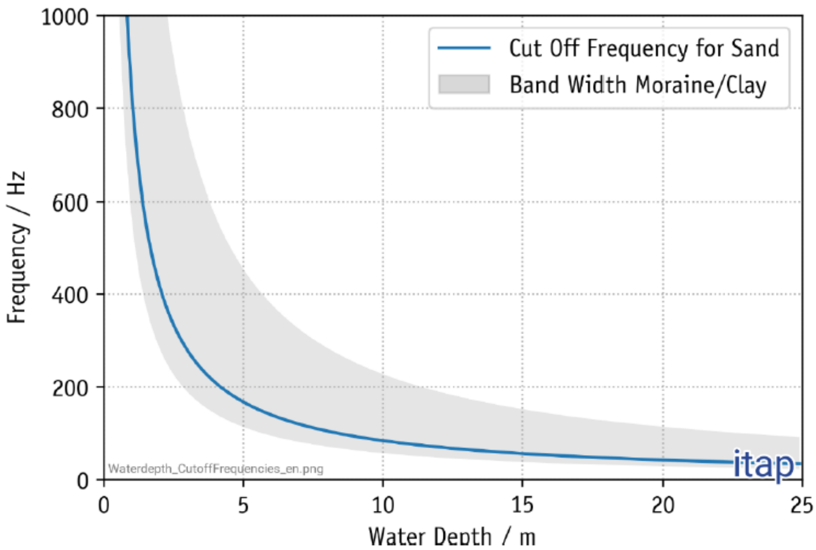


Figure 5.2: Cut off frequency and its dependency on sediment type and water depth [Bellmann, et al., August 2020].

5.1.2.3 Hammer energy

Increasing the hammer energy applied to a pile, will transfers more energy into the pile and therefore also results in a higher noise emission. In Figure 5.3, which shows the SEL versus penetration depth and blow energy, it can be observed how increasing the blow energy, also increases the measured SEL.

This relationship is approximated by 2-3 dB increase in measured SEL every time the blow energy is doubled. [Bellmann, et al., August 2020].

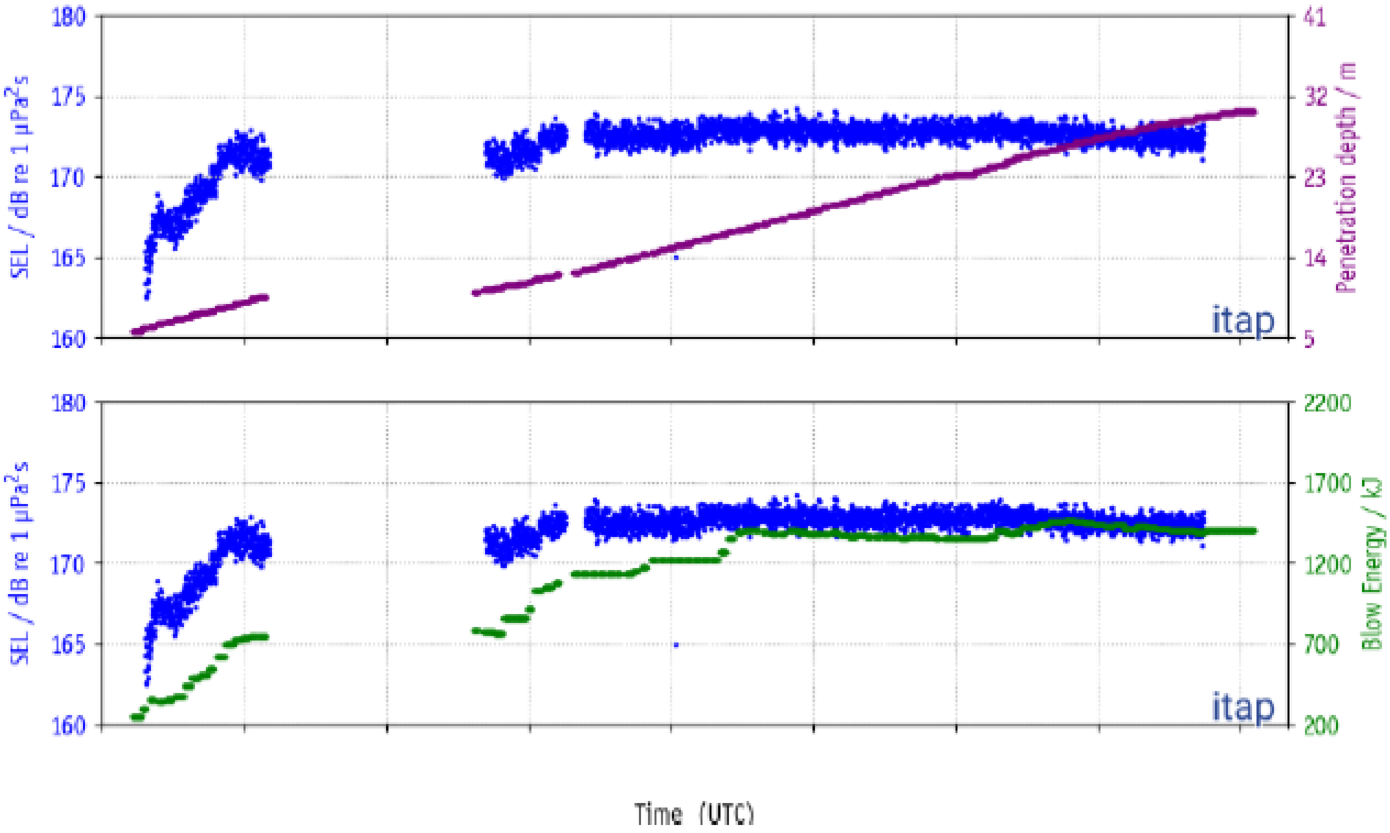


Figure 5.3: Relationship between SEL versus penetration depths and blow energy [Bellmann, et al., August 2020].

5.1.2.4 *Impact hammer type*

Modern impact pile drivers typically consist of a large mass, or weight, suspended inside a hydraulic chamber, where the pressurized hydraulic fluid is used to push up the weight to the desired height, after which it is dropped. The impact is then transferred through an inner construction of shock absorbers and an anvil connected to the pile top. This motion transfers a large part of the applied energy to drive the pile downwards [Adegbulugbe, et al., 2019].

While the two hammers will deliver the same energy to the pile, the maximum amplitude will be lower for the large impact hammer due to extended contact duration between hammer and pile-head [Bellmann, et al., August 2020]. Different impact hammers can give up to several decibels difference [Bellmann, et al., August 2020]. Using a large impact hammer with a heavy falling mass at 50-60% of its full capacity, will for acoustic reason therefore lead to lower noise output compared to that from a smaller impact hammer using 100% capacity to achieve the same blow energy [Bellmann, et al., August 2020].

5.1.2.5 *Pile length and degree of water immersion*

A pile installation can be carried out through either above sea level piling, which is when the pile head is located above water level, or below sea level piling, where the pile head is located below the water line. The former is typically the case for monopiles, while the latter is often the case for jacket piles [Bellmann, et al., August 2020]. A combination of the two is also possible, where the pile head is above water at the beginning of the pile installation and is fully submerged in the late stages of the piling.

Above sea level piling automatically means that part of the pile is in contact with the entire water depth, and thus has a large radiating area. For below water level piling, this is not the case, as parts of the water column might no longer be occupied by the pile, but rather the hammer. For this reason, a higher noise emission is to be expected as long as the pile head is above water level [Bellmann, et al., August 2020].

5.1.3 Pile driving frequency spectrum

Due to the natural variations of measured frequency content, Figure 5.4 (grey lines), between sites, piles, water depths, hammer energy levels and other factors, it is almost guaranteed that the frequency response measured for one pile will differ from that of any other pile, even within the same project area.

Since it is practically impossible to predict the exact frequency spectrum for any specific pile installation, an averaged spectrum (red line), for use in predictive modelling, is proposed by [Bellmann, et al., August 2020], divided into pile type (monopile / pin pile).

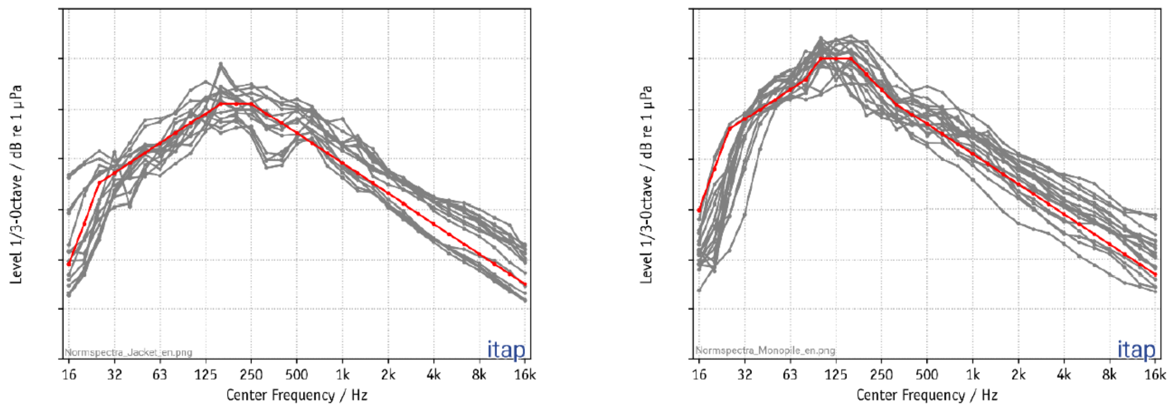


Figure 5.4: Measured pile driving frequency spectrum (grey lines) at 750m, with the averaged spectrum shown as the red line [Bellmann, et al., August 2020]. The spectrum ranges from 110-180 dB.

The spectrum shown to the left in Figure 5.4 is the pile driving frequency spectrum (grey lines) measured at 750 m for pin piles with diameters up to 3.5 m. The red line indicates the averaged spectrum, and is proposed to be used as a theoretical model spectrum for sound propagation modelling of pin piles.

The right side of Figure 5.4 is showing the pile driving frequency spectrum (grey lines) measured at 750 m for monopiles with diameters of minimum 6 m. The red line indicates the averaged spectrum, and is proposed to be used as a theoretical model spectrum for sound propagation modelling, as a best available estimate.

5.1.4 Pile driving source mitigation

This section provides a brief description of different Noise Abatement Systems (NAS) which in one way or another reduce the noise emission from pile driving events. Knowledge on the best achievable source mitigation, currently available, is also presented.

The most frequently applied technique uses bubble curtains. Air is pumped into a hose system positioned around the pile installation at the bottom of the sea. The hoses are perforated and air bubbles leak and rise towards the surface. This forms a curtain through the entire water column from seabed to sea surface. Due to the change in sound speed in the water-air-water bubble interface, a significant part of the outgoing noise is reflected backwards and kept near the pile, while the remaining noise energy going through the bubble curtain is greatly attenuated [Tsouvalas, 2020].

Part of the noise emission from pile driving occurs through the sediment, which is then reintroduced to the water column further from the pile. It is therefore important, that bubble curtains are not placed too close to the source, as this would reduce their effectiveness on the soil borne noise contribution. Big Bubble Curtains (BBC) can mitigate some of this noise as it is partly reintroduced to the water column after a few metres. BBC usually surround the construction site completely leaving no gaps where noise is emitted unhampered. Currents can cause a drift in bubbles, but this difficulty can be overcome if the BBC is installed in an oval rather than a circle. This system was used for example in Borkum West II, where a noise reduction of on average 11 dB (unweighted broadband) was achieved with the best configuration. This project tested different configurations. The success depended on three parameters: size of holes in the hosepipe (determines bubble sizes), spacing of holes (determines density of bubble curtain) and the amount of air used (air pressure). The best configuration was found to be with relatively small holes, a small spacing and using a substantial air pressure [Diederichs, et al., 2014].

The effect of bubble curtains can be increased further if a second bubble curtain is installed even further from the installation, thereby forming a Double Big Bubble Curtain (DBBC). The effect is greatest if the distance between the systems is at least three times the water depth [Koschinski S et al., 2013].

Another type of NAS are pile sleeves, which act as a physical wall around the pile. One such system is the Noise Mitigation Screen (IHC-NMS) where a double walled steel sleeve with an air-filled cavity is positioned around the pile, thus using the impedance difference in the water-steel-air-steel-water interfaces to reduce the sound propagation. This system was used for example at the German wind park Riffgat. Noise mitigation was assessed to be around 16-18 dB (unweighted broadband) [Verfuß, 2014]. Often, a pile sleeve NAS is applied in combination with a bubble curtain solution to increase the overall mitigation effect.

Another type of NAS is the Hydro Sound Damper (HSD), which is in many ways similar to the bubble curtain, however instead of using hoses with air, the curtain consists of fixed position air-filled balloons or foam-balls. The size, spacing and density of the foam balls or air-filled balloons then dictate the achievable noise mitigation. With the HSD system, it is possible to “tune” the NAS to work optimally at specific frequencies, thus allowing for project specific optimal solutions.

Cofferdams are a special type of pile sleeve. They also surround the pile, however in comparison to the IHC-NMS, the water in between the pile and the sleeve is extracted, so that the interface from pile to water becomes air-steel-water. These sleeves are deemed to reduce noise by around 20 dB (unweighted broadband), as demonstrated in Aarhus Bay [Verfuß, 2014]. However, tests further offshore and in connection with the construction of wind parks have yet to be carried out [Verfuß, 2014]. An inherent challenge with this solution is however that it can be difficult to keep the water out of the cofferdam, as local sediment conditions can prevent perfect seal.

For commercially available and proven NAS, a summary of achieved mitigation levels throughout completed installations is given in [Bellmann, et al., August 2020], as shown in Figure 5.5. It must, however, be noted that the reported broadband mitigation, ΔSEL is given for a flat frequency spectrum, in order to compare the efficiency of the different mitigation systems on different pile installations. That is, the source level mitigation achievable for a source with equal acoustic energy in all octave bands, also called pink noise. Pile driving spectra however, as described in section 5.1.3, are far from a flat octave band spectrum, and the effective noise mitigation achieved in terms of sound level measured with and without the system in use at a specific installation will therefore differ from the listed mitigation. In Figure 5.6, the broadband flat spectrum attenuation achieved with the different NAS, are instead given in 1/3 octave bands, thus showing the achieved mitigation per frequency band.

Lastly, it is important to recognize, that development of new and improved noise mitigation systems is an ongoing process, and with every OWF installed, new knowledge and often better solutions become available.

No.	**Noise Abatement System resp. combination of Noise Abatement Systems** (applied air volume for the (D)BBC; water depth)	**Insertion loss ΔSEL [dB]** (minimum / average / maximum)	**Number of foundations**
1	IHC-NMS (different designs) (water depth up to 40 m)	13 ≤ 15 ≤ 17 dB IHC-NMS8000 15 ≤ 16 ≤ 17 dB	> 450 > 65
2	HSD (water depth up to 40 m)	10 ≤ 11 ≤ 12 dB	> 340
3	optimized double BBC*1 (> 0,5 m^3/(min m), water depth ~ 40 m)	15 – 16	1
4	combination IHC-NMS + optimized BBC (> 0,3 m^3/(min m), water depth < 25 m)	17 ≤ 19 ≤ 23	> 100
5	combination IHC-NMS + optimized BBC (> 0,4 m^3/(min m), water depth ~ 40 m)	17 – 18	> 10
6	combination IHC-NMS + optimized DBBC (> 0,5 m^3/(min m), water depth ~ 40 m)	19 ≤ 21 ≤ 22	> 65
7	combination HSD + optimized BBC (> 0,4 m^3/(min m), water depth ~ 30 m)	15 ≤ 16 ≤ 20	> 30
8	combination HSD + optimized DBBC (> 0,5 m^3/(min m), water depth ~ 40 m)	18 – 19	> 30
9	GABC skirt-piles*2 (water depth bis ~ 40 m)	~ 2 – 3	< 20
10	GABC main-piles*3 (water depth bis ~ 30 m)	< 7	< 10
11	„noise-optimized“ pile-driving procedure (additional additive, primary noise mitigation measure; chapter 5.2.2)	~ 2 - 3 dB per halving of the blow energy	

Figure 5.5: Achieved source mitigation levels on completed projects using different NAS [Bellmann, et al., August 2020].

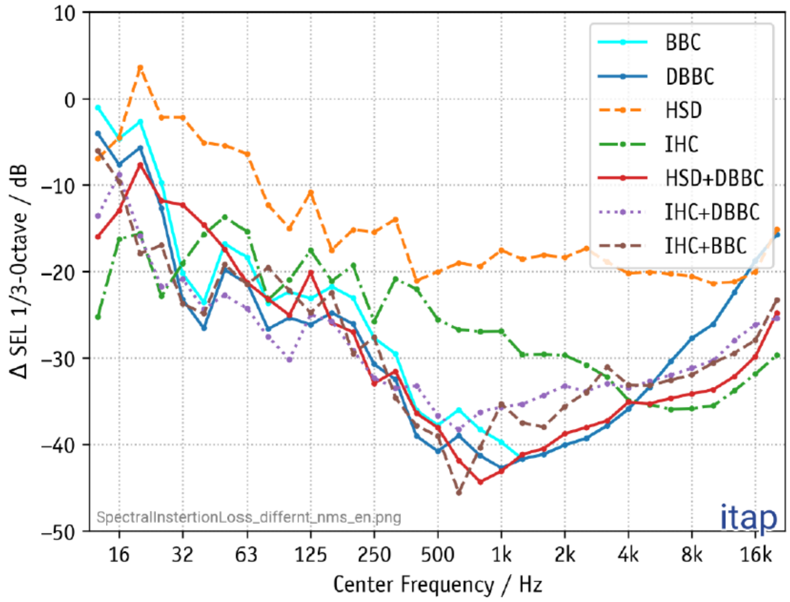


Figure 5.6: Frequency dependent noise reduction for different NAS, [Bellmann, et al., August 2020].

5.2 Underwater noise modelling scenarios

On Hesselø OWF the foundation structure for the turbines, is expected to be monopiles of either 10 m, 13 m or 15 m diameter, which requires pile driving activities for the installation. The details of the different project scenarios are outlined below, based on information received by Energinet Eltransmission A/S.

Based on the knowledge presented in section 5.1, a source model is proposed for each of the scenarios.

Prior to detailed sound propagation modelling, each scenario is evaluated from a noise emission point of view, to determine the worst case scenario with regards to the impact on marine mammals and fish, see section 5.2.4.

In the following, the different monopiles foundation scenarios considered in this project are described in detail, followed by an evaluation of which is considered to be worst-case with regards to underwater noise emission. Last in this section is a description of the source positions given.

5.2.1 Scenario 1: 10 m monopile

In scenario 1, turbines are installed on a 10 m monopile foundation, which is a single-shell hollow steel pile. The technical specification and the pile driving procedure used for this scenario is given in Table 5.1.

Table 5.1: Technical specifications and pile driving procedure for scenario 1

Technical specification for scenario 1			
Foundation		Monopile	
Number of piles		1	
Impact hammer		IHC S-4000 (6000kJ)	
Pile Diameter		10 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

5.2.1.1 Pile driving source level and spectrum, scenario 1

In section 5.2.1 the technical specification and the pile driving procedures are stated for scenario 1. By applying the knowledge presented in section 5.1.1 and 5.1.3, regarding source level and source frequency spectrum, the following SEL, at 750 m was derived to be $\mathrm{SEL_{@750m}} = 181.6\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$. Back-calculating this level to 1 m, results in $\mathrm{SEL_{@1m}} = 224.8\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$.

As the project is on a very early stage, detailed drivability analysis for each foundation is not yet available, and a worst-case approach with regards to source level is therefore taken, based on all available data for the pile installation procedure and site specific conditions. To ensure a worst-case approach, a 2 dB increase to the source level is therefore included, resulting in $\mathrm{SEL}_{@1\mathrm{m}} = 226.8\ \mathrm{dB\ re.}\ 1\ \mu\mathrm{Pa}^2\mathrm{s}$. The source level is presented both with and without frequency weighting in Table 5.2 for reference.

Table 5.2: Sound exposure level for the source, with and without weighting.

Frequency weighting	Source level ($\mathrm{SEL}_{@1\mathrm{m}}$) [dB re. 1µPa^{2}s]
	Unmitigated
Unweighted	226.8
VHF Cetaceans	179.9
Phocid Pinniped	205.7

5.2.2 Scenario 2: 13 m monopile

In scenario 2, turbines are installed on a 13 m monopile foundation, which is a single-shell hollow steel pile. The technical specification and the pile driving procedure used for this scenario is given in Table 5.3.

Table 5.3: Technical specifications and pile driving procedure for scenario 2

Technical specification for scenario 2			
Foundation		Monopile	
Number of piles		1	
Impact hammer		IHC S-4000 (6000kJ)	
Pile Diameter		13 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

5.2.2.1 *Pile driving source level and spectrum, scenario 2*

In section 5.2.2 the technical specification and the pile driving procedures are stated for scenario 2. By applying the knowledge presented in section 5.1.1 and 5.1.3, regarding source level and source frequency spectrum, the following SEL, at 750 m was derived to be $\mathrm{SEL}_{@750\mathrm{m}} = 183.8\ \mathrm{dB\ re.}\ 1\ \mu\mathrm{Pa}^2\mathrm{s}$. Back-calculating this level to 1 m, results in $\mathrm{SEL}_{@1\mathrm{m}} = 227.1\ \mathrm{dB\ re.}\ 1\ \mu\mathrm{Pa}^2\mathrm{s}$.

As the project is on a very early stage, detailed drivability analysis for each foundation is not yet available, and a worst-case approach with regards to source level is therefore taken, based on all available data for the pile installation procedure and site specific conditions. To ensure a worst-case approach, a 2 dB increase to the source level is therefore included, resulting in $\mathrm{SEL}_{@1\mathrm{m}} = 229.1\ \mathrm{dB\ re.}\ 1\ \mu\mathrm{Pa}^2\mathrm{s}$. The source level is presented both with and without frequency weighting in Table 5.4 for reference.

Table 5.4: Sound exposure level for the source, with and without weighting.

Frequency weighting	Source level ($\mathrm{SEL}_{@1\mathrm{m}}$) [dB re. 1µPa^{2}s]
	Unmitigated
Unweighted	229.1
VHF Cetaceans	182.2
Phocid Pinniped	208.0

5.2.3 Scenario 3: 15 m monopile

In scenario 3, turbines are installed on a 15 m monopile foundation, which is a single-shell hollow steel pile. The technical specification and the pile driving procedure used for this scenario is given in Table 5.5.

Table 5.5: Technical specifications and pile driving procedure for scenario 3

Technical specification for scenario 3			
Foundation		Monopile	
Number of piles		1	
Impact hammer		IHC S-4000 (6000kJ)	
Pile Diameter		15 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

5.2.3.1 *Pile driving source level and spectrum, scenario 3*

In section 5.2.3 the technical specification and the pile driving procedures are stated for scenario 3. By applying the knowledge presented in section 5.1.1 and 5.1.3, regarding source level and source frequency spectrum, the following SEL, at 750 m was derived to be $\mathrm{SEL}_{@750\mathrm{m}} = 185.1\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$. Back-calculating this level to 1 m, results in $\mathrm{SEL}_{@1\mathrm{m}} = 228.3\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$.

As the project is on a very early stage, detailed drivability analysis for each foundation is not yet available, and a worst-case approach with regards to source level is therefore taken, based on all available data for the pile installation procedure and site specific conditions. To ensure a worst-case approach, a 2 dB increase to the source level is therefore included, resulting in $\mathrm{SEL}_{@1\mathrm{m}} = 230.3\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$. The source level is presented both with and without frequency weighting in Table 5.6 for reference.

Table 5.6: Sound exposure level for the source, with and without weighting.

Frequency weighting	Source level ($SEL_{@1m}$) [dB re. 1μPa^{2}s]
	Unmitigated
Unweighted	230.3
VHF Cetaceans	183.4
Phocid Pinniped	209.2

5.2.4 Evaluation of worst case scenario

All foundation scenarios for this project include large diameter monopiles. In sound propagation modelling, these are all implemented using the same reference frequency spectrum, with only the source level being different. The larger the monopile diameter, the higher the source level. A monopile with a diameter of 15 m will therefore be the worst case scenario.

5.2.5 Source positions

It was chosen to carry out underwater sound propagation modelling for installations at four different source positions, each considered to be likely worst case locations within each region of the wind farm area, from an underwater sound propagation perspective. The source positions were chosen from their location relative to maximum expected sound propagation, and are shown in Figure 5.7. The locations are spread throughout the area to cover the variations in environmental conditions within the site. From Figure 5.7 it can be noted that the OWF is located within a relatively short distance to different Natura 2000 areas, which is also considered when choosing the source positions. The bathymetry within the OWF area is relatively flat, varying between a depth of 25 m to 33 m.

The different positions were chosen for the following reasons:

- Position 1 is chosen since it has a varying top sediment within a few meters from the source and because it is close to the Natura 2000 areas: "Stora Middelgrund", "Farvandet nord for Anholt" and "Anholt og havet nord for".
- Position 2 is placed where the bathymetry within the OWF area is the deepest, and because it is the closest to the Natura 2000 area: "Stora Middelgrund".
- Position 3 is chosen since the top sediment is varying significantly within a few meters from the source, and because the bathymetry within the OWF area is the lowest here. It is also relatively close to the Natura 2000 areas: "Lysegrund" and "Schultz og Hastens Grund samt Briseis Flak".
- Position 4 is placed in the easternmost point of the OWF because of the Natura 2000 area "Nordvästra Skånes havsområde". In this position the top sediment is relatively constant.

The Natura 2000 areas "Lysegrund", "Schultz og Hastens Grund samt Briseis Flak" and "Farvandet nord for Anholt" are not relevant in regard to marine mammals, and are only mentioned for reference. These areas will therefore not be included in any noise exposure analysis in section 0.

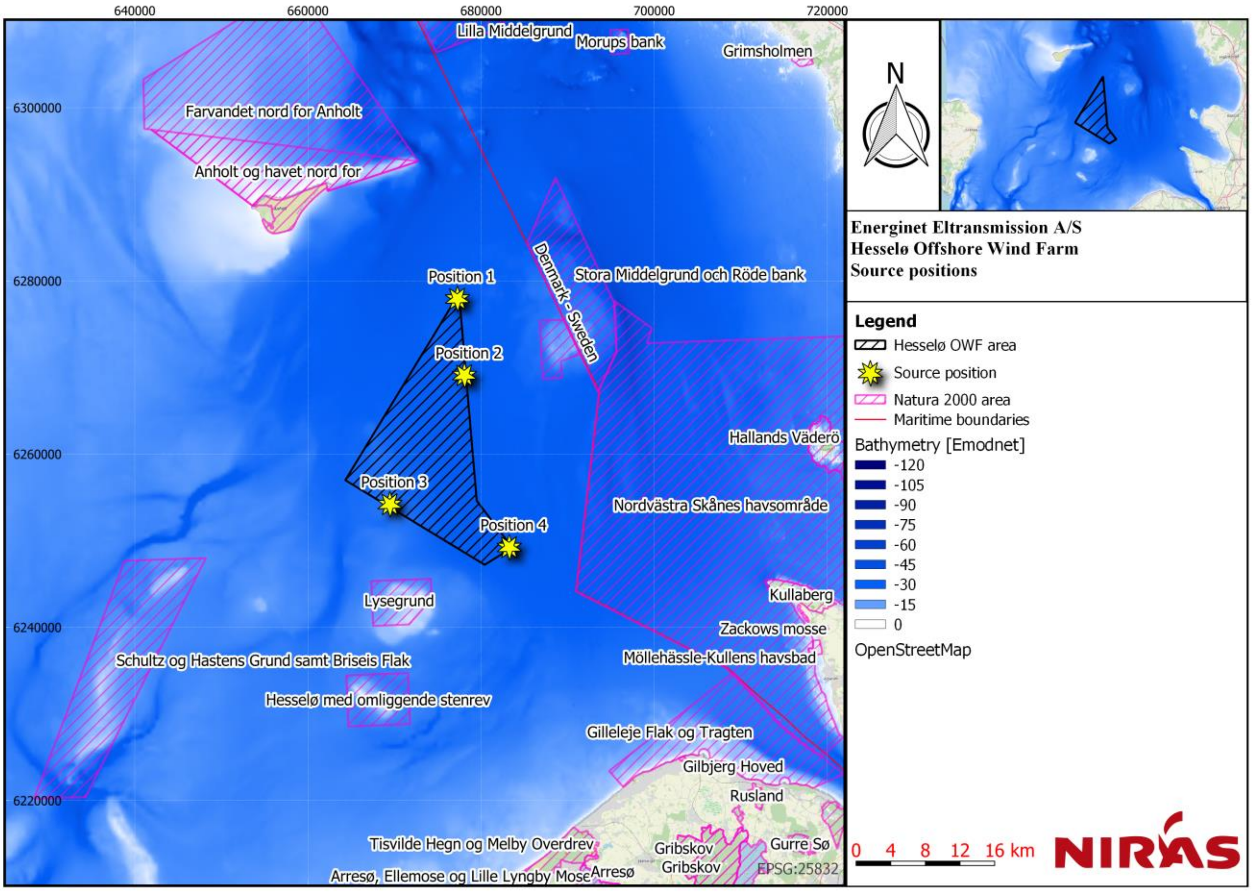


Figure 5.7: Source positions chosen for sound propagation modelling.

5.3 Calculation parameters

In the following, the project specific input parameters are summarized.

5.3.1 dBSea settings

For this project, the dBSea settings listed in Table 5.7 were used.

Table 5.7: dBSea settings

Technical specification		
Octave bands	1/3	
Grid resolution (Range step, depth)	50 m x 1 m	
Number of transects	180 (2°)	
Sound Propagation Model Settings		
Model	Start frequency band	End frequency band
dBSeaRay (Ray tracing)	630 Hz	16 kHz
dBSeaModes (Normal Modes)	16 Hz	500 Hz

5.3.2 Bathymetry

The bathymetry implemented for this project, is shown in Figure 5.8, and includes the wind farm site and 50 km to each side (extracted from the bathymetry map in section 3.3.4.1). In the area of relevance, the bathymetry ranges from a depth of -120 m, indicated by the darker colours, to depth of 0 m (land), indicated by the lighter colours.

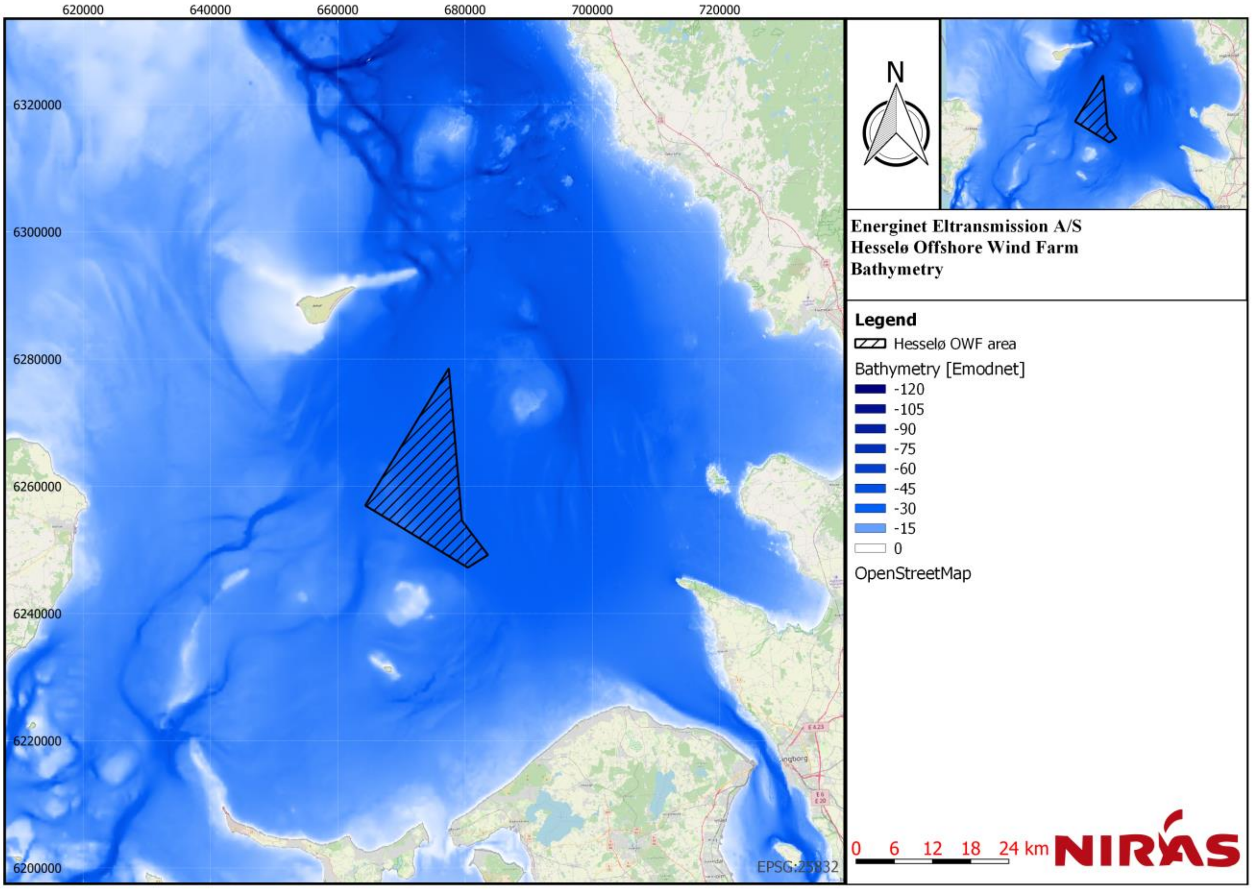


Figure 5.8: Bathymetry map for Hesselø project area and surroundings.

5.3.3 Sediment

It can often be difficult to build a sufficiently accurate seabed model as the seabed composition throughout a project area is rarely uniform and the information available is often scarce. The thickness of the layers, from seabed all the way to bedrock, is estimated based on existing literature on research conducted in the area as well as available seismic profiles. Inside the OWF and investigation corridor, Energinet Eltransmission A/S provided detailed information on the first 7 meters. In [COWI, 2020] and [Nielsen, et al., 2011] information is provided for local layer depths through sediment profiles, see Figure 5.9 and Figure 5.10. These profiles are from seismic survey transects obtained near and inside the project area, and are therefore included in the sediment model layer composition.

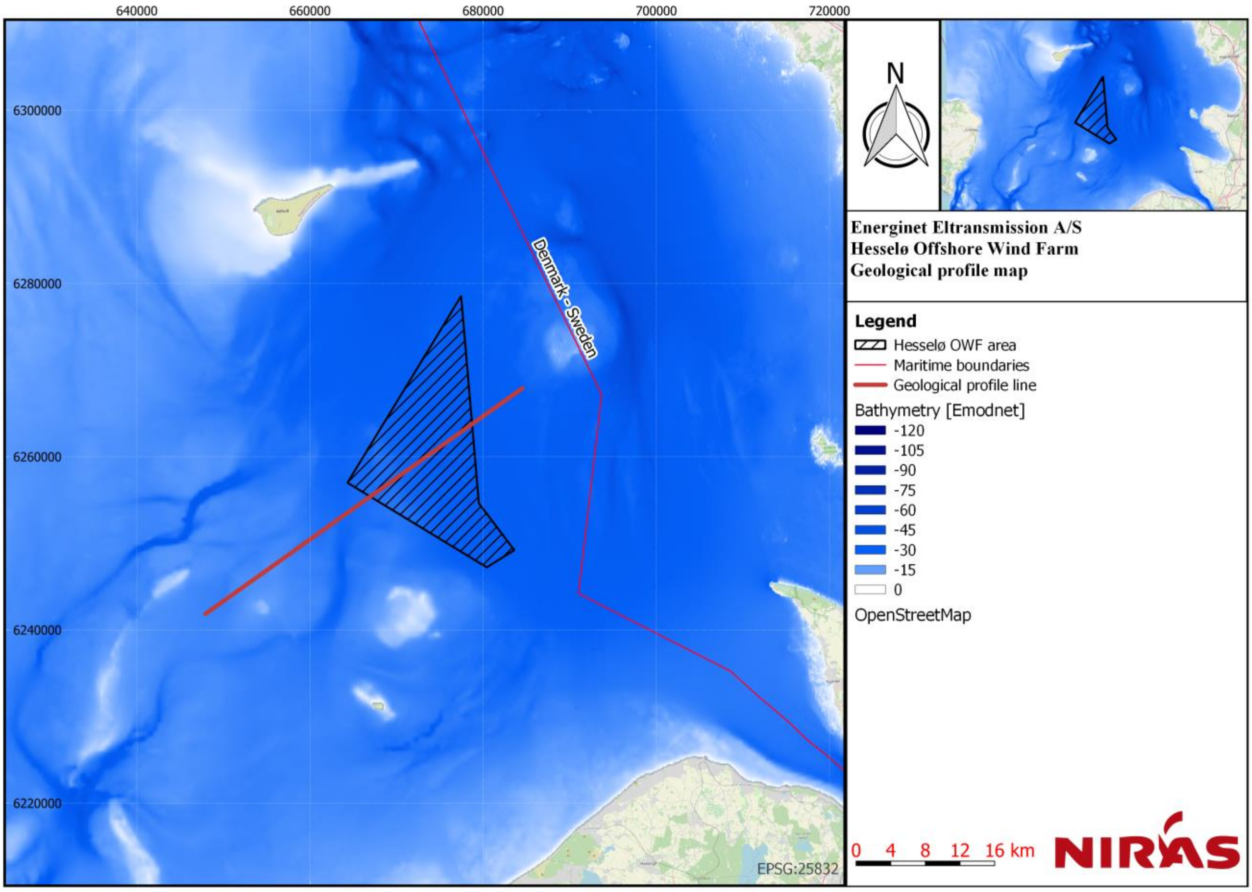
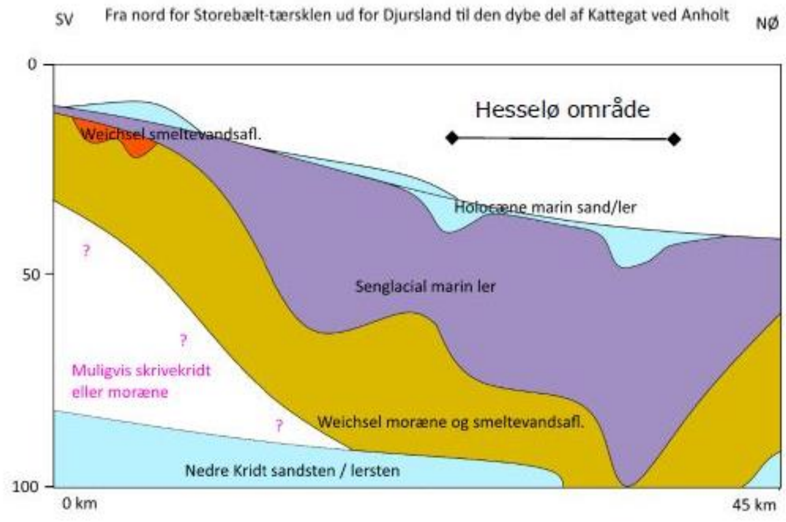


Figure 5.9: Geological sediment profile.



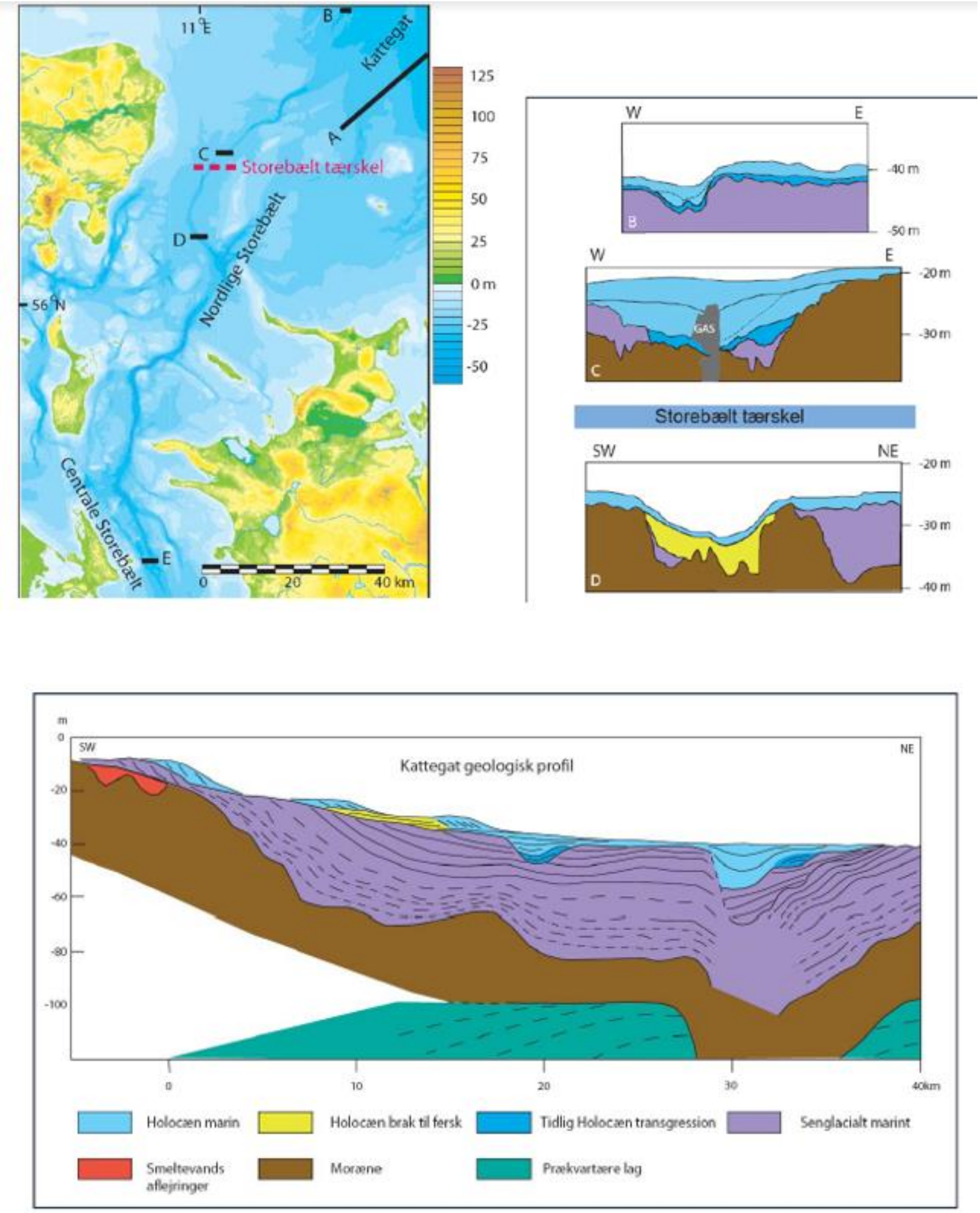


Figure 5.10: Interpreted geological sediment profiles from [Nielsen, et al., 2011].

To be able to make a detailed model that takes the seabed substrate into account as well as the varying bathymetry, a 2214 point sediment model was made. Figure 5.11 shows the distribution of the sediment points with the corresponding seabed sediment from Folk 7 [EMODnet, 2021].

The sediment model uses the information from the seabed substrate map and the provided information from Energinet Eltransmission A/S to determine the top layer type, while the literature was used to determine average thickness at the different positions.

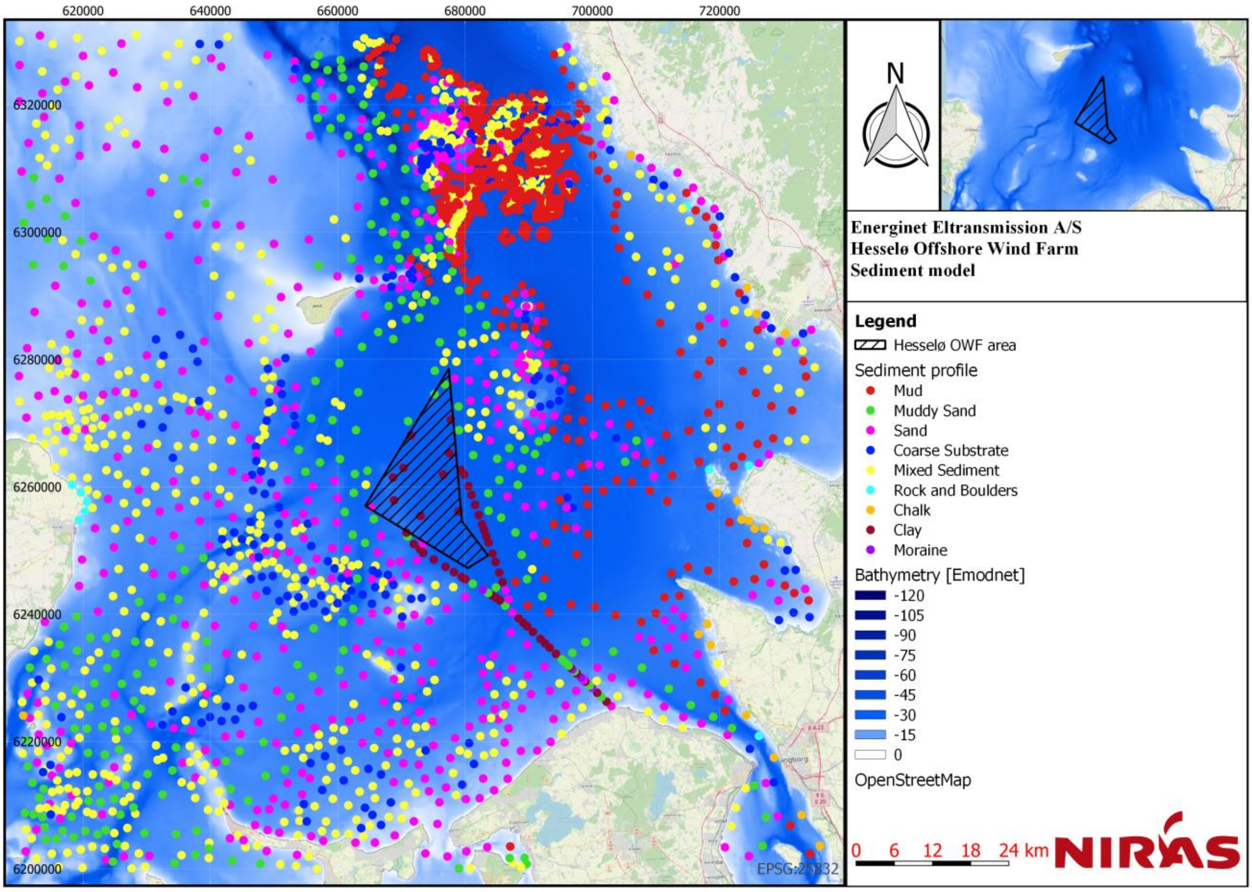


Figure 5.11: Sediment model for Hesselø project area and surroundings.

From Figure 5.11 it is worth noting that the Hesselø OWF area has a significant amount of clay in the top layer, and it is expected that this might cause an increased sound propagation compared to areas with sand, silt or mud.

5.3.4 Sound speed profile

Figure 5.12 shows the extracted sound speed profiles at the available positions. Note that the gridded layout of the sound speed profiles indicates their respective position geographically.

Examining Figure 5.12, this would indicate March as the worst case month and June-July as the best case. As no specific installation time is yet known, it was decided, in cooperation with Energinet Eltransmission A/S, to work with the worst case approach. In Figure 5.13 the sound speed profiles for the worst case month of March are shown.

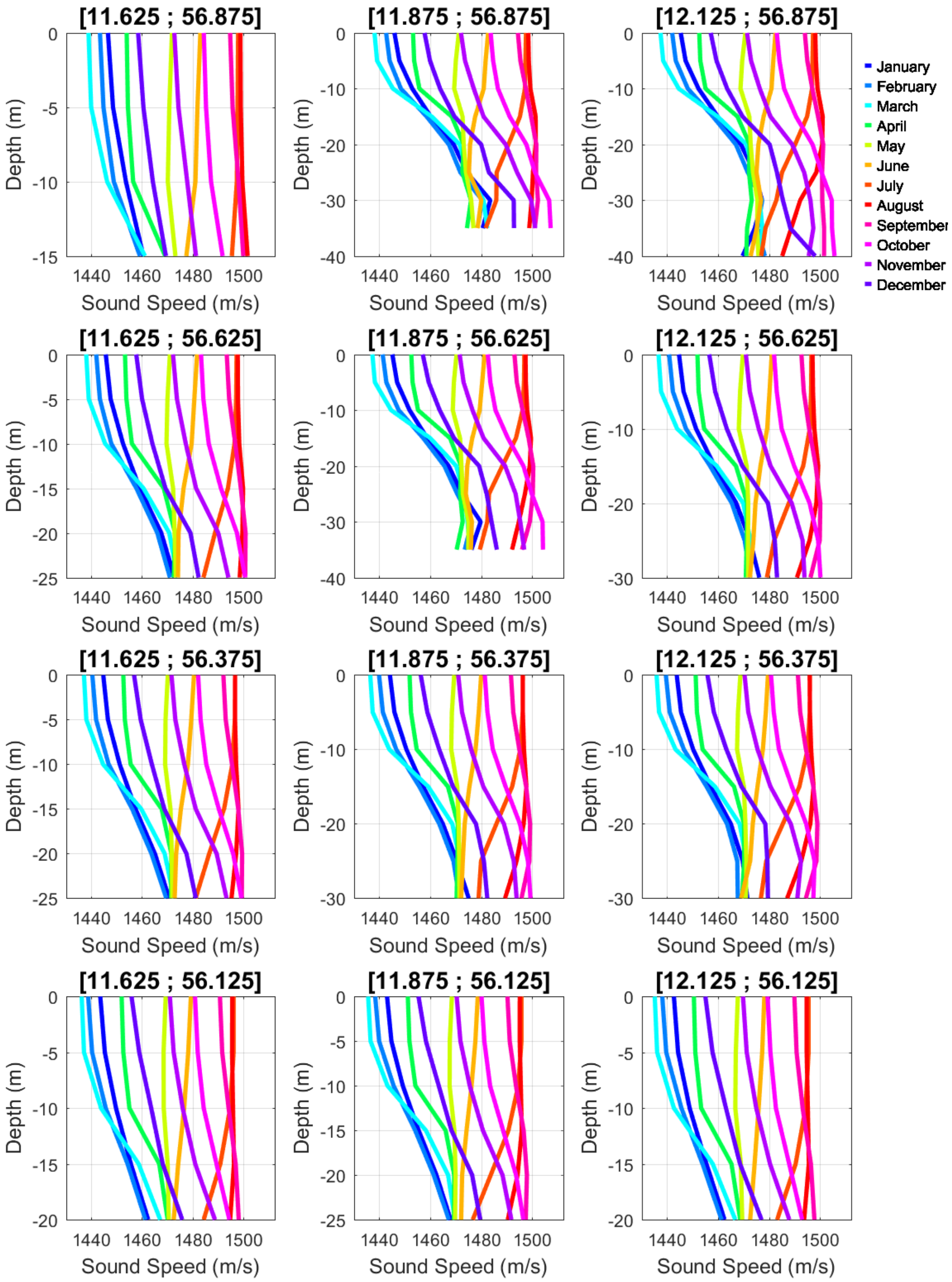


Figure 5.12: Sound Speed Profile for planned Hesselø OWF area.

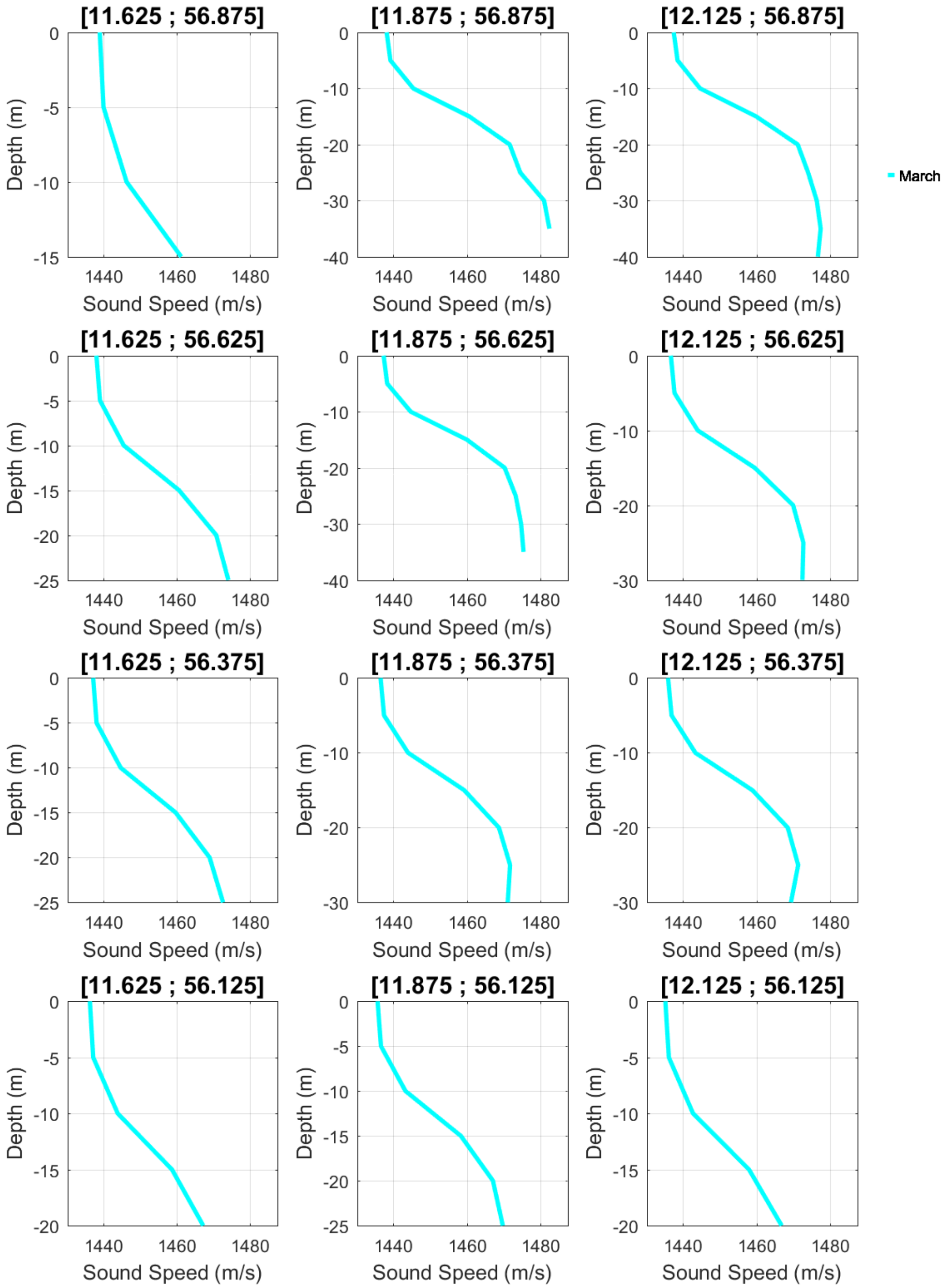


Figure 5.13: Sound speed profile for the worst case month in the area of the planned Hesselø OWF.

6 Results of construction phase underwater noise emission

Sound propagation modelling for the unmitigated sources was modelled in a 2° resolution (180 transects) to a distance of 20 km in any direction from each source position, and for a 50 x 1 m grid (distance x depth interval). By examining the transmission loss for each transect, the mitigation requirement is calculated for each of them, by calculating the $SEL_{c24h,weighting}$ and comparing this to the harbour porpoise PTS value of $SEL_{c24h,VHF}$ = 155 dB re 1 μPa²s, and the harbour seal PTS value of $SEL_{c24h,PW}$ = 185 dB re 1 μPa²s.

Impact distances are generally listed as the maximum impact distance over all transects, and it is this distance that is used in determining the mitigation requirement.

This process is carried out for all installation locations and all three modelled monopile diameters, and the results are presented in section 0 and 6.2.2 for fish and marine mammals respectively.

For installation scenarios where source mitigation is required, an appropriate NAS, that delivers at least the required level of mitigation, is applied. Impact distances for all thresholds will be determined using this NAS. In addition to the NAS selected this way, additional NAS may also be applied separately, if so required to reduce any threshold impact distances further.

6.1 Source level mitigation requirements

The mitigation requirements, per location and pile diameter, are shown in Table 6.1 as the worst case in any direction from the pile installation. The 10 m monopile has mitigation requirements which are up to $\Delta SEL_{VHF} = 8.6\ dB$ and $\Delta SEL_{PW} = 6.9\ dB$. Increasing the diameter to 13 m, the mitigation requirements increase by 2.3 dB both VHF- and PW-weighted. A further 1.2 dB of mitigation is required if the monopile diameter is increased to 15 m. By comparing the mitigation requirement with the empirical data from different NAS, as described in section 5.1.4, it can be concluded that the efficiency of a BBC would be sufficient to mitigate all relevant monopile diameters to prevent PTS in marine mammals.

Table 6.1: Calculated mitigation requirement (worst case).

Foundation type	Position	Cumulative Sound Exposure Level, $SEL_{C24h,VHF}$ [dB re. 1 μPa²s]	Mitigation Requirement $\Delta SEL_{VHF} = SEL_{C24h,VHF} - 155$ [dB re. 1 μPa²s]	Cumulative Sound Exposure Level, $SEL_{C24h,PW}$ [dB re. 1 μPa²s]	Mitigation Requirement $\Delta SEL_{PW} = SEL_{C24h,PW} - 185$ [dB re. 1 μPa²s]
10 m monopile	1	163.3	8.3	191.8	6.8
	2	163.5	8.5	191.9	6.9
	3	163.5	8.5	191.9	6.9
	4	163.6	8.6	191.9	6.9
13 m monopile	1	165.6	10.6	194.1	9.1
	2	165.8	10.8	194.2	9.2
	3	165.8	10.8	194.2	9.2
	4	165.9	10.9	192.2	9.2
15 m monopile	1	166.8	11.8	195.3	10.3
	2	167.0	12.0	195.4	10.4
	3	167.0	12.0	195.4	10.4
	4	167.1	12.1	195.4	10.4

As described in section 5.2.5, Hesselø OWF is located near several Natura 2000 areas appointed to protect marine mammals. In addition to carrying out sound propagation modelling with the chosen BBC NAS, additional modelling is performed applying the HSD-DBBC NAS, which provides further mitigation.

When applying the HSD-DBBC and BBC NAS to each of the monopile installation scenarios, the following source levels, see Table 6.2, are obtained.

Table 6.2:Source level with and without frequency weighting and noise abatement systems for each monopile diameter.

Frequency weighting	Source level ($SEL_{@1m}$) [dB re. 1µPa²s]					
	10 m		13 m		15 m	
	HSD-DBBC	BBC	With HSD-DBBC	With BBC	With HSD-DBBC	With BBC
Unweighted	207.0	208.0	209.3	210.3	210.5	211.5
VHF Cetaceans	147.1	155.3	149.4	157.6	150.6	158.8
Phocid Pinniped	180.2	181.5	182.5	183.8	183.7	185.0

6.2 Impact ranges

Applying the required source level mitigation to each of the monopile installation scenarios, allows for determining the impact distances for each of the threshold values described in section 3.2.2 and 3.2.3.

For each of the monopile installation scenarios, 10 m, 13 m and a 15 m, calculations were carried out with an HSD-DBBC NAS and BCC NAS, at each of the four chosen positions. Numerical values for the impact thresholds are given in Table 6.3 and Table 6.4 for fish and marine mammals respectively.

In addition to the numerical values, noise contour maps for behaviour reaction of harbour porpoise are presented for the worst case scenario; installation of a 15 m monopile. The noise contour maps are shown in Figure 6.1 - Figure 6.4 and Figure 6.5 - Figure 6.8 when HSD-DBBC and BBC are applied respectively.

As previously mentioned, threshold distances for PTS and TTS describe the minimum distance from the source, a marine mammal or fish must at least be at, prior to onset of pile driving, in order to avoid the respective impact. It therefore does not represent a specific measurable sound level, but rather a safe starting distance.

The threshold distance for behaviour, on the other hand, describes the specific distance, up to which, the behavioural response is likely to occur, when maximum hammer energy is applied to a pile strike. It should be noted, that for pile strikes not at full hammer energy, the impact distance will be shorter.

6.2.1 Fish

Table 6.3: Resulting threshold impact distances for fish using an HSD-DBBC and BBC NAS on a 10 m, 13 m and 15 m monopile respective in the worst case month of March.

Species	Fleeing Speed [m/s]	Position	Mitigation measure	$SEL_{C24h,\text{unweighted}}$ [m]					
				10 m		13 m		15 m	
				TTS	Injury	TTS	Injury	TTS	Injury
Cod	0.38	1	HSD-DBBC	3150-3450	< 25	4800-5500	< 25	5950-7050	< 25
		2		3000-3300	< 25	4500-5100	< 25	5550-6350	< 25
		3		2500-2950	< 25	3600-4550	< 25	4250-5700	< 25
		4		2400-2650	< 25	3800-4250	< 25	4600-5350	< 25
		1	BBC	3950-4400	< 25	6150-7300	< 25	7500-9500	< 25
		2		3750-4250	< 25	5750-6650	< 25	7150-8300	< 25
		3		3100-3750	< 25	4450-5850	< 25	5200-7350	< 25
		4		3150-3450	< 25	4850-5600	< 25	5750-7100	< 25
	0.9	1	HSD-DBBC	725-1000	< 25	1950-2550	< 25	2750-3800	< 25
		2		650-875	< 25	1850-2250	< 25	2600-3250	< 25
		3		375-650	< 25	1100-1850	< 25	1600-2700	< 25
		4		300-450	< 25	1050-1500	< 25	1600-2350	< 25
		1	BBC	1300-1700	< 25	2900-3950	< 25	3950-5700	< 25
		2		1200-1500	< 25	2700-3450	< 25	3650-4850	< 25
		3		725-1150	< 25	1650-2850	< 25	2200-4100	< 25
		4		625-900	< 25	1700-2550	< 25	2450-3800	< 25
Herring	1.04	1	HSD-DBBC	375-600	< 25	1350-1950	< 25	2100-3100	< 25
		2		350-475	< 25	1250-1650	< 25	1950-2600	< 25
		3		175-350	< 25	700-1300	< 25	1100-2100	< 25
		4		150-225	< 25	625-1000	< 25	1100-1750	< 25
		1	BBC	775-1150	< 25	2200-3200	< 25	3200-4850	< 25
		2		725-975	< 25	2050-2750	< 25	2950-4100	< 25
		3		375-700	< 25	1150-2200	< 25	1650-3400	< 25
		4		325-500	< 25	1150-1900	< 25	1800-3100	< 25
Larvae and eggs	0	1	HSD-DBBC	-	325-375	-	450-525	-	550-625
		2		-	325-375	-	475-500	-	575-600
		3		-	300-375	-	425-500	-	500-600
		4		-	325-350	-	425-475	-	525-550
		1	BBC	-	400-425	-	550-575	-	650-700
		2		-	375-400	-	550-575	-	650-675
		3		-	375-425	-	500-575	-	600-675
		4		-	350-375	-	500-525	-	575-600
"-" Threshold is not obtained for this species									

Sound propagation modelling for the unweighted SEL thresholds, indicate a certain level of variation of sound propagation within the site. The local variations, for fish, are due to local differences in environmental conditions. It is assessed that any other position is unlikely to result in greater impact distances.

6.2.2 Marine mammals

Table 6.4: Resulting threshold impact distances for marine mammals using an HSD-DBBC NAS or a BBC NAS in combination with either a 10 m, 13 m or 15 m monopile. The modelling is based on the environmental conditions for March, which is the worst case month in regard to transmission of underwater noise.

Hearing group	Fleeing speed [m/s]	Position	Mitigation measure	Distance to impact threshold [m]								
				SEL_{C24h}*						$SPL_{RMS-fast}$*		
				10m	13m	15m	10m	13m	15m	10m	13m	15m
				TTS			PTS			Behaviour		
Very High-Frequency Cetaceans[1]	1.5	1	HSD-DBBC	<50	<50	<50	<25	<25	<25	6400	7950	8800
		2		<50	<50	<50	<25	<25	<25	6550	8050	8850
		3		<50	<50	<50	<25	<25	<25	6750	8200	9050
		4		<50	<50	<50	<25	<25	<25	6750	8200	9100
		1	BBC	<50	90	140	<25	<25	<25	9400	11000	11900
		2		50	110	160	<25	<25	<25	9300	10900	11800
		3		60	120	180	<25	<25	<25	9800	11400	12400
		4		<50	110	170	<25	<25	<25	9800	11400	12300
Phocid Pinniped[2]		1	HSD-DBBC	<50	<50	<50	<25	<25	<25	-	-	-
		2		<50	<50	<50	<25	<25	<25	-	-	-
		3		<50	<50	<50	<25	<25	<25	-	-	-
		4		<50	<50	<50	<25	<25	<25	-	-	-
		1	BBC	<50	<50	<50	<25	<25	<25	-	-	-
		2		<50	<50	<50	<25	<25	<25	-	-	-
		3		<50	<50	<50	<25	<25	<25	-	-	-
		4		<50	<50	<50	<25	<25	<25	-	-	-

"-" Threshold is not obtained for this species.
* Threshold level is frequency weighted
"1" Representative species are Harbour porpoise
"2" Representative species are Harbour seal

Sound propagation modelling for the frequency weighted thresholds, show low variation in behaviour, PTS and TTS distances for both seals and harbour porpoise, between the four source positions, when HSD-DBBC and BBC NAS are applied.

6.2.3 Affected area

In addition to the impact distance results in Table 6.3 and Table 6.4, calculations of worst case area of effect have also been carried out. This is given as the total area affected by noise over the behaviour threshold limit when applying HSD-DBBC or BBC NAS. The numerical value of the total affected area is given in Table 6.5.

Table 6.5: Area affected for impact threshold criteria for harbour porpoise (behaviour) using an HSD-DBBC or BBC NAS on a 10 m, 13 m and 15 m monopile for the worst case month of March.

Position	Mitigation measure	Area of behaviour threshold effect for harbour porpoise [km^2]		
		10 m	13 m	15 m
		Behaviour [$SPL_{RMS-fast,VHF}$]		
Position 1	HSD-DBBC	124	190	234
Position 2		130	194	237
Position 3		140	206	250
Position 4		139	205	252
Position 1	BBC	267	366	430
Position 2		265	362	424
Position 3		291	392	455
Position 4		295	395	457

Calculations were also carried out for the worst case overlap with the nearby Natura 2000 sites. Here, the calculated behaviour threshold impact area for harbour porpoise at position 1 – 4 is estimated with regards to overlap with each Natura 2000 site of importance to marine mammals.

The presented overlap areas are only to be considered from a worst case perspective, as it is not certain whether a turbine will be placed in that specific location. It must also be noted that for any other turbine at larger distances from the respective Natura 2000 areas, the overlap will be smaller. The Natura 2000: "Store middelgrund" and "Nordvästra Skånes havsomrade", are of relevance for the Hesselø OWF, which can be seen in Figure 5.7, page 35, and the worst case overlap is given in Table 6.6 when applying HSD-DBBC or BBC NAS for the worst case month of March. Figures showing the overlap with Natura 2000 sites for a 10 m, 13 m and 15 m monopile when using HSD-DBBC and BBC for the worst case position in relation to Natura 2000 area, are provided in Appendix 1, Appendix 2 and Appendix 3 respectively.

Table 6.6: Overlap with Natura 2000 sites (worst case) for any location within the site further from the Natura 2000 site using HSD-DBBC or BBC NAS for the worst case month of March.

Natura 2000 site	Mitigation measure	Natura 2000 site total area [km^2]	Overlap of harbour porpoise behaviour impact with Natura 2000 site					
			10 m		13 m		15 m	
			Overlap [km^2]	Overlap [%]	Overlap [km^2]	Overlap [%]	Overlap [km^2]	Overlap [%]
Nordvästra Skånes havsområde	HSD-DBBC	1342.6	0	0	0	0	4	0.3
Nordvästra Skånes havsområde	BBC	1342.6	10	0.7	28	2.1	40	3.0
Store Middelgrund (Dansk)		21.5	1	4.7	7	32.6	12	55.8
Store Middelgrund (Svensk)		114.2	0	0	3	2.6	10	8.8
Store Middelgrund (Dansk + svensk)		135.7	1	0.7	7	5.2	13	9.6

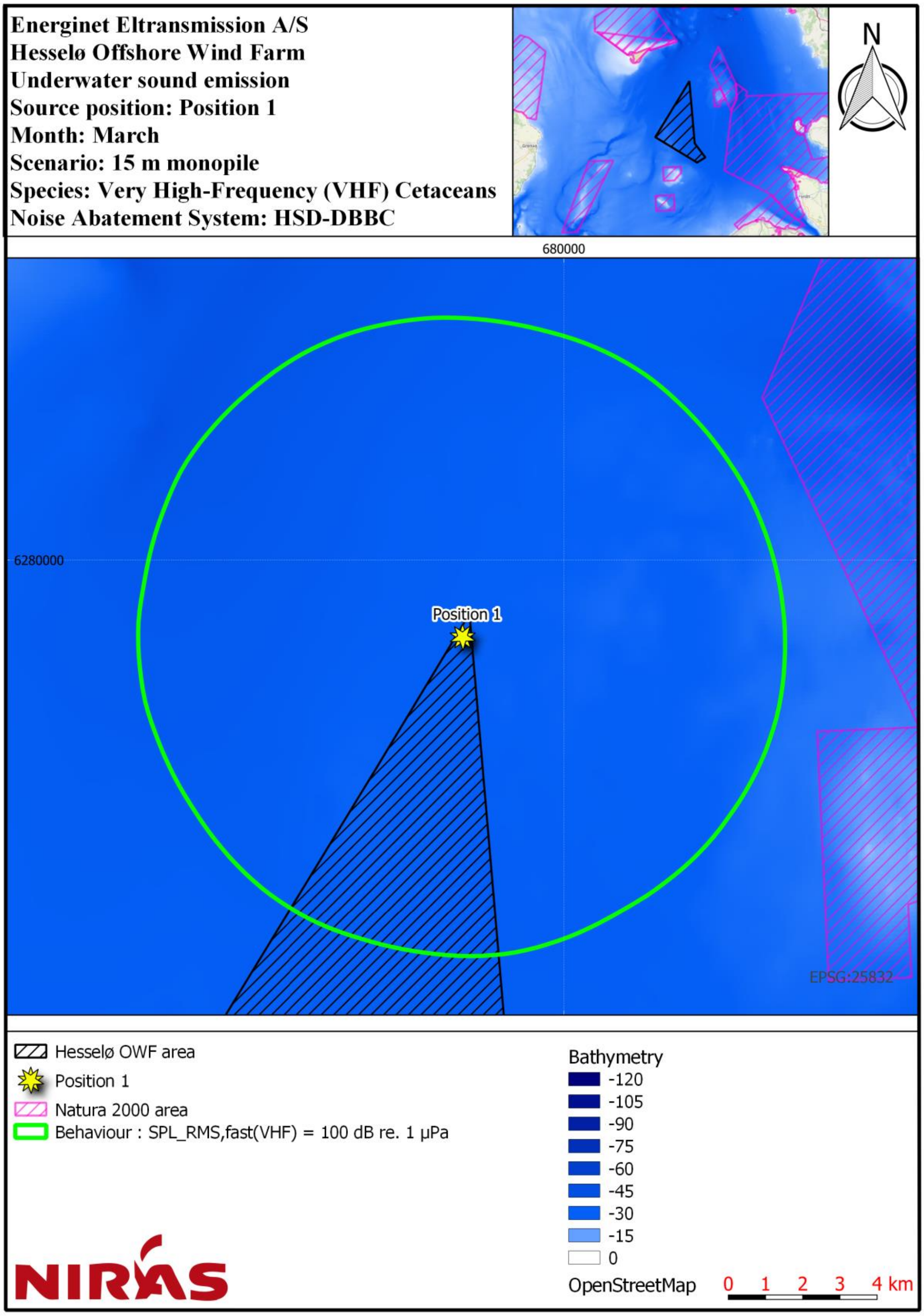


Figure 6.1: Noise contour map for position 1, showing impact distances for behaviour with VHF-weighting and HSD-DBBC NAS on a 15 m monopile.

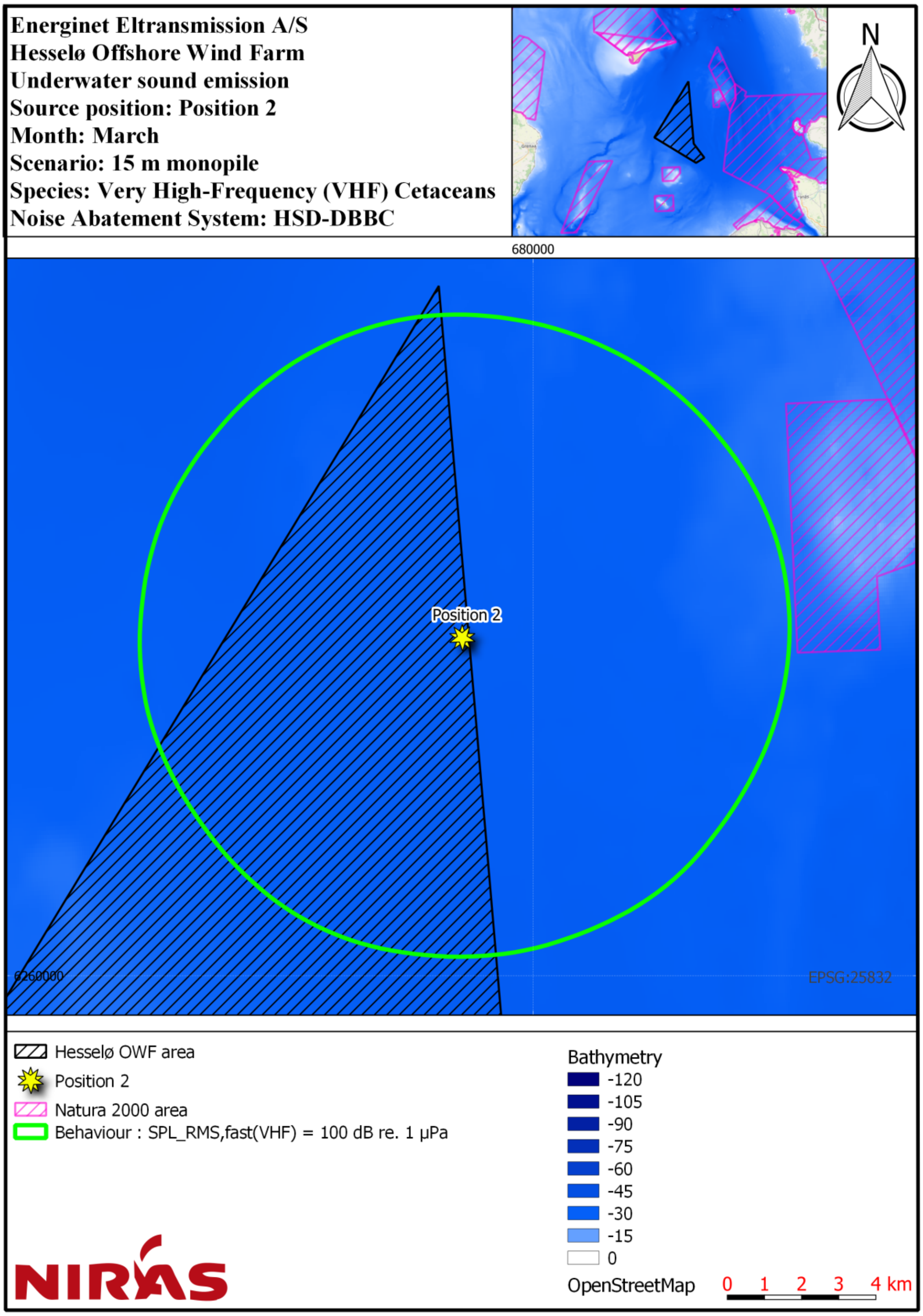


Figure 6.2: Noise contour map for position 2, showing impact distances for behaviour with VHF-weighting and HSD-DBBC NAS on a 15 m monopile.

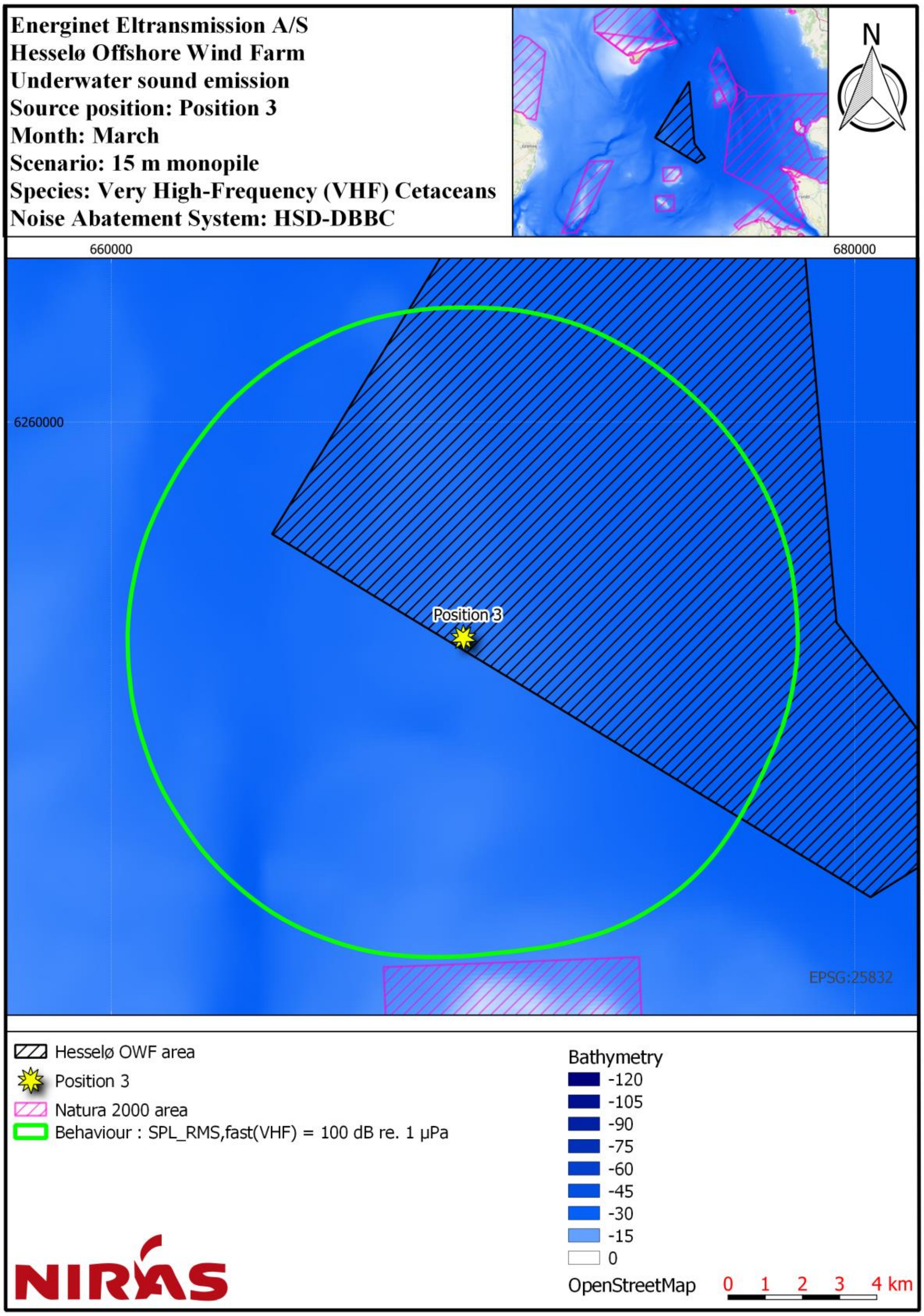


Figure 6.3: Noise contour map for position 3, showing impact distances for behaviour with VHF-weighting and HSD-DBBC NAS on a 15 m monopile.

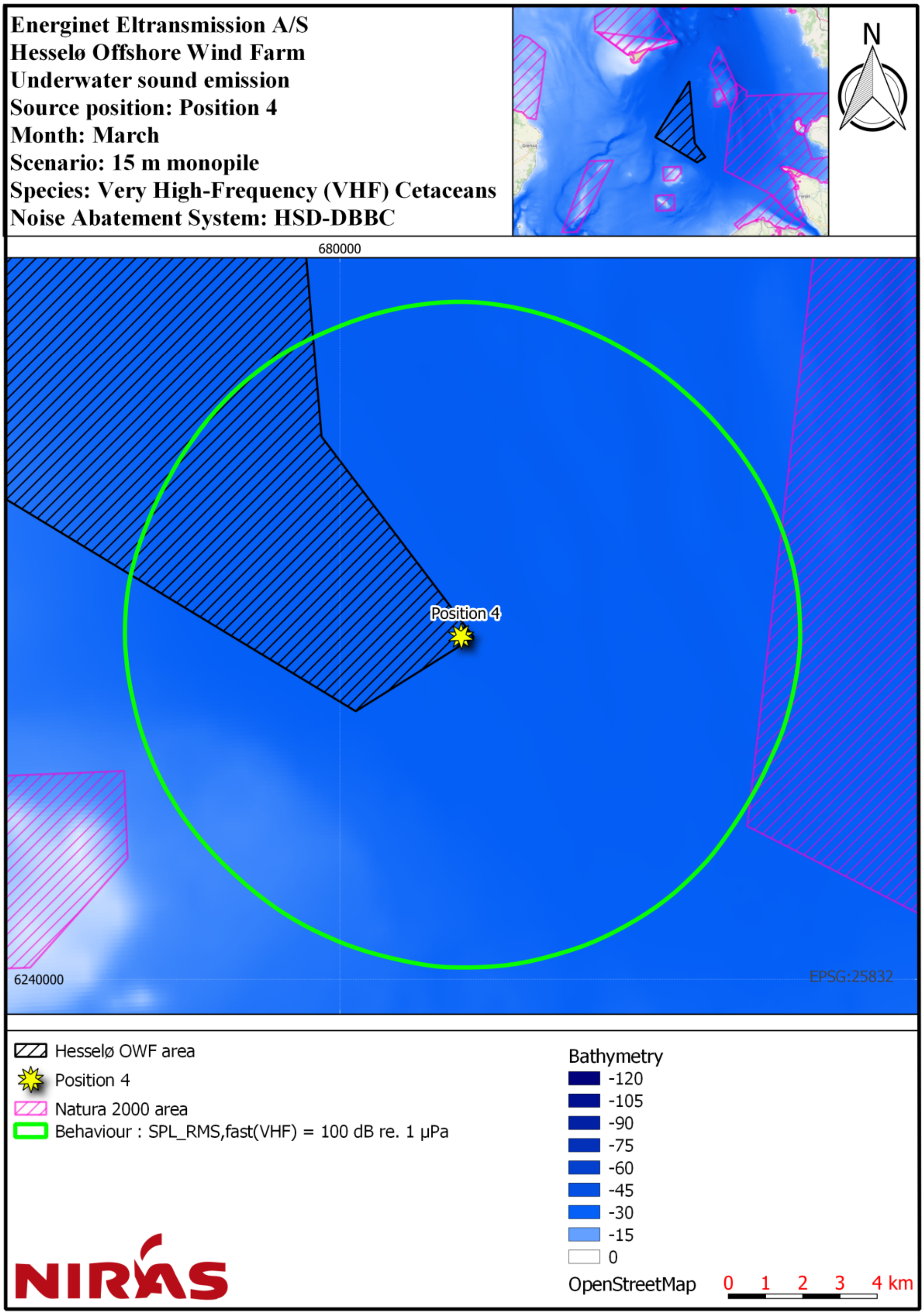


Figure 6.4: Noise contour map for position 4, showing impact distances for behaviour with VHF-weighting and HSD-DBBC NAS on a 15 m monopile.

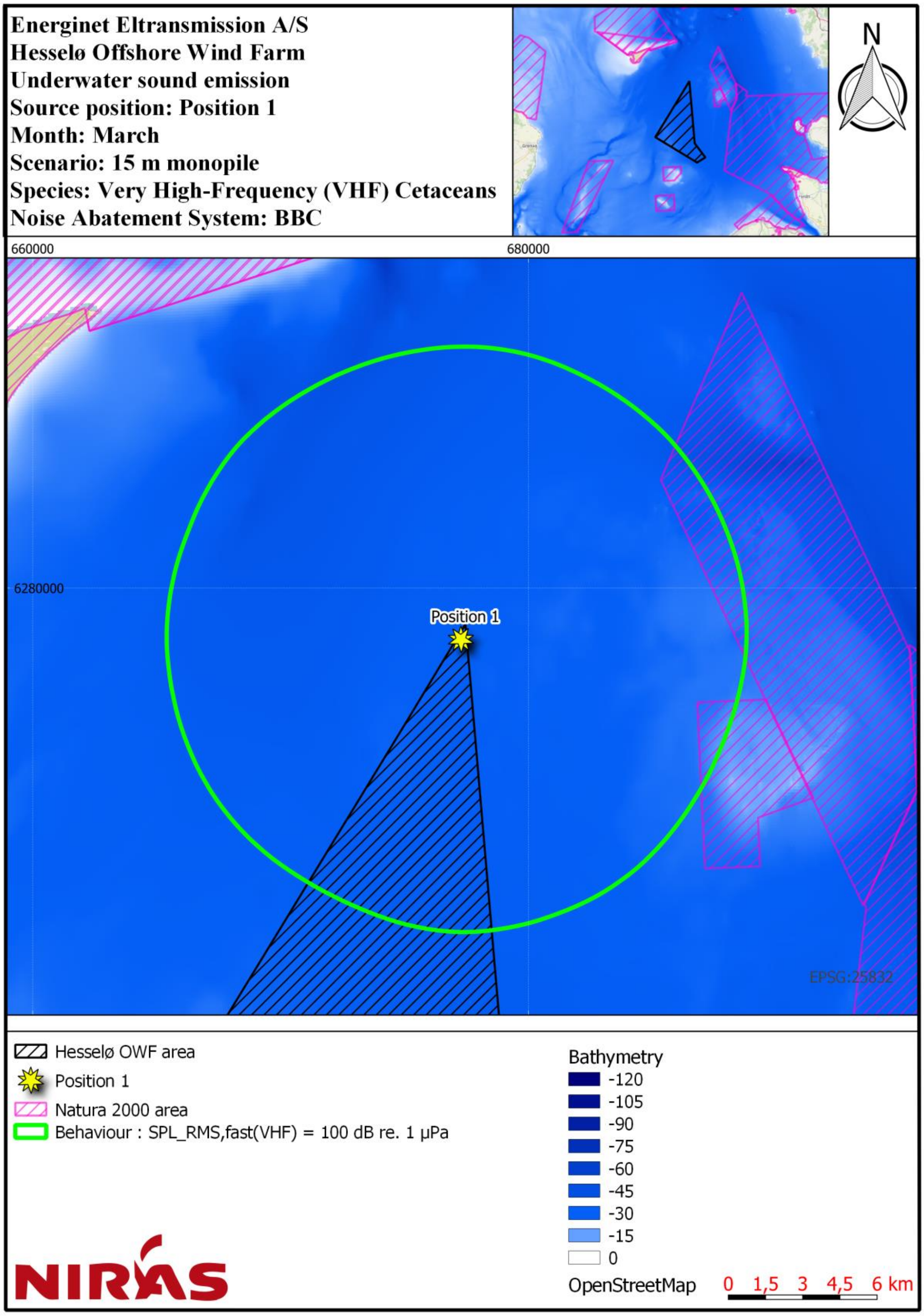


Figure 6.5: Noise contour map for position 1, showing impact distances for behaviour with VHF-weighting and BBC NAS on a 15 m monopile.

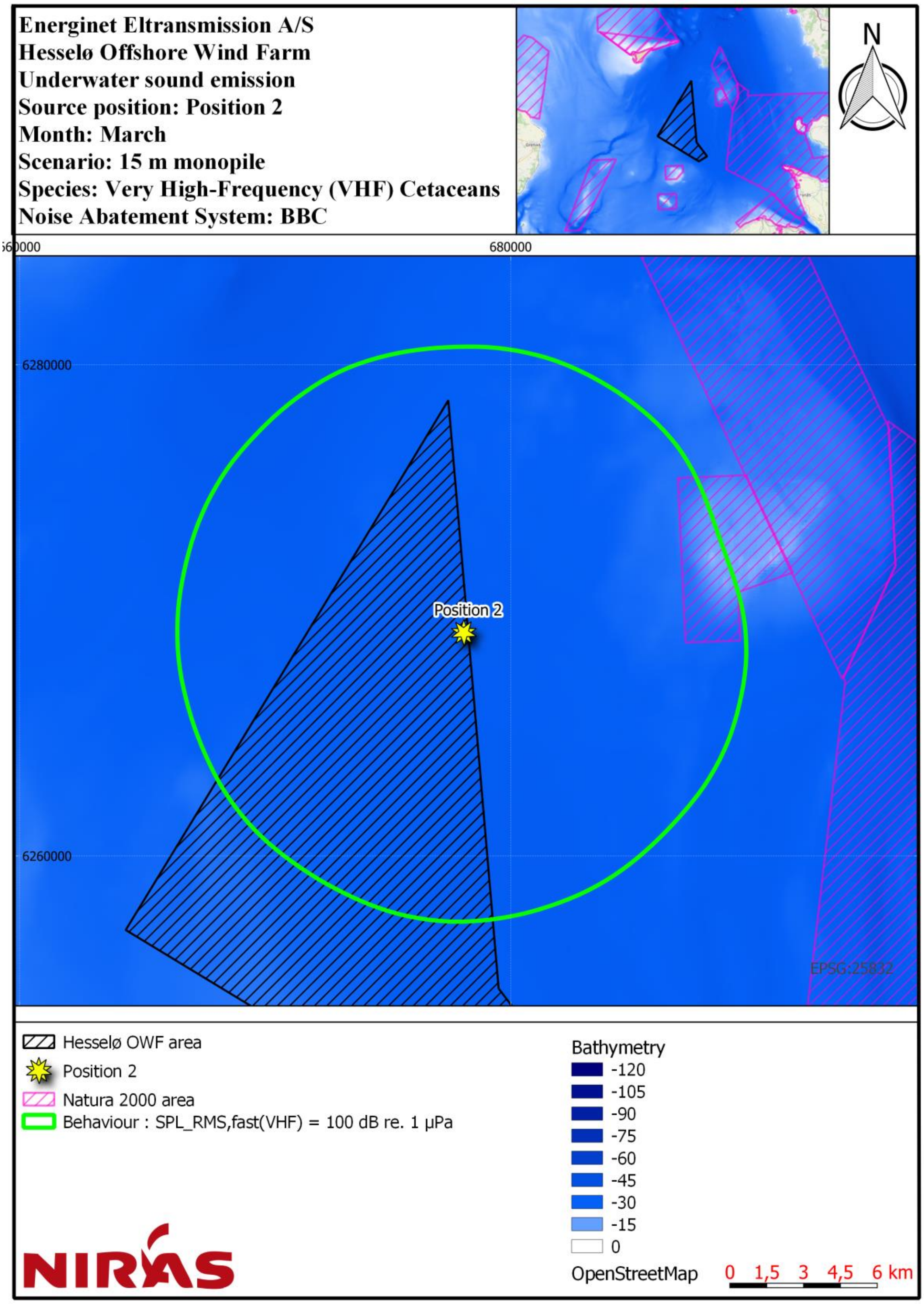


Figure 6.6: Noise contour map for position 2, showing impact distances for behaviour with VHF-weighting and BBC NAS on a 15 m monopile.

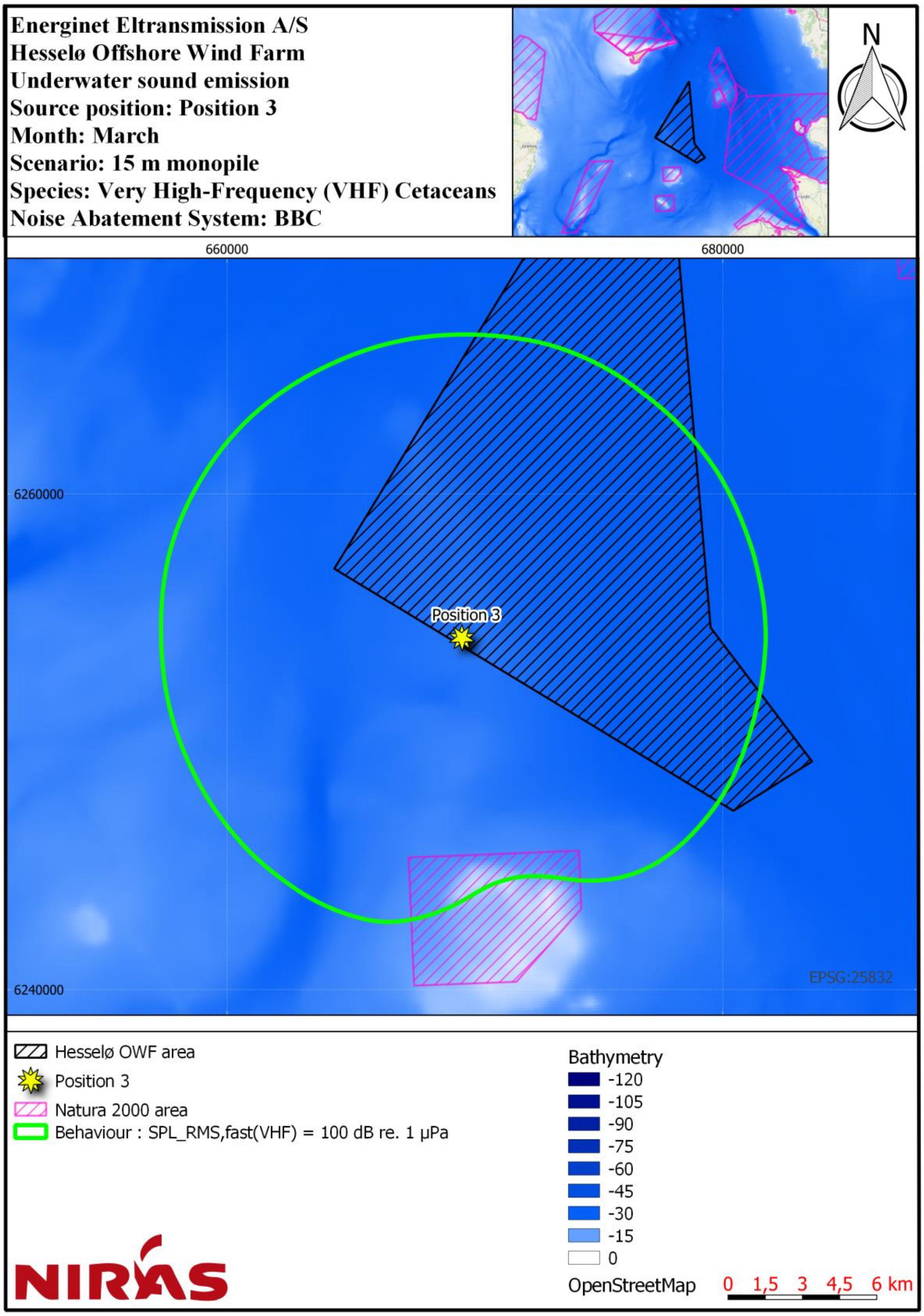


Figure 6.7: Noise contour map for position 3, showing impact distances for behaviour with VHF-weighting and BBC NAS on a 15 m monopile.

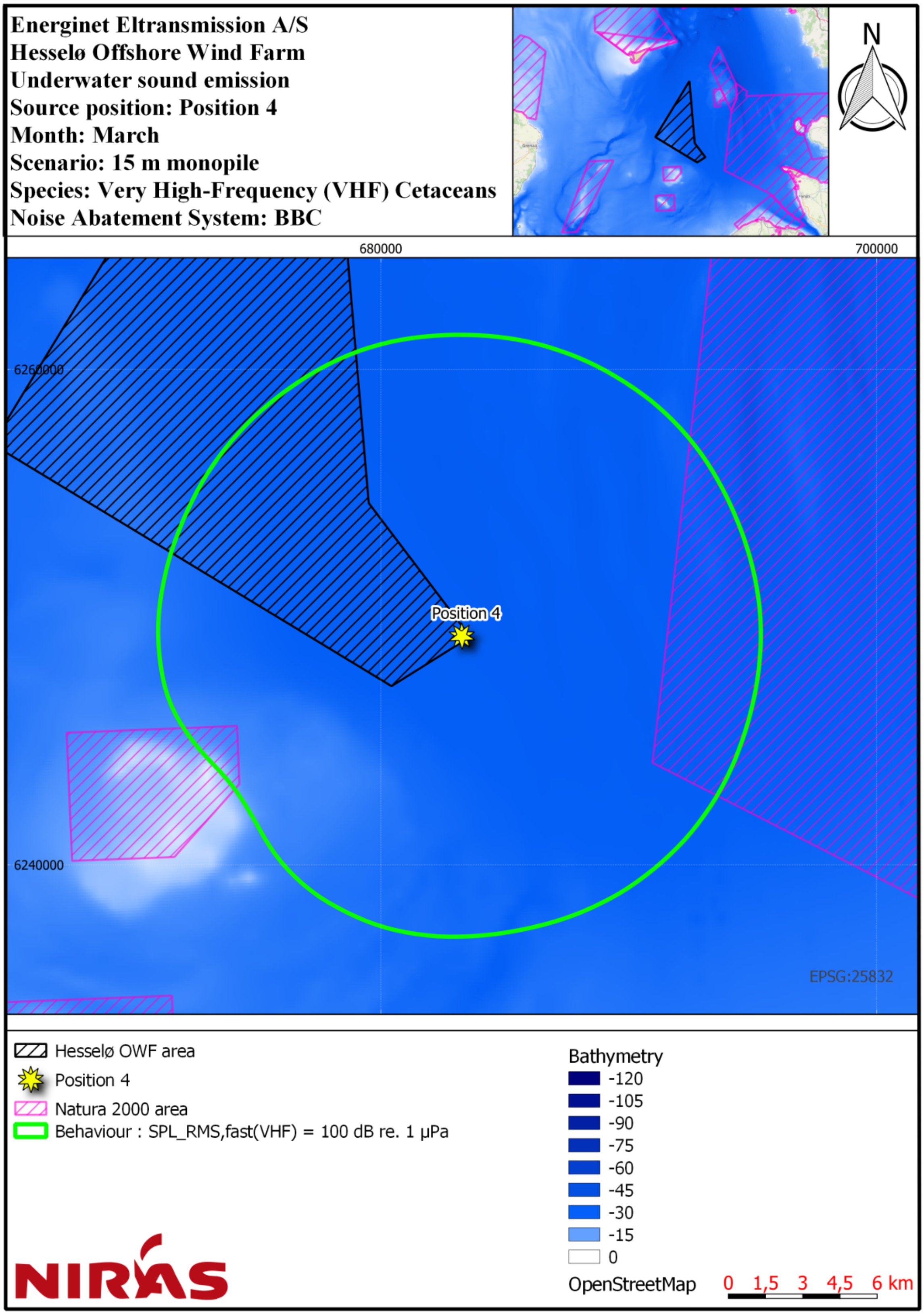


Figure 6.8: Noise contour map for position 4, showing impact distances for behaviour with VHF-weighting and BBC NAS on a 15 m monopile.

7 Operation phase

Noise from offshore wind turbines in operation comes primarily from two sources: vibrations from mechanical components in the nacelle, propagating through the tower and radiating into the water through the foundation, and noise from service ships operating around and inside the offshore wind farm.

7.1 Turbine noise

Underwater noise from offshore wind turbines is relatively poorly studied. The by far most comprehensive study is by [Pangerc, et al., 2016], who measured noise from a 3.6 MW Siemens wind turbine in Sherringham Shoal offshore wind farm. An example of the noise recordings is shown in Figure 7.1. The noise level fluctuates with the wind speed and at high wind speeds; there is a strong tonal component present at around 160 Hz, with an overtone at 320 Hz. The regular fluctuations at very low frequencies are due to flow noise artefacts, caused by the strong tidal current in the area. Figure 7.2 shows the recordings organized by wind speed. In this plot it is clear that noise increases with wind speeds up to the level where the turbine is running at 100% nominal capacity, after which increasing the wind speed further has no effect on the noise or maybe even results in a slight decrease.

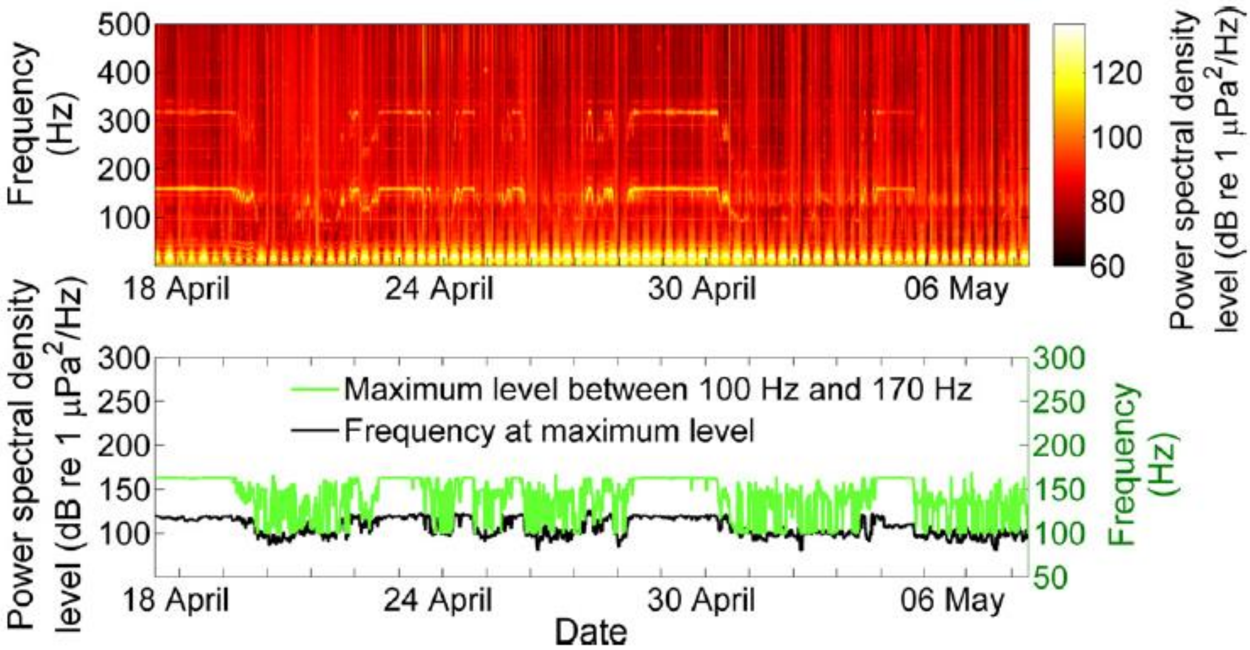


Figure 7.1: Measurement of underwater noise 50 m from a Siemens SWT 3.6-107 wind turbine over a 3-week period. From Pangerc et al. [2016]. The regularly fluctuating pattern at frequencies below 30 Hz is an artefact caused by fluctuating levels of flow noise due to the tide and is thus unrelated to the turbine.

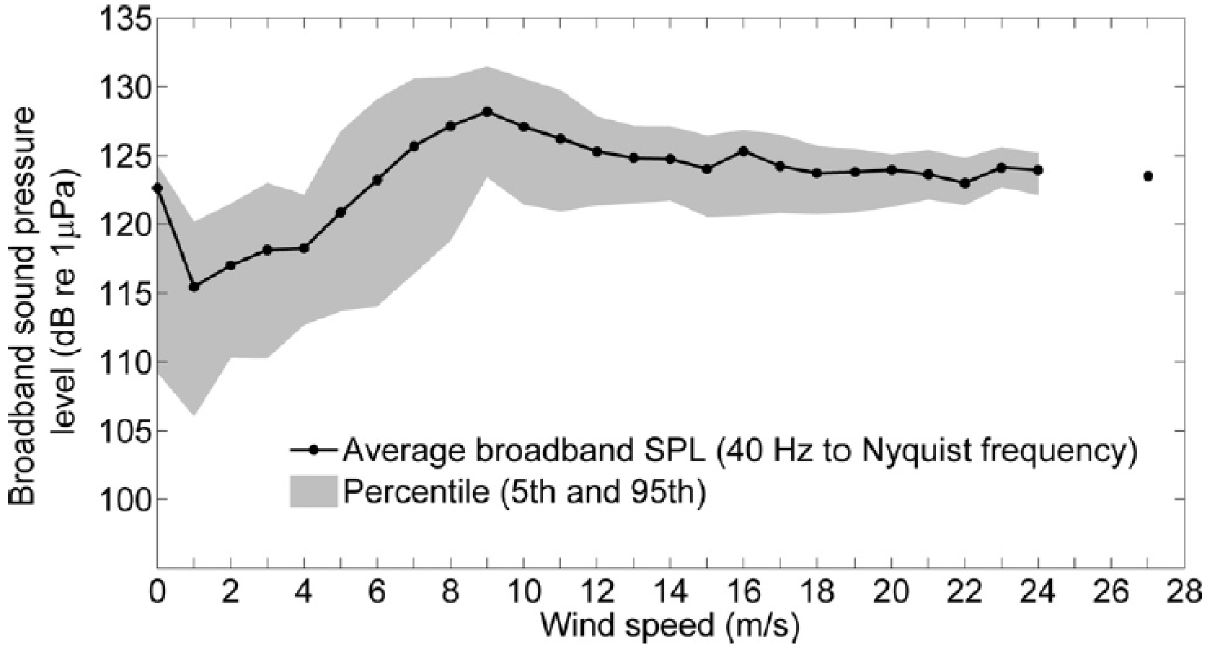


Figure 7.2: Measured broadband noise level from a Siemens SWT 3.6-107 turbine operating at different wind speeds. Bandwidth of the recordings was 40 Hz to 3.5 kHz (Nyquist frequency). From Pangerc et al. [2016].

All available literature on wind turbine underwater noise was recently reviewed by [Tougaard, et al., 2020]. All measurements are shown in Figure 7.3. For several reasons it is very difficult to predict the noise likely to be radiated from turbines in Hesselø offshore wind farm. The type of turbine to be used is yet unknown, but likely to be larger in nominal capacity than the turbines from which measurements are available (range 0.5 to 6.15 MW) and analysis of the available data indicate a significant increase in radiated noise with increasing turbine size (14 dB per factor 10 increase in nominal capacity, Tougaard et al. 2020). All but one of the turbines from which measurements are available were also of a type with gearbox (one-stage or multi-stage), whereas future turbines are likely to be of the direct drive type. The single study on a direct drive turbine (Haliade 150, 6MW, [Elliott, et al., 2019] is insufficient to conclude on this, but does suggest that the noise is more broadband and lacks the distinct tonal components seen in the noise from turbines with a gearbox.

Despite these uncertainties, it is considered likely that noise levels will be comparable to what has been measured so far in other turbines, which means that it is unlikely that the turbine noise will exceed the median ambient noise level in the planning area for Hesselø OWF except within a few hundred meters from the turbines. On quiet days, the turbine may be audible at greater distances, but one should recall that radiated noise is also lower at lower wind speeds (Figure 7.2).

Within the radius where the noise from the turbine exceeds ambient noise, the turbine noise is likely to be audible to seals and possibly also fish [Madsen, et al., 2006]. However, due to their poor hearing at low frequencies, harbour porpoises are unlikely to be able to hear the turbine noise unless extremely close to the turbines.

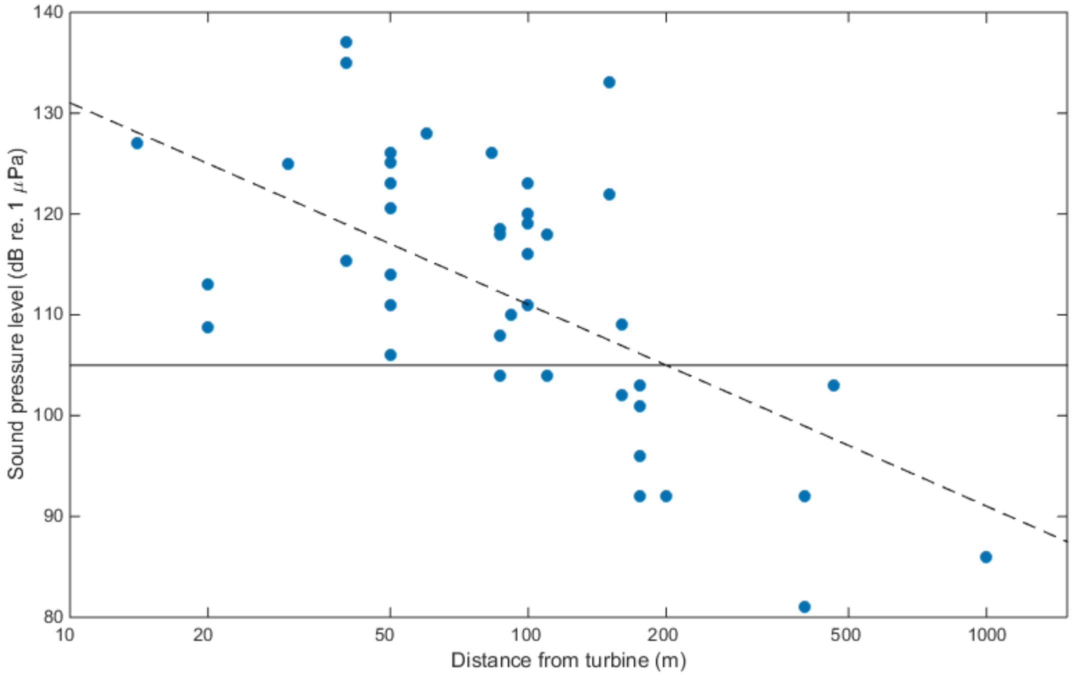


Figure 7.3: Received levels of underwater noise from offshore turbines, measured from 16 different wind farms. Measurements were conducted under very different conditions, including depth and wind speed), and therefore difficult to compare. Nevertheless, the received level decreases with distance roughly following spherical spreading loss, as indicated by the dashed line. The horizontal line indicates the median noise level in the 200 Hz-2 kHz band inside the Hesselø Offshore wind farm area (from Figure 4.2, middle plot, page 23). Data replotted from Tougaard et al. [2020].

7.2 Service boat noise

Service boats operating inside the offshore wind farm may be a significant source of underwater noise. However, the levels and temporal statistics of this contribution to the soundscape has not yet been quantified. It is well known that harbour porpoises will react negatively to high levels of ship noise [Dyndo, et al., 2015], [Wisniewska, et al., 2018]. On the other hand, it has also been documented that harbour porpoises are continuously present around active and noisy oil and gas production platforms [Todd, et al., 2009], [Clausen, et al., 2021]. Without dedicated studies it is therefore not possible to estimate the contribution to the soundscape by the service boats and their role in disturbance of marine mammals.

8 Conclusion

8.1 Baseline underwater noise

Soundscape modelling of underwater noise in Kattegat indicates that ambient noise in the planning area for Hesselø OWF is dominated by ship noise in the frequency range 200 Hz to 2 kHz, originating from ships in the shipping lanes to the west and east of the area. Absolute levels are comparable to other shallow parts of the Baltic with moderate levels of ship traffic. No relevant measurements are currently available from the area, but are expected to become available within the next years from the ongoing monitoring program in the planning area as well as from the TANGO project, which studies noise from the nearby shipping lane.

8.2 Construction phase - underwater noise

Sound propagation modelling was carried out for a 10 m, 13 m and 15 m diameter monopile to determine compliance with authority requirements for impact on harbour porpoise and harbour seal. Calculations showed mitigation requirements of $\Delta SEL_{VHF} \geq 8.6$ dB, 10.9 dB and 12.1 dB for 10 m, 13 m and 15 m monopiles respectively to avoid underwater noise levels above PTS in harbour porpoise impact. For harbour seal, the corresponding mitigation requirements were calculated to be $\Delta SEL_{PW} \geq 6.9$ dB, 9.2 dB and 10.4 dB.

Sound propagation modelling for pile driving with an active noise abatement system (NAS) with a mitigation effect corresponding to a big bubble curtain (BBC) was carried out, as well as calculations with a hydro sound damper + double big bubble curtain (HSD-DBBC) NAS.

<u>Impact distances for pile driving with BBC equivalent NAS</u>
Permanent Threshold Shift (PTS) is unlikely to occur in marine mammals located further than 25 m away from the pile installation at the onset of piling activities, for all pile sizes. Temporary Threshold Shift (TTS) is unlikely to occur for marine mammals located further than 60 m, 120 m and 180 m away from the pile installation at the onset of piling activities, for installation of 10 m, 13 m and 15 m monopiles respectively.

Harbour porpoise behaviour impact is likely to occur up to distances of 9.8 km for a 10 m monopile, 11.4 km for a 13 m monopile and up to 12.4 km for a 15 m monopile.

For cod, TTS is likely to occur to individuals located closer to the pile installation, at the onset of piling, than 4.4 km, 7.3 km and 9.5 km for installation of 10 m, 13 m and 15 m monopiles respectively. Physical injury is unlikely to occur for cod located further than 25 m from the installation.

For herring, TTS is likely to occur to individuals located closer to the pile installation, at the onset of piling, than 1.2 km, 3.2 km and 4.9 km for installation of 10 m, 13 m and 15 m monopiles respectively. Physical injury is unlikely to occur for herring located further than 25 m from the installation.

For larvae and eggs, injury distances up to 425 m, 575 m and 700 m, for installation of 10 m, 13 m and 15 m monopiles respectively, may occur.

<u>Impact distances for pile driving with HSD-DBBC equivalent NAS</u>
Permanent Threshold Shift (PTS) is unlikely to occur in marine mammals located further than 25 m away from the pile installation at the onset of piling activities, for all pile sizes. Temporary Threshold Shift (TTS) is unlikely to occur for marine mammals located further than 50 m away from the pile installation at the onset of piling activities, for all three monopile sizes.

Harbour porpoise behaviour impact is likely to occur up to distances of 6.8 km for a 10 m monopile , 8.2 km for a 13 m monopile and up to 9.1 km for a 15 m monopile.

For cod, TTS is likely to occur to individuals located closer to the pile installation, at the onset of piling, than 3.5 km, 5.5 km and 7.1 km for installation of 10 m, 13 m and 15 m monopiles respectively. Physical injury is unlikely to occur for cod located further than 25 m from the installation.

For herring, TTS is likely to occur to individuals located closer to the pile installation, at the onset of piling, than 0.6 km, 2.0 km and 3.1 km for installation of 10 m, 13 m and 15 m monopiles respectively. Physical injury is unlikely to occur for herring located further than 25 m from the installation.

For larvae and eggs, injury distances up to 375 m, 525 m and 625 m, for installation of 10 m, 13 m and 15 m monopiles respectively, may occur.

8.3 Operation phase underwater noise

Underwater noise from operating turbines in a future wind farm at Hesselø cannot be accurately predicted. However, by comparison with available measurements on existing wind turbines, it appears likely that noise levels will be low and unlikely to affect marine mammals beyond some few hundred meters in worst case. An increase in epifauna, primary production and hence food availability, because of the turbine foundations, has not been addressed, but may counterbalance any (low-level) deterrence caused by the turbine noise. However, it has not been studied whether such an increase in biomass and production actually has a beneficial impact on porpoises.

Noise from service boats operating inside the wind farm is an overlooked source of noise in the wind farm. Lack of data/experimental studies on this topic means that it is not possible to quantify the habitat deterioration caused by service boats.

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Appendix 1: Affected Natura 2000 map for a 10 m monopile

Figure A. 1: Noise contour map for position 2, together with the overlap showing impact distances for behaviour with VHF-weighting together with the overlap with Natura 2000 sites when applying a BBC NAS on a 10 m monopile.

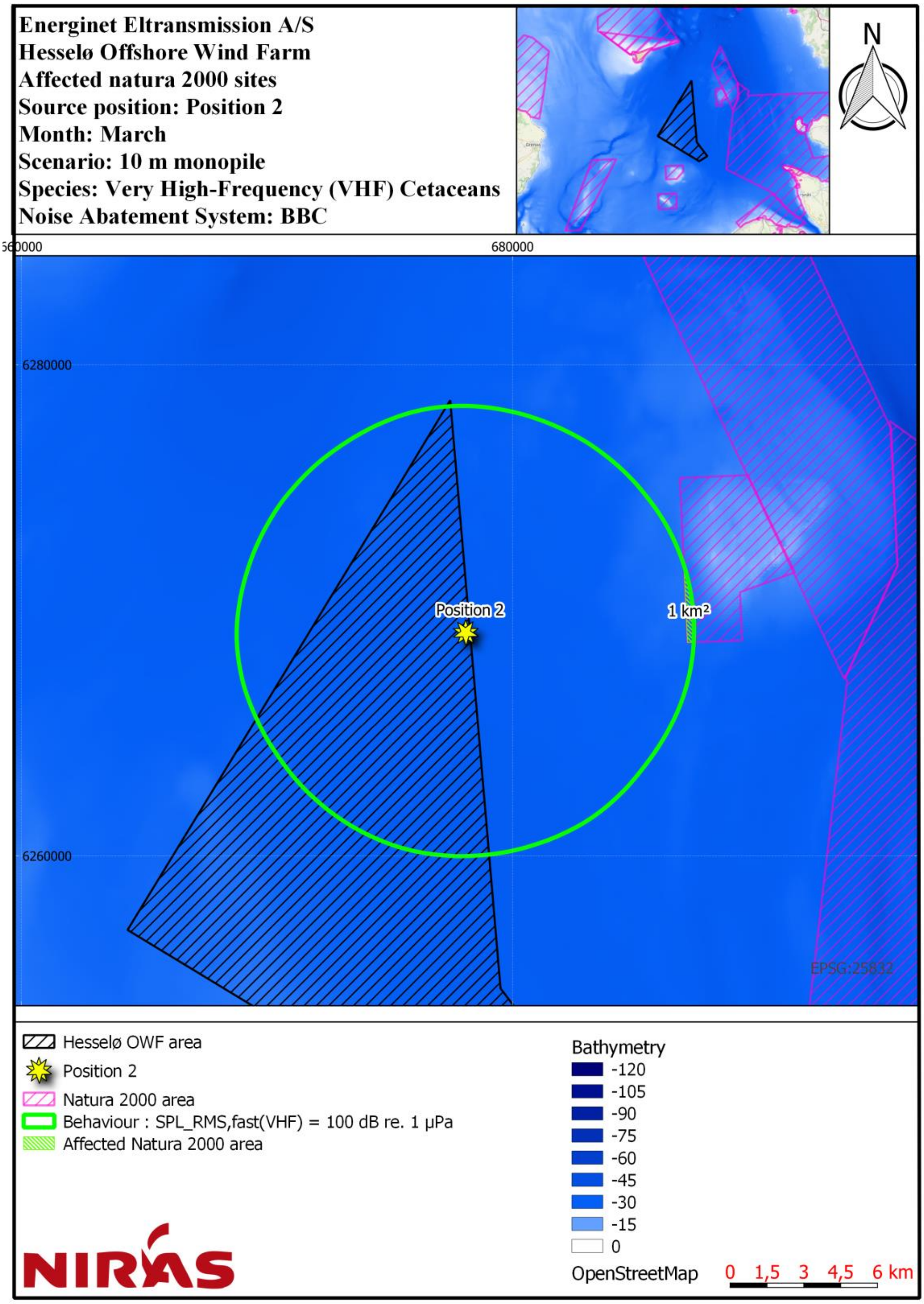
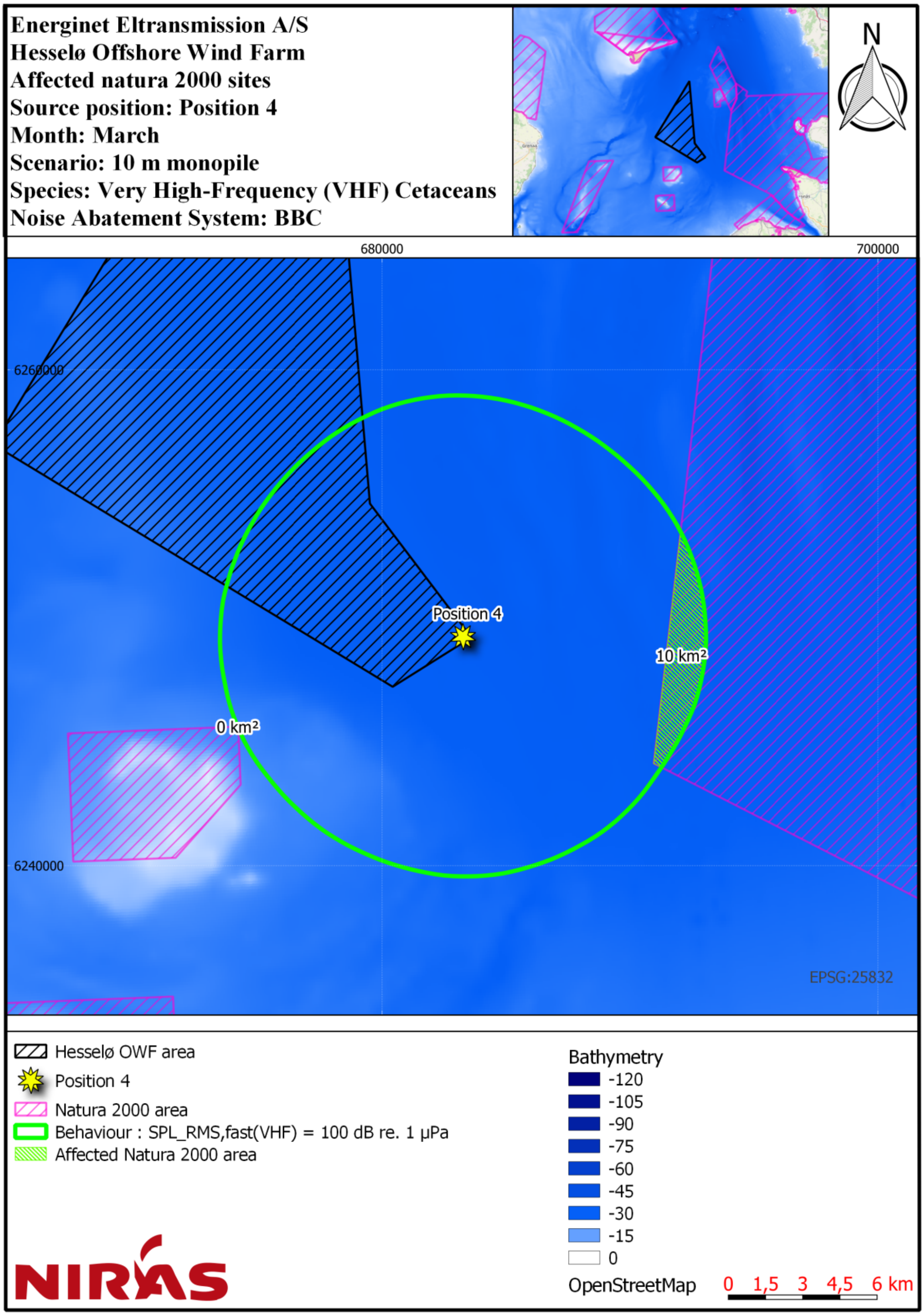


Figure A. 2: Noise contour map for worst position 4, together with the overlap showing impact distances for behaviour with VHF-weighting together with the overlap with Natura 2000 sites when applying a BBC NAS on a 10 m monopile.



Appendix 2: Affected Natura 2000 map for a 13 m monopile

Figure A. 3: Noise contour map for position 1, together with the overlap showing impact distances for behaviour with VHF-weighting together with the overlap with Natura 2000 sites when applying a BBC NAS on a 13 m monopile.

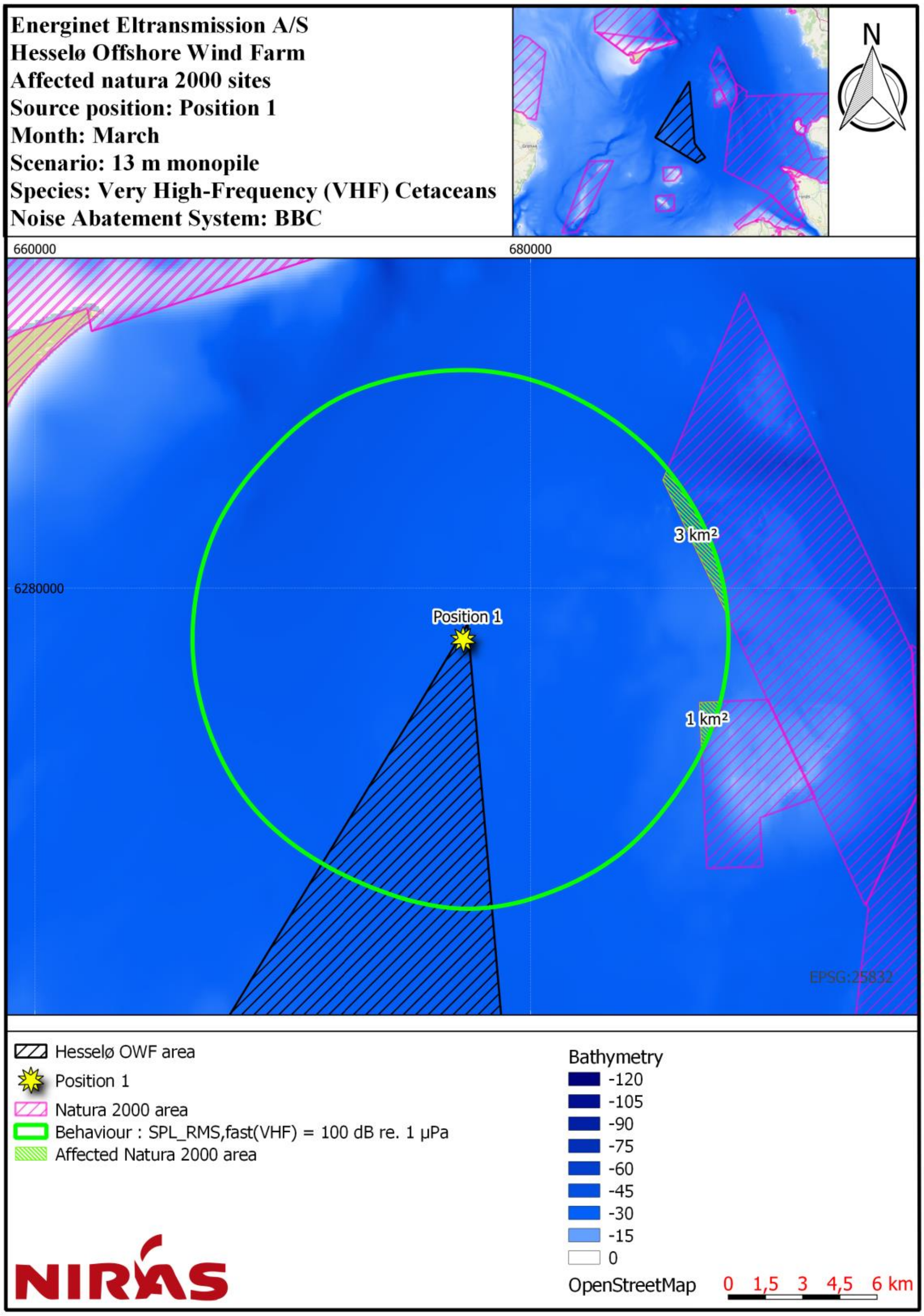


Figure A. 4: Noise contour map for position 2, together with the overlap showing impact distances for behaviour with VHF-weighting together with the overlap with Natura 2000 sites when applying a BBC NAS on a 13 m monopile.

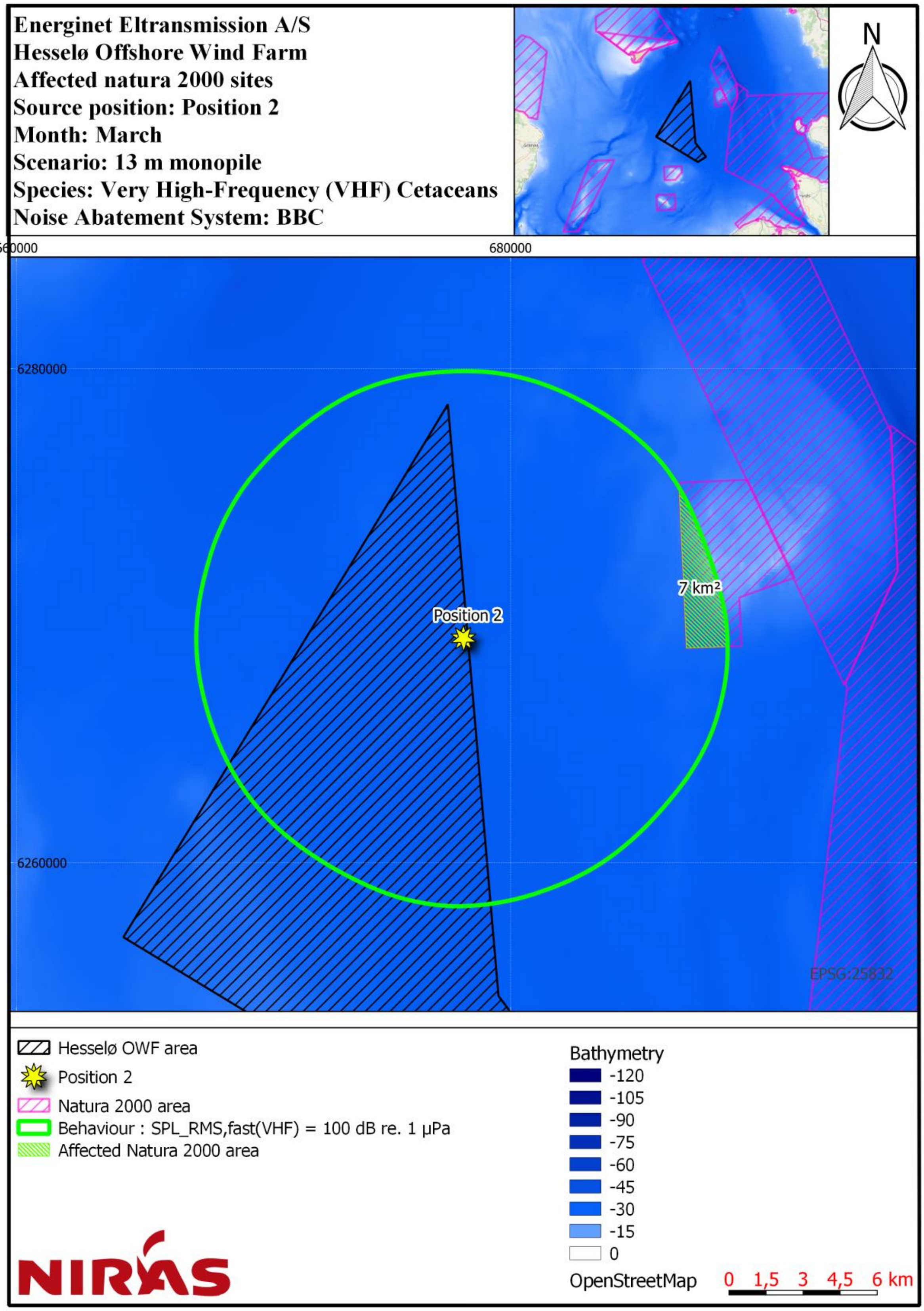
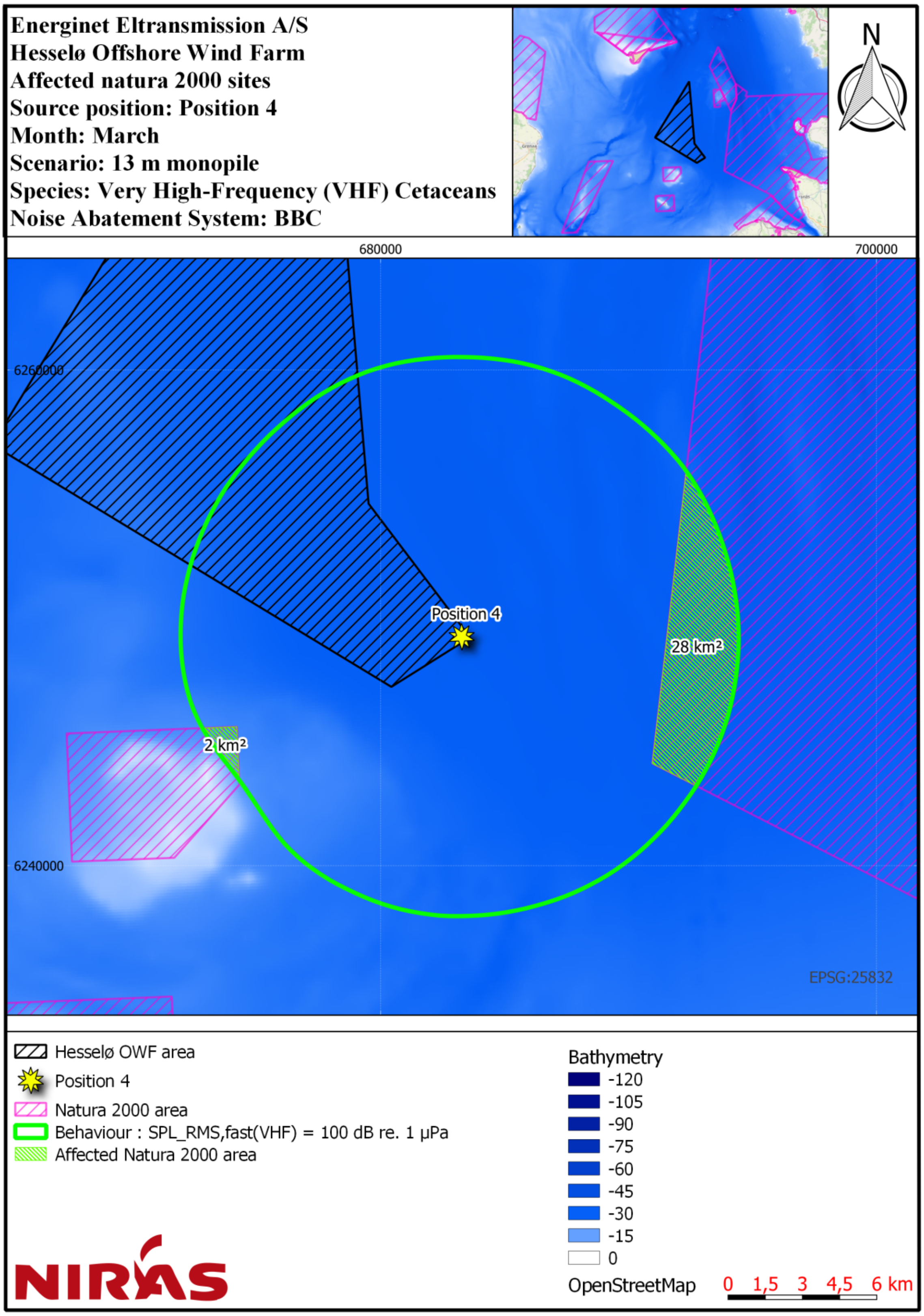


Figure A. 5: Noise contour map for position 4, together with the overlap showing impact distances for behaviour with VHF-weighting together with the overlap with Natura 2000 sites when applying a BBC NAS on a 13 m monopile.



Appendix 3: Affected Natura 2000 map for a 15 m monopile

Figure A. 6: Noise contour map for position 4, together with the overlap showing impact distances for behaviour with VHF-weighting together with the overlap with Natura 2000 sites when applying an HSD-DBBC NAS on a 15 m monopile.

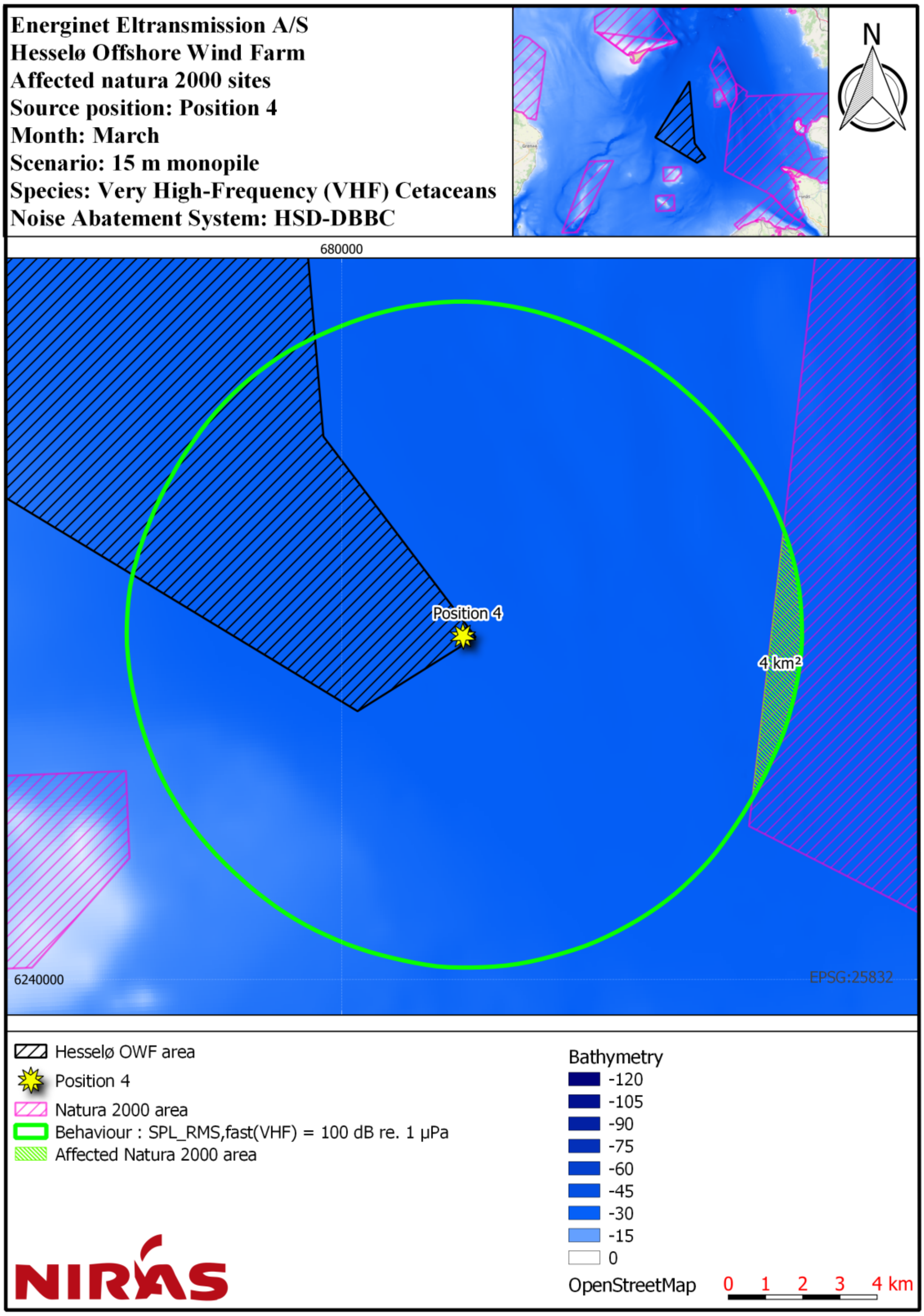


Figure A. 7: Noise contour map for position 1, together with the overlap showing impact distances for behaviour with VHF-weighting together with the overlap with Natura 2000 sites when applying a BBC NAS on a 15 m monopile.

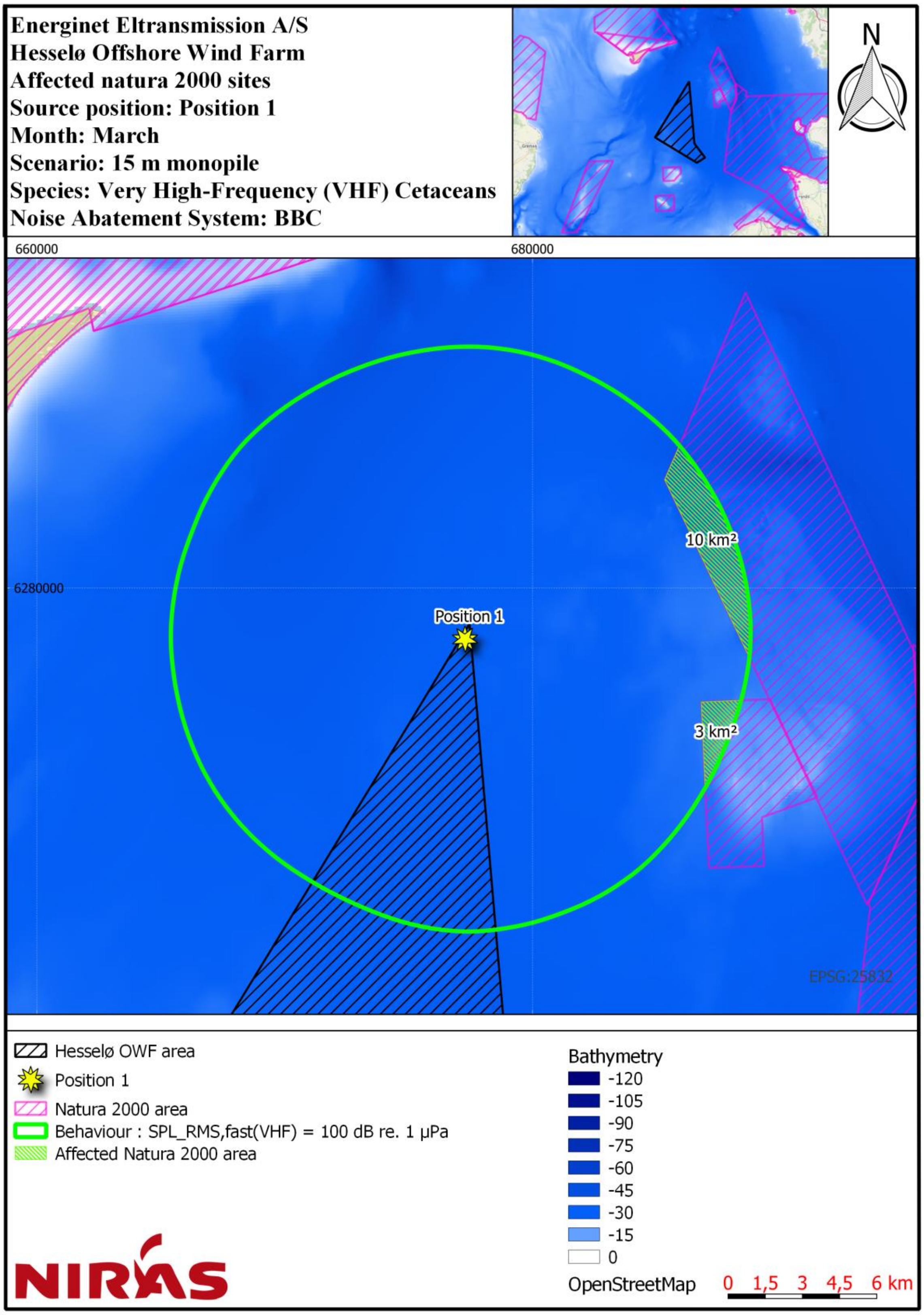


Figure A. 8: Noise contour map for position 2, together with the overlap showing impact distances for behaviour with VHF-weighting together with the overlap with Natura 2000 sites when applying a BBC NAS on a 15 m monopile.

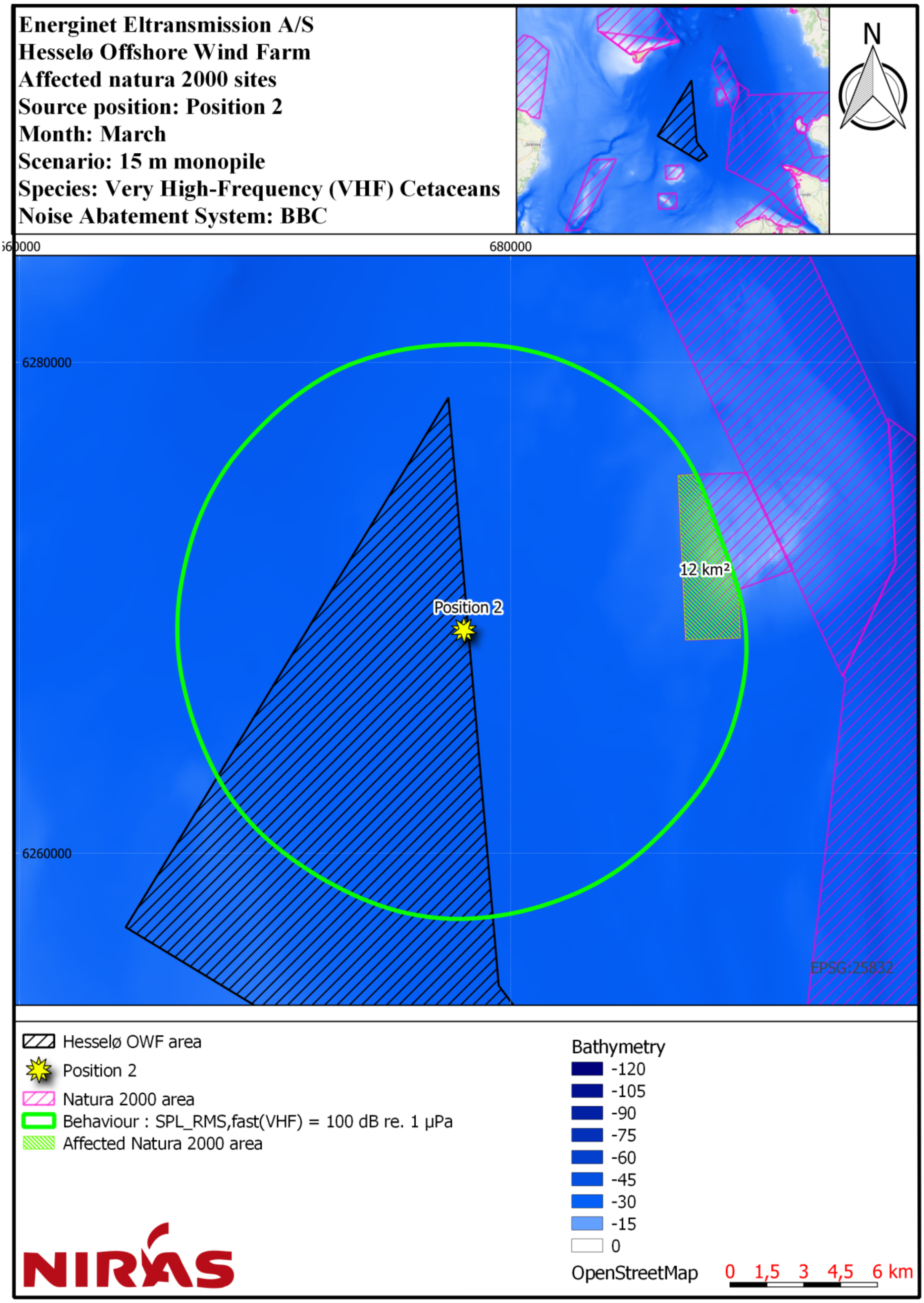
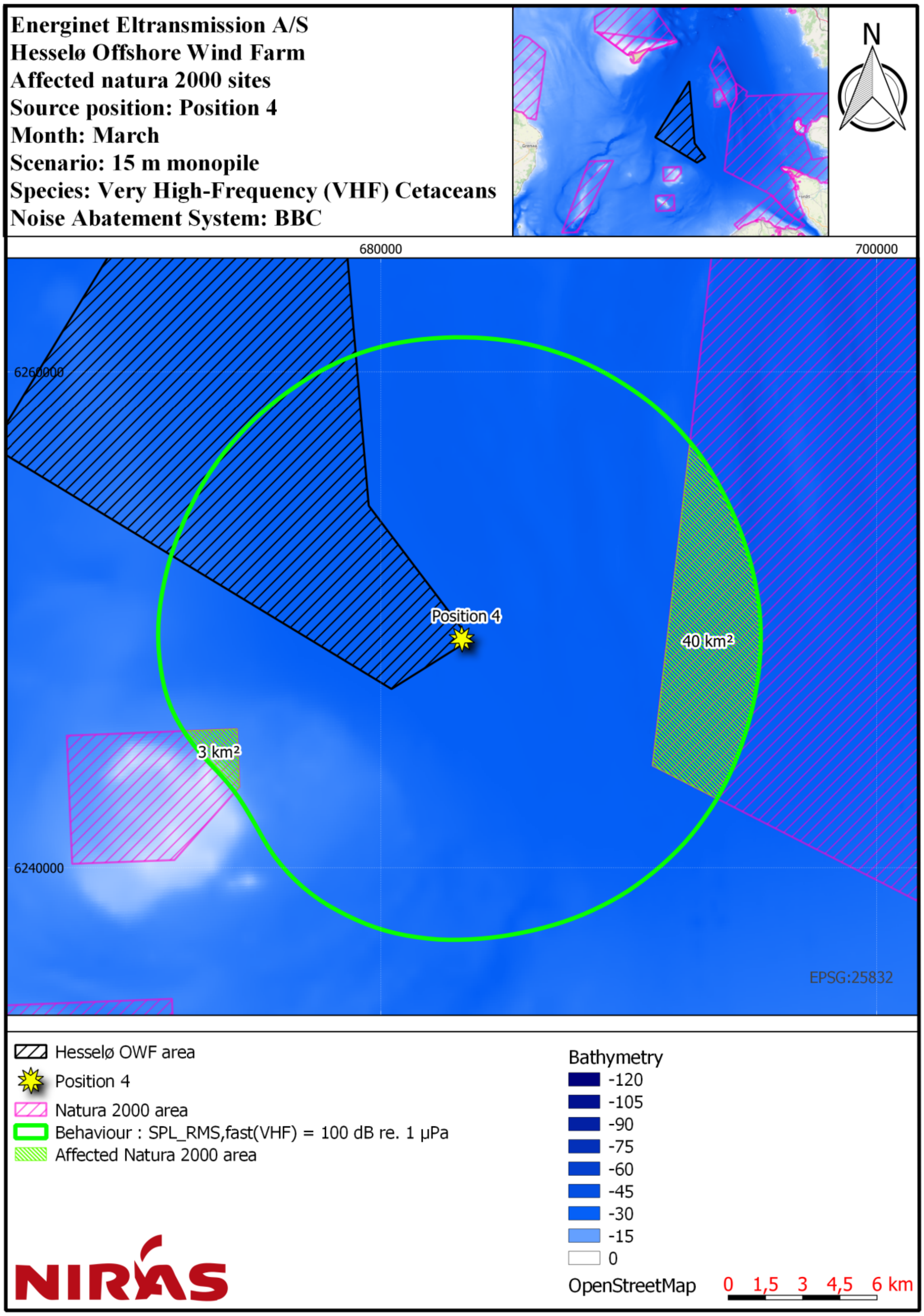


Figure A. 9: Noise contour map for position 4, together with the overlap showing impact distances for behaviour with VHF-weighting together with the overlap with Natura 2000 sites when applying a BBC NAS on a 15 m monopile.



Appendix 4: Underwater noise methodology agreement

Fra: Søren Keller <ske@ens.dk>
Sendt: 9. september 2021 07:47
Til: Signe Dons <sid@energinet.dk>
Cc: Søren Enghoff <snhf@ens.dk>; Therese Kofoed Jensen <tkj@ens.dk>
Emne: SV: Hesselø OWF: Marsvin og sæler - Beregningsmetode for undervandsstøj fra pælenedramning af fundamenter

Vær opmærksom på afsender, links og filer.

Hej Signe
Vi kan pt. ikke sige hvordan vi lander de nye guidelines, og vi mangler at tage stilling til nogle centrale punkter. Derfor kan vi ikke forbygge den situation, at jeres beregninger adskiller sig fra guidelines. Jeres rådgiver Niras har fået tilsendt et udkast til guidelines, så spørg Niras, om det giver anledning til en ændring af tilgangen nedenfor – ellers så synes jeg, at I skal køre med det I har foreslået.

Bh.
Søren Keller, 33926690

Fra: Signe Dons <sid@energinet.dk>
Sendt: 2. september 2021 13:35
Til: Søren Enghoff <snhf@ens.dk>; Søren Keller <ske@ens.dk>
Cc: Pernille Skyt <XPESK@energinet.dk>; Stine Rabech Nielsen <srn@energinet.dk>; Therese Kofoed Jensen <tkj@ens.dk>
Emne: Hesselø OWF: Marsvin og sæler - Beregningsmetode for undervandsstøj fra pælenedramning af fundamenter
Prioritet: Høj

Kære Søren og Søren

Vores rådgiver skal i gang med deres vurderinger af påvirkninger på marsvin. De er allerede bagud, jf. vores tidsplan, og en bekræftelse på nedenstående metodetilgang er derfor af stor vigtighed, og vi har brug for en tilbagemelding hurtigst muligt,

Venlig hilsen

Signe Dons
Konsulent
Miljø og Geoscience
+4526823670
sid@energinet.dk

Fra: Signe Dons
Sendt: 27. august 2021 15:19
Til: Søren Enghoff <snhf@ens.dk>; 'Søren Keller' <ske@ens.dk>
Cc: Pernille Skyt <XPESK@energinet.dk>; 'Maria Wilson (MAWI)' <MAWI@NIRAS.DK>; Mark Aarup Mikaelsen (MAM) <MAM@NIRAS.DK>; Stine Rabech Nielsen <srn@energinet.dk>
Emne: Hesselø OWF: Marsvin og sæler - Beregningsmetode for undervandsstøj fra pælenedramning af fundamenter

Kære Søren og Søren

Hermed fremsendes forslag til beregningsmetode for undervandsstøj fra pælenedramning af fundamenter i forbindelse med Hesselø OWF. Heraf vil nedenstående blive anvendt i arbejdet;

- Beregninger udføres som modelberegninger med passende modeller fra dBSea (Ray, PE, NM).
- Beregninger udføres i frekvensområdet 16 Hz – 16 kHz.
- For både sæler og marsvin udføres beregninger for TTS og PTS med frekvensvægtede tærskelværdier efter Southall 2019 samt NOAA 2018.
- For marsvin anvendes en tærskelværdi for adfærdsændringer efter Tougaard et al 2015, hvor tærskelværdien er: SPL(rms,fast,vægtet) = 100 dB.
- Beregninger udføres kun ud til radius af ca. 20 km fra pælenedramning uden dæmpning.
- Beregninger foretages med udgangspunkt i 1,5 m/s flugthastighed for både marsvin og sæler.

- Beregning af dæmpningskrav foretages med udgangspunkt i 1,5 m/s flugthastighed for både marsvin og sæler, og en startafstand på 300 m (effektiviteten af en pinger) ved begyndelse af soft start, således følgende er opfyldt:
    - Der forekommer ingen PTS for dyr der er mindst 300 m fra pælen ved opstart af soft start.

- Med udgangspunkt i dæmpningskrav, vælges en passende dæmpningsløsning, som minimum overholder dæmpningskravet. Valget sker ud fra statistiske opnåede dæmpninger ved øvrige dokumenterede projekter.
- Der udføres nye beregninger for PTS, TTS, adfærd for sæler og marsvin og i nødvendigt omfang fisk, hvor den valgte dæmpningseffekt anvendes (dæmpet scenarie).
- Påvirkningsafstande dokumenteres udelukkende for det dæmpede scenarie og de efterfølgende vurdering baseres kun på det dæmpede scenarie, da pælenedramning uden dæmpning ikke er et realistisk scenario.
- Dæmpningsløsninger som anvendes i dæmpede beregninger ses udelukkende som eksempler, og usikkerheden omkring faktisk ydeevne indgår ikke på akademisk niveau / der må vælges en passende løsning af koncessionshaver når der foreligger valg af endelig fundament og hammer, drivability analyser og detaljeret oceanografisk viden samt viden om tidspunkt på året hvor installationen vil foregå. Energistyrelsen skal stille krav om at der findes en dæmpningsmetode, som kan levere den dæmpning, som beregningerne og dermed vurderingerne baseres på.

Energinet og NIRAS stiller gerne op til et møde, hvor ovenstående beregningsmetode kan blive præsenteret,

Venlig hilsen

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