KATTEGATT SYD OFFSHORE WIND FARM

Effects of pile driving, gravity foundations and sediment spill on marine mammals

Scientific Report from DCE – Danish Centre for Environment and Energy No. 447 2021

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Abstract: Construction and operation of an offshore wind farm between the two Swedish Natura 2000 sites *Lilla Middelgrund* and *Stora Middelgrund & Röda Bank* has been assessed with respect to potential impacts on marine mammals from underwater noise and sediment spill. Underwater noise is assumed the main source of potential impact from construction, in particular percussive piling of turbine foundations. Impact was modelled for July and December by estimating the cumulated sound exposure for marine mammals near the construction site and by assessing disturbance to animals in time and space. Construction in December is predicted to result in significantly larger affected areas than construction in July due to differences in hydrography and hence sound propagation properties. Impact was assessed with noise abatement in shape of Big Bubble Curtains (BBC), as well as with best available technology (BAP) noise abatement with hydro sound dampeners (HSD) and Double Big Bubble Curtains (DBBC). With BBC noise abatement 29 % and 44 % of the *Lilla Middelgrund* and *Stora Middelgrund & Röda Bank,* respectively, will be exposed to noise levels above the reaction threshold for harbour porpoises. With the use of HSD + DBBC noise abatement in Summer, this effect can be reduced to 2.8 % and 5.3 %, respectively for the two Natura 2000 sites. With such mitigation measures in place, the construction is not considered to have long-term impacts on the abundance or population development of marine mammals in the area. Likewise, the operation of the wind farm is considered to be without significant long-term impact on marine mammals.

Keywords: Offshore renewables, pile driving, underwater noise, harbour porpoises, harbour seals, grey seals, Natura 2000 sites

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Preface

This report was commissioned by Vattenfall Vind A/B. It contains an assessment of potential impact on marine mammals from construction of an offshore wind farm at the site Kattegatt Syd (KAYD) between the two Swedish Natura 2000 sites *Lilla Middelgrund* and *Stora Middelgrund & Röda Bank*, in Swedish Kattegat. NIRAS contributed with appendix 1. Conclusions with respect to impact on animals remain the sole responsibility of DCE. The assessment of impact is largely based on methodology and information also used for similar assessments for offshore wind farms on Swedish Kriegers Flak and Swedish Stora Middelgrund. Description of methodology and background information is therefore largely identical to the report on the Stora Middelgrund offshore wind farm, updated wherever relevant. For assessment of impact on Natura 2000 sites, the approach of the British Joint Nature Conservation Committee's guidelines for disturbance of Nature 2000 sites is used in the absence of national guidelines.

Vattenfall was given the opportunity to comment on the first version of this report. The comments received were all in the form of wishes for further explanation and justification of statements, not questioning assessments or conclusions, which remains the responsibility of the authors.

Summary

Construction and operation of a proposed offshore wind farm at the Swedish site Kattegatt Syd between the two Natura 2000 sites *Lilla Middelgrund* and *Stora Middelgrund and Röda Bank* has been assessed with respect to impacts on marine mammals and Natura 2000 sites.

Abundance of marine mammals

One cetacean, the harbour porpoise (*Phocoena phocoena*, tumlare) is common in the waters of the Kattegatt Syd offshore windfarm site. In the southern part of Kattegat, these porpoises belong to the Belt Sea population which is assessed on national red lists as Least Concern (LC).

Two species of seals, harbour seal (*Phoca vitulina*, knubbsäl) and grey seal (*Halichoerus grypus*, gråsäl) use the area. The harbour seal is common and red-listed as Least Concern (LC), whereas the grey seal appears in low numbers and red-listed as Vulnerable (VU).

Sensitivity to impact

Underwater noise is likely to be the main source of impact on marine mammals from wind farm construction, but the impact of sediment spill is also assessed. Unabated percussive pile driving is known to generate very high sound pressures, likely capable of inflicting permanent damage to the hearing of seals and porpoises and has been shown to cause behavioural disturbances at distances of tens of km from the pile driving site.

Various mitigation measures for pile driving are available, including use of deterring devices, soft-start and reduction of radiated noise by means of for example air bubble curtains and other noise abatement systems.

Magnitude of impact on harbour porpoises and seals was assessed for sediment spill, as well as for effects of underwater noise from installation of foundations by pile driving. The assessed effects are direct damage (acoustic trauma), hearing loss (permanent threshold shift, PTS), disturbance of behaviour and masking of other sounds. Hearing loss was assessed by considering total cumulated sound exposure levels (SELcum) over the duration expected for piling of one foundation (14 m diameter, app. 6 hours), taking movements of the animals into consideration and applying appropriate auditory frequency weighting to the acoustic measurements. Disturbance of behaviour was evaluated through assessing area and time exposed to levels above the reaction threshold.

Impact was also assessed for the nearby Natura 2000 sites. Here, the impact was assessed as the area over which the noise level exceeded the reaction threshold of harbour porpoises. The impact was assessed in accordance with the guidelines recently put forward by the British Joint Nature Conservation Committee (JNCC) (JNCC 2020b).

Impact from construction

For the noise exposure assessment, modelling was performed for three positions (north, middle and south) and two seasons (Summer/July and Winter/December). The two seasons were picked to represent the most extreme hydrographical conditions with respect to sound propagation, with December being the worst (upward-refracting conditions) and July the most favourable (downward-refracting conditions) due to a complete mixing of the water column at this time of the year, which leads to less favourable conditions for long-range sound propagation (iso-velocity, or downward-refracting conditions).

Modelling was performed for a monopile diameter of 14 m, which at the time of writing this report was the worst-case scenario for the monopiles to be installed.

Based on experience from similar projects it was assumed that construction will require substantial mitigation of noise impact, in the form of noise abatement systems. Scenarios without noise abatement was therefore judged as unrealistic and therefore not included in the assessment. Modelling was thus performed for pile driving with industry standard noise abatement (Big Bubble Curtains) and with best available technology (BAT) for noise abatement. Currently, the technology identified as best available is a system of Hydro Sound Dampeners and Double Big Bubble Curtain (HSD-DBBC system) deployed around the monopile to reduce radiated noise from the piling. The results of modelling using the HSD-DBBC system also pertains to piling with an equivalent, but other abatement system that mat be developed before the windfarm will be constructed.

Assuming use of the assessed noise abatement systems, the following can be stated from the assessment:

- It is considered unlikely that marine mammals will be exposed to sound pressures able to inflict acute injury (acoustic trauma involving damage to lungs and other air-filled structures and gas-embolism) as noise abatement will be used.

- Modelling predicts that seals and porpoises would have to be located within 25 m of the bubble curtains surrounding the mono pile during piling, at onset of pile-driving (when soft start begins) in order to be exposed to sound levels capable of inducing permanent hearing loss (PTS). It is considered unlikely that animals will be this close to the site at onset to pile driving, due to the presence of multiple working vessels and the bubble curtains. The **impact on the population of seals and porpoises** is assessed to be **negligible.**

- Noise from pile driving will cause disturbances to the natural behaviour of both seals and porpoises. Under worst-case conditions for sound propagation, which is abatement with big bubble curtains in December, less than 1 % of the porpoise population in the Southern Kattegat and the Belt Seas was predicted to be exposed to sound pressures above the behavioural reaction threshold, amounting to an exposed area of 208 km^2 for a period of about 120 days if piling of the 60 foundations takes place every other day. The impact of pile driving in December with use of big bubble curtains on both seal populations and the Belt Sea harbour porpoise population is therefore assessed as **minor**. With use of best available technology and best environmental practice, which is pile driving in July, with the

HSD-DBBC noise abatement system or equivalent, the impacted area will decrease (predicted to be 19-26 km^2) and hence the fraction of the population being affected will decrease as well. Under these conditions, the impact on seal and porpoise populations is assessed to be **minor**.

- The main noise from installation of gravity foundations is considered to be from vessels. It is assessed likely that under worst-case conditions vessel noise from installation of gravity foundation will affect a total area of 24 km^2, which is assessed as a **minor** impact.

- It is considered unlikely that pile driving noise will be capable of masking sounds relevant to porpoises to any noticeable degree and the magnitude of this impact on porpoises was thus assessed as **negligible**.

- There is a possibility that communication sounds from both grey seals and harbour seals can be masked by pile driving noise and noise from gravity foundations. This communication is especially important during the mating season and takes place primarily close to breeding and haul-out sites. Given the large distance from the construction site to nearest haul-outs, the overall impact of masking from the pile driving noise on both seal populations is assessed to be **negligible**.

- There is no evidence suggesting that the three marine mammal species assessed are affected by low water turbidity, and the impact of the sediment spill from construction of the offshore wind farm, is assessed as **negligible**.

Impact from operation

There is a lack of long-term studies examining the effect on harbour porpoises of operating offshore windfarms, especially taking service vessels into account, as well as the increase in size of the turbines. The existing studies varies in effect from attraction (likely due to a lack of trawling) to a reduced number of animals as compared with reference stations. The impact is therefore assessed with some uncertainty to **negligible** for harbour porpoises, and it would be of benefit if the area were to be closed off for all fishing activities. Based on studies of effects from existing offshore wind farms in operation, no negative effects of the wind farm is predicted on seals once in operation and the effect is thus assessed as **negligible.** The cumulative effect of adding an additional offshore wind farm to already existing offshore wind farms in the area is likewise considered **negligible** for the seal population in Kattegat.

Impact on Natura 2000 sites

The Natura 2000 sites Lilla Middelgrund, Stora Middelgrund & Röda Bank, could be affected by construction of the offshore wind farm. Under worst case conditions, which is pile driving abated with Big Bubble Curtains in December, both sites will be affected by exposure to noise levels above the behavioural reaction thresholds for porpoises to an extent of more than 20 %, which is used as the recommended maximum disturbance threshold as put forward by JNCC and used in the absence of national guidelines from Sweden. This is according to the JNCC guidelines assessed as an **unacceptable** impact.

Application of Best Available Technology for noise abatement during pile driving, which would be Double Big Bubble Curtains in combination with hydro sound dampeners (or similar), and piling during a period with a downward refracting sound speed profile in July (Best Environmental Practice) will reduce the emitted noise considerably. This would reduce the fraction of the Natura 2000 sites Lilla Middelgrund and Stora Middelgrund & Röda Bank exposed to noise levels above the behavioural reaction threshold, to between 3 - 5 % for 14 m monopiles. The impact is according to the JNCC guidelines thus assessed to be **acceptable.**

Under worst-case conditions vessel noise from installation of gravity based foundations none of the nearby Natura 2000 sites will be affected by the vessel noise above the 20 % threshold and the effect is assessed as **acceptable**

1 Background

Vattenfall Vind AB proposes establishing an offshore wind farm between Lilla Middelgrund and Stora Middelgrund in Swedish Kattegat (see **Figure 1.1**). This report provides background information about the marine mammals in the area and an assessment of impact from constructing and operating the wind farm on these marine mammals, in particular harbour porpoises. Known effects pertains primarily to noise from pile driving during installation of the foundations (Madsen, et al. 2006; Tougaard, et al. 2009; Dähne, et al. 2013), with much smaller impacts expected from other construction activities, such as installation of the turbines themselves and laying of cables, both within the wind farm and grid connection to shore. The focus of this assessment is therefore on the impact of pile driving, however gravity based foundations are also assessed, as this could be an alternative to monopile foundations for the current project. In that case, the impact of other activities, such as the noise from construction vessels etc. may be larger than for a pile driving scenario. However, the combined impact of noise from construction is almost certain to be smaller for other scenarios than the impact assessed for pile driving, due to the significantly larger impact ranges of pile driving noise compared to all other known noise sources during construction. A pile driving scenario can therefore be considered a worst case scenario. The only other potential noise source of disturbance considered in the assessment besides pile driving noise and noise placing gravity based foundations, is non-acoustic and is sediment resuspension that will occur during installation of cables in the seabed and in the case of installation of monopile foundations by drilling.

1.1 Marine Mammals relevant to the project

Three species of marine mammals are common in Kattegat and relevant for the proposed offshore wind farm. These species are harbour porpoise (Swedish: tumlare), harbour seal (Swedish: knubbsäl), and grey seal (Swedish: gråsäl). These will be covered below. In addition to the three common species, a number of species occur infrequently and unpredictably in Kattegat (Kinze, et al. 2018). These are not treated in this assessment.

The harbour porpoise is the most common cetacean and is present throughout Kattegat. It is listed in Annex II and IV of the EU Habitats Directive (92/43/EEC), Aannex II of the Bern convention, Aannex II of the Bonn convention and Annex II of the Convention on the International Trade in Endangered Species (CITES). Furthermore, it is covered by the terms of the Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (ASCOBANS, a regional agreement under the Bonn Convention) and by HELCOM (The Helsinki Commission; protection of the marine environment of the Baltic Sea from all sources of pollution). The EU Habitats Directive requires habitat protection for a range of habitat types and species listed in Annexes I and II respectively, and strict protection for a range of species listed in Annex IV. The two seal species are listed under Annex II and the harbour porpoise is listed in both Annex II and IV, which means that the harbour porpoise is protected throughout its range, as well as additional protection within special areas of conservation designated for harbour porpoises (Natura 2000 sites).

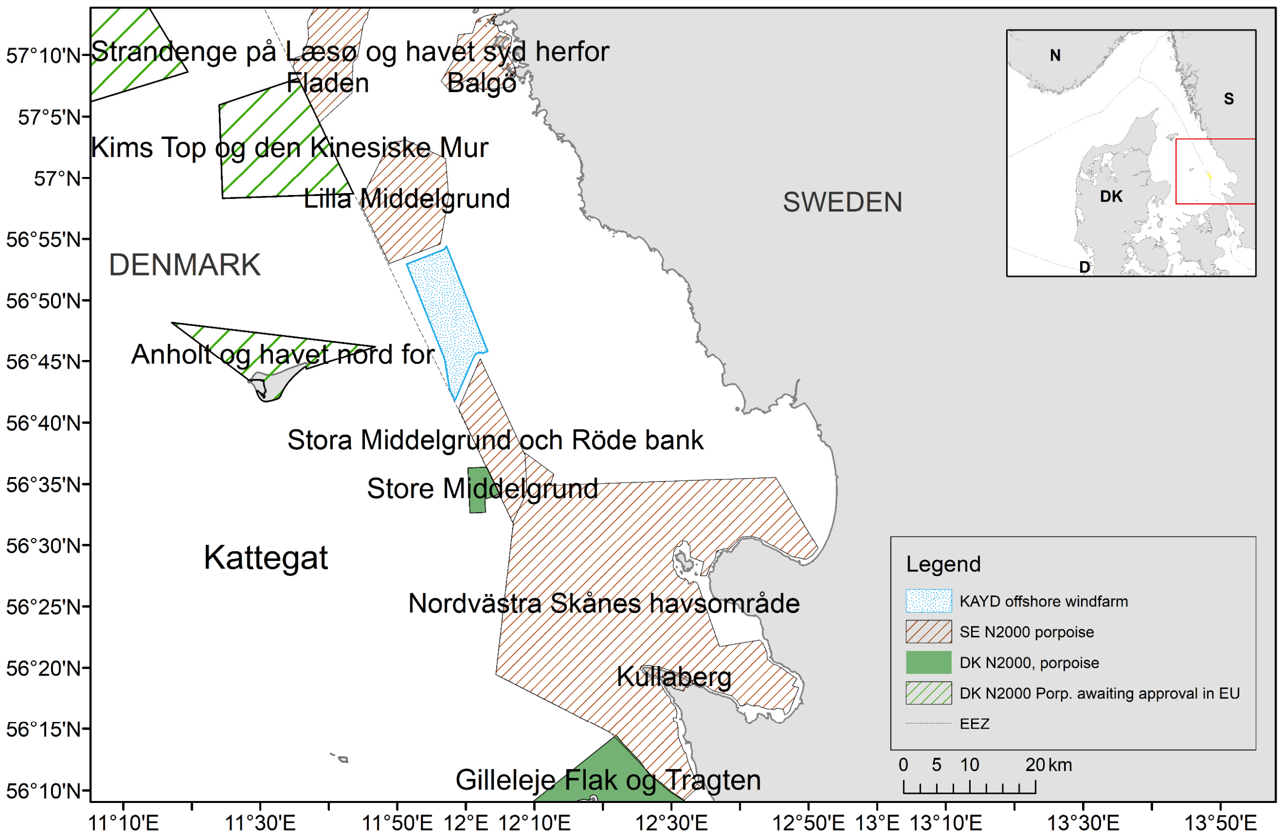
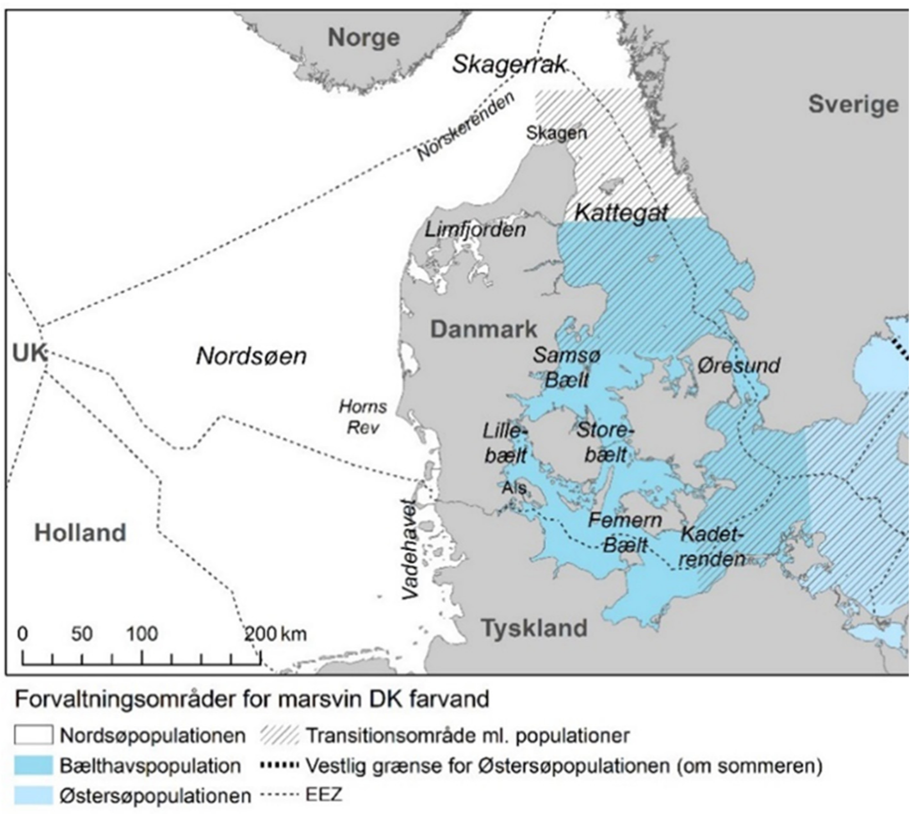


Figure 1.1. Map of Swedish and Danish Natura 2000 sites appointed for harbour porpoises in southern Kattegat. Another two N2000 areas have been appointed in Denmark for harbour porpoises, but are awaiting approval by the EU. The offshore wind farm site is shown with blue outline.

Figure 1.2. Map of management areas for the three populations of harbour porpoises. The North Sea population (white) overlaps with the Belt Seas population (dark blue) in southern Kattegat (hatched area). Map courtesy of Signe Sveegaard.



1.2 Harbour porpoises (*Phocoena phocoena*, L. 1758)

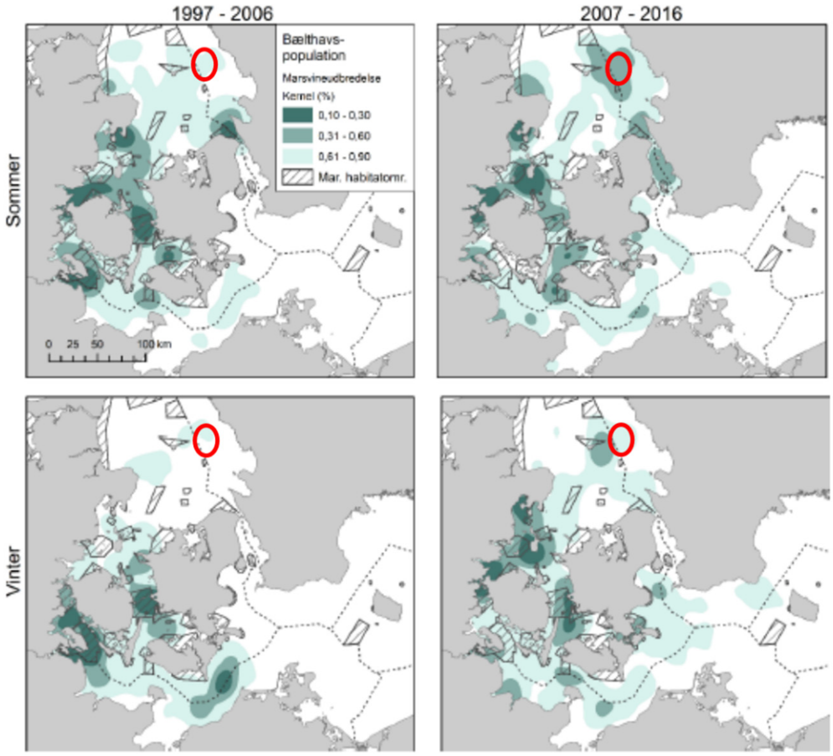
There are three different populations of harbour porpoises in the region: The North Sea, Belt Sea and Baltic Proper populations. Management areas have been suggested for the Belt Sea population (Wiemann, et al. 2010; Galatius, et al. 2012; Sveegaard, et al. 2015) and the Baltic Proper population (Carlén, et al. 2018) (**Figure 1.2**). The population inhabiting the southern Kattegat, relevant to this assessment, belongs to the Belt Sea Population. The management area of the Belt Sea population includes the Belt Sea, the Sound, southern Kattegat and the western Baltic Sea and the density for southern Kattegat and the Belt Seas was assessed as 1.04 animals per square kilometre during SCANS III with a total population estimate of 42.324 porpoises (Hammond, et al. 2017). The national red list status of the Belt Sea population of harbour porpoises is Least Concern (LC) in both Sweden and Denmark and the population development is considered stable (Hammond, et al. 2017). The conservation status is considered favourable.

The density of porpoises varies within the Belt Sea population area (Sveegaard, et al. 2011). Within the Swedish Waters there are three relevant Natura 2000 sites appointed for porpoises close to the Kattegatt Syd OWF; to the north Lilla Middelgrund (SE0510126) of 17840,2 ha and to the south, Stora Middelgrund & Röda Bank (SE0510186) with a combined area of 11,410 ha. Further to the southeast, there is another large area 'Nordvästra Skånes havsområde' (SE0420360) of 134240.8 ha also appointed for harbour porpoises (Figure 1.1 and **Table 1.1**). In Danish waters, the Natura 200 site Store Middelgrund (No.193) comprises a 2,094 ha area (**Table 1.1**). Other new Danish Nature 2000 areas have been appointed for harbour porpoises west of the wind farm area: Kims Top & the Chinese Wall and Anholt (see **Figure 1.1**), however these are waiting for approval by the EU.

1.2.1 Distribution

There are several studies shedding light on the distribution of harbour porpoises in southern Kattegat, the Sound and the Great Belt, as the Belt Sea population has been surveyed with multiple methods during the last four decades, which is described below. The collected knowledge is considered robust and suitable as a basis for this EIA. Vattenfall Vind AB also began passive acoustic monitoring in the prospective offshore wind farm site in December 2020 to be conducted for a full year. The data collected until 14th April 2021 are included in this report. The remaining ten months of data will be presented in a separate report after the end of the full monitoring year. Month-to-month variation over the year is thus not yet available for the actual wind farm area. The other lines of data from this area are described in the following: The large-scale SCANS surveys I-III covered the area with boat-based surveys three times (Hammond, et al. 2002; Hammond, et al. 2013; Hammond, et al. 2017). Similar surveys were conducted by aerial surveys (Viquerat, et al. 2014). Since 1997 Aarhus University have equipped about 150 porpoises with satellite transmitters to inform about their distribution and movements (Synthesized by Edrén, et al. 2010; Sveegaard, et al. 2011; Sveegaard, et al. 2018b) (**Figure 1.3**).

Figure 1.3. Distribution of satellite tracked harbour porpoises in the Belt Sea management area analysed as kernel densities (the darker the colour, the higher the density) in two ten-year periods in summer (April-September) and winter (October-March). The Kernel categories are defined as high (contains 30% of all positions from porpoises in the smallest possible area), medium (31-60%) and low (61- 90%). The number of porpoises and positions per analysis: 1997-2006, summer: 39 animals/1958 pos., 1997-2006, winter: 18 animals/765 pos., 2007-2016, summer: 43 animals/1540 pos., 2007-2016, winter: 33 animals/1076 pos. The approximate position of Kattegatt Syd OWF is encircled in red. Figure and figure text from Sveegaard et al. 2018.



In 2005 and 2012 acoustic surveys with a towed array was conducted to map the distribution of harbour porpoises in inner Danish Waters as part of SCANS II (Teilmann, et al. 2008). In 2007, an acoustic survey was conducted every second month to map the distribution of harbour porpoises across the year in inner Danish waters (Sveegaard, et al. 2011) (**Figure 1.4**). Since the appointment of 16 Danish Natura 2000 sites for harbour porpoises in 2010, six of these areas have since 2012 been surveyed by means of passive acoustic monitoring as part of the NOVANA program (Hansen 2018; Hansen and Høgslund 2019). In the light of increased bycatch near Store Middelgrund, just south of Kattegatt Syd OWF a special study was conducted from February 2016 to January 2017 to examine when and where porpoises were present near Store Middelgrund. Much of this information was summarised and analysed in Sveegaard, et al. (2018b), which led to an update of the MaxEnt habitat suitability model of preferred habitat for porpoises (**Figure 1.5**).

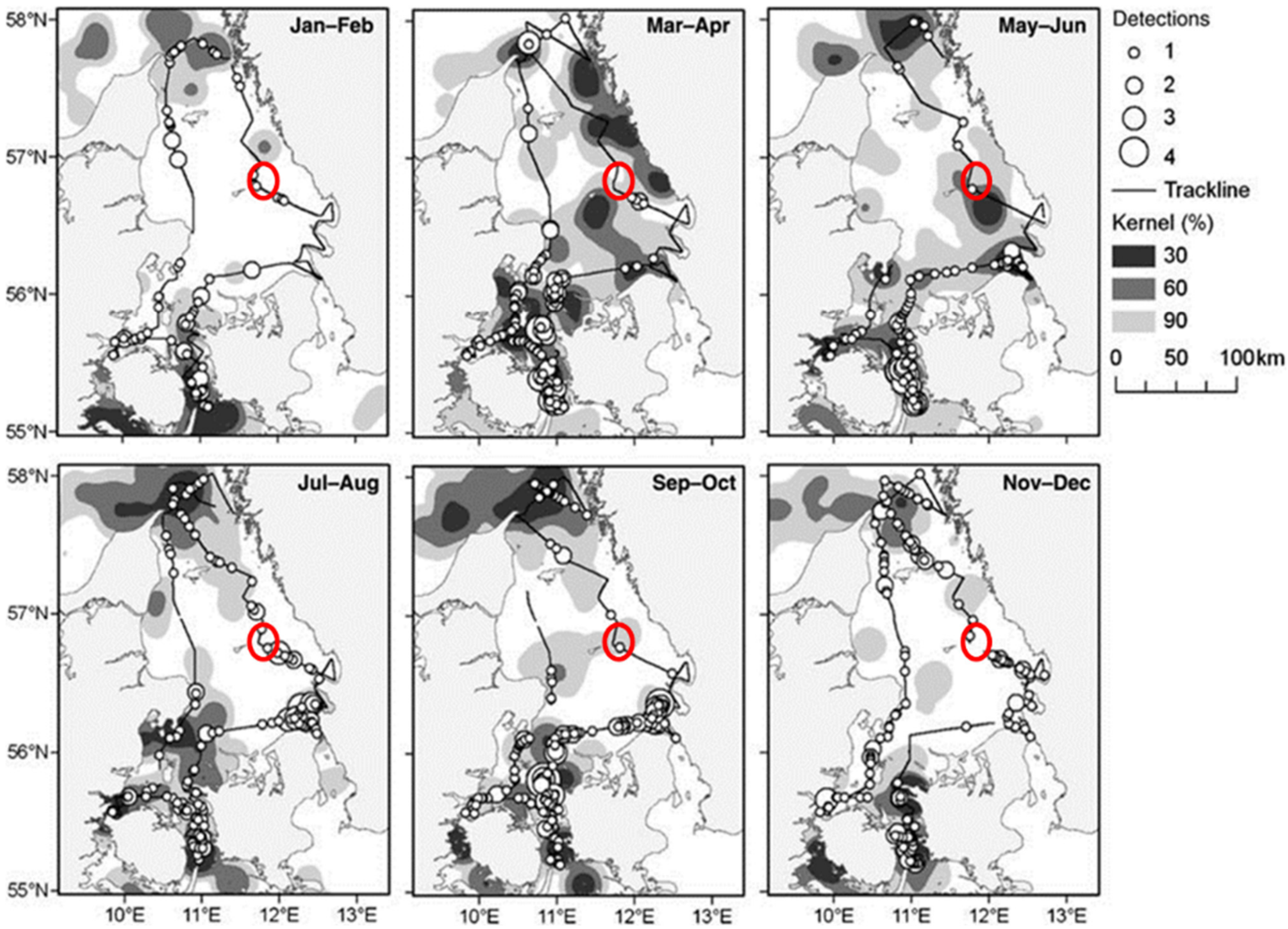


Figure 1.4. The distribution of detections of harbour porpoises (white dots) during six acoustic ship surveys conducted in 2007. The size of the dots corresponds to the number of detections per kilometre. The survey track line is shown in black. The underlying kernel-density, percentage-volume contours were generated from 64 satellite-tracked porpoises during the years 1997–2007; high-density areas (30%) are shown in dark grey and the lower densities (60 and 90%) in increasingly lighter grey. The approximate location of Kattegatt Syd OWF is encircled in red. Notice that the most important periods is Mar-Apr, May-Jun and Jul-Aug. The map projection is universal transverse Mercator, Zone 32N, WGS84. Figure and text from Sveegaard et al. 2011.

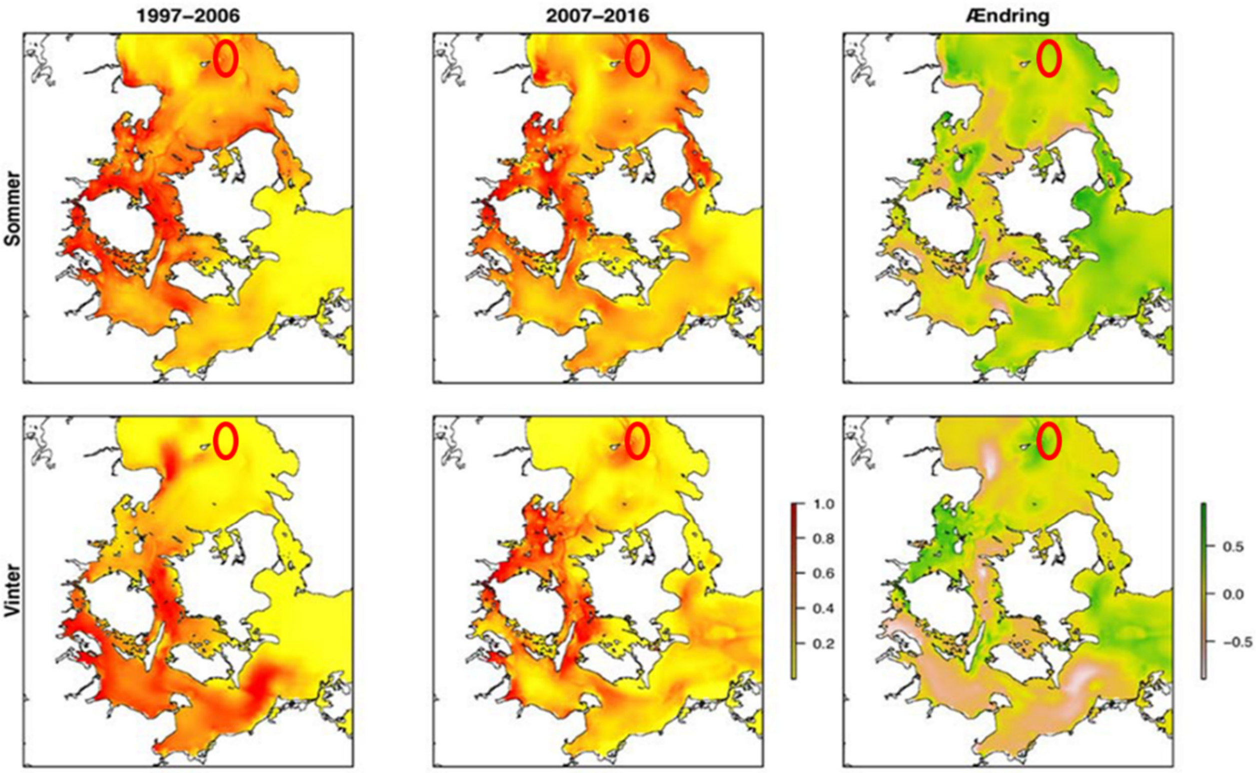
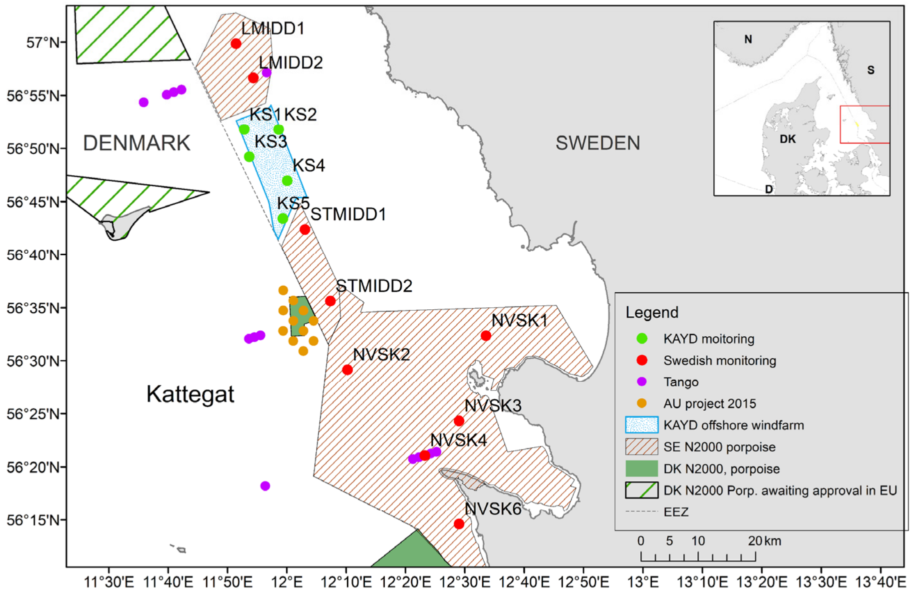


Figure 1.5. Suitable harbour porpoise habitats in the Belt Sea management area modelled with MaxEnt model for two 10-yr periods; summer and winter. Red signifies most suitable habitat. The right panel shows changes from the first to the second period, where green signifies the areas that have become relatively more important during the last decade. Generally, the eastern part of the area, Kattegat and Samsø Belt have become more important. However, this does not imply that the other areas have lost their importance to harbour porpoises. The model is built on data from satellite tracked animals, along with a suite of environmental co-variables. The approximate location of Kattegatt Syd OWF is encircled in red. Figure and text from Sveegaard, et al. (2018b).

In Sweden, passive acoustic monitoring of harbour porpoises in appointed Natura 2000 sites (**Figure 1.6**) began in spring 2019. There are four stations relevant for Kattegatt Syd; two stations are located in the Swedish Stora Middelgrund Natura 2000 site and two stations are located in the Lilla Middelgrund Natura 2000 site (**Figure 1.6**). These data are public domain and have been included below. In general, data from Denmark and Sweden points to the relevant areas in southern Kattegat being of relatively high density of harbour porpoises confirmed by both visual and acoustic surveys (Sveegaard, et al. 2011; Sveegaard, et al. 2018b)

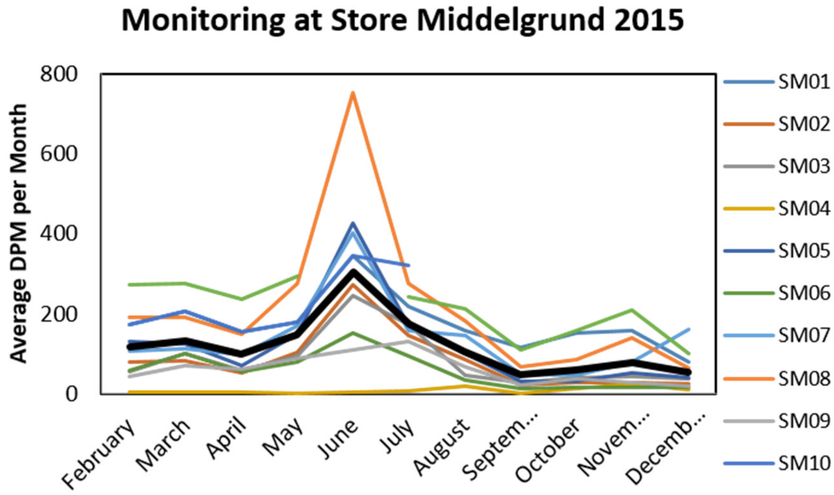
Figure 1.6. Map of present and previous PAM stations near the proposed Kattegatt Syd offshore wind farm. There are KAYD monitoring stations within the suggested offshore windfarm. These have been running since December 2020. Swedish monitoring stations at Lilla and Stora Middelgrund running since spring 2019, and TANGO stations running from 2019-2021 in a joint Danish/Swedish study. Eleven Danish PAM locations were active in 2015 (Sveegaard, et al. 2017).

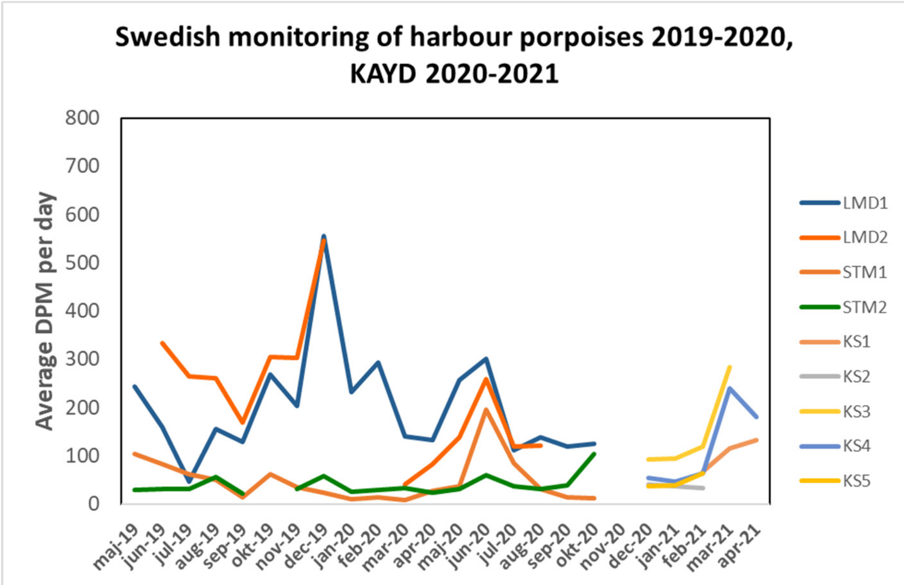


1.2.2 Yearly pattern in presence at Kattegatt Syd

Harbour porpoises move around throughout the year and their temporal presence and abundance is important to consider in relation to establishment of offshore wind farms. Porpoise calves are entirely dependent on their mother during their first approximately ten months of life, where they are nursed and slowly learn to forage independently (Lockyer 2003; Teilmann, et al. 2007). They are therefore vulnerable to disturbances that may lead to mother-calf separation during these months. In the inner Danish waters including Kattegat, porpoises give birth from April to October peaking in July, shown by necropsies of stranded and bycaught animals (Lockyer 2003). From dedicated porpoise surveys in 1987-89 (Kinze 1990), and 1994 (Hammond et al. 1995) it was shown that percentage of new-born calves increased from May (9.1 %) to June (6.9 - 10.6 %) and reached a peak in July (11.5 - 23.8 %) and August (18.2 - 23.5 %) (Kinze 1990). The period May-August should thus be considered the peak calving period for harbour porpoises in Kattegat. Calves of a few months of age follow their mother closely, and only when the mother dives to forage, is the calf left alone at the surface for short periods (Camphuysen and Kropp 2011). When the calf is about ten months old it still swims with its mother and have a correlated diurnal dive pattern, however it is not known if the dives themselves are synchronized (Teilmann et al. 2007). At eleven months of age the mother-calf dive pattern is less correlated, and it is likely around this time the calf now dives independently and eventually breaks away. Before this age, calves are unlikely to survive on their own. The period March-May is the period with the most bycatch in Kattegat, which is interpreted as the period where calves from the previous year begin to separate form their mother and, therefore are especially prone to bycatch. In fact yearlings are the most common age-class in bycatch from Kattegat (Berggren 1994). Harbour porpoises are assessed vulnerable to disturbances from underwater noise all year.

Figure 1.7. Average number of detection positive minutes per month for PAM stations near and in the Kattegatt Syd offshore wind farm area. Top: Danish data from a project conducted in 2015 at the Danish part of Store Middelgrund (SM). Bottom: KAYD (KS stations) monitoring data from the first period December 2020 to 11 April 2021 shown together with Swedish monitoring data collected in 2019-2020 at four monitoring stations located within the Swedish Natura 2000 sites Lilla Middelgrund (LMD stations) and Stora Middelgrund & Röda Bank (STM stations, see figure 1.6). The Swedish Stations have been monitored since Spring 2019. The KAYD (KS) stations have been monitored since December 2020. Unfortunately, KS1 did not work during the first deployment, KS2 was trawled during second deployment and KS3 and KS5 were trawled during both deployments and the averages presented here therefore do not cover full months. Kattegatt Syd data is collected by Aarhus University for Vattenfall Wind AB. Swedish monitoring data are made available from Havs- and Vattenmyndigheden. All available Swedish monitoring data were downloaded from www.Sharkweb.se.





There are five independent studies providing data on yearly presence of harbour porpoises near Kattegatt Syd OWF, which are described below. The data are not quantitatively comparable to each other, as data was collected and quantified differently. Nevertheless, the yearly peaks in presence are comparable and points to the area being most important for harbour porpoises during summer months. Data from the monitoring in the proposed Kattegatt Syd offshore windfarm site indicate that porpoises are there to the same extent during winter and spring as in the Stora Middelgrund & Röda Bank Natura 2000 site.

The five studies on presence of harbour porpoises in Kattegat are summarised here:

- In 2007 towed acoustic array data was collected close to Kattegatt Syd offshore wind farm site every second month (**Figure 1.4**) (Sveegaard, et al. 2011). The data showed several peaks in presence in the area: March-April, July-August and November-December.
- Aarhus University has equipped porpoises with satellite tags since 1997. Two periods of data was compared in **Figure 1.3** (Sveegaard et al. 2018) by

mapping positions as Kernel densities, i.e. densities of positions from the tagged porpoises: 1997-2006 & 2007-2017. The data from 2007-2016 show a peak in presence near the Kattegatt Syd Offshore Windfarm site during the summer period. The analysis behind the data presented in **Figure 1.5** was performed for a large area, and it is on this background not possible to zoom in on the Kattegatt Syd offshore wind farm site to resolve the detailed distribution of porpoises in this area.

- Aarhus University conducted a study at the Danish Natura 2000 site Store Middelgrund in 2016 with eleven PAM stations near and at Store Middelgrund, which showed a peak in presence in June at all stations (Figure 1.6 (Sveegaard, et al. 2017). Presence varied greatly over the year, but the variation was consistent among the eleven PAM stations, and the yearly pattern of presence therefore appears robust for the area in that year. Porpoise presence in terms of PAM data was also modelled against a suit of environmental variables. Model examples of four different months are shown in **Figure 1.8**. The modelling therefore also showed that the area was most important in the summer months May-July, peaking in June (Sveegaard, et al. 2017).
- Sweden has conducted monitoring within the nearby Swedish Stora Middelgrund and Röda Bank and Lilla Middelgrund Natura 2000 sites since spring 2019 (Figure 1.6). There is a small peak in presence during June-July at the two stations at Stora Middelgrund and a larger peak during winter at the two stations at Lilla Middelgrund. The data was analysed in the exact same fashion and all dataloggers had been recently calibrated.
- The monitoring study by Vattenfall provides the first data form the offshore wind farm site itself. The data are collected and analysed with the exact same methodology as the Swedish monitoring data is, and the data are directly comparable. Data is collected at five stations (Figure 1.5) and is included in Figure 1.6 and **Figure 1.9**. Each station is equipped with a large surface buoy with light and the positions were approved by the Swedish authorities before deployment. Despite hereof, two of the five stations had been trawled away at the first service round in February 2021, and a third had been trawled away during the second deployment. Luckily, though, the dataloggers were later retrieved when people found them washed ashore. The data shows that the Kattegatt Syd offshore windfarm area do have porpoises, however at low levels during December-January, at levels comparable to the Swedish monitoring sites at Lilla Middelgrund. Station KS2 and KS3 had the most detections and at higher levels than Lilla Middelgrund during March-April (Figure 1.6).
- Looking at data from all monitoring stations in Kattegat from Spring 2019 and onwards (**Figure 1.9**), Lilla Middelgrund had the most detections in winter 2019-20, and it appears that there is variation in presence throughout the year at all monitored stations, as well as across years.

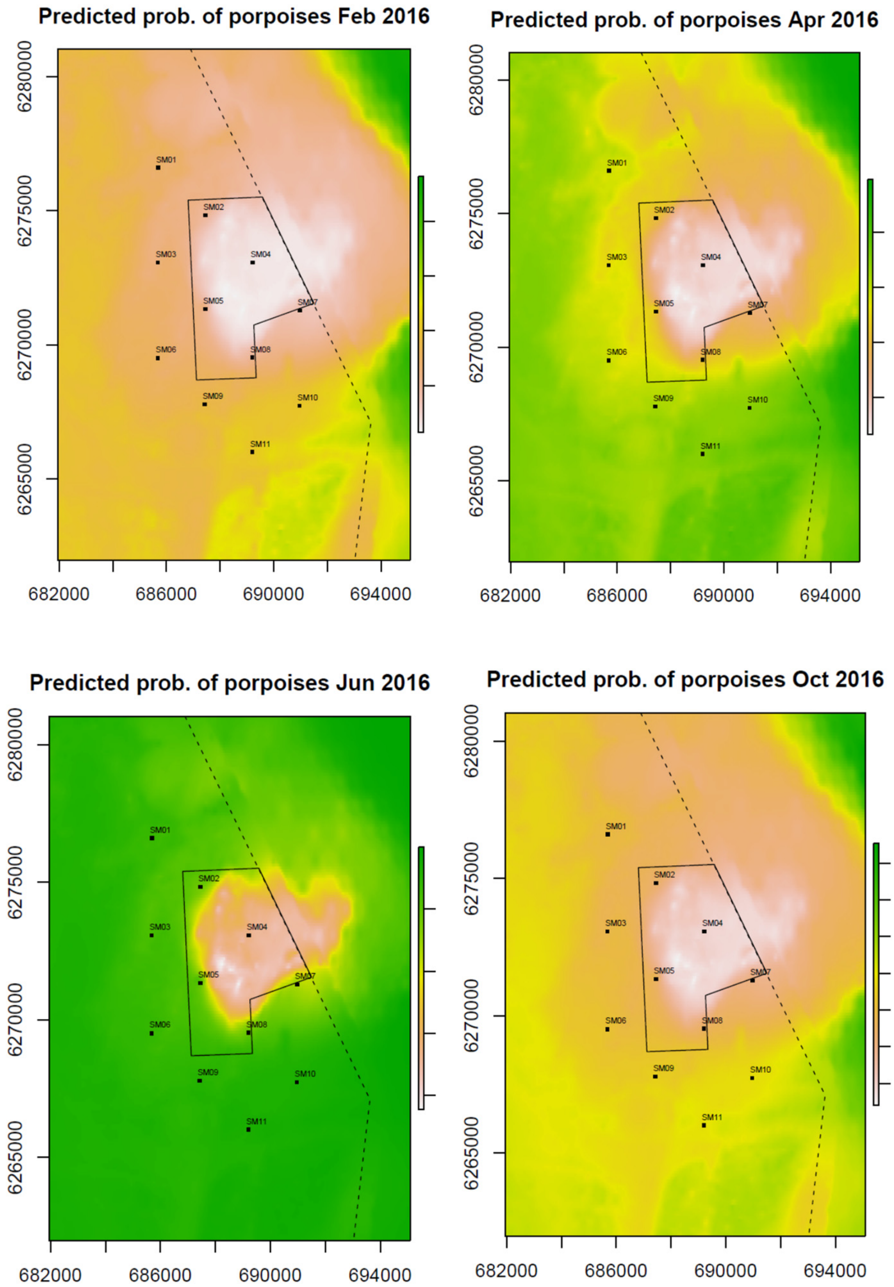
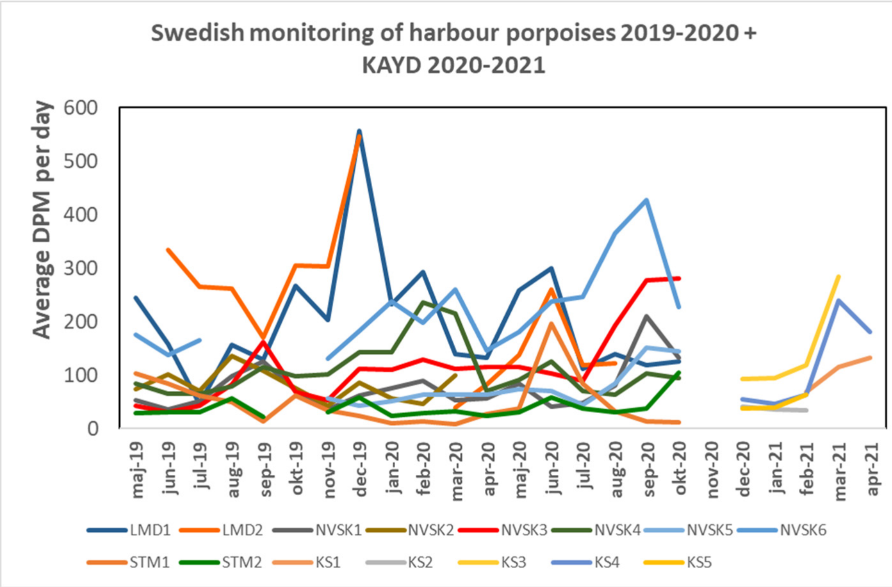


Figure 1.8. Results of a local habitat suitability model for harbour porpoises at the Danish Natura 2000 site Store Middelgrund during four different months. Green is highest probability of porpoise presence and white is lowest. June is the month with highest probability of presence over the study year 2016. The model included PAM data and a number of environmental variabilities. From Sveegaard, et al. (2017).

1.2.1 Conclusion on seasonality

Three independent studies show that the Kattegatt Syd offshore Wind farm site may be important for harbour porpoises during spring, however there are no data available yet for the summer and autumn yet. Passive acoustic monitoring data provides the best data for annual variance, however, the data available from the Swedish monitoring covers only one full year, and it remains to be seen whether there is a pattern in yearly presence at Stora and Lilla Middelgrund. The Vattenfall monitoring study at Kattegatt Syd will be compared to the Swedish monitoring study to assess the importance of the offshore wind farm site across the year, when a full years' data is available. With the present data it appears that the offshore wind farm site is important for porpoises in March-April.

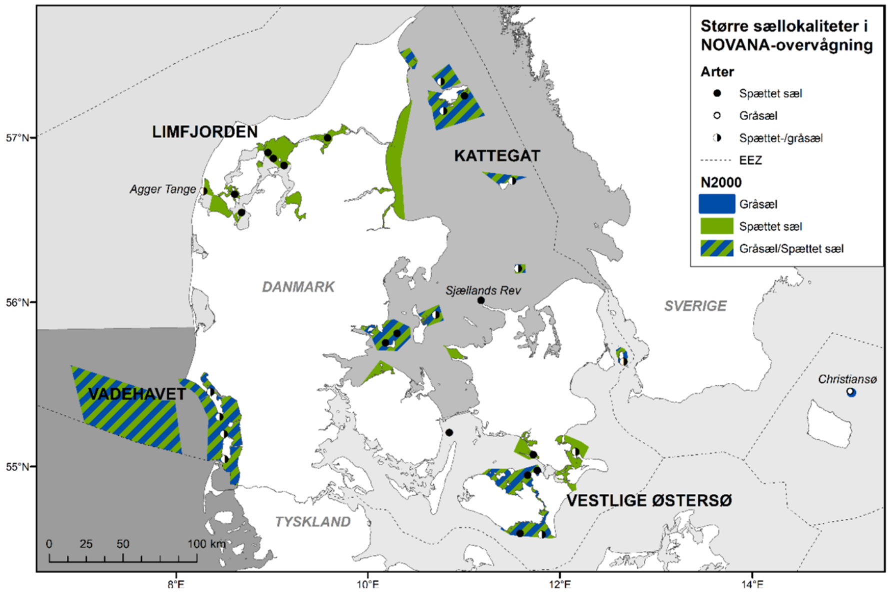
Figure 1.9. Mean number of Detection Positive Minutes per day at all monitoring stations in the vicinity of the Kattegatt Syd offshore wind farm site. Swedish monitoring in North West Skåne (NVSK), Lilla Middelgrund (LMD) and Stora Middelgrund (STM) began in spring 2019. Kattegatt Syd (KS) monitoring began in December 2020. See station positions in figure 1.6. Data made available from Havs- and Vattenmyndigheden and from the Vattenfall monitoring study at the Kattegatt Syd offshore Windfarm site. All available Swedish monitoring data downloaded from Sharkweb.



1.3 Harbour seals (*Phoca vitulina*, L. 1758)

The harbour seal is the most common seal species in Kattegat. It does not appear on the Swedish Red List of 2020 (SLU Artdatabanken 2020), which mean that it is Least Concern. It appears on the Danish red list where it is also Least Concern (Moeslund, et al. 2019). It is listed in annex II and V of the Habitats Directive (92/43/EEC), annex II of the Bern convention (19th September 1979), annex II of the Bonn convention and annex II of the Convention on the international Trade in Endangered Species (CITES). Seal hunting, however, is allowed in Sweden with permission from the Swedish Environmental Protection Agency (Naturvårdsverket). Hunting has been abandoned in Denmark since 1976 (Jepsen 2005), however a limited number of licences for regulation due to conflicts with fisheries are given annually. Special areas of conservation have been appointed for the protection of the harbour seal in Sweden and Denmark (**Figure 1.10**). Several important Danish haul-out sites, also outside Natura 2000 sites, are further protected from any disturbance (some only during the breeding and moulting seasons) as national wildlife and seal reserves.

The harbour seals in Danish Waters are divided in four different populations/management units: Wadden Sea, Limfjord, Kattegat and Western Baltic, based on genetic studies and satellite tracking (Tougaard, et al. 2008; Dietz, et al. 2012; Olsen, et al. 2014; Dietz, et al. 2015). The population in Kattegat, to which the seals at Kattegatt Syd offshore windfarm site belong, is shared with Sweden. In 2019 it was estimated to consist of 17353 individuals in Kattegat and the Danish Straits. This estimate is from the ICES working group on marine mammal ecology (WGMME) (ICES 2020), when multiplied by 1.75 which is appropriate (Anders Galatius pers. comm.).



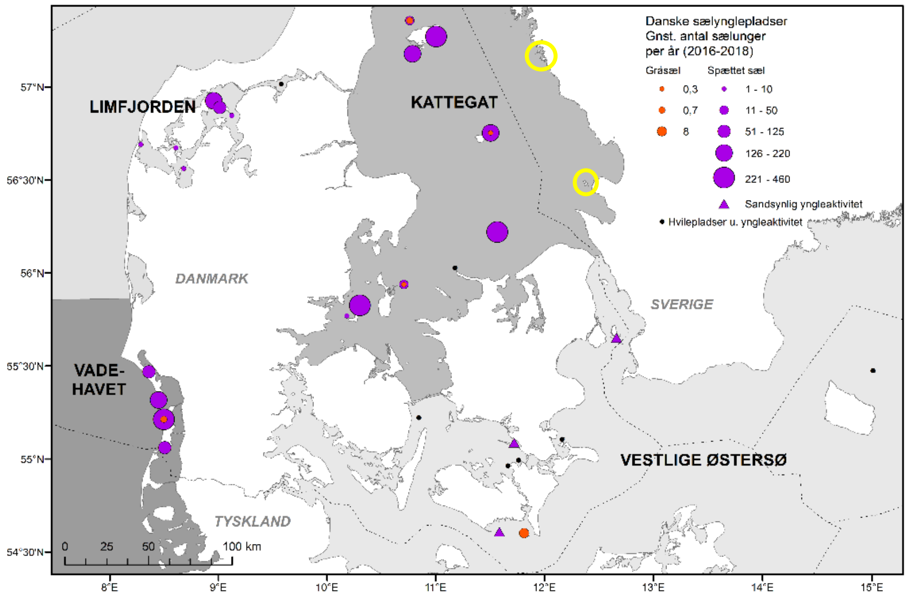
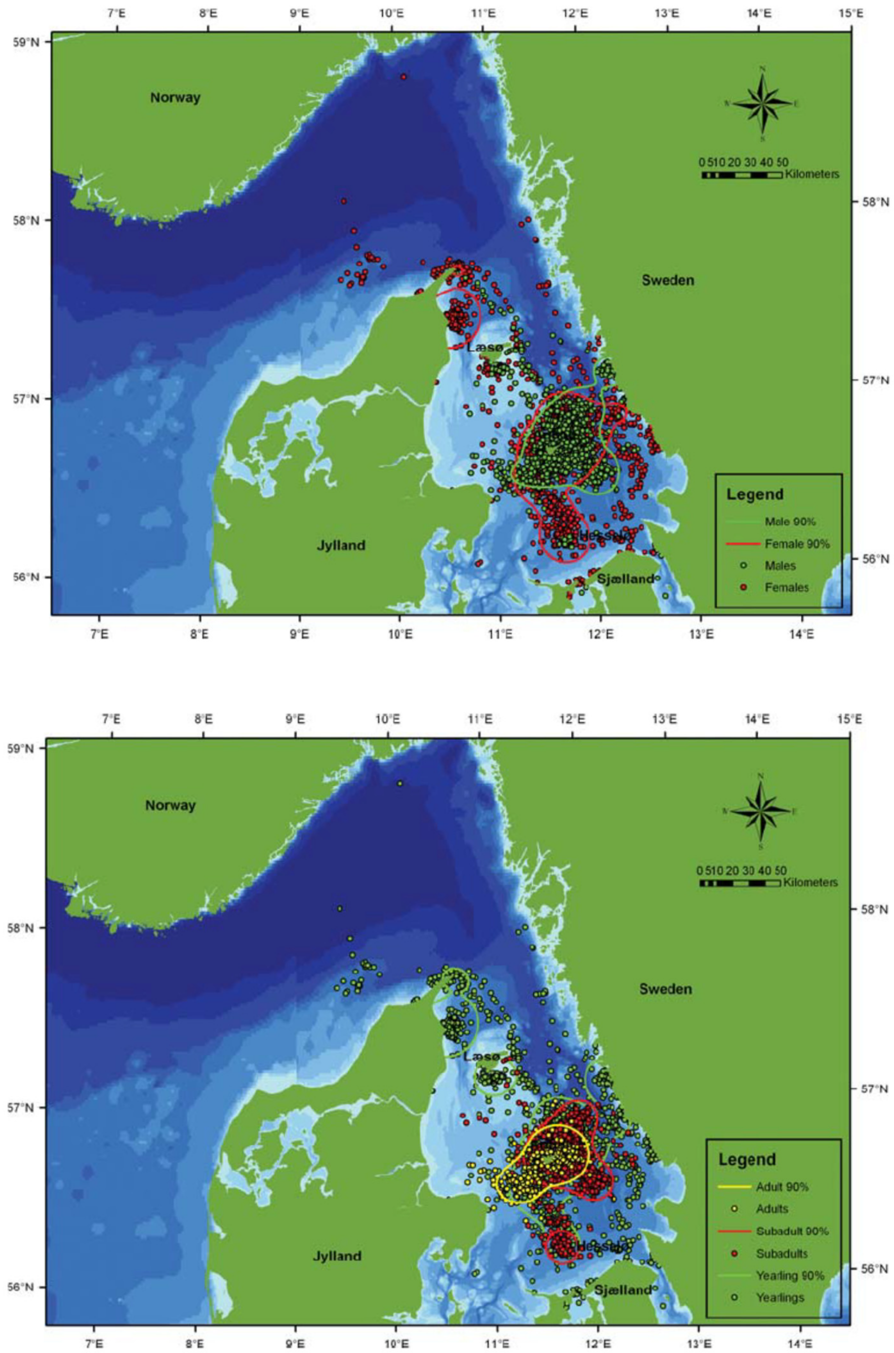


Figure 1.10. Top: Map of Natura 2000 sites appointed for harbour and grey seals. The grey colours signify the four management areas for harbour seals. Bottom: Map of breeding sites in Danish Waters. Number of pups (average over three years, 2016-2018) is shown as purple circles. There are two relevant breeding sites in Western Sweden: Varberg and Hallands Väderö (shown with yellow circles on map). Very few grey seal pups are born in Kattegat (red circles). Maps courtesy of Signe Sveegaard.

1.3.1 Distribution

Harbour seals at Anholt has been tagged with Argos satellite transmitters in 2005, 2006 and 2008 (Dietz, et al. 2012) and in 2014 (not published). The data showed that harbour seals use the area at Kattegatt Syd offshore Windfarm site (**Figure 1.11**). These data were later used to build a habitat suitability model based on environmental variables and location and size of haul-out sites (please see methodology at https://niva.brage.unit.no/niva-xmlui/handle/11250/2678968). The output of the model is shown in **Figure 1.12** below. High suitability means high likelihood of encountering seals, if the seal population is close to carrying capacity. The drawback of the model is that it is based almost entirely on yearlings and sub adult seals, which means that it may not be truly representative for adult seals. From the data itself (Dietz, et al. 2012 and 2014 (not published)), however, it appears very likely that harbour seals spent significant time in / near the Kattegatt Syd offshore windfarm site (**Figure 1.11**).

Figure 1.11. 90 % kernel home ranges for top: 27 female and male harbor seals tagged at Anholt in September 2005 and 2006 and in April 2008. Bottom: Same data divided to age class; 17 yearlings, 8 subadults and 2 adults. Copied from Dietz et al. 2013.



1.3.2 Yearly pattern in presence in southern Kattegat

The tagging data from Anholt was collected in April and September and the tags were transmitting between 42 and 268 days per seal. Due to the seals moulting their fur in the summer months, it is not possible to attach transmitters in this period and no data on habitat use is therefore available for the entire summer. The information about distribution of harbour seals is not extensive and assessments relying on fine-scale patterns in the distribution maps must be interpreted with caution, especially when interpreting modelling results. This applies even more to the temporal trends in abundance, where the important breeding period in summer is largely absent from the data.

1.3.3 Conclusion on seasonal presence and vulnerability

There is too little data and from too few adult harbour seals to judge the temporal importance of the Kattegatt Syd offshore windfarm site. Harbour seals are most vulnerable when they give birth, nurse their pup and moult at their haul-out. Since there are no haul-outs in or close to the prospective offshore windfarm site, harbour seals are considered equally vulnerable to disturbnces from underwater noise throughout the year.

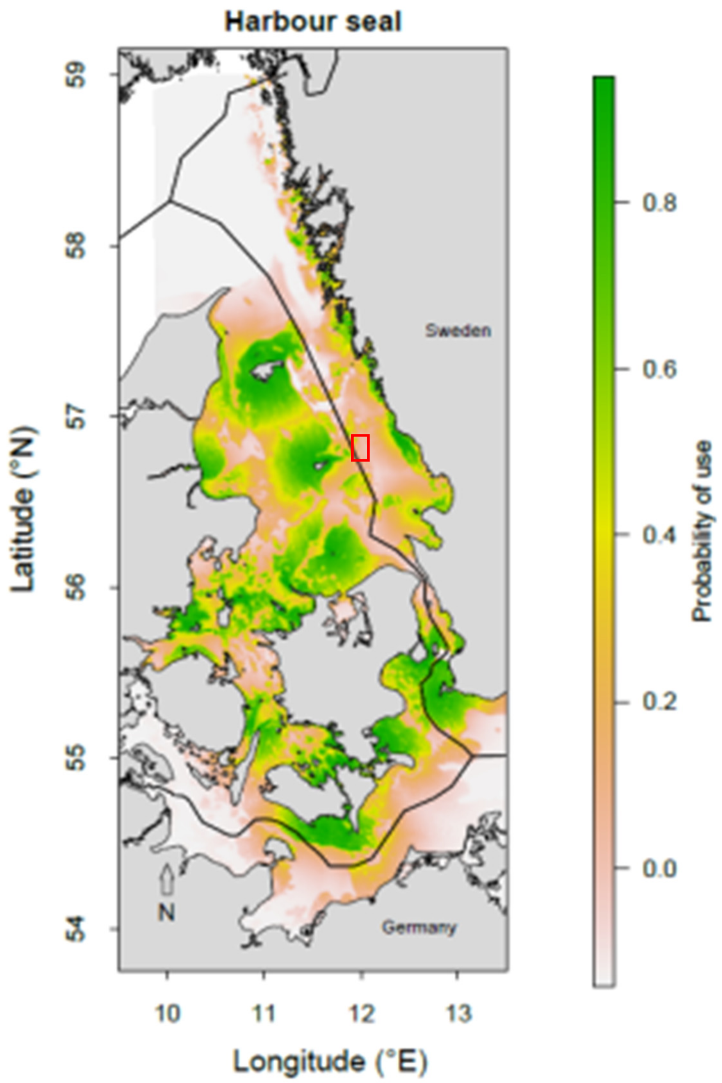


Figure 1.12. Habitat suitability for harbour seals modelled from satellite tracked harbour seals tagged at Anholt (Dietz, et al. 2012) and Rødsand. High suitability means high likelihood of encountering seals when the seal population is healthy. Modelling performed by Floris van Beest (AU). Method described here: https://niva.brage.unit.no/niva-xmlui/handle/11250/2678968).

1.4 Grey seal *Halichoerus grypus* (Fabricius, 1791)

The grey seal was exterminated from Kattegat in the beginning of the 20th century by hunting. The population is now increasing, but consist mostly of visiting seals from the large populations in the Baltic Sea and North Sea. A very small number of grey seal pups are born in Kattegat: Since surveillance began in 2011 only six grey seal pups were born at Borfeld near Læsø, three at Anholt and one at Bosserne near Samsø, all in Danish waters.

The grey seal population is listed as Vulnerable in the 2020 Danish Red List. The Swedish Red List 2020 considers only the Baltic population, which is listed as Least Concern (SLU Artdatabanken 2020). In the Swedish Red List it is described that the population is increasing and sometimes grey seals are observed along the West coast of Sweden. The grey seal is listed in annex II and V of the Habitats Directive (92/43/EEC), annex II of the Bern convention (19th September 1979), annex II of the Bonn convention and annex II of the Convention on the international Trade in Endangered Species (CITES). Grey seal hunting is allowed in Sweden with permission from the Swedish Environmental Protection Agency (Naturvårdsverket) and several hundred grey seals are shoot per year in the Baltic proper. Hunting was abolished in Denmark in 1967 and Denmark amended HELCOMS recommendation (9th January 1988) to ban seal hunting throughout the Baltic Sea, although dispensation is given to shoot grey seals that cause problems in the fisheries. From 2020 up to app. 45 grey seals may be shot per year in Denmark, mainly near Bornholm, but few are also shot around Zealand. Special areas of conservation have been appointed for the protection of the grey seal in Sweden and Denmark. As for harbour seals, a number of grey seal haul-out sites are further protected as national wildlife or seal reserves.

1.4.1 Distribution

No data exist on grey seal distribution in Kattegat, except for presence at the haul-out sites. In the Swedish part of Kattegat, a maximum of app. 20 grey seals has been observed during harbour seal counts in August (Anders Galatius, Pers. comm.). In the Danish part of Kattegat, the population is increasing (from very low numbers) and in 2018, 79 grey seals were observed in the Danish part of Kattegat. In the period 2010-2017 up to 127 grey seals were observed on a single day at Borfeld, Læsø, the most important haul-out site for grey seals in Kattegat (Hansen and Høgslund 2019).

1.4.2 Yearly pattern in presence in southern Kattegat

There is not enough data to evaluate the importance of the Kattegatt Syd offshore windfarm site for grey seals across the year.

1.4.3 Conclusion on seasonal presence and vulnerability

There is too little data from grey seals to judge the temporal importance of the Kattegatt Syd offshore windfarm site. Grey seals are generally most vulnerable when they give birth, nurse their pup and moult at their haul-outs. Since there are no haul-outs in or near the prospective offshore windfarm site, grey seals are considered equally vulnerable to disturbances from underwater noise throughout the year.

1.5 Other marine mammal species

Fin whale, humpback whale, minke whale, killer whale, white-beaked dolphin, common dolphin, striped dolphin, and bottlenose dolphin are on rare occasions observed in Kattegat (Kinze, et al. 2018). The species are all listed in appendix II of the Habitats Directive. However, their occurrence is sporadic and irregular and no general patterns in abundance can be given. The likelihood that these species will be encountered during construction of the wind farm is very low and even if they should occur by chance, the mitigation measures taken to protect harbour porpoises are considered to provide appropriate protection for these species as well.

1.6 Protected areas in eastern Kattegat

Because harbour porpoises are listed in annex II of the habitats directive, areas of special importance to porpoises must be designated as protected ‘habitat areas’, as part of the Natura 2000 network. Sweden has appointed numerous Natura 2000 sites for harbour porpoises, harbour seals and grey seals (**Figure 1.1** and **Table 1.1**) relevant for the Kattegatt Syd offshore windfarm site. To the north of the Kattegatt Syd offshore Windfarm site are Lille Middelgrund (SE0510126) and Fladen (SE0510127) N2000 sites. To the south Stora Middelgrund and Röda Bank (SE0510186) and the Northwestern Marine Area of Skåne (Nordvästra Skånes havsområde, SE0420360).

Within Danish Waters, the closest Natura 2000 site appointed for harbour porpoises is at Store Middelgrund (#169) and to the south Gilleleje Flak and the Sound (# 171). Two new Natura 2000 sites have been appointed nearby, “Anholt and the sea north hereof” to the north and “Kims top and the Chinese Wall” further north (see figure 1.2), but these are awaiting approval by the EU. There are protected areas for seals around Anholt (No. 193, **Figure 1.10**).

The suggested Kattegatt Syd offshore windfarm site is placed on relatively even seabed with 30-40 m of waters, between the Swedish Natura 2000 sites Lilla Middelgrund and Stora Middelgrund and Röda Bank I a north-south direction and between two majo shipping routes Tango and Sierra in an east-west direction. The bottom is covered for the largest part with sediment classified as ‘mud to muddy sand’. In the northern part there is a smaller area covered with mixed sediment fringed by sand sediment.

Table 1.1. List of Natura 2000 sites relevant for the Swedish and Danish Waters in Kattegat. Notice that the area “Anholt and sea to the north” is not yet confirmed by the EU for harbour porpoises

Natura 2000 area	Distance to wind farm area	Designating species
Stora Middelgrund och Röda Bank	1 km	Harbour porpoise
Lilla Middelgrund	1 km	Harbour porpoise
Anholt and sea to the north (DK)	9 km	Harbour porpoise, harbour seal
Store Middelgrund (DK)	10 km	Harbour porpoise
Nordvästra Skånes havsområde	14 km	Harbour porpoise, grey and harbour seals
Kims Top and the Chinese Wall	14 km	Harbour porpoises
Balgö	24 km	Harbour porpoise grey and harbour seals
Fladen	25 km	Harbour porpoise

2 Primer on underwater acoustics

It is beyond the scope of this report to give a full introduction to underwater acoustics and the impact of noise on marine mammals. However, some fundamental background is required to understand the modelling and assessment performed, which is given below.

2.1 Sound fields and units

Underwater acoustics differ from aerial acoustics in a number of important ways. The much higher density of water means that the speed of sound is higher (about 1500 m / s vs. about 340 m / s in air), which also means that the wavelength is about five times larger in water compared to air. However, more important is that the dissipative loss experienced as the sound waves propagate through water is much smaller in water than in air. Therefore, whereas even very loud sounds in air are rarely audible beyond a few kilometres from the source, underwater sound may be detectable hundreds or even thousands of km from the source, in particular for the low frequencies and in deep oceans. Even in shallow waters, the noise from pile driving is readily detectable above ambient noise beyond distances of 100 km from the pile driving (Bailey, et al. 2010; Bellmann, et al. 2020).

A second consequence of the high density of water is that any air to water interface, such as the sea surface, or air bubbles in the water will reflect the sound almost completely, whereas underwater sound pass almost unattenuated through most biological tissue, as the density of this is almost equal to that of water.

A third consequence of the high density of water is that because water is almost incompressible it is easier to create high pressures in water than in air. In air, a larger fraction of the acoustic energy relates to the periodic movement of the medium (the so-called particle motion) than to the generation of pressure. Two signals of the same acoustic energy, one in air and the other in water, will differ dramatically with respect to associated pressure and particle motion. In air, the particle motion will be much higher than in water, and the pressure will be much smaller. For these reasons, it is difficult to compare measures of signal magnitude in air and water (i.e. to determine which of the two is the loudest), as one has to be very specific as to what is compared: energy, pressure or particle motion. This error, where incomparable measures from air and mater are mixed is likely to be the most common error relating to assessment of the impact of underwater noise on marine mammals.

2.2 Sound pressure and energy

Sound is pressure fluctuations and can be characterised by the time-varying deviation from the ambient pressure, p(t) (see **Figure 2.1**), These pressure deviations are measured in Pascal (Pa). Often, this is converted into a sound pressure level on the logarithmic dB-scale:

Equation 2.1

$$L = 20 \log_{10}(\frac{p}{p_0})$$

Where p_0 is the reference pressure, by convention 1 µPa for underwater sound. The unit of sound pressure level is ths dB re. 1 µPa (read dB relative to 1 microPascal).

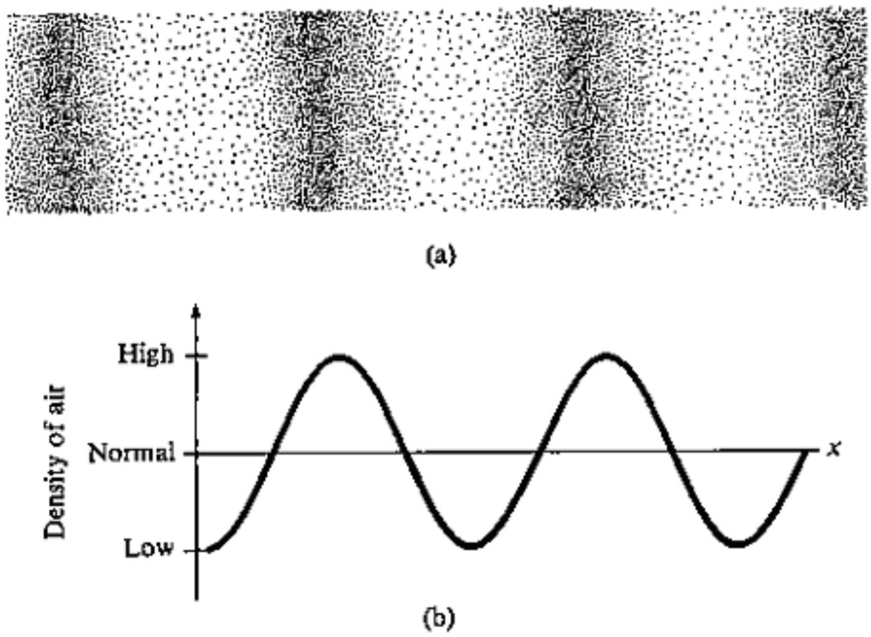


Figure 2.1. Illustration of the air density in a propagating sound wave The line marked 'normal' corresponds to the ambient (barometric) pressure of the surrounding air or water.

Because of the difference in density of air and water, as described above, the pressures generated by applying the same acoustic energy to water is much higher than in air. This means, that dB values for underwater sounds tend to be considerably larger than what one is accustomed to in air, which can give the false impression of immensely high noise levels. In general, dB values for sound measured in water cannot be compared to dB values on the well-known scale for sound in air. Instead, the sound pressure levels of underwater sounds should only be compared to other underwater sounds. Some reference points for comparison are given in Table 2.1.

Table 2.1. Typical sound pressure levels of various biological and man-made sources.

	Source level at 1 meters distance
Explosion of 100 g TNT	275 dB re. 1 µPa
Echolocation click of sperm whale	235 dB re. 1 µPa
Commercial echosounder	220 dB re. 1 µPa
Echolocation click of harbour porpoise	190 dB re. 1 µPa
Blue whale call	180 dB re. 1 µPa
Harbour seal mating call	145 dB re. 1 µPa
Natural background noise in shallow waters on a calm day	100 dB re. 1 µPa

The energy, E, of a sound of duration, τ, is measured in Joule / m^2 and can be computed from the pressure signal as[1]:

[1] Strictly speaking, this equation is only valid for a plane, propagating sound wave, i.e. not too close to the source and not in a confined space. It is a good approximation as long as one is more than several times the wavelength away from the source and in water deeper than a few times the wavelength.

Equation 2.2

$$E = \frac{\int_0^\tau p(t)^2 dt}{\rho c}$$

Where ρc, known as the acoustic impedance, is the product of the density of water, ρ, and the sound speed, c. More commonly used in relation to impact assessments, however, is the sound exposure level (SEL), expressed in dB as:

Equation 2.3

$$SEL = L_{E,p} = 10 \log \int_0^\tau \frac{p^2(t)}{p_0^2} dt$$

Where p(t) is the instantaneous pressure at time t of a signal of duration τ and p_0 is the reference pressure (1 µPa, in water). The unit of SEL is thus dB re. 1µPa²s. By use of this reference, the acoustic impedance of **Equation 2.2** cancels out in the calculations, and can be conveniently ignored. It is possible to show that this unit is indeed a unit of energy, being proportional to J/m² by means of a constant depending on the acoustic impedance of water.

Note that the units of sound pressure level (dB re. 1 µPa) and sound exposure level (dB re. 1 µPa²s) are different, as they express two entirely different physical properties (pressure vs. energy). Thus, they cannot be compared. Note also that other references may occur in the literature as well. Comparison of non-comparable dB-values is likely to be the second-most important source of errors in assessment of underwater noise (comparison between air and water being the first, cf. above).

2.3 Frequency spectra

The distribution of energy in a sound signal across frequencies can be analysed and displayed in different ways. A very common and useful way to display the frequency distribution is by the power density spectrum, which is the amplitude spectrum of the Fourier transformed time signal (see for example Bloomfield 1976). Short signals can be transformed directly, whereas longer signals must be cut into smaller parts and averaged after transformation (by what is referred to as a Welch average, Welch 1967). The power density spectrum is usually normalised to 1 Hz analysis bandwidth, which gives the y-axis a unit of dB re. 1 µPa²/Hz.

A common alternative to the power density spectrum, where analysis band is constant, is to use analysis bands where the ratio of bandwidth to centre frequency is constant (so-called constant-Q filter bank). Commonly used filter bandwidth are 1/3 octave and 1/1 octave. It is beyond the point of this report to go in details about pros and cons of the different frequency spectra. The only important point in this context is to note that spectra calculated with different methods cannot be compared directly, but must be properly transformed to adjust for the different analysis bandwidths. Converting a 1/3-octave band level to spectrum density level can be done by the following relation:

Equation 2.4

$$L_{1Hz} = L_{\frac{1}{3}octave} - 10 \log_{10}(0.23 f_c)$$

Where f_c is the centre frequency of the 1/3-octave band, $L_{1/3octave}$.

In a similar way, the levels of a 1/1-octave band spectrum can be converted to spectrum density levels by:

Equation 2.5

$$L_{1Hz} = L_{1\,octave} - 10 \log_{10}(0.70 f_c)$$

2.4 Source level and transmission loss

In its most simple form, sound pressures decrease with increasing distance from the source. This is primarily due to two factors: geometrical spreading, where the initial acoustic energy is spread over an increasingly larger surface, as the sound propagates away in all directions from the source; and absorption, the gradual and inevitable loss of energy as heat as the sound moves through the water. In practice, a large number of additional factors influence the propagation of sound away from a sound source. This is the reason why one has to resort to more complex modelling tools, in order to predict sound levels away from the source, as has been done in section 7. In a generalized form, however, sound propagation can be understood from this simple equation:

Equation 2.6

$$\boldsymbol{RL}(\boldsymbol{r}) = \boldsymbol{SL}(\boldsymbol{1m}) - \boldsymbol{TL}(\boldsymbol{r})$$

Which states that the received level (RL) at some distance, r, from the source (measured in metres) equals the level at the reference distance 1 m (known as the source level, SL) minus the transmission loss TL, which is what is lost going from 1 m to distance r, for whatever reason. Often, it is not meaningful to think of the source level as an actual sound level, which can be measured 1 m from the source. This is certainly the case for pile driving. A monopile is clearly not a point source, but has a diameter and length well above 1 m. Thus, it does not make sense to speak about an actual source level 1 m from the monopile. The term *point source equivalent source level* is thus more appropriate and it should be understood as the back-calculated source level of an equivalent point source with the same far field characteristics as the monopile source. SL thus carries no information about actual sound levels near the monopile but can nevertheless be used to predict sound levels at distances of some hundred meters and beyond by means of appropriate transmission loss models. The source level is thus a fundamental input parameter to modelling of transmission loss.

2.5 Hearing in marine mammals

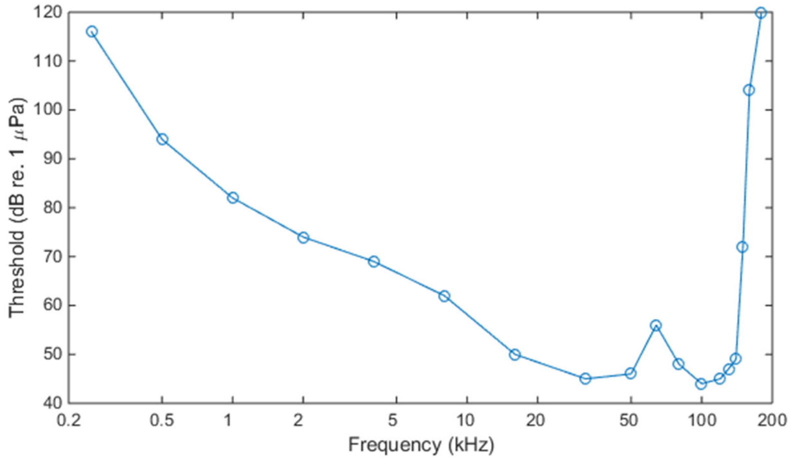
Marine mammals rely heavily on underwater hearing for orientation, prey capture and communication underwater. Consequently, they have very good underwater hearing and are sensitive to noise, as a disturbing factor and, if sufficiently loud, also by directly inflicting injury to the animals. The most fundamental description of hearing abilities of marine mammals is their audiograms, which express the hearing threshold at different frequencies.

2.5.1 Hearing in porpoises

Porpoises, like all toothed whales (Odontocetes), have good underwater hearing and use sound actively for orientation and prey capture (echolocation). Harbour porpoises produce short, ultrasonic clicks (130 kHz peak frequency, 50-100 µs duration (Møhl and Andersen 1973; Kyhn, et al. 2013); and are able to orient and find prey in complete darkness. Data from porpoises tagged with acoustic data loggers indicate that they use their echolocation almost continuously (Akamatsu, et al. 2007; Linnenschmidt, et al. 2013; Wisniewska, et al. 2016).

Harbour porpoise hearing is very sensitive and covers a broad frequency range (Figure 2 **2**). Best hearing is in the frequency range between about 10 kHz to around 160 kHz.

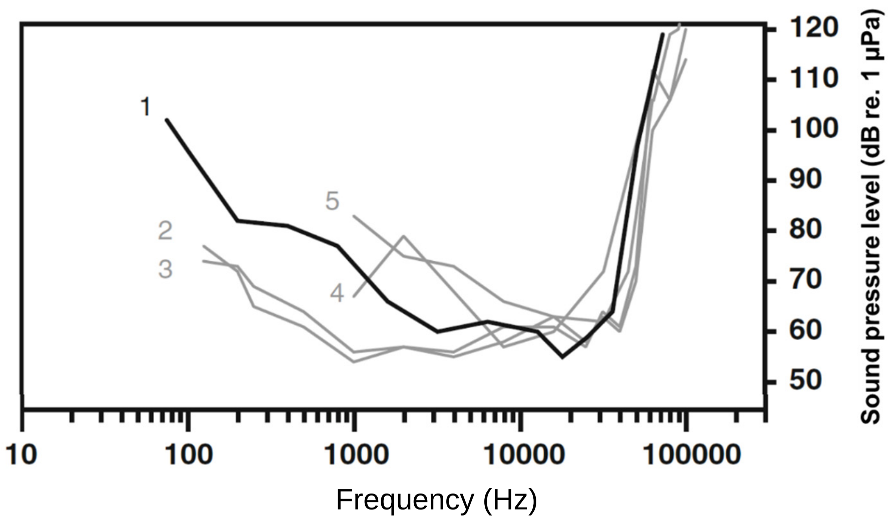
Figure 2 2. Audiogram for harbour porpoise, adapted from Kastelein, Hoek, de Jong, et al. (2010). The audiogram shows the hearing threshold, i.e. the minimum audible level as a function of frequency. Best sensitivity (lowest threshold) is in the range 10-160 kHz.



2.5.2 Hearing in seals

Seals have ears well adapted to an aquatic life. These adaptations include a cavernous tissue in the middle ear which allows for balancing the increased pressure on the eardrum when the animal dives (Møhl 1967) and a separate bone conduction pathway for sound transmission to the middle ear in water. The audiogram of harbour seals shows good underwater hearing in the range from a few hundred Hz to about 50 kHz (Figure 2 **3**). No audiogram is available for grey seals, but given their close taxonomic relationship and similar ear anatomy, it is a reasonable first assumption that their hearing is comparable to harbour seal hearing.

Figure 2 3. Audiograms for harbour seals. Numbers refer to different studies. 1: Reichmuth, et al. (2013), 2+3: Kastelein, et al. (2009), 4: Terhune (1988), and 5: Møhl (1968), From Reichmuth, et al. (2013).



3 Impact of underwater noise

Underwater noise can impact marine mammals in different ways. In assessments as the present, it is customary to separate effects into different types, which are treated separately. The first split is between damage (injury) caused by loud sound and effects on behaviour of animals. It is useful to subdivide damage into severe effects (acoustic trauma, tissue damage) and effects entirely on the auditory system (noise inflicted hearing loss). It is also useful to divide behavioural effects into behaviours elicited by the noise (startle, deterrence etc.) and interference with the perception of sound itself (masking). The mechanisms through which the different effects manifests themselves differ as well. This has important implications for how exposure to the noise should be evaluated and in particular on the metrics used for exposure limits, as discussed briefly below in section 3.1.

There are additional effects of long-term exposure to noise, well-known from humans and experimental studies on terrestrial animals, such as increase in stress hormone levels and cardiovascular responses. Such effects are very poorly studied in marine mammals and therefore it is not possible to include them in assessments. As these effects relate to chronic exposure to noise, they are, however, likely to be less relevant for temporary exposures such as pile driving.

3.1 Instantaneous intensity vs. accumulated dose

When discussing effects of noise it is important to make a distinction between the acute sound pressure level and the accumulated acoustic energy. A useful analogy comes from toxicology, where some substances are acutely toxic, in which case one is concerned only with the concentration of the toxin in the air breathed or food ingested. Other substances accumulate in the body, in which case the total dose accumulated over time becomes important. In acoustics, there are impacts, such as behavioural reactions, where the best predictor of a response is the instantaneous[2] sound pressure level, adequately frequency weighted (Tougaard, et al. 2015); whereas other impacts, most notably hearing threshold shifts (TTS and PTS), are better predicted by the accumulated (time-integrated) acoustic energy (Tougaard, et al. 2015; Southall, et al. 2019).

This difference in how effects are best predicted, either based on the acute exposure (sound pressure level) or by cumulated dose (sound exposure level), means that it is not possible to define a single threshold, which can cover all effects. It is possible to have long-term sound exposure at low levels, which creates little behavioural effects, but which induce hearing threshold shifts (Kastelein, et al. 2016) and equally possible to have short sounds, which induce behavioural reactions, but without any effects on hearing thresholds. The impact of pile driving on both behaviour and the risk of injury (hearing loss) must thus be treated separately.

[2] With instantaneous should be understood the sound pressure level averaged over a very short time, less than one second and equal to the temporal integration time of the mammalian ear.

3.2 Acoustic trauma

Very loud, impulsive sound (shock wave) is capable of inflicting direct damage to biological tissue (acoustic trauma). There is some uncertainty with respect to the physical entity responsible for the damage, i.e. whether a very large peak pressure (measured in Pascal) in itself is damaging, or whether it is the differential acceleration of tissues with different density, in which case the acoustic impulse (measured in Pascal· seconds) is the appropriate measure. There is limited information about blast injuries in marine mammals, but it is assumed that the sensitivity of smaller marine mammals, such as seals and porpoises, is comparable to the sensitivity of human divers, as the lung volume is believed to be a major factor determining vulnerability (Yelverton, et al. 1973). A recent review of blast injury on human divers (Lance, et al. 2015) indicate a 10 % risk of survivable injury at an exposure to 30 Pa· s, or a corresponding peak pressure of at least 226 dB re 1 µPa. Such high acoustic pressures are only encountered in connection to underwater explosions, not relevant for the offshore wind farm, or perhaps very close to the monopile (tens of meters) during unabated pile driving, which is not considered relevant in this assessment, as it is unlikely that any marine mammal will be this close at the onset of pile driving (see also section 3.8 on mitigation measures).

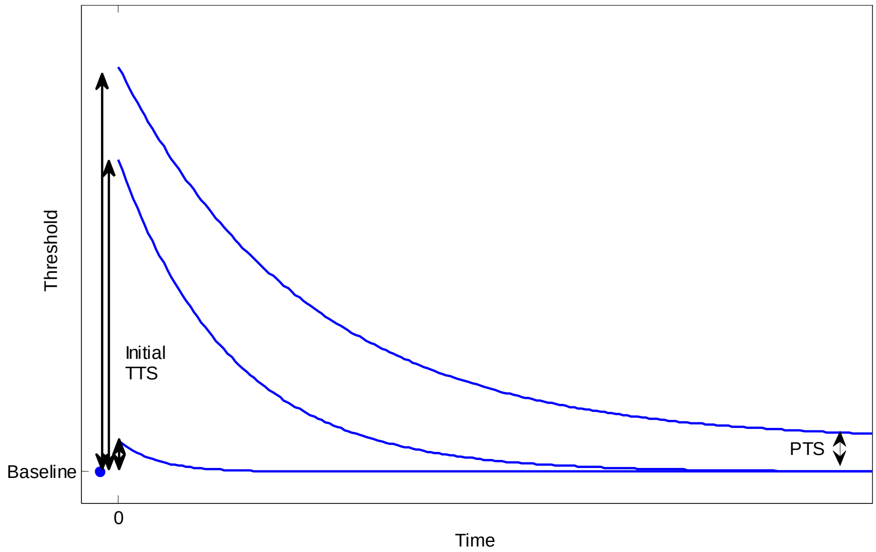
3.3 Noise induced hearing loss

The mammalian inner ear is adapted to be extremely sensitive to sound, and it is therefore a well-established assumption that injury from exposure to sound will manifest itself in the inner ear before any other tissue (Southall, et al. 2007). A precursor for actual injury to the auditory system is the so-called temporary threshold shift (TTS), which is the well-known temporary reduced hearing following exposure to loud sound (such as for example a rock concert or an explosion). TTS is also referred to as “auditory fatigue” and is believed to be related to metabolic changes in the hair cells of the inner ear and / or higher neural pathways (Ryan, et al. 2016). Recovery from small amounts of TTS is fast (minutes to hours) and complete, whereas large threshold shifts (40-50 dB) increases the risk that recovery is incomplete and therefore leaves the animal with a smaller, but permanent hearing loss (Permanent Threshold Shift, PTS).

A schematic illustration of the time course of TTS is shown in Figure 3.1. The amount of TTS immediately after end of the noise exposure is referred to as initial TTS. It expresses the amount by which the hearing threshold is elevated and is measured in dB. The larger the initial TTS, the longer the recovery period.

At higher levels of noise exposure, the hearing threshold does not recover fully, but leaves a smaller or larger amount of permanent threshold shift (PTS, see **Figure 3.1**). This permanent threshold shift is a result of damage to the sensory cells in the inner ear (Kujawa and Liberman 2009). An initial TTS of 40 dB or higher is generally considered to constitute a significantly increased risk of generating a PTS (reviewed in National Marine Fisheries Service 2016).

Figure 3.1. Schematic illustration of the time course in recovery of TTS. Zero on the time axis is the end of the noise. The threshold returns gradually to baseline level, except for very large amounts of initial TTS where a smaller, permanent shift (PTS) may persist. As the figure is schematic, there are no scales on the axes. Time axis is usually measured in hours to days, whereas the threshold shift is measured in tens of dB. From Skjellerup, et al. (2015)



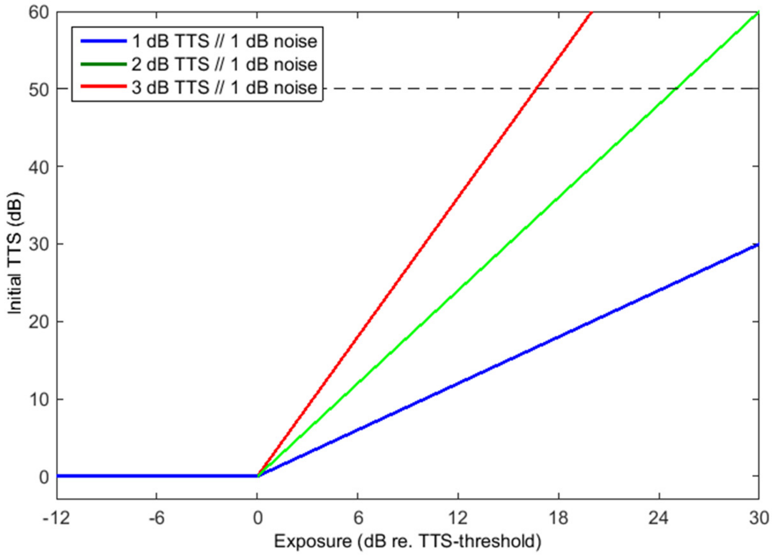
3.3.1 Relationship between TTS and PTS

Thresholds for inducing TTS and PTS are thus central for assessment of risk of auditory injury. Deriving such thresholds has been the subject of a large effort from many sides (see reviews by Southall, et al. 2007; Finneran 2015; Southall, et al. 2019). A comparatively large effort has gone into investigating TTS caused by low frequency noise, including that from pile driving, in small cetaceans, such as harbour porpoises, bottlenose dolphins and belugas (*Delphinapterus leucas*). TTS is in general localised to frequencies around and immediately above the frequency range of the noise inducing the TTS (often referred to as the fatiguing noise). This means that TTS induced by low frequency noise typically only affects the hearing at low frequencies (Kastelein, Gransier, Hoek, et al. 2013).

As PTS thresholds for ethical reasons cannot be measured by direct experiments, the agreed approach to estimate thresholds for PTS is by extrapolation from TTS thresholds to the noise exposure predicted to induce 40-50 dB of TTS and thus a significant risk of PTS. This extrapolation, however, is not trivial, as it is complicated by the fact that the relationship between exposure and amount of initial TTS is not proportional (see review by Finneran 2015). Thus, one dB of added noise above the threshold for inducing TTS can induce more than one dB of additional TTS (see **Figure 3.2**). Note how the choice of slope has a very large influence on the estimated threshold for PTS. In **Figure 3.2** the estimated PTS threshold is anywhere between 17 dB above the TTS threshold (red curve, 3 dB of TTS per added dB of noise) and 50 dB above the TTS threshold (blue curve, 1 dB of TTS per added dB of noise). The slope of the TTS growth-curve differs from experiment to experiment and slopes as high as 4 dB of TTS per dB of additional noise has been observed in a harbour porpoise (Lucke, et al. 2009).

Criteria for auditory injury for marine mammals are based on TTS because the required sound levels to induce TTS can be measured reliably in captive animals. From these measurements, it is customary to extrapolate to levels required to induce PTS. For porpoises and impulsive sound this is done by adding 15 dB to the level required to induce TTS, which is considered highly conservative and thus precautionary for the animals.

Figure 3.2. Schematic illustration of the growth of initial TTS with increasing noise exposure. Three different slopes are indicated. Note that the real curves are not necessarily linear. Broken line indicate threshold for inducing PTS, assumed in this figure to be at 50 dB initial TTS. From Skjellerup et al. (2015).



Two additional aspects of TTS and PTS are of central importance in assessments. The first aspect is the question of how to account for mismatch between the dominant frequency of a noise and the frequency range of best hearing for the animals, which leads to the issue of frequency weighting, discussed below in section 3.3.2. The second aspect is the cumulative nature of TTS / PTS. It is well known that the duration of exposures and the duty cycle (proportion of time during an exposure where the sound is on during intermittent exposures, such as pile driving) has a large influence on the amount of TTS / PTS induced, and thus must be factored into the threshold somehow, discussed in section 3.3.3 below.

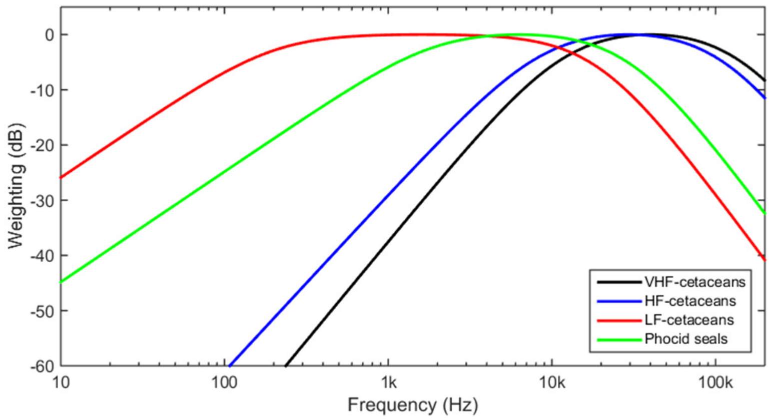
3.3.2 Frequency dependence and auditory weighting

Animals do not hear equally well at all frequencies. For humans, where an enormous empirical evidence is available in the form of thousands of patients with known noise exposure and measured hearing loss, the consensus is that weighting with a curve roughly resembling the inverted audiogram, the so-called dBA-weighting, provides the best overall prediction of risk of injury (see Houser, et al. 2017 for an extensive review). The situation for marine mammals is much less fortuitous, as very few instances of hearing loss have been documented and the noise exposure history of these animals were in most cases unknown. See, however, Kastak, et al. (2008) and Kastelein, Gransier and Hoek (2013) for notable exceptions.

The first auditory weighting curves were proposed by Southall, et al. (2007); the so-called M-weighting curves. While conceptually important, the curves themselves are now considered obsolete and have been replaced by weighting functions based on inversed audiograms (Tougaard, et al. 2015; National Marine Fisheries Service 2016; Southall, et al. 2019).

In line with the original proposal of Southall et al. (2007), separate curves have been derived for different groups of marine mammals (**Figure 3.3**). Five groups were defined, two for seals and three for cetaceans. Of the two seal curves, one for true (phocid) seals and one for eared (otariid) seals, only the first (phocids) is relevant, as it includes both harbour and grey seal. The three cetacean groups are defined on the basis of their (presumed) hearing abilities: low-frequency (LF) cetaceans include all the baleen whales, very high (VHF) cetaceans comprises the so-called narrow-band high-frequency species (see for example Madsen, et al. 2005), which includes the harbour porpoises. The remaining odontocetes are grouped in the mid-frequency (MF) and high frequency (HF) cetacean groups.

Figure 3.3. Frequency weighting curves proposed by National Marine Fisheries Service (2016) and Southall, et al. (2019).



3.3.3 Equal energy hypothesis and cumulative SEL

A substantial effort has gone into quantifying sound levels required to elicit TTS in marine mammals. The initial experiments were primarily conducted on bottlenose dolphins, belugas and California sea lions (*Zalophus californianus*) (all reviewed by Southall, et al. 2007), but recently also a large number of results are available from other species, most notably harbour porpoises (see comprehensive review by Finneran 2015). The initial recommendations of Southall, et al. (2007) reflected an uncertainty as to what single acoustic parameter best correlated with amount of TTS induced and resulted in a dual criterion: one expressed as instantaneous peak pressure and another as acoustic energy of the sound (integral of pressure squared over time, see below). In the reviews of Tougaard, et al. (2015) and Finneran (2015) this uncertainty is no longer present and it is generally accepted that everything else being equal the amount of TTS correlates better with the acoustic energy than with the peak pressure. The acoustic energy is most often expressed as the sound exposure level (SEL), given as **Equation 2.3** above. SEL equals the time integral of the sound intensity. For a signal of constant intensity and duration, the energy thus simply equals the duration times the intensity. **Figure 3.4** illustrates four signals, which all have the same energy and thus according to the equal energy hypothesis should have the same ability to induce TTS.

The signal energy should be cumulated up to some upper limit. This limit is debated. In human audiometry it is customary to use 24 hours, in conjunction with the sensible assumption that people are often exposed to loud noise during their workday and then spend the night resting in a quiet place. This assumption is less relevant for marine mammals, but the 24 h maximum was also applied in a precautionary approach by Southall, et al. (2007) and retained by National Marine Fisheries Service (2016) and Southall, et al. (2019), stressing that it is likely to be very conservative (in the sense that it leads to overprotection). An experiment with harbour porpoises (Kastelein, et al. 2016) indicate that the integration time should be at least several hours, however. For pile driving it is thus reasonable to use the entire duration of a pile driving event (i.e. piling of one foundation), which may last several hours, but not include the time between installations, as the completely dominating source of acoustic energy is from the pile driving strikes. Furthermore, as the turnaround time (time from start of pile driving at one foundation to start on the next foundation) is almost always more than 24 hours, the energy is not integrated from one foundation to the next.

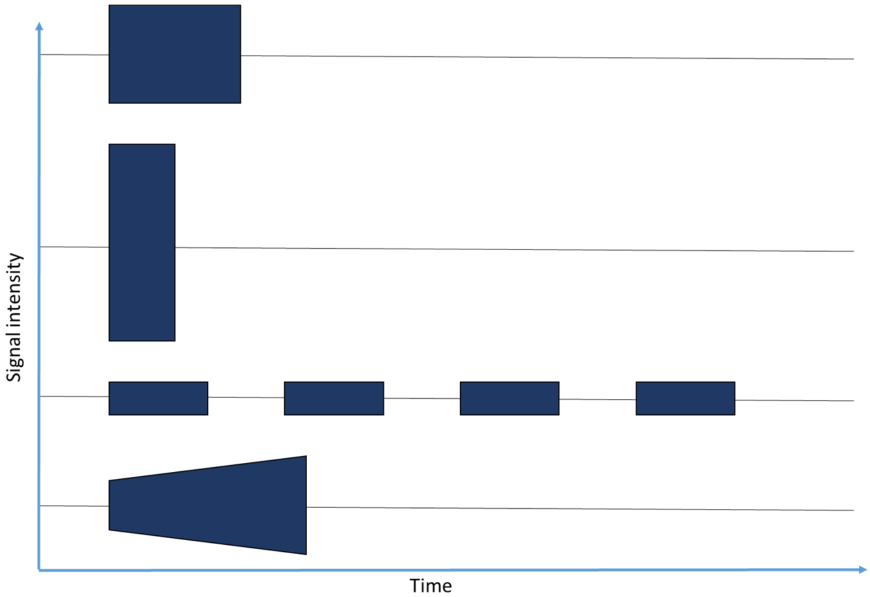


Figure 3.4. The equal energy hypothesis implies that all four examples of signals shown to the right have the same ability to induce TTS, as they are of equal energy (the areas of the four signals are the same).

3.3.4 Impulsive sounds vs. non-impulsive sounds

Experimental evidence indicates a difference between so-called impulsive sounds and non-impulsive sounds in their capability to induce TTS (and hence likely also PTS), where impulsive sounds have the largest impact. Impulsive sounds are poorly defined (see for example Southall, et al. 2007), but share some common features which include a sharp onset and short duration (small time-bandwidth product). Good examples of impulsive sounds are shock waves from explosions and pile driving at close range. In contrast, some intense and short sounds, which are not considered impulses, are sonar pings and seal scarer sounds. Although short sounds, they are often narrow-band and with less sharp onset, i.e. without the typifying characteristics of impulsive sounds. A complicating factor with respect to separating impulsive sounds from non-impulsive sounds is the effect of sound propagation on impulsiveness. As an acoustic impulse propagates through the water, it gradually loses the defining features of an impulse, as any sound has a tendency to expand in time with distance from the source, due to differences in sound speed with frequency and multipath propagation. This means that at some distance from an impulsive sound source, the sound can no longer be considered impulsive[3]. However, the conservative (precautionary) approach to this phenomenon is to ignore it and use the lower (and hence precautionary) impulsive threshold throughout the assessment.

[3] Impulsiveness is therefore not a property of the sound source itself, but a product of the generated sound and the sound propagation.

3.3.5 TTS and PTS thresholds for harbour porpoises

At the time of completion of the review by Southall et al. (2008) no experimental data was available on TTS in harbour porpoises or any other HF-cetacean and a threshold had to be extrapolated from data on TTS in bottlenose dolphins and beluga whales. This has changed dramatically and harbour porpoise is now one of the best-studied species when it comes to TTS. See Finneran (2015) and Tougaard, et al. (2015) for recent reviews.

A pivotal study is Lucke, et al. (2009), which showed that TTS could be induced in a harbour porpoise by exposure to a single pulse from an airgun at a received unweighted (broadband) sound exposure level of 154 dB re. 1 $\mu Pa^2 s$ (see note[4]). This threshold has been the foundation of legislation regarding pile driving in for example Germany (German Federal Ministry for the Environment and Nuclear Safety 2013) and has thus been instrumental in driving the development of effective sound attenuation devices (see section 3.6 below). However, not all authors are comfortable with extending a threshold derived from a single, loud pulse to a very long sequence of weaker, repeated pulses. A later study by Kastelein, et al. (2015) thus measured TTS in a porpoise after exposure to a 1 hour sequence of pile driving pulses and reported a considerably higher threshold of 180 dB re. 1 $\mu Pa^2 s$, unweighted and cumulated over all pulses (SELcum). A range of experiments supports the conclusion that thresholds for single pulses, intermittent pulses / noise, and continuous noise cannot be compared directly and thus that the simple assumption that total noise SEL determines the TTS induced (the equal energy hypothesis described above) cannot explain all variation seen in experimental results. Other studies with longer sounds in the low frequency range (1-4 kHz; Kastelein, et al. 2012; Kastelein, Gransier, Hoek, et al. 2013; Kastelein, et al. 2014) have thus resulted in significantly higher thresholds than the threshold of Lucke, et al. (2009). There is yet no full understanding of this difference between single, short impulses and longer signals, but it could be related to the recent demonstration of a rapid reduction in hearing sensitivity in dolphins after being conditioned to a loud noise by a warning signal (Nachtigall and Supin 2014). This could explain why the noise exposure experienced by the inner ear to a single transient noise could be significantly higher than to a longer noise or a repeated series of pulses, as the animal, upon perceiving the first part of the noise, consciously or unconsciously reduces the sensitivity of the ear. Functionally, this is to some degree equivalent to the stapedial reflex of terrestrial mammals, which contracts the stapedius muscle in the middle ear when a loud and potentially damaging sound is heard, but it is unknown whether the stapedius muscle is involved in cetaceans.

Another problem rooted in ignoring the repetitive pulses of a real pile driving, is the cumulative impact of many, closely spaced pulses. Finneran, et al. (2010) showed in an experiment with single noise pulses, repeated noise pulses and continuous noise that the amount of TTS induced by repeated pulses is higher than the TTS caused by a single pulse, demonstrating that impact is accumulating across pulses (**Figure 3.5**). However, the TTS induced by the multiple pulses was less than the TTS induced by a continuous noise signal with the

[4] There is some variation in this threshold, depending on authors and values between 152 and 155 can be found in different sources. The variation is due to different definitions of TTS-threshold, ranging from lowest level where a threshold elevation, no matter how small, can be reliably detected, to a more conservative definition of the exposure required to elevate the threshold 6 dB above average baseline level. These differences are without practical significance.

same total energy as the pulse train, demonstrating that there is some recovery from TTS between pulses, or that the sensitivity of the ear is reduced deliberately by the animal upon receiving the first few pulses.

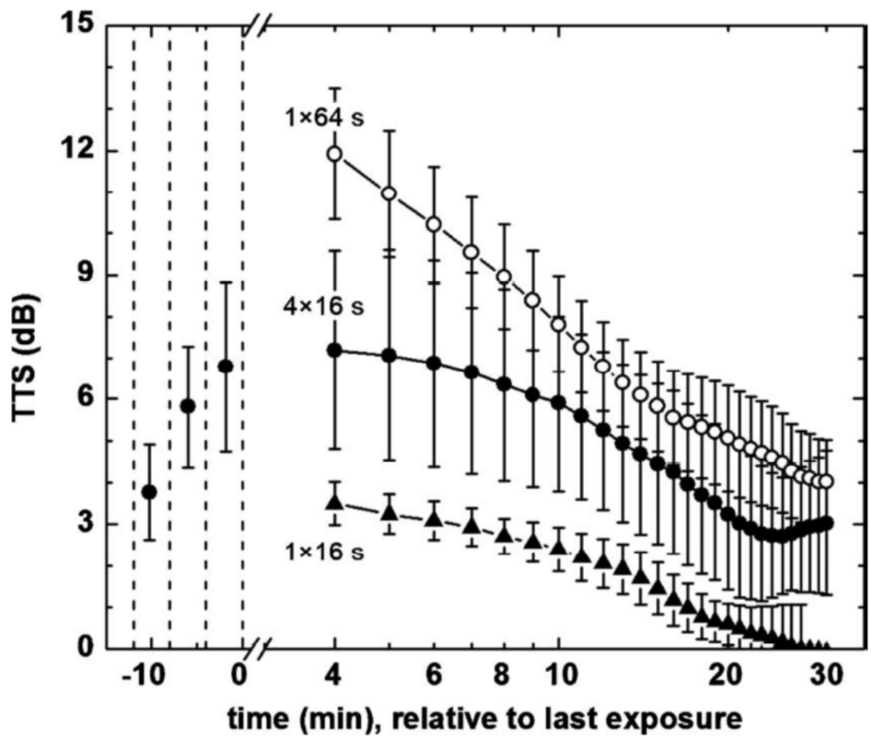


Figure 3.5. TTS in a bottlenose dolphin after exposure to either one 16 s pulse (triangles), four 16 s pulses (closed circles) or one 64 s pulse (open circles). From Finneran, et al. (2010).

Based on a comprehensive review of the entire literature on TTS and PTS in marine mammals, guidance on thresholds have recently been provided in the US (National Marine Fisheries Service 2016; Southall, et al. 2019). All measurements of TTS in marine mammals were combined with all available information on auditory sensitivity in marine mammals (audiograms) to create appropriate frequency weighting curves and TTS-growth curves. An example of such a curve, based on data from porpoises, is shown in **Figure 3.6**.

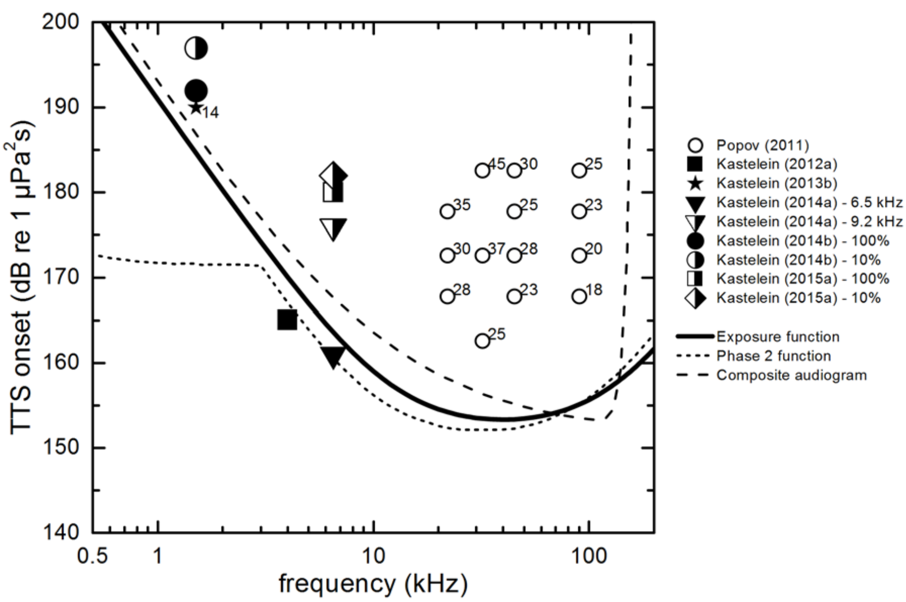


Figure 3.6. Results of all TTS studies conducted before 2016 with non-impulsive sounds on harbour porpoises. Open symbols were obtained with electrophysiolgical methods (ABR), closed and semi-closed symbols with behavioural methods. Numbers indicate the amount of TTS induced (in dB) for data points not representing thresholds. Solid line indicate the HF-cetacean weighting function. From National Marine Fisheries Service (2016).

Weighted onset TTS thresholds were derived for each species group for impulsive sounds and non-impulse sounds, respectively and from the TTS-growth functions onset PTS thresholds were estimated as the sound exposure level required to elicit 40 dB of TTS, which was considered indicative of a significantly increased risk of developing PTS. PTS thresholds were extrapolated from TTS thresholds by fitting TTS-growth curves (similar to the idealised curves shown in Figure 3.2) to the experimental data. Two different sets of thresholds were derived: one set for impulsive sounds (based on the single data point by Lucke, et al. 2009) and another for non-impulsive sounds based on the data shown in Figure 3.6. The distinction between impulsive and non-impulsive sounds relates to the observation also discussed above that a single, short and loud noise pulse may be more damaging than longer, continuous noise of the same sound exposure level. Both sets of thresholds are given in Table 3.1. They are expressed as weighted and cumulated SEL over 24 hours ($L_{E,p,w,24\,h}$).

Table 3.1. Weighted thresholds for TTS and PTS for very high frequency hearing cetaceans, which includes harbour porpoises. From National Marine Fisheries Service (2016) and Southall, et al. (2019).

Type of noise	TTS-threshold	PTS-threshold
Impulsive noise	140 dB re. 1 µPa²s	155 dB re. 1 µPa²s
Non-impulsive noise	153 dB re. 1 µPa²s	173 dB re. 1 µPa²s

These thresholds are weighted and thus not directly comparable to the thresholds suggested Andersson, et al. (2016). The suggested threshold for TTS in Andersson, et al. (2016) is 175 dB re. 1 µPa²s, unweighted and is based on the work of a Danish working group (Skjellerup, et al. 2015; Skjellerup and Tougaard 2016), who again based their recommendations on a precautionary interpretation of the results of Kastelein, et al. (2015). This experiment, which was mentioned, but not included in the analysis presented by National Marine Fisheries Service (2016), measured TTS in porpoises induced by exposure to playback of real pile driving sounds for 1 hour at a total SEL of 180 dB re. 1 µPa²s[5]. This level is unweighted and thus not directly comparable to the guidance thresholds reported by National Marine Fisheries Service (2016). However, Tougaard and Dähne (2017) derived a weighted level of the threshold from (Kastelein, et al. 2015) (see **Figure 3.7**) of 140 dB re. 1 µPa²s. This value happens to be identical to the TTS threshold for impulsive noise derived by National Marine Fisheries Service (2016) (**Table 3.1**), adding additional support to both the threshold value itself and the frequency weighting procedure.

[5] Cumulating acoustic energy across several pulses is commonly referred to as cumulated SEL, or SEL_{cum}.

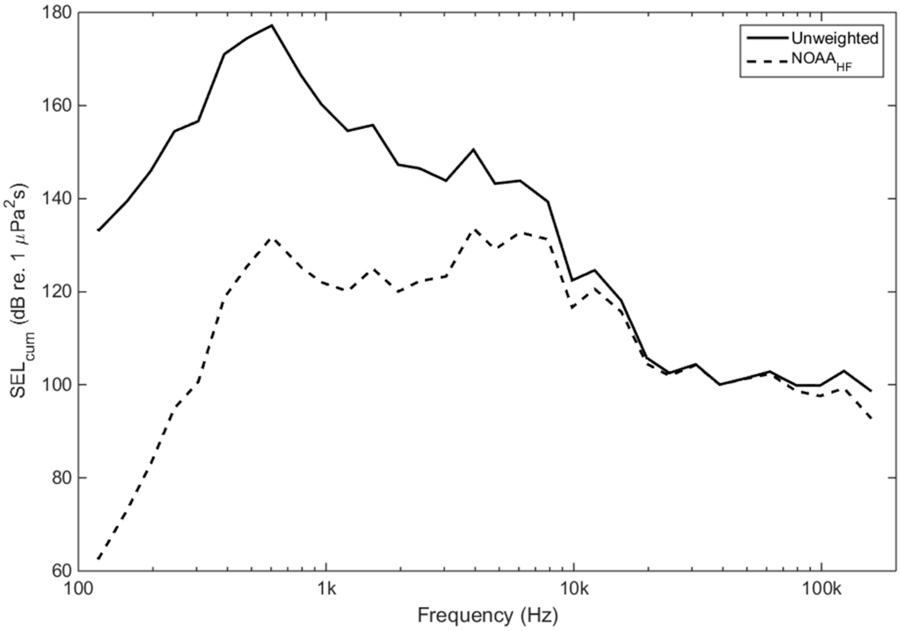


Figure 3.7. Third-octave spectrum of the stimulus used by Kastelein, et al. (2015), adjusted to a total SELcum of 180 dB re. 1 µPa^{2}s (solid line) and the same spectrum weighted with the HF-cetacean weighting function of National Marine Fisheries Service (2016). Modified from Tougaard and Dähne (2017).

3.3.6 TTS and PTS thresholds for seals

Southall et al. (2007) estimated TTS and PTS thresholds for seals in general, but these estimates were based on data from bottlenose dolphins, beluga and California sea lions. Since 2007 actual measurements from harbour seals have become available and better estimates are now available (National Marine Fisheries Service 2016; Southall, et al. 2019).

PTS was induced due to an experimental error by Kastak, et al. (2008), where a harbour seal was exposed to a 60 second tone at 4.1 kHz at a total SEL of 202 dB re. 1 µPa^{2}s. A second experiment (in a different facility and on a different animal) produced a very strong TTS (44 dB), also by accident, by exposure to 60 minutes of 4 kHz octave band noise at a SEL of 199 dB re. 1 µPa^{2}s (Kastelein, Gransier and Hoek 2013). The level of TTS is considered to have been very close to inducing PTS.

A number of experiments have determined TTS in harbour seals for various types of noise of shorter and longer duration, summarized by Finneran (2015) and evaluated by National Marine Fisheries Service (2016) with the same methods as described for porpoise thresholds. The guidelines recommend the thresholds given in **Table 3.2**, expressed as phocid-weighted cumulated SEL over maximum 24 hours. As for VHF-cetaceans, two sets are available, one set for impulsive noise and one set for non-impulsive noise.

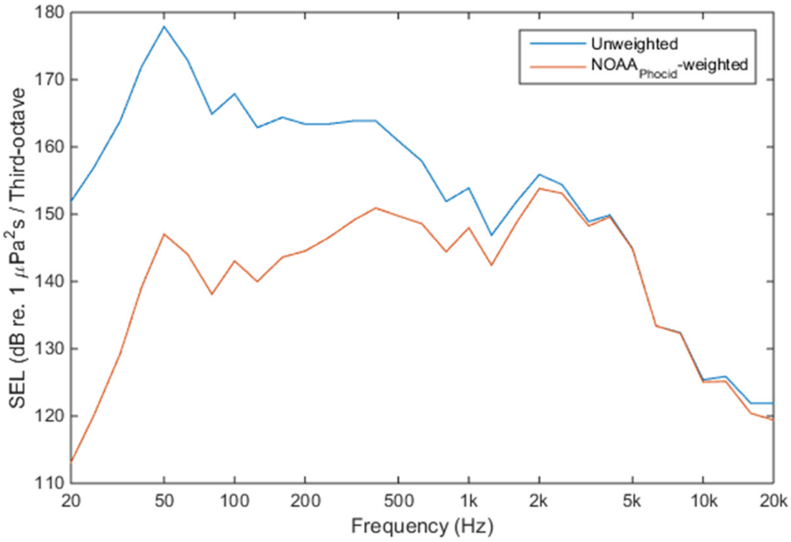
Table 3.2. Weighted thresholds for TTS and PTS in phocid seals. From National Marine Fisheries Service (2016).

Type of noise	TTS-threshold	PTS-threshold
Impulsive noise	170 dB	185 dB
Non-impulsive noise	181 dB	201 dB

Experiments on a ringed seal (*Pusa hispida*) and a spotted seal (*Phoca largha*) exposed them to air gun pulses at SEL up to a maximum of 181 dB re. 1 µPa^{2}s (unweighted), but did not induce TTS in any of the seals (Reichmuth, et al.

2016). **Figure 3.8** shows the third-octave spectrum of the most powerful airgun signal used by Reichmuth, et al. (2016), adjusted on the Y-axis to a total SEL of 181 dB re. 1 μPa²s for the unweighted signal (obtained as the sum of all third-octave bins: $10\log_{10}(\sum 10^{L_{third-octave}/10})$). In the same way the $NOAA_{phocid}$-weighted SEL could be found as the sum of the weighted third-octave bins, equal to 162 dB re. 1 μPa²s. This level, clearly below the threshold for TTS, is thus consistent with the impulsive noise threshold derived by National Marine Fisheries Service (2016) (**Table 3.2**).

Figure 3.8. Third-octave spectrum of the loudest airgun pulse used by Reichmuth, et al. (2016), both as unweighted (blue) and $NOAA_{phocid}$-weighted (red).



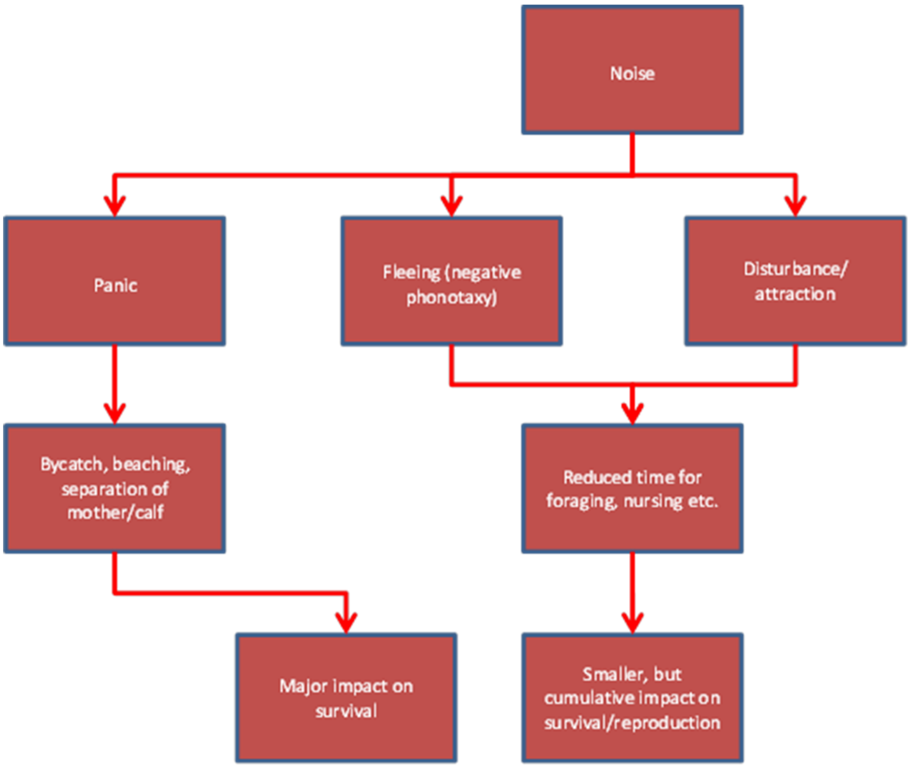
There are no results available from grey seals and results from California sea lions (Finneran, et al. 2003) are considered less likely to be representative for grey seals than the harbour seal data. Consequently, the results from harbour seals should be considered valid for grey seals, until actual data may become available.

3.4 Disturbance of behaviour

Permanent or temporary damage to marine mammal hearing may not necessarily be the most detrimental effect of noise. Noise levels below the TTS threshold may affect and alter the behaviour of animals, which can carry implications for the long-term survival and reproductive success of individual animals, and thereby ultimately on the population status (National Research Council 2003) (see **Figure 3.9**.). Effects can occur directly from severe reactions as for example panic or fleeing (negative phonotaxis), by which there is an increased risk of direct mortality due to for example bycatch in gill nets or separation of dependent calves from mothers. More common, however, is probably less severe effects where animals are displaced from habitats, or their foraging behaviour disrupted due to noise (as demonstrated for example by Wisniewska, et al. 2018).

However, at present, the knowledge about how immediate, short-term behavioural changes translate into population level effects is very incomplete and inference from exposures to population level is extremely difficult. Conceptually, it is not difficult to envision that the effect of repeated disturbances to animals will reduce the time available to whatever behaviours important for the short- and long-term survival of the animals, such as feeding, mating and nursing offspring. Quantifying these relationships can be very difficult, as the individual disturbance only in extreme cases will produce a measurable effect in itself. Separation between mother and dependent calf / pup with loss of the offspring as a result is one notable exception. Most of the time, the disturbance will likely only mean that a little less food is consumed, a little less milk transferred to the calf / pup, and perhaps loss of a mating opportunity. These impacts are cumulative, however, and repeated disturbances will therefore add up and, at some point, effects will become measurable. This has been referred to as the "death by a thousand cuts" (Todd 2016).

Figure 3.9. Schematic illustration of mechanisms by which noise-induced changes to behaviour can lead to effects on short-term and long-term survival and reproduction (fitness) in marine mammals. From Skjellerup et al. (2015).

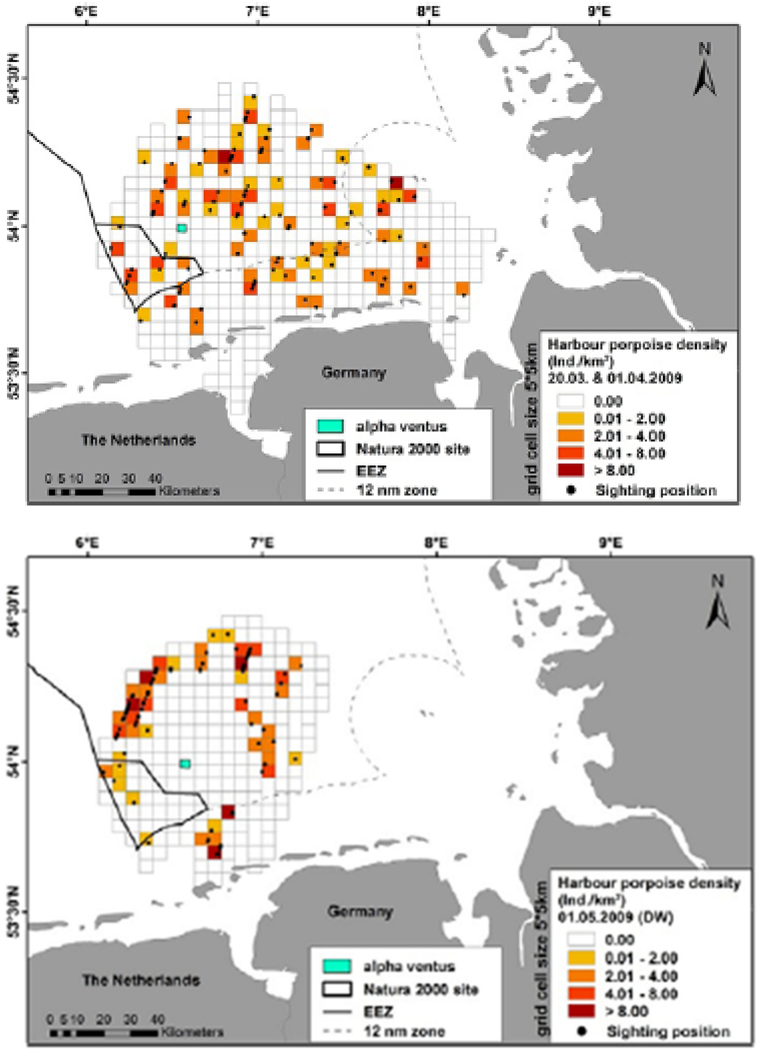


Although quantitative models are under development to allow a better understanding of the link between behavioural disturbances and population developments, such as the agent-based DEPONS model for porpoises (Nabe-Nielsen, et al. 2018), such models are not yet accurate enough to provide reliable results at the level of individual wind farms. The limiting factor is the lack of accurate knowledge on the abundance and behaviour of marine mammals and details in their reaction towards acoustic disturbance. For the time being, we are thus limited to describing reaction thresholds and spatial and temporal extents of the zone of impact.

3.4.1 Behavioural effects of pile driving noise on porpoises

The reaction of porpoises to pile driving has been studied during construction of several wind farms. In the first projects pilings were performed unabated, i.e. without any attenuation in the form of for example air bubble curtains (see section 3.6). Irrespective of the size of the monopiles, the results showed displacement and / or disturbance of the behaviour of porpoises out to distances of at least 20 km from the piling site (Tougaard, et al. 2009; Brandt, et al. 2011a; Dähne, et al. 2013; Haelters, et al. 2015). A single illustrative example, from the German wind farm Alpha Ventus, is shown in **Figure 3.10**.

Figure 3.10. Porpoises observed from aerial survey before (top) and during (bottom) pile driving at the German offshore wind farm Alpha Ventus. The blue square indicates the position of pile driving operation. From Dähne, et al. (2013).



Duration of the deterrence / disturbance appears to be in the range of some hours to at most a day after end of the pile driving (Brandt, et al. 2011a; Dähne, et al. 2013; Brandt, et al. 2018). Based on the maximum reaction distances, a lowest sound level capable of disturbing porpoises has been estimated to be about 140 dB re. 1 µPa²s, expressed as single pulse, unweighted sound exposure level by Dähne, et al. (2013). While this threshold is likely to be applicable to pile driving noise in general, for piling without noise abatement measures, the fact that it is not appropriately frequency weighted means that it cannot be used to predict reactions when noise abatement measures are used. This is because the efficacy of noise abatement generally increases with frequency, which means that the beneficial effect of the dampening is likely to be underestimated unless an appropriate frequency weighting is included (Tougaard and Dähne 2017).

A review of results from behavioural reactions to noise in wild porpoises was performed by Tougaard, et al. (2015). This review proposes a generic response threshold of a sound pressure level 40-50 dB above the hearing threshold (audiogram) of the porpoise[6], which corresponds to about 100 dB re. 1 µPa VHF-weighted. This generalized and frequency-weighted threshold is found as the

[6] Such a level above the hearing threshold is sometimes referred to as “sensation level”.

sum of the threshold of hearing across frequencies of best hearing (about 45 dB re. 1 µPa, Kastelein, Hoek, de Jong, et al. 2010) and a sensation level of 45 dB.

In addition to frequency weighting, the sounds must also be averaged over an appropriate time window, approximating the auditory integration time of porpoises (Tougaard, et al. 2015; Tougaard and Beedholm 2019), which is on the order of 0.1 s. This is coincidentally very close to the duration of pile driving pulses, which means that any adjustment for sound duration is of little importance for this type of sounds.

Assessment of behavioural disturbance is then performed through a spatially explicit modelling of sound pressure levels around the pile driving site when maximum hammer energy is used. The iso-level contour corresponding to a sound pressure level of 100 dB re. 1 µPa VHF-weighted thus expresses the estimated zone around the pile driving site, where porpoises can be expected to react to the noise. This spatially explicit zone can be used to derive average and maximum disturbance ranges, but can also be combined with similar spatially explicit information about porpoise abundance. If one knows the exposed area and the density of animals per km^2 in the disturbed area, one can estimate the absolute number of animals that will be exposed to pile driving noise above the behavioural reaction threshold. This estimate only represents an average of what can be expected and is associated with substantial uncertainty. This uncertainty comes on one hand from the natural variation in distribution of porpoises in the area and the uncertainty in modelling the distribution, and on the other hand, from variation between porpoises in how responsive they are to the noise. In general, the reaction appears to be graduated with distance from the pile driving site, such that fewer animals respond and / or the response of the individual animals becomes less severe, the further from the pile driving site (e.g. Dähne, et al. 2013). The estimated numbers should thus not be taken as indications of the actual number of porpoises, which will be affected by the pile driving, as this can never be predicted in advance, but instead as an indication of the scale of the impact on the local population.

3.4.2 Behavioural effects of pile driving noise on seals

Comparatively little is known about the reaction of seals to pile driving noise. Blackwell, et al. (2004) studied the reaction of ringed seals (*Pusa hispida*) to pile driving on an artificial island in the arctic and saw limited reactions to the noise. In contrast to this are results from satellite tracked harbour seals, which showed aversive behaviour up to 25 km from the pile driving sites during pile driving (Russell, et al. 2016). The latter study thus indicates roughly similar impact zones for seals and porpoises.

In principle, the same type of analysis as done for porpoises could be performed for seals, providing estimates of the number of seals likely to be disturbed by the pile driving noise. Two central prerequisites are required for such an analysis: a map of distribution of harbour seals in Kattegat and a threshold for behavioural reactions to pile driving noise. While the first is available (**Figure 1.12**), no generalized threshold for reactions has been suggested for seals. Although the results of Russell, et al. (2016) suggest that the reaction distance for harbour seals to unabated pile driving is comparable to that of porpoises, it is unknown how the differences in frequency spectrum of the abated vs. unabated noise can be factored into a prediction of a threshold for a pile driving with a noise abatement system. Effects on seals through behavioural disturbance by pile driving noise has therefore only been assessed in a qualitative manner.

3.5 Masking

Masking is the phenomenon where noise can affect the ability of animals to detect and identify other sounds negatively. The masking noise must be audible, roughly coincide with (within tens of milliseconds), and have energy in roughly the same frequency band, as the masked sound. Even if these requirements are fulfilled, the animal has additional possibilities for obtaining what is known as "release from masking". This covers a range of behavioural modifications and processing capabilities of the auditory system. In case of conspecific communication, the sender can increase the source level of the communication signal (known as the Lombard effect). The receiver can move away from the noise source and thereby reduce masking or simply orient itself so to receive the noise from a different direction than the signal it is trying to receive (spatial release from masking). See Erbe, et al. (2016) for a current review.

Masking potential of pile driving noise has not been studied specifically; however, some preliminary conclusions can be drawn. Porpoises depend critically on their echolocation, but their echolocation clicks are in the extreme ultrasonic range, above 100 kHz, considerably above the range where pile driving noise is located. This means that it is very unlikely that pile driving noise would mask echolocation of porpoises.

Passive listening by both seals and porpoises could potentially be masked by pile driving noise. The duty cycle of pile driving is relatively low, around 5-10 %, which leaves large gaps in between pulses, where signals can be detected (a process known as gap-listening). It is thus difficult to imagine a complete masking of passive listening by pile driving noise.

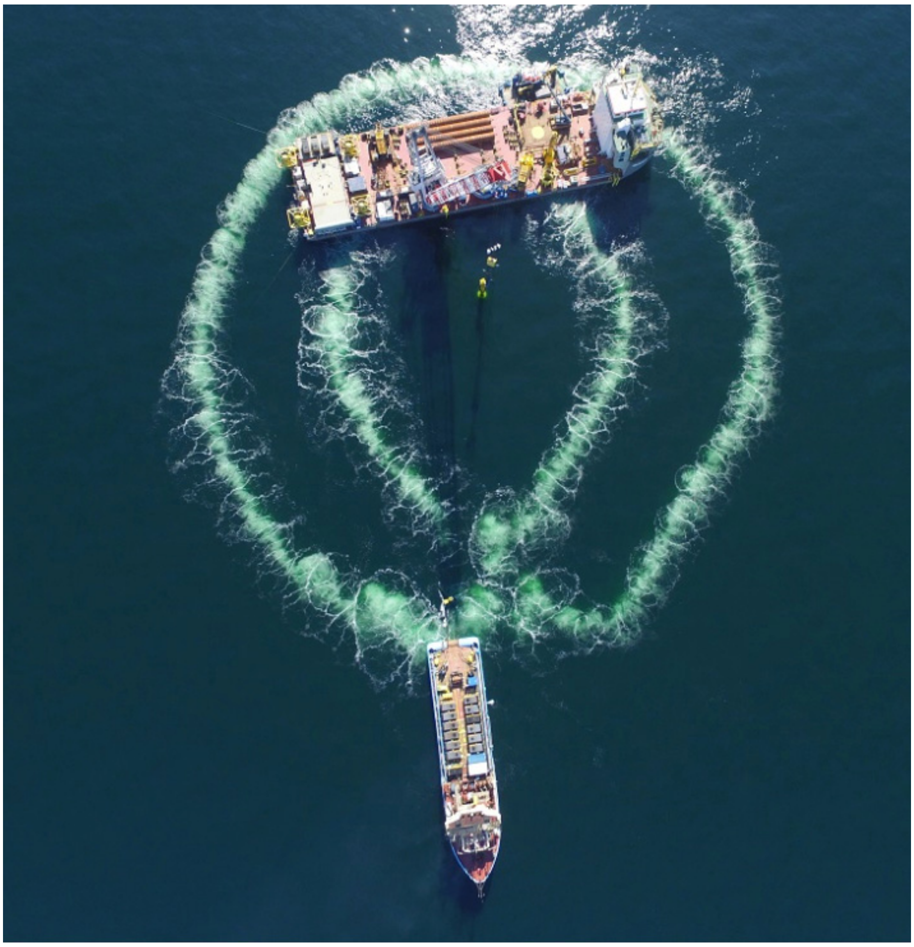
With respect to the consequences of masking of low-frequency passive hearing in seals and porpoises little can be concluded. Porpoises have poor hearing below a few kHz and it is unknown what they may use this low-frequency hearing for. Seals on the other hand use sound in the low-frequency range for communication and this could potentially be interfered with by the pile driving noise. However, harbour seals and grey seals are not known to vocalize outside the context of mating and this takes place close to the haul-out sites on shore. Pile driving occurring far off-shore thus appears unlikely to have any potential to interfere with communication during mating displays.

3.6 Mitigation measures

If noise exposure is assessed to be above levels likely to result in significant impact on populations of marine mammals (see section 2, below) the impact can be reduced by different mitigation measures. In general, there are three different principles available to mitigate impact of noise, irrespective of the type of sound, not listed in any order of priority:

- Reduction of generated noise
- Reduction of radiated noise
- Reduction of received noise.

Figure 3.11. Example of active bubble curtain (Double Big Bubble Curtain) deployed around the jack-up platform used for pile driving. Air bubbles are visible in the surface as the white ring. The ship in the front is used for deployment and recovery of the hose system and contains the very large compressors needed to feed the bubble curtain with compressed air. Hydrotechnik Lübeck.



Reduction of the radiated noise amounts to changing the foundation type, the method of installation, or other modification to the procedure itself. While a change from steel monopile to a different design would change the noise emission significantly, it is out of the scope of this report to assess this as a mitigation measure.

3.6.1 Reduction of radiated noise

Reduction of the radiated noise can be achieved by employing baffles, absorbers or some other noise abatement system, which prevents noise from propagating from the monopile out into the surrounding waters. Several such systems are available (see Bellmann, et al. 2020; Koschinski and Lüdemann 2020 for a recent review).

An example of the effect of a bubble curtain, such as the one shown in **Figure 3.11**, on the frequency spectrum of the emitted noise pulses is shown in **Figure 3.12**. The attenuation is seen to be increasingly effective with increasing frequency, due to the smaller wavelength. As the peak frequency of pile driving noise is very low (160 Hz in the example) the effect of the bubble curtain is small on the broadband (unweighted) sound pressure level. However, if signals are weighted with appropriate frequency weighting curves (see 3.3.2), the effect becomes considerably larger (**Figure 3.12**). This is due to the lesser audibility of the lower frequencies to both seals and porpoises, which means that more weight is put into the higher, more audible parts of the frequency spectrum, which also happens to be the frequencies where the bubble curtain is most effective.

Figure 3.12. Median third-octave band spectra of pile driving noise measured 750 m from pile driving at the GlobalTech 1 offshore wind farm (tripod foundations). Spectra are shown without bubble curtain (Ref) and three different configurations of the bubble curtain. From Nehls and Bellmann (2016).

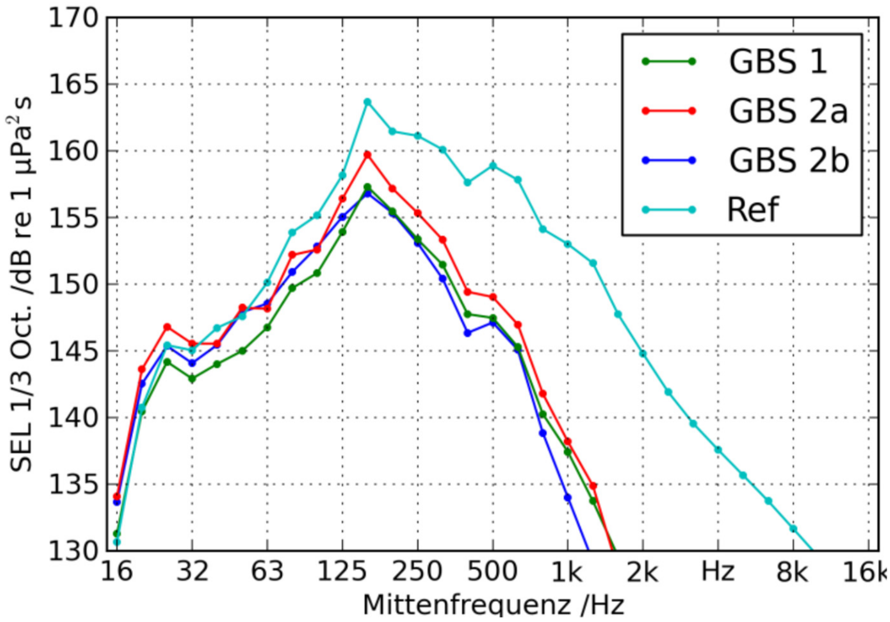
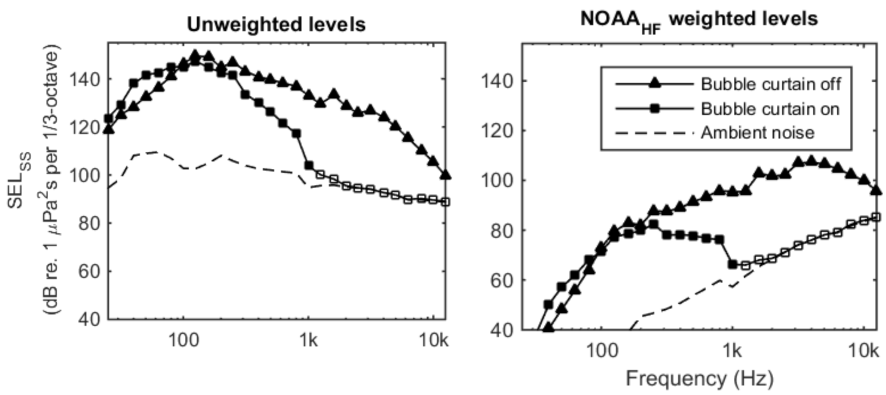


Figure 3.13 illustrates the difference between evaluation of the effect of bubble curtains on unweighted and weighted levels, respectively. The effect of the bubble curtain is the same in both cases: predominantly attenuating noise above 1 kHz, but in the unweighted spectra the overall level (sum of all third-octave bands) is affected very little, whereas there is a pronounced effect on the weighted spectra (2.3 dB vs. 25.9 dB, respectively; Tougaard and Dähne 2017). Note that due to the inherent logarithmic nature of the dB-scale, the sum of all third-octave bands is almost entirely dominated by the band with the highest level. The result is that the peak in the weighted spectra shifts from 4-5 kHz without bubble curtain to about 200 Hz with bubble curtain, whereas the peak in the unweighted spectra remains unchanged around 200 Hz.

Figure 3.13. Effect of applying the VHF-cetacean weighting curve of Southall, et al. (2019), which is identical to $NOAA_{HF}$ (National Marine Fisheries Service 2016), to spectra of pile driving noise (6 m diameter monopile) with and without a Double Bubble Curtain. Open symbols indicate levels dominated by ambient noise rather than pile driving noise. From DanTysk offshore wind farm (Dähne, et al. 2017)



3.6.2 Deterrence and other reduction at the receiver

The third approach, where noise is mitigated at the animals, includes methods and protocols to ensure that no (or very few) animals are present closer than some safety distance during noise exposure. This can be achieved very effectively in locations with a pronounced seasonal pattern in abundance, where noisy activities are placed only in those parts of the year where no (or very few) animals are around. Alternatively, for large species of whales, it may be possible to visually detect and track animals over large areas around the noise source and either postpone noisy activities, if they are about to start, or abort activities (if technically possible), whenever one or more whales are observed within some critical safety distance (see for example Bröker, et al. 2015). Harbour porpoises and seals are extremely cryptic at sea and can be very difficult to observe at the surface if there are any kind of waves. Sighting rates of porpoises from a ship thus decreases dramatically when sea surface conditions goes from sea state 1 (only ripples on the surface) to sea state 2 (small wavelets, but still no white caps) (Teilmann 2003) and even under ideal conditions effective detection distances beyond a few hundred meters cannot be achieved from a vessel near the piling site. Passive acoustic monitoring of the echolocation sounds of porpoises is somewhat less affected by sea state, but effective detection distances are equally short, or even shorter than for visual observations (Kyhn, et al. 2011). Visual and / or acoustic monitoring for porpoises or seals is thus not a reliable mitigation tool to reduce impact from pile driving.

Left is then the approach of actively deterring animals out beyond the safe distance prior to commencing pile driving at full force. This is usually accomplished by two different means: use of a soft-start or ramp-up of the piling sequence or deployment of a dedicated deterrent device.

Pile driving typically includes a shorter or longer soft start period, where a few blows are delivered at low hammer energy after which the pile may be aligned in the exact position and angle. Once the pile is properly in place, the main piling commences and unless problems are encountered, the piling will proceed with constant stroke intervals and gradually increasing hammer energy, as the pile penetrates the seabed and friction increases. The soft start is introduced solely for technical reasons but has the additional beneficial effect of deterring animals away from the piling site before the main piling begins, effectively reducing SEL_{cum} for the individual animal. The soft start sequence is typically very variable; sometimes only a few rapid blows are needed to get the pile in place for penetration but sometimes extensive realigning of the pile is required before the main piling can begin. This means that it can be difficult to model the soft start period. However, modelling the soft-start as a series of low-level strikes with constant strike rate, will lead to an overestimation of SEL_{cum} and is thus precautionary.

Because the soft start procedure can be difficult to plan in details beforehand and may sometimes be very short, it is typically recommended to supplement the soft start with an active deterrent device, most commonly in the form of a seal scarer. Seal scarers are powerful underwater sound emitters originally developed to keep seals away from fishing gear. They are effective in deterring seals out to distances of some hundred meters; see review by Mikkelsen, et al. (2015) and section 3.6; and are even more effective in deterring harbour porpoises. Porpoises are effectively deterred out to at least 1300 m (Hermannsen, et al. 2015; Mikkelsen, et al. 2017) and may affect porpoise behaviour as far away as 10-12 km (Dähne, et al. 2017). This large zone of disturbance of the seal scarer for porpoises means that the seal scarer may constitute a non-trivial source of disturbance in itself (Dähne, et al. 2017; Mikkelsen, et al. 2017) and should only be used to the extent it can aid in mitigating more serious effects, such as hearing loss (see 5.6.2). In this assessment it is assumed that both porpoises and seals are deterred by the presence of several vessels working in the area employed with noise abatement as well as with piling at the time the soft start begins. Therefore, the use of seal scarers are not recommended for the construction of Kattegatt Syd offshore windfarm provided either of the two types of mitigations is used as assumed in this assessment.

4 Assessment methodology and criteria

This assessment evaluates impact on the three most common populations of marine mammals in the area: harbour seals, grey seals and harbour porpoises for each of the four acoustic impacts: acoustic trauma, hearing loss, behavioural disturbance and masking. Based on the description of likely designs of the wind farm a worst-case scenario was selected, based on the following criteria:

- Worst sound propagation conditions (bathymetry and hydrography)
- Worst location of foundations, based on sound propagation conditions in relation to the nearby Natura 2000 sites
- Worst case foundation type and installation procedure (hammer energy and number of strikes required to complete piling)
- For all scenarios, noise abatement has been assumed, i.e. either Double Big Bubble Curtains (DBBC) or a combination of Double Big Bubble Curtains (DBBC) and Hydro Sound Dampeners (HSD) (or abatement with equivalent effect). Scenarios without mitigation is deemed unrealistic, because of the impact and therefore not included in the assessment.

Additional construction scenarios are included. These are identical to the worst-case scenario, except that construction is done under sound transmission conditions less favourable for long-range transmission, at a certain distance to the nearest Natura 2000 site or both. The combined scenario is included as an example of the currently best available technology and best environmental practise for reducing impact of pile driving. As an alternative to pile driving, also gravity foundations are assessed.

The impact of the different scenarios on the different marine mammal populations is assessed based on the criteria listed in **Table 4.1**. The list is specific for pile driving.

Table 4.1. Classification of the magnitude of impact, based on impact on individuals and the population

Impact magnitude	Description
Negligible	Short-term duration of impact, but insignificant impact on individual animals, without long-term consequences for the population.
Minor	Possible short-term duration of impact and /or disturbance of limited part of the area available for the animals. Insignificant impact on individuals, unlikely to have any negative consequences for the long time development of the population.
Moderate	Possible longer-term duration of impact, and / or with disturbance of significant part of the area available for the animals. Significant, but non-lethal impact on individuals, unlikely to have negative consequences for the long time development of the population.
Major	Long-term duration of impact, and / or with disturbance of significant parts of the available area. Significant impact, likely to have negative consequences for the long time development of the population, or potentially lethal impact on individuals.

The populations' conservation status must be factored into the assessment. A population in favourable status, such as harbour seals and harbour porpoises in Kattegat, can accommodate considerable impact on individuals without any long-term consequences for the development of the population. This is in contrast to the situation for example for the critically endangered harbour porpoise population in the Baltic Proper. Here, any impact considered to have significant impact on the survival and reproductive success of an individual, must be considered a significant impact on the population as a whole.

Criteria and assessment methodology for the four different types of impacts is listed below.

4.1 Acoustic trauma

The exposure thresholds suggested for human divers (Lance, et al. 2015) are considered applicable and precautionary for marine mammals, because the size of the animals and in particular the volume of their lungs are comparable to humans. Thus, exposure to an impulsive sound with an acoustic impulse above 30 Pa· s, or a corresponding peak pressure of at least 226 dB re 1 µPa is considered unwanted, as this exposure level is associated with a 10% risk of (survivable) tissue damage (Lance, et al. 2015).

As peak pressures are notoriously difficult to model accurately for complex sound sources, such as a very long and large diameter steel monopile, the peak pressure is estimated by extrapolation from actual measurements from pile driving in other wind farms.

4.2 Hearing loss

The long-term effects of various degrees of temporary or permanent hearing loss on survival and reproductive success of marine mammals is unknown. It is thus difficult to assess how these impacts may affect the population of seals and porpoises. Large hearing losses, however, will inevitably affect the ability of the animal to carry out its normal range of behaviours and hence cause a decrease in fitness. Although this may not directly lead to the death of the individual, it may reduce the life span and reproductive success of the animal.

TTS and PTS primarily affects hearing around and immediately above the frequency range of the fatiguing noise. In a study with playback of pile driving sounds to harbour porpoises, the TTS developed at 4 kHz and 8 kHz, but not at 16 kHz or 128 kHz (Kastelein, et al. 2015). This means that any hearing loss induced by pile driving is unlikely to affect the echolocation abilities of porpoises, but the loss could potentially affect detection ranges for acoustic cues from the environment. As seals use low frequency calls for communication (see for example Van Parijs, et al. 2001; Sabinsky, et al. 2017), their hearing is sensitive at the low frequencies (figure 2.3) and seals are likely to be sensitive to permanent hearing losses from unabated pile driving.

4.2.1 Biological significance of TTS

In a very precautionary approach, some consider TTS an unwanted impact on the animals (see for example German Federal Ministry for the Environment and Nuclear Safety 2013). However, the actual consequences for a porpoise of suffering a small elevation in hearing threshold at low frequencies, which recovers completely within a few hours at most (Popov, et al. 2011), are likely to be very low. TTS induced by pile driving noise occurs at very low frequencies, well outside the frequencies used for echolocation and communication (Kastelein, et al. 2015). Neither echolocation, nor communication between mother and calf will thus be affected by TTS induced by pile driving noise, as their communication signals are in a frequency band much above, where TTS may be inflicted. The overall effect of inducing small amounts of TTS in porpoises as a consequence of pile driving is thus assessed negligible for the long-term survival and reproduction of the animal, and thus in turn also without any effects at the level of the population. However, during the last few years attacks on porpoises by grey seals have been observed as the cause of death in stranded porpoises. Approaching grey seals could go undetected by porpoises with TTS, but since the number of grey seals are still low in Kattegat, the consequence of a potential increase in successful attacks caused by TTS is considered negligible and not considered further in this assessment. The possible energetic consequences for seals and porpoises of small amounts of TTS (less than 40 dB) in the frequency range below 10 kHz are thus considered insignificant, as the duration of the impact is low (less than an hour, Popov, et al. 2011).

For these reasons, a criterion for assessment based on PTS is adopted, and TTS is hence considered a first warning of very high noise levels. Exposure to noise at levels likely to induce 40 dB or more of TTS is considered to carry an increased risk of inducing PTS in the animals. Modelling results of noise levels likely to induce such high TTS levels, should thus be considered a warning of potential PTS. In line with recommendations of the National Marine Fisheries Service (2016) and Southall, et al. (2019) the exposure limits in **Table 4.2** were adopted.

Table 4.2. Adopted exposure limits for hearing loss, defined as the threshold for inducing PTS in seals and porpoises.

Species	PTS Threshold	Comments
Harbour porpoise	155 dB re 1 $\mu Pa^2 s$	VHF-cetacean-weighted
Harbour seal	185 dB re 1 $\mu Pa^2 s$	Phocid seal-weighted
Grey seal	185 dB re 1 $\mu Pa^2 s$	Phocid seal-weighted

Both seal and porpoise exposure limits are the lowest (most precautionary) PTS thresholds suggested by National Marine Fisheries Service (2016), i.e. the thresholds applicable to impulsive noise.

4.2.2 Cumulative exposure across several pile drivings

It is well known from humans and terrestrial animals that TTS, if induced repeatedly, also may lead to PTS (Kujawa and Liberman 2009). Such a threshold stretching across multiple pile driving operations and thereby spanning many days, is not possible to establish based on empirical data. It is, nevertheless, possible to consider quantitatively the likelihood that the *same* individual happens to be close enough to the monopile to develop a significant amount of TTS at more than one occasion. It could happen, but with very low likelihood, because both seals and porpoises are scarred away by the noise. The risk that any seal or porpoise therefore develops PTS as a result of multiple instances of TTS inflicted by pile driving appears to be so low that it can safely be ignored.

4.2.3 Estimation of received exposure

The method for estimating the cumulated sound exposure level follows the recommendations of Skjellerup, et al. (2015) with the exception that auditory frequency weighting is adopted (following National Marine Fisheries Service 2016; and Southall, et al. 2019). SELcum is thus modelled over the time a complete pile driving of one monopile is estimated to take, and taking into account that the exposed animals will flee from the noise during piling. The accumulation of acoustic energy over the duration of the pile driving, which typically lasts several hours, is a deviation from the recommendations of the National Marine Fisheries Service (2016), where 24 hours is recommended. Limiting the accumulation period to the pile driving itself (including soft-start) simplifies calculations, as no knowledge about other noise sources is required and as these other sources (most importantly ship noise) are energetically insignificant in relation to the energy radiated in the pile driving noise, the error committed by excluding these sources is negligible.

For assessment of pile driving noise effects on porpoises, this means that the relevant measure is an estimate of the sum of the acoustic energy of all pile driving pulses that a porpoise may be exposed to during installation of a single foundation. This is done below with the method devised by Skjellerup, et al. (2015). Details can be found in section 5 in Tougaard and Mikaelsen (2018) and in 111 in this report, but in brief consists of the following steps:

1. The source level and frequency spectrum of the pile driving noise for the relevant monopile diameter is estimated from available data.

2. A transmission loss function is estimated from modelling sound propagation from one or more locations inside the proposed offshore wind farm, using bathymetry data and realistic assumptions about hydrography, sediment structure etc.

3. By combining a piling scenario, where a generic sequence of pile driving strokes are delivered to the monopile with gradually increasing hammer energy and a simple model for escape behaviour of porpoises, the VHF-weighted sound exposure level of each individual pulse can be estimated at the position of the porpoise.

4. The total exposure is found as the sum of all pulses received at the porpoise.

5. This cumulated sound exposure level (SELcum) can be compared to the lowest level capable of inducing PTS (155 dB re. 1 $\mu Pa^2 s$, VHF-weighted) to determine whether porpoises are likely to experience PTS or not.

6. The steps 3-5 are repeated for seals, using the appropriate auditory weighting and threshold for PTS.

The entire set of calculations can be repeated for different scenarios, such as location within the offshore windfarm, with different types of noise abatement techniques etc.

4.3 Behavioural disturbance

The comprehensive review of Southall, et al. (2007) suggested a "response severity scale", which was intended to classify and rank the severity of behavioural reactions to underwater sounds. The scale was based on immediate reactions, however, which means that the long-term consequences (e.g. metabolic cost) of the disturbance was not factored in, which makes the scale less useful in assessing long-term impact (Tougaard, et al. 2015). The scale has also been criticised for not taking behavioural context into account, reflecting the fact that it is of importance what behaviour is interrupted by the sound (Ellison, et al. 2012). Instead, the criteria listed in **Table 4.3** were developed, in order to classify the magnitude of the impact at the scale of the (local) population of animals as well as on their available habitat.

Table 4.3. Criteria for assessing intensity of behavioural disturbance from pile driving noise on populatons. The intensity is assessed at the level of the animals, number of animals and on the size of the affected area. 'Area' in this table does not pertain to areas within Natura 2000 sites. Impacts on Natura 2000 sites are evaluated separately.

Impact magnitude	Criteria/conditions
Negligible	An insignificant number of animals is affected and/or disturbances are very short (such as startle responses), without any significant effect on the time budget of the affected animals. The total impact on the habitat is therefore insignificant.
Minor	Disturbance of small parts of the available habitat and/or over short periods, unlikely to affect the overall integrity of the available habitat and hence the energy budget of the animals significantly.
Moderate	Significant disturbance of considerable parts of the available habitat and/or over extended periods, effectively reducing the available habitat and hence the energy budget of a significant number of animals.
Major	Extensive disturbance of large areas and over long time, effectively reducing the available habitat and hence energy budget of a significant number of animals, sufficient to affect reproductive success and survival.

The key to assessing magnitude of the impact is a judgement of the possible energetic consequences (additional energy expenditure and reduced food intake) of the disturbance and the likelihood that these would be reflected in significant changes to vital parameters (survival and fecundity).

4.4 Masking

Impact from masking caused by impulsive noise from pile driving is very difficult to assess. Continuous noise can be assessed through the concept of the range reduction factor, which is a dimensionless ratio of the maximum communication range under conditions masked by anthropogenic noise and under natural ambient noise conditions (Møhl 1981). Adaptation of this concept has not been done by anyone for impulsive noise and no other usable frameworks for assessment of masking from impulsive noise are available. Assessment has thus been performed by means of more descriptive, qualitative measures, as listed in **Table 4 4**. By factoring in the fraction of a population affected and its conservation status, the intensity can be translated into the impact magnitudes in **Table 4 4**. Thus, a small masking intensity, but affecting a large fraction of a vulnerable population can translate into a moderate or even major impact. Similarly, even a large masking intensity, but affecting only a small fraction of a population in favourable conservation status can translate into a minor population impact.

Table 4 4. Criteria for assessing intensity of masking by pile driving noise.

Intensity	Criteria/conditions
Negligible	Lack of overlap in frequency between masking noise and sounds potentially masked and/or noise only rarely above natural ambient at location of animals.
Minor	Overlap in frequency between masking noise and sounds potentially masked, but noise only above natural ambient at location of animals for short periods.
Moderate	Overlap in frequency between masking noise and sounds potentially masked. Noise above natural ambient at location of animals for longer periods of time and considered able to reduce communication/detection range of important signals significantly.
Major	Overlap in frequency between masking noise and sounds potentially masked. Noise likely to reduce communication/detection range of important signals over extended periods of time and to a degree where normal behaviour of the animals are significantly affected.

4.5 Disturbance of Natura 2000 sites

Disturbances of Natura 2000 sites are of special importance, as EU member states are required to protect Natura 2000 sites from severe negative impact, which may otherwise jeopardize the long-term integrity of the areas or the viability of the population of animals inside the protected area. Therefore, the disturbance of Natura 2000 sites from pile driving noise is considered sepaately in this impact assessment.

The EU Natura 2000 protection objectives makes intuitively sense for sessile or relatively stationary species, such as reef-dwelling fish, indicating that neither the habitat itself (the reef), nor the organisms (the fish) should be disturbed, even if only temporarily, to a degree where the fish population cannot be safely assumed to recover fully following the impact. For marine, wide-roaming species, such as marine mammals, however, the interpretation is less intuitive, in particular when the impact is a disturbance caused by for example underwater noise, which only affects the animals (by deterring them) and not the habitat itself. Porpoises and seals are wide-roaming, which means that they will not spend all their time inside the Natura 2000 site and they certainly do not rely on the site for day-to-day survival in the same way as a reef-dwelling fish relies on a reef, for example. In other words, disturbance of animals inside a Natura 2000 site may lead to their (temporary) displacement from the area, but they will be displaced to adjacent areas, which they are expected to utilize as well under normal conditions. The only difference is that the affected animals will end up spending less time in the Natura 2000 site and more time in the adjacent areas, compared to the undisturbed situation. The adjacent areas must be presumed to be less favourable than the Natura 2000 sites (almost by definition, as the Natura 2000 sites should be the most important areas to the species), which, everything else being equal, should mean that displacement from the Natura 2000 site will result in a reduced carrying capacity of the region as a whole (Tougaard, et al. 2013).

Changes in population sizes caused by such displacements to inferior habitats, when caused by single projects, such as an offshore wind farm, are so small that they are impossible to measure directly by surveys or otherwise.

Instead they have to be modelled, through agent-based population models, such as the DEPONS framework (Nabe-Nielsen, et al. 2018). However, these models are still in their infancy and the results do not yet have a sufficient precision to allow assessment of individual projects either. This means that there is currently no consensus on a data-driven approach to derive estimates of permissible disturbance to porpoises inside habitat areas.

Nevertheless, the British Joint Nature Conservation Committee (JNCC), were requested advice on exactly this issue and have provided guidance in a recent report (JNCC 2020c). The key recommendations are summarized as:

A) The project must not disturb more than "20 % of the relevant area of the site in any given day", and

B) The project must not cause disturbance above "an average of 10 % of the relevant area of the site over a season".

Whereas the justification for the numbers should be found in the JNCC report (JNCC 2020c) and the background report (JNCC 2020a), the following will provide an interpretation of the guidance in relation to the Kattegatt Syd Offshore Wind Farm.

"Disturbance"
By disturbed area is understood the area where the sound pressure level, frequency weighted according to the most recent reviews (National Marine Fisheries Service 2016; Southall, et al. 2019) and expressed as a short-term rms-average (Tougaard, et al. 2015; Tougaard and Beedholm 2019), is predicted to exceed the threshold for behavioural reactions of porpoises. There is little consensus on the numerical value of this threshold. The sole review of the available data suggested a value approximately 50 dB above the hearing threshold for porpoises (Tougaard, et al. 2015), which translates into a threshold of $L_{eq\text{-}125ms}$ 100 dB re. 1µPa, VHF-weighted (Southall, et al. 2019), which has been used in other impact assessments, such as the Swedish Kriegers Flak Offshore Wind Farm (Tougaard and Mikaelsen 2018; Tougaard and Mikaelsen 2020).

"Relevant area"
In the context of the Kattegatt Syd offshore Windfarm the relevant area is interpreted as the Lilla Middelgrund Natura 2000 site to the north and the Stora Middelgrund & Röda Bank Natura 2000 site to the south (see **Table 1.1**). Besides, impact is also assessed for other relevant Natura 2000 sites in the area (**Table 1.1**).

"20 % ... in any given day"
In a precautionary way, this is interpreted such that the disturbed area should remain below 20 % of the Natura 2000 sites for pile driving of each of the turbine foundations.

"Season"
The season is defined by JNCC as either winter (October-March) or summer (April-September). However, we interpret the season in a more restrictive way, as the construction period spanning from the day of the first pile driving to the day of the last pile driving.

"An average of 10 %"

No specific guidance is provided by JNCC regarding interpretation of the average. We interpret the average in a precautionary way as the average of the daily maximum disturbance caused by pile driving, on days when they occur, and all other noise-generating activities related to the construction (primarily ships) on days when they are present.

$$Disturbed\ fraction = \frac{1}{N}\sum_{i=T_1}^{T_N}\frac{\max(A_{disturbed})_{i^{th}\ day}}{A_{total}} \cdot 100\ \%$$

where $A_{disturbed}$ is the area predicted to be disturbed from pile driving and all other activities related to the construction, A_{total} is the total area of the Natura 2000 sites, N is the number of days between the first piling (on day T_1) and the last piling (on day T_N).

Reduction of piling noise in Natura 2000 sites

Based on the definitions above, NIRAS calculated disturbance percentages for the nearby Natura 2000 sites (Appendix 1 Sound propagation modelling) considering monopile installation of 14 m monopiles at three locations within the Kattegatt Syd offshore windfarm site. The calculations were done for two months, July and December, representing best and worst cases scenarios, respectively, with regards to sound propagation conditions. The differences between the months pertains to differences in the mixing of the water column, which affects the sound transmission probabilities such as the refraction of sound towards the surface.

Assessment of impact in Natura 2000 sites

Since national Swedish guidelines for evaluating impacts on Natura 2000 sites are missing, this assessment builds on the JNCC guidelines (JNCC 2020b), which is the presently only guidelines in this respect. The impact will be evaluated according to these guidelines, which means that;

< 20 % disturbance = acceptable disturbance for single days
> 20 % disturbance = unacceptable for single days.

Across the construction phase, the disturbance is evaluated as average disturbance per day across the duration of the construction phase;

< 10 % = acceptable
> 10 % = unacceptable.

Impact from gravitation foundations

Due to the proximity of the windfarm to two Natura 2000 sites, alternatives to pile driving is considered. One such option is gravitation foundations to reduce the emitted noise. The main noise source associated with the installation of gravity based foundations is considered to be the installation vessels themselves. These vessels are used to prepare the seabed and to position the piles. Therefore, in this assessment, vessel noise is the noise source considered in terms of potential impacts on marine mammals.

5 Noise exposure model

The core of the assessment framework is an exposure model (**Figure 5.1**) developed according to principles outlined in the Danish guidelines (Skjellerup, et al. 2015). The implementation of the exposure model is described in detail in appendix 1 and is aimed at quantifying the exposure to individual marine mammals during pile driving in a way that considers key factors. These factors include properties of the sound source, mitigation measures such as soft start, sound transmission properties of the environment, evasive behaviour by the animals and the thresholds for developing PTS, TTS and behavioural disturbance. All details on selection of input parameters can be found in Appendix 0.

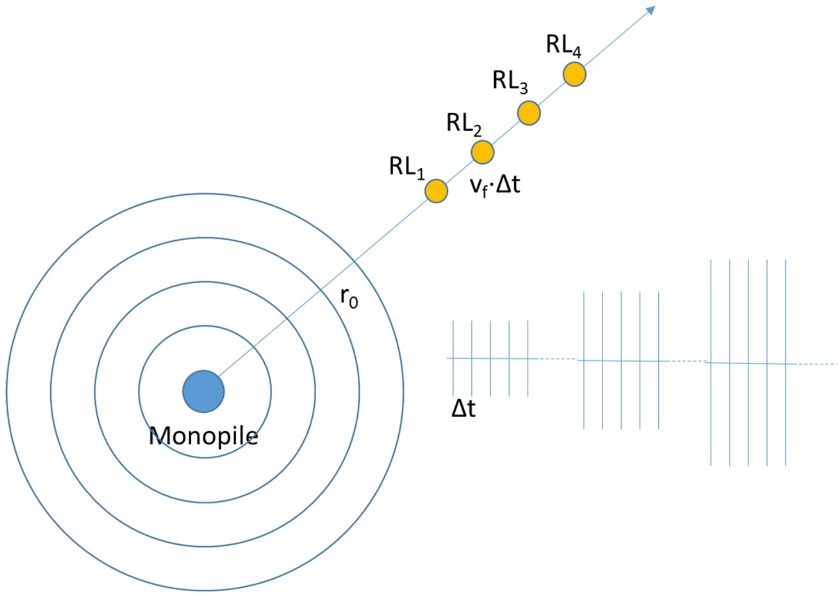


Figure 5.1. Schematic top view of model of noise exposure to a marine mammal. The animal is at distance r_0 at the time of the first piling strike and receives a series of pulses with decreasing level (RL), as it moves away with a constant speed v_f. The source level of pulses increases with time, consistent with a soft start scenario.

5.1 Cumulated sound exposure level

The aim of the exposure model is to estimate the total acoustic energy, or cumulated sound exposure level (SEL_{cum}) that an animal has been exposed to at the end of a pile driving. This cumulated sound exposure level is the sum of the energy of the individual pile driving pulses, E_i, at the position where the animal is at corresponding time t_i.

Equation 5.1

$$\boldsymbol{SEL_{cum} = 10\log_{10}\frac{\sum E_i}{E_0}}$$

Where E_0 is the reference energy level (1 µPa²s).

The received energy E_i for an animal at distance r_i from the pile at the time of the i'th pulse can be found from the source energy level at 1 m of the i'th pulse (SL_i) minus the transmission loss (TL):

Equation 5.2

$$\boldsymbol{E_i = SL_i - TL(r_i)}$$

SL_i is the source energy flux level back-calculated (see 5.2 below) to 1 m given in dB re 1 µPa²s.

Combining **Equation 5.1** and **Equation 5.2** and gives the SEL_{cum} after reception of the N'th pile driving pulse:

Equation 5.3

$$\boldsymbol{SEL_{cum}(N) = 10\log_{10}\sum_{i=1}^{N} 10^{\frac{SL_i - TL(r_i)}{10}}}$$

5.2 Source level

Source level expresses the energy flux level (i.e. acoustic energy flowing through a 1 m^2 surface perpendicular to the direction of sound propagation) or sound pressure level, both expressed 1 m from the source. For complex sound sources, such as monopiles, the source level is always back-calculated to 1 m from measurements made several hundred meters away, as there is no physical point, which can be said to be 1 m from the centre of the sound source (the monopile). This means that the source level represents the point source equivalent level, i.e. the sound level 1 m from a true point source, which has the same far field properties as the monopile.

If the source level emitted during piling can be assumed to scale directly with the energy delivered to the monopile by the hammer, then SL_i can be found from the maximum source energy flux level back-calculated to 1 m (SL_{max}) at maximum hammer impact energy and the actual hammer energy of the i'th stroke, S_i.

Equation 5.4

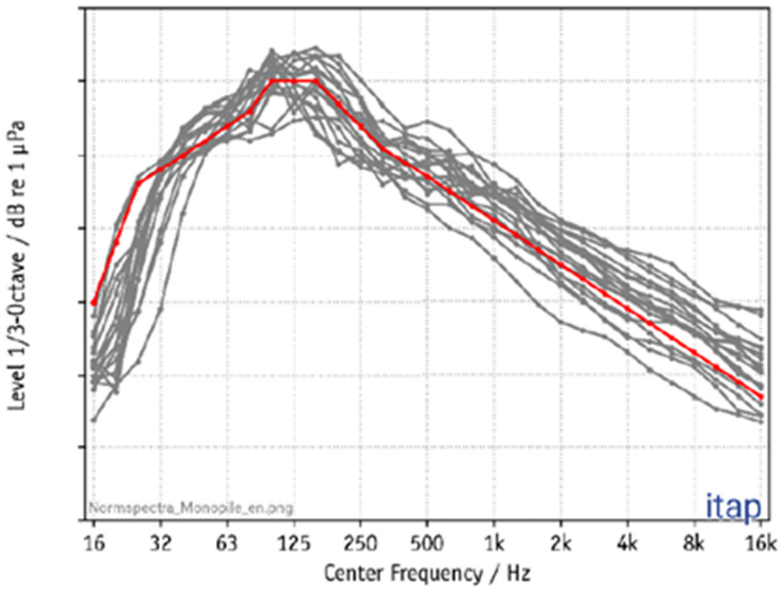
$$\boldsymbol{SL_i = SL_{max} + 10\log_{10}\frac{S_i}{100\%}}$$

A realistic scenario for a pile driving operation is thus needed. This means that an entire sequence of piling strikes with time of occurrence and hammer energy is required. The soft start sequence can be very variable; sometimes only a few rapid blows are needed to get the pile in place for penetration but sometimes extensive realigning of the pile is required before the main sequence can begin. This means that it can be difficult to model the duration of the soft start. However, modelling the soft start as a series of low-level strikes with constant strike rate will likely lead to an overestimation of SEL_{cum} and is thus precautionary.

5.3 Source specification at maximum hammer energy

Modelling was performed for a monopile diameter of 14 m. Source level and spectrum were estimated and extrapolated from recordings from a number of pile drivings in the North Sea, as described in Tougaard and Mikaelsen (2018). Maximum hammer energy was set to 6000 kJ per strike and a total of 10350 strikes per pile was expected. The estimated source spectrum at maximum hammer energy was obtained from (Bellmann, et al. 2020) and is shown in Figure 5.2. The broadband (unweighted) source level (SL_{max}) was estimated to be 227.7 dB re. 1 µPa^{2}s, also estimated from Bellmann et al. 2020 by extrapolating the relationship between pile diameter and source level (figure 1 in Bellmann, et al. 2017).

Figure 5.2. Idealized pile driving frequency spectrum (red) used for modelling of sound transmission from 14 m monopile. Source: (Bellmann, et al. 2020).



The propagation model was only run with a source spectrum and level estimated to be representative of piling with a noise abatement system (NAS) of either Big Bubble Curtains or Double Big Bubble Curtains and Hydro Sound Dampeners in place.

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 in source level is therefore included, resulting in $SEL_{@1m}$ = 229.7 dB re. 1 µPa^{2}s. The source level is presented in all relevant metrics and combinations between frequency weighting and source levels unmitigated, with BBC NAS, and with HSD-DBBC NAS in for reference.

Table 5 1. Source Level for 14 m monopile, with and without frequency weighting and mitigation.

Frequency weighting	Source level ($SEL_{@1m}$) [dB re. 1µPa^{2}s]		
	Unmitigated	With Big Bubble Curtain (BBC)	With Hydro Sound Damper Double Big Bubble Curtain (HSD-DBBC)
Unweighted	229.7 dB	210.3 dB	209.1 dB
VHF Cetaceans	183.6 dB	159.9 dB	151.6 dB
Phocid Pinniped	208.5 dB	184.0 dB	182.1 dB

5.4 Pile driving scenario

For Kattegatt Syd offshore windfarm site a total of 60 monopiles each of 14 m diameter is expected to be piled down. The following sequence of hammer energy (S_i in **Equation 5.4**) was used for the 14 m monopile:

Soft start phase (10 minutes)

- 150 pile strikes at 10% hammer energy and strike rate of 15 / min.

Ramp-up phase (20 minutes)

- 75 pile strikes at 20% hammer energy and strike rate of 15 / min
- 75 pile strikes at 40% hammer energy and strike rate of 15 / min
- 75 pile strikes at 60% hammer energy and strike rate of 15 / min
- 75 pile strikes at 80% hammer energy and strike rate of 15 / min.

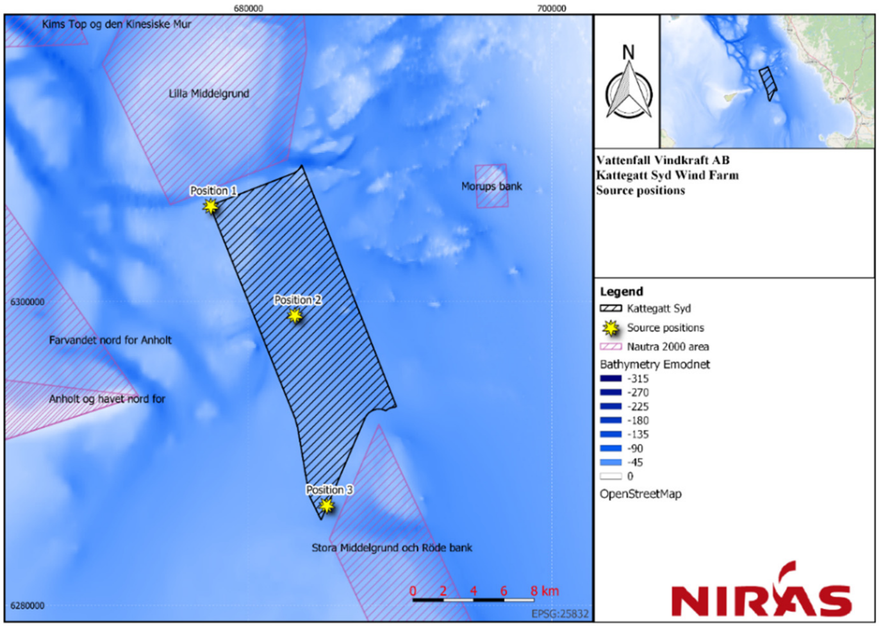
Full hammer energy phase (4.2 hours)

- 9900 pile strikes at 100% hammer energy (6000 KJ) and strike rate of 30 / min.

This pile driving scenario has a total duration of 6 hours.

Three sites were chosen for the modelling (Figure 5.1), and for all, modelling was performed for July, and for the southern and northern location, also December was modelled. The two months represents very different scenarios with regards to sound transmission properties, where summer is best case and winter is worst case. The border of the windfarm site is placed 1 km from the border of the surrounding Natura 2000 sites, and the northern and southern modeling sites are thus very close to the border and therefore presents worst case with regards to effects on the Natura 2000 sites.

Figure 5.3. Positions for the noise exposure modelling. Notice that not all Natura 2000 sites are appointed for marine mammals.



5.5 Transmission loss

Transmission loss can be modelled in different ways, ranging from a proper modelling based on bathymetry, hydrography and sediment properties to heuristic models based on actual measurements under conditions comparable to the project under assessment. Simple, heuristic models have the advantage of being transparent, which is a desirable feature in relation to an impact assessment. A key purpose of impact assessments is to allow not only authorities but also independent experts to judge the methods used in the assessment. This transparency can also be achieved by using well documented and open source modelling tools, but is compromised if modelling is performed by proprietary modelling tools. It is thus a fair demand for modelling within the context of an EIA that sufficient details about modelling methodology and input variables are supplied to allow others to verify the modelling results and compare these to results from alternative modelling methods.

When it comes to pile driving in shallow waters, there is considerable evidence that pile driving noise follows a rather simple transmission loss model. See for example Bailey, et al. (2010) and Nehls and Bellmann (2016). A generalised model can be realised with two constants specific to the construction site, κ and α:

Equation 5.5

$$TL(r) = \kappa \log_{10} r + \alpha r$$

κ expresses the slope of the geometric spreading loss and α is the volume absorption coefficient.

Sound exposure for the exposure assessment was modelled for two selected positions by NIRAS and for two months (July and December). The methodology is described in Appendix 0.

All modelled maps for combinations of the three pile driving positions two seasons (July and December), and three different frequency weightings (unweighted, VHF-cetacean and Phocid seals) are shown in Appendix 1**Error! Reference source not found.**. Position 1 and 3 are only modelled for December as piling at these positions will impact the nearby Natura 2000 sites.

Ambient noise (both natural and man-made) has not been included in the modelling of pile driving noise. Ultimately, the extent of the pile driving noise will be limited by the ambient noise, but this noise is expected to be at least 20 dB below the 150 dB re. 1 μPa^{2}s contour, which was the lowest level included in the modelled maps. Ambient noise levels in the region are discussed further below in section 9.1, in connection with noise from operational turbines.

Transmission loss curves for the worst case scenario (the direction where loss was smallest) were estimated by **Equation 5.5**.

5.6 Deterrence of animals

An important element of the model is the incorporation of animal responsive movement to the pile driving sound. If the animal moves away from the pile driving site the received noise will (on average) go down and hence reduce the overall sound exposure of the animal. For small cetaceans there is ample evidence that they respond by moving away from loud noise sources (Johnston 2002; Olesiuk, et al. 2002; Brandt, et al. 2012; Tougaard, et al. 2012). The reaction to pile driving noise has been documented in several studies (Tougaard, et al. 2009; Brandt, et al. 2011a; Dähne, et al. 2013) and all are consistent with porpoises moving out to distances of tens of kilometers from pile driving sites during piling. If a constant speed of fleeing away from the source, v_f is assumed then the distance r_i at time of the i'th pulse is:

Equation 5.6

$$r_i = \begin{cases} r_0 + v_f(t_i - t_0) \; for \; t_i \le \frac{r_{max} - r_0}{v_f} + t_0 \\ r_{max} \; for \; t_i > \frac{r_{max} - r_0}{v_f} + t_0 \end{cases}$$

Where r_0 is the distance of the animal at t_0, start of the piling, t_i is the time of the i'th pulse and r_{max} is the maximum distance, beyond which animals no longer move away from the noise. Combining **Equation 5.6** with the transmission loss model (**Equation 5.5**) gives the following expression for transmission loss of the i'th pulse:

Equation 5.7

$$TL_i = \kappa \log_{10} r_i + \alpha r_i = \kappa \log_{10}\big(r_0 + v_f(t_i - t_0)\big) + \alpha\big(r_0 + v_f(t_i - t_0)\big)$$

Equation 5.2, **Equation 5.4** and **Equation 5.7** can be integrated into one equation expressing the cumulated noise exposure level (SEL_{cum}) experienced by an animal after N blows of the piling sequence.

Equation 5.8

$$SEL_{cum}(N) = 10 \log_{10} \sum_{i=1}^{N} 10^{\frac{SL_{max} + 10 \log_{10} \frac{S_i}{100\%} - \kappa \log_{10}(r_i) - \alpha r_i}{10}}$$

where r_i is given by **Equation 5.6**. For a given piling scenario where SL_{max} and SL_i are specified and a given location where sound transmission is known (constants κ and α) the sound exposure level experienced by an animal at the end of a pile driving operation will be determined by the distance from the pile at start, r_0 and the flee speed v_f. All else being equal, the closer the animal is at start and the slower the animal moves away, the larger the cumulated sound exposure.

Equation 5.8 is the core of the model. As inputs are required a source energy level at maximum hammer energy (SL_{max}), a transmission loss model (given by the parameters α and κ), a sequence of pile driving strikes, each represented by their hammer energy (S_i) and a starting distance, r_0, and flee speed of the animal, v_f. Output of the model is the cumulated SEL experienced by this particular animal at the end of the pile driving sequence, corresponding to the complete piling of one foundation. This SEL_{cum} can then be compared to the thresholds for TTS and PTS, respectively (sections 3.3.5 and 3.3.6 above), by which it can be judged whether the animal would be likely to experience TTS / PTS or not.

The key features of the model is transparency and flexibility. The method for computing SEL_{cum} remains constant but the input elements can be replaced to fit a particular piling project and updated as newer and better information becomes available.

The assumptions underlying derivation of source parameters and transmission loss are described in details in Tougaard and Mikaelsen (2018), whereas the flee velocity and start distance are discussed in the following, as well as described in the appendix 1.

5.6.1 Flee velocity, v_f

A critical parameter in the modelling is the speed at which animals are assumed to flee from the sound source. This has not been measured directly, but various measures of sustained swimming speed in porpoises and other odontocetes are available.

Kastelein, et al. (2018) measured the swimming speed of a porpoise in a small tank during 30 minutes of exposure to pile driving sound. During this period the average swimming speed of the porpoise was 7.1 km / h, equal to 2 m / s. The experimental conditions were very unlike a real pile driving in the sense that the animal could only swim in circles in the 10x12 m pool and thus never managed to distance itself from the sound source. Nevertheless, it shows that porpoises are capable of a sustained swimming speed of 2 m/s for at least 30 minutes. Otani, et al. (2000) measured swimming speed on an unrestrained, wild porpoise over a period of 23 hours, during which the animal was undisturbed. The average swimming speed was 0.9 m/s and maximum speed 4.3 m/s. In contrast to the study of Kastelein, et al. (2018) the animals were undisturbed and measurements are thus likely to be in the low end of what the animals are capable of if actively fleeing from a disturbing sound.

Other species of odontocetes are capable of considerable sustained speeds. Lockyer and Morris (1987) measured maximum swimming speeds in bottlenose dolphins over short periods of about 4 m/s, going down to about 1 m/s for a single observation of sustained swimming over 20 minutes. Killer whales are easily capable of sustained average swim speeds of 1.6 m/s (Williams and Noren 2009), despite their much larger size. Overall, it seems a precautionary assumption that porpoises can sustain a swimming speed for an extended period of 1.5 m/s, roughly corresponding to one body length per second. Even if the swimming speed decreases after some tens of minutes the animal will by then be so far away that the decrease in speed will have very little effect on the total modelled sound exposure (as discussed in section 0 below).

Few data are available on swimming speed of seals. A single study on grey seals, however, is fully consistent with 1.5 m/s as also being a reasonable, precautionary estimate for seals (Gallon, et al. 2007).

5.6.2 Distance at first exposure, r_0

The exposure modelling used for this assessment assumes a noise abatement system in the shape of either a Big Bubble Curtain or hydro sound dampeners in combination with Double Big Bubble curtains to reduce the size of the impacted area. Assuming that PTS is unacceptable, the animals must be scared out of the zone of PTS, at the time of the first hammer impact. This is shown here, to be around < 25 m with either of the modelled noise abatement systems (Table 6.1). With several vessels in the area to operate both the hammer as well as the noise abatement system, it is assumed, in accordance with Bas et al. 2017, that porpoises will be displaced by at least 500 m from a given vessel. It is therefore unlikely that porpoises will be within the < 25 m (or < 100 m) of the pile at first impact, which could inflict PTS (TTS). Such studies do not exist for harbour or grey seals, however based on the number of vessels present, it is here assumed that seals are equally displaced by at least 500 m from a given vessel, and thereby outside the range where PTS (< 25 m) or TTS (< 50 m) could be inflicted. The modelling therefore do not include use of seal scarer or pingers to deter animals before the first piling.

5.6.3 Maximum flee distance, r_{max}

For porpoises the maximum flee distance is at least 20 km for pile driving without bubble curtains or other reduction of radiated noise levels (Tougaard, et al. 2009; Brandt, et al. 2011a; Dähne, et al. 2013; Haelters, et al. 2015). Fewer data are available for pile driving with noise reduction in the form of bubble curtains. One study indicated a reduction to about 12 km with the use of a bubble curtain (Dähne, et al. 2017), whereas another study (compiling data from 7 offshore wind farms) indicated that the maximum distance does not decrease by the use of bubble curtains, but the proportion of affected animals and the duration of the disturbance decreases (Brandt, et al. 2018). Using a lower value of r_{max} is precautionary (as this will overestimate the exposure in the last part of the pile driving) and thus a value of 12 km was selected.

Little data is available for seals. One study on harbour seals indicated roughly similar reaction distances as for porpoises, i.e. at least 20 km (Russell, et al. 2016), but no data are available for pile driving with a bubble curtain or hydro sound dampeners. In the absence of data the same values were assumed for seals and porpoises.

5.7 Gravitation foundations

Alternatives to piling are considered due to the position of the potential wind-farm between the Lilla Middelgrund and the Stora Middelgrund & Röde Bank Natura 2000 sites. One such alternative is installation by gravitation. As the primary source of underwater noise from such installations is considered to be vessel noise, the impact will be assessed based on available evidence on disturbance distances for vessels.

6 Results of the exposure model

NIRAS modelled impact ranges for seals and harbour porpoises as described in detail above and in Appendix 1 Sound propagation modelling. All scenarios modelled are shown in Appendix 1 Sound propagation modelling and final impact distances for all scenarios are listed in **Table 6.1**.

Figure 6.1 shows a worst case example of the results of the exposure modelling with BBC abatement in December. It is obvious that a large part of the Natura 200 site Stora Middelgrund & Röda Bank is exposed to noise levels above the porpoise disturbance threshold and the JNCC recommendation that a maximum of 20 % of a Natura 2000 site should be with noise levels this high is exceeded. Compare with **Figure 7.1** and **Figure 7.2** to see effect of BAT noise abatement and season.

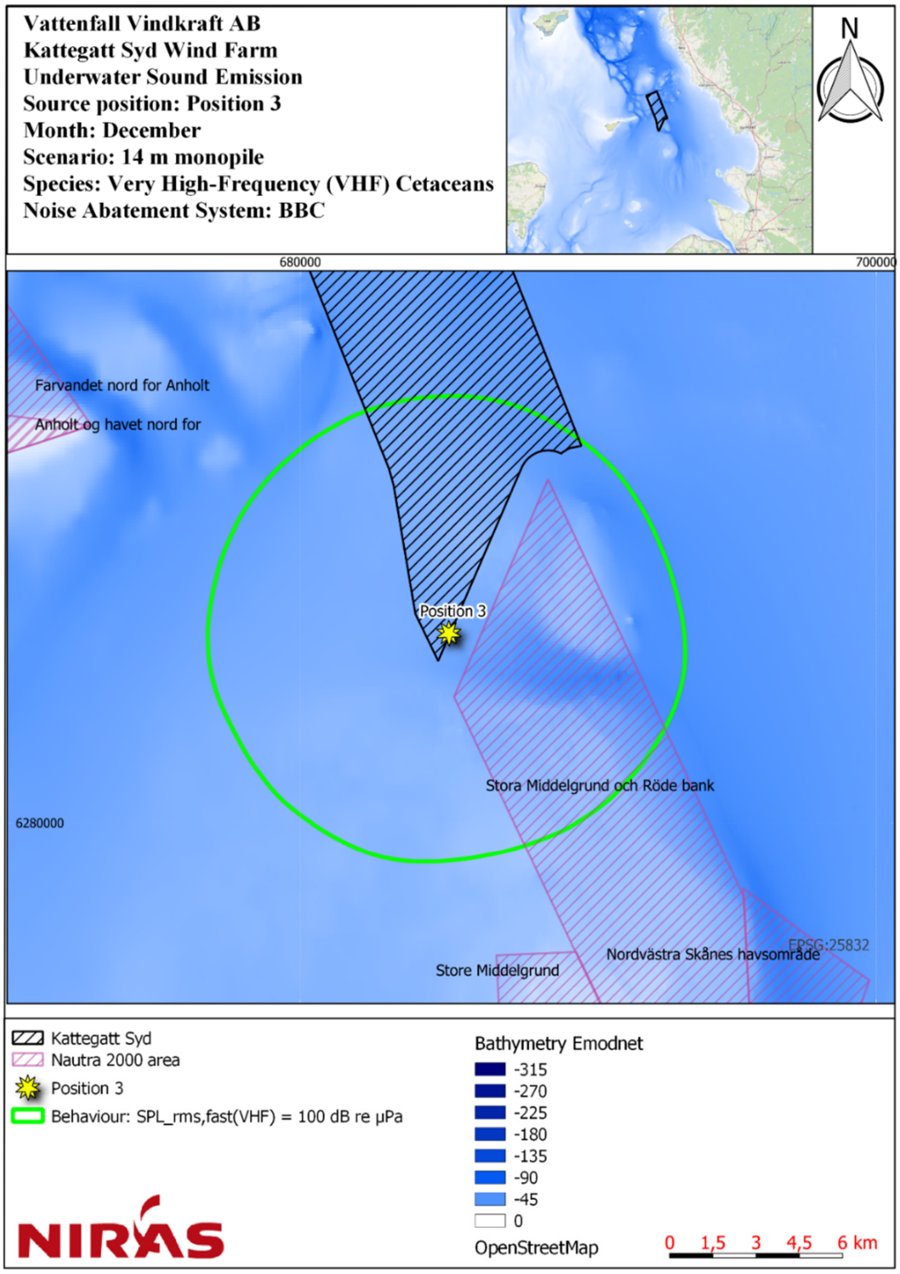


Figure 6.1. Example from the exposure modelling: Noise contour map for position 3 in December, showing impact distance for behaviour with VHF-weighting and BBC. The green line denotes the behavioural threshold for harbour porpoises.

Table 6.1. Threshold impact distances for 14 m monopile installation scenarios for porpoises and seals. SEL was weighted with the appropriate frequency weighting (VHF cetaceans and phocid seals, respectively). All results include source mitigation equal to the effect of either BBC or HSD + DBBC. Position 2 was modelled for July only and positions 1 and 3 for July and December. See Appendix 1 Sound propagation modelling for further explanations and underlying assumptions

Hearing group	Representative species	Fleeing speed [m/s]	Position	Month	Mitigation	Distance to impact threshold [m]		
						SEL_{C24h}*		$SPL_{RMS-fast}$*
						TTS	PTS	Behaviour
Very High-Frequency Cetaceans	Harbour porpoise	1.5	Position 1	December	BBC	90	< 25	7950
			Position 1	December	HSD-DBBC	< 50	< 25	5550
			Position 1	July	BBC	60	< 25	3700
			Position 1	July	HSD-DBBC	< 50	< 25	2600
			Position 2	July	BBC	70	< 25	4250
			Position 2	July	HSD-DBBC	< 50	< 25	2950
			Position 3	December	BBC	90	< 25	8350
			Position 3	December	HSD-DBBC	< 50	< 25	5700
			Position 3	July	BBC	60	< 25	4000
			Position 3	July	HSD-DBBC	< 50	< 25	2750
Phocid Pinniped	Harbour seal		Position 1	December	BBC	< 50	< 25	-
			Position 1	December	HSD-DBBC	< 50	< 25	-
			Position 1	July	BBC	< 50	< 25	-
			Position 1	July	HSD-DBBC	< 50	< 25	-
			Position 2	July	BBC	< 50	< 25	-
			Position 2	July	HSD-DBBC	< 50	< 25	-
			Position 3	December	BBC	< 50	< 25	-
			Position 3	December	HSD-DBBC	< 50	< 25	-
			Position 3	July	BBC	< 50	< 25	-
			Position 3	July	HSD-DBBC	< 50	< 25	-

"-" A generic threshold for behavioural responses is not available for seals. * Threshold level is frequency weighted (VHF-weighting)

A number of conclusions are evident from table 6.1:

- The effect of the best noise abatement system (Hydro Sound Dampeners + Double Big Bubble Curtain) is considerable, for mitigating disturbance of porpoises.
- The difference between the months of December and July is considerable with respect to behaviour, with app. double the impact range in December versus July for porpoises and presumable the same for

seals (not addressed in the model, as no behavioural threshold for seals exist) with July being the best month in terms of the size of the disturbed area (Best Environmental Practice).

- There is little difference in disturbance range between turbine position 1, 2 and 3.

7 Results of the analysis of disturbance

Disturbance can be assessed as the area exposed to noise levels above the behavioural reaction threshold, but it is also of relevance to estimate the number of animals exposed to these noise levels. Estimating the number of exposed animals requires knowledge about the abundance and distribution of the animals, which then can be combined with the exposed area to yield an estimate. This estimate can be as an absolute number of animals, or the fraction of the population.

Abundance information for marine mammals comes from surveys and is usually expressed either in the form of an average density based on survey observations, or as a density surface, modelled from the observed data together with environmental co-variates. Here, we used the average density obtained from the SCANS surveys conducted in summer 2016 of app. 1 harbour porpoise per square kilometer as well as the abundance of porpoise in south Kattegat and the Belt Seas of app. 42.000 individuals (Hammond, et al. 2017). The density and abundance in winter has not been measured, so the calculations are estimated to be similar across the year. In Figure 7.1 the results of a habitat suitability model (Sveegaard, et al. 2018a) is shown for the inner Danish Waters, with the approximate position of the Kattegatt Syd offshore windfarm indicated. The model builds on satellite tracked porpoises. The results of the model show that the wind farm area is important for porpoises in summer, and slightly less in winter. The calculated affected number of animals may therefore be a worst case estimate (**Table 7.1**).

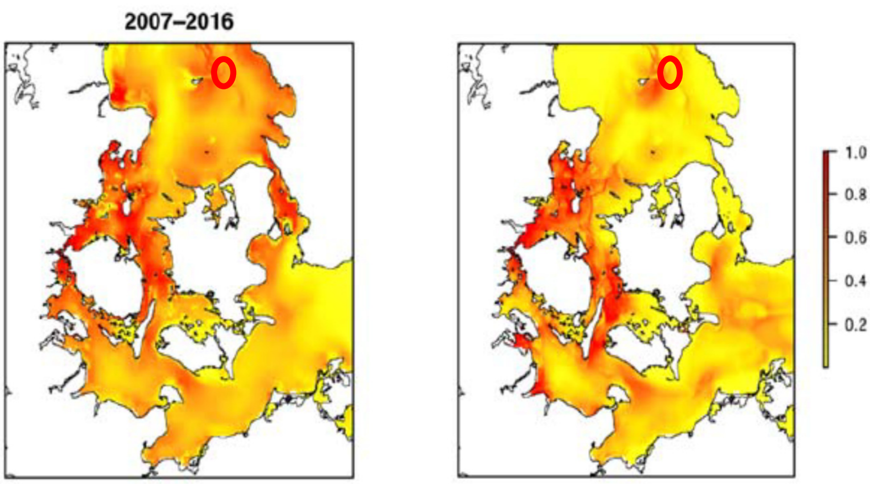
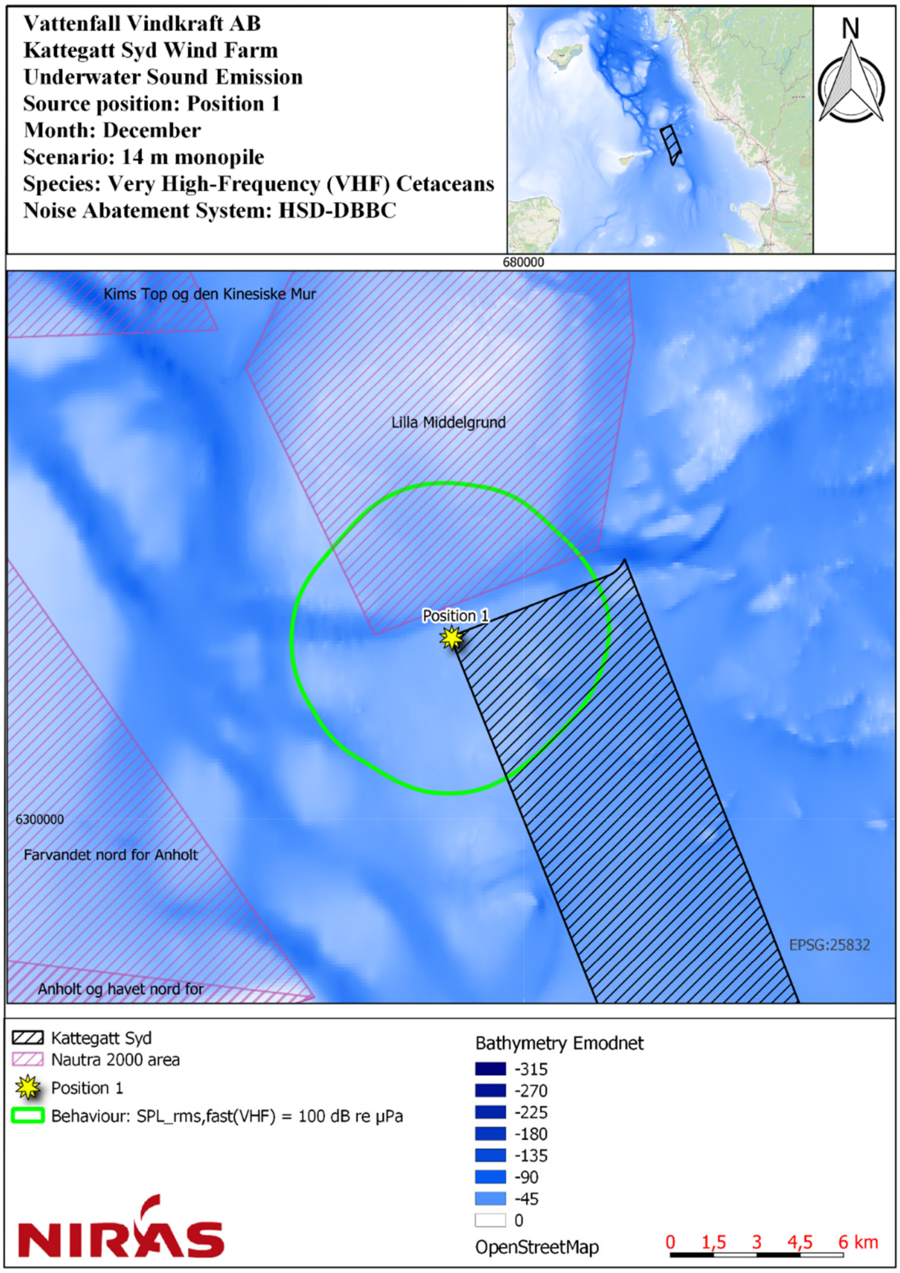


Figure 7.1. Habitat suitability models for porpoises, summer 2007-2016 (see section 1.2.1, Figure 5.1). Left is summer and right is winter. The scale represents the relative likelihood of the habitat being suitable for porpoises based on MaxEnt modelling of satellite tracked porpoises and environmental parameters. Map from (Sveegaard, et al. 2018b).

7.1 Modelled exposure of porpoises

$SPL_{RMSfast,VHF}$, weighted with the porpoise audiogram (VHF-weighting (Southall, et al. 2019)) was modelled throughout the SE-Kattegat around the wind farm area under different conditions to assess the behavioural threshold for disturbances of porpoises. This threshold was also used as the maximum deterrence range for seals, as no threshold presently exists for seals. The worst case with only BBC abatement is in December at position 3 (Figure 6). In **Figure 7.1** results of modelling at the same position is shown with BAP abatement with DBBC + HSD (or similar) and in **Figure 7.2** the results are shown for BAP and BEP for modelling in July with DBBC+HSD abatement.

Figure 7.1. Example of modelling result with BAT noise abatement, but in the worst season at position 3. The green line denotes the behavioural threshold at 100 dB $SPL_{RMS,fast\ (VHF)}$ for porpoises after inclusion of BBC abatement. The size of the area where behavioural disturbances are expected for harbour porpoises is 97 km^2 and the overlap with the Natura 2000 site Stora Middelgrund and Röda Bank is 31 km^2 or 27.2 %.



This worst case scenario was based on a 14 m diameter pile and 6000 kJ hammer energy and only abated with Big Bubble Curtains (Figure 6.1).

The mitigating effect of selecting a time of year where sound propagation properties are less favourable for long-range transmission, are evident (compare **Figure 7.1** with **Figure 7.2**). The difference between worst case (December) and best case (July) is a factor 2 in range for the same abatement type. The difference between positions is insignificant compared to the differences caused by the noise abatement system and sound propagation conditions.

The area within which the behavioural and TTS threshold for harbour porpoises has been exceeded is shown in **Table 7.1** along with the percentage of the porpoise population that is affected. As can be seen the disturbed area for the same abatement system is four to five times as large in December as in

July, where the smallest affected area can be obtained with the best available mitigation (DBBC + HSD or similar) in July..

Table 7.1. Disturbance of porpoises from pile driving, expressed as area where modelled pile driving noise level is above the reaction threshold or above the TTS threshold for harbour porpoise. Two types of noise abatement is shown: Big Bubble Curtains (BBC) and Hydrosound Dampeners and Double Big Bubble Curtains (HSD-DBBC). Affected percentage of the porpoise population of south Kattegat and the Belt Sea is also shown

Position	Month	Mitigation	Area of threshold effect for harbour porpoise [km^2]		
			Behaviour [$SPL_{RMS-fast,VHF}$]	% of the porpoise population disturbed	TTS [$SEL_{C24h,VHF}$]
Position 1	December	BBC	187 km^2	< 1 %	< 0,1 km^2
	July		37 km^2	< 1 %	< 0,1 km^2
Position 2	July		53 km^2	< 1 %	< 0,1 km^2
Position 3	December		208 km^2	< 1 %	< 0,1 km^2
	July		40 km^2	< 1 %	< 0,1 km^2
Position 1	December	HSD-DBBC	89 km^2	< 1 %	< 0,1 km^2
	July		19 km^2	< 1 %	< 0,1 km^2
Position 2	July		26 km^2	< 1 %	< 0,1 km^2
Position 3	December		97 km^2	< 1 %	< 0,1 km^2
	July		21 km^2	< 1 %	< 0,1 km^2

7.2 Modelled exposure of harbour seals

As for porpoises, the sound exposure, weighted appropriately with the audiogram for seals, could be modelled for the various scenarios. Because of the better low-frequency hearing of seals compared to porpoises (compare Figure 2 2 and Figure 2 39), the weighted pile driving noise propagates significantly further from the piling site than for the porpoise weighted noise. In the absence of a generalized threshold for behavioural reactions in seals, it is not possible to translate the propagated levels into estimates of reaction distances for seals. However, for this assessment we assume that seals may be disturbed at approximate the same ranges as porpoises and use the maps modelled for porpoises.

7.3 Impact on Natura 2000 sites

In the lack of national guidelines, we have for this assessment adopted the recommendation by JNCC 2020 that no more than maximum 20 % of a given Natura 2000 site must exceed the behavioural threshold for porpoises within any day during installation of the piles (JNCC 2020b) (see chapter 0 above).

Based on the definitions listed in chapter 0, NIRAS calculated disturbance percentages for the relevant Natura 2000 sites (appendix 1) considering installation of a 14 m monopile for three locations within the proposed offshore windfarm site in Kattegat. The minimum range between the modelled position and the border of the Natura 2000 site was 1 km. The disturbed area where noise levels are expected to be above the reaction threshold for harbour porpoises, i.e. the fraction of the Natura 2000 site affected by installation of a single pile, was calculated with the use of either Big Bubble Curtains (BBC) or adoption of Best Available Technology, presently Double Big Bubble Curtains and Hydro Sound Dampeners (DBBC + HSD). The calculations were also done for two months, December and July, representing worst and best case scenarios, respectively, with regards to sound propagation conditions. The differences between the months pertains to differences in the mixing of the water column, which affects the sound transmission probabilities such as the refraction of sound towards the surface.

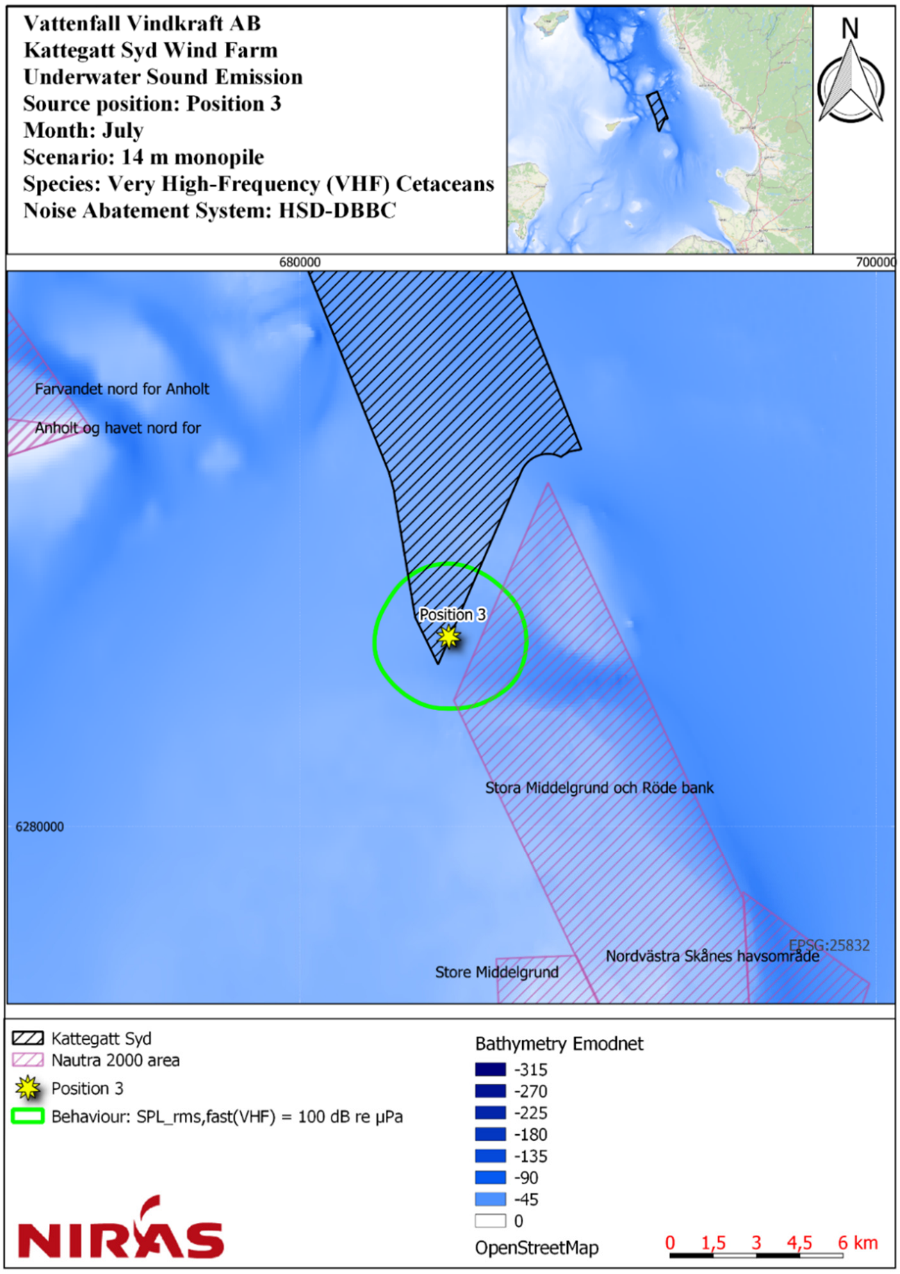
Listed in **Table 7.2** are the estimated disturbed fractions of the nearest Natura 2000 sites in southern Kattegat (see also **Table 1.1**). Only in the sites Stora Middelgrund & Röda Bank and Lilla Middelgrund Natura 2000 sites are the 20 % disturbance threshold exceeded. For no other Natura 2000 sites is the limit of 20 % disturbed area approached with the assessed noise abatement in place.

Table 7.2. Fraction of the closest nearby Natura 2000 sites in southern Kattegat exposed to noise levels above the behavioural reaction threshold for porpoises, modelled with use of a noise abatement system of either BBC or HSD-DBBC for December and July. Only worst case for any location within the site further from the Natura 2000 site than 1 km impact distance for harbor porpoises.

Natura 2000 site	Noise abatement system	Natura 2000 site total area [km^2]	Overlap of harbour porpoise behaviour impact with Natura 2000 site [km^2]		Overlap of harbour porpoise behaviour impact with Natura 2000 site [%]	
			Dec	July	Dec	July
Lilla Middelgrund	BBC	178	52	11	29.2 %	6.2 %
	HSD-DBBC	178	27	5	15.2 %	2.8 %
Anholt og havet nord for	BBC	134	0	0	0	0
	HSD-DBBC	134	0	0	0	0
Stora Middelgrund och Röda Bank	BBC	114	50	12	43.9 %	10.5 %
	HSD-DBBC	114	32		27.2 %	5.3 %

The used criteria for not having a negative impact on Natura 2000 sites (described in section 0 above) is that an overlap of the avoidance behaviour threshold with any Natura 2000 site must not exceed 20 % for any one pile installation (JNCC 2020b). From **Table 7.2**, it is seen that for the BBC noise abatement system, this threshold is exceeded at both Lilla Middelgrund and Stora Middelgrund & Röda Bank in December, however if using an HSD-DBBC system instead, still during winter, the impact is reduced. For Lilla Middelgrund, the 20 % threshold is no longer exceeded with the DBBC + HSD abatement system or similar.

Figure 7.2. Best case example for piling following BAT and BEP principles. Area (green outline), wherein the behavioural disturbance threshold is exceeded during piling of each 14 m monopile installation, $SPL_{RMS\text{-}fast}$ (VHF-weighting) in July. Area is given mitigation with hydro sound dampeners and double big bubble curtains in place, or similar mitigation. The harbour porpoise behavioural threshold is used to define maximum disturbance of Natura 2000 sites following JNCC 2020. Overlay with nearby Natura 2000 site is shown and amounts to 5.3 %.



For Stora Middelgrund, however, the 20 % overlap is still exceeded with an overlap of 27.2 % during December, whereas for July only a 5.3 % overlap occurs. For the months in between July and December, the overlap in %, will gradually change, however it is not possible to determine where the exact time of a 20 % overlap will occur. This is primarily due to the fact, that while calculations are based on best available historical data, the actual conditions during installation are unknown. Depending on weather conditions up to, and during, installation, the sound propagation both regionally and locally can vary significantly.

The current assessment is built on normal (BBC) as well as best available technology (HSD + DBBC) to reduce the impact on the environment. With the present day best available technology it is not possible to obtain noise levels to be below the threshold put forward by JNCC for the winter period and with the present modeling positions. However, with time better noise abatement systems may be developed, allowing additional mitigation, enabling disturbance from the construction to be below the 20 % threshold. When modelled for this assessment it is theoretically only a few dB extra noise abatement that are needed at the source (see Appendix 1 Sound propagation modelling). This implies, that the additional mitigation effect to be achieved must be related to the VHF-frequency weighting function.

An alternative to applying extra mitigation, would be increasing the distance between pile driving activities and the border to the Natura 2000 site to 2 km, which would reduce the overlap to 20 % (see appendix 1).

It is possible to express the combined mitigation requirement for each position and month as a single value SEL that must not be exceeded at 750 m distance, in order to comply with an overlap of maximum 20 % of the nearby Natura 2000 site for the harbour porpoise behaviour metric: $SPL_{RMS,fast(VHF)} = 100\ dB\ re.1\ \mu Pa$. The values are only valid for the months modelled, however will be useable, albeit conservative, for any month with a higher sound transmission loss. The 750 m SEL threshold values are shown in **Table 7.3**, for the different positions and months modelled. It is important to notice, that the allowed noise level at 750 m increases for foundation positions further inside the windfarm area, i.e. further from the border of the Natura 2000 site, than the modelled position.

Table 7.3. Sound Exposure Level ($SEL_{SS,VHF,750m}$) from a single pile strike using maximum hammer energy for each of the modelled scenarios closest to Natura 2000 sites, so that no more than 20 % of the specific Natura 2000 is exposed to noise above the behaviour threshold for harbour porpoises.

Hearing group	Representative species	Natura 2000 site	Month	Position	Sound Exposure Level, at 750 m
					$SEL_{SS@750m}\ [dB\ re.1\mu Pa^2s]$*
Very High-Frequency Cetaceans	Harbour porpoise	Lilla Middelgrund	December	1	112.0 dB
			July	1	124.5 dB
		Stora Middelgrund	December	3	108.7 dB
			July	3	120.0 dB

For July the expected disturbance from piling of a 14 m pile in the middle of the windfarm area is presented in Figure 7.3. The model results show that the disturbed area is significantly smaller than in December (see appendix 1), which is caused by a complete mixing of the water column at this time of the year, which leads to less favourable conditions for long-range sound propagation (iso-velocity, or downward-refracting conditions).

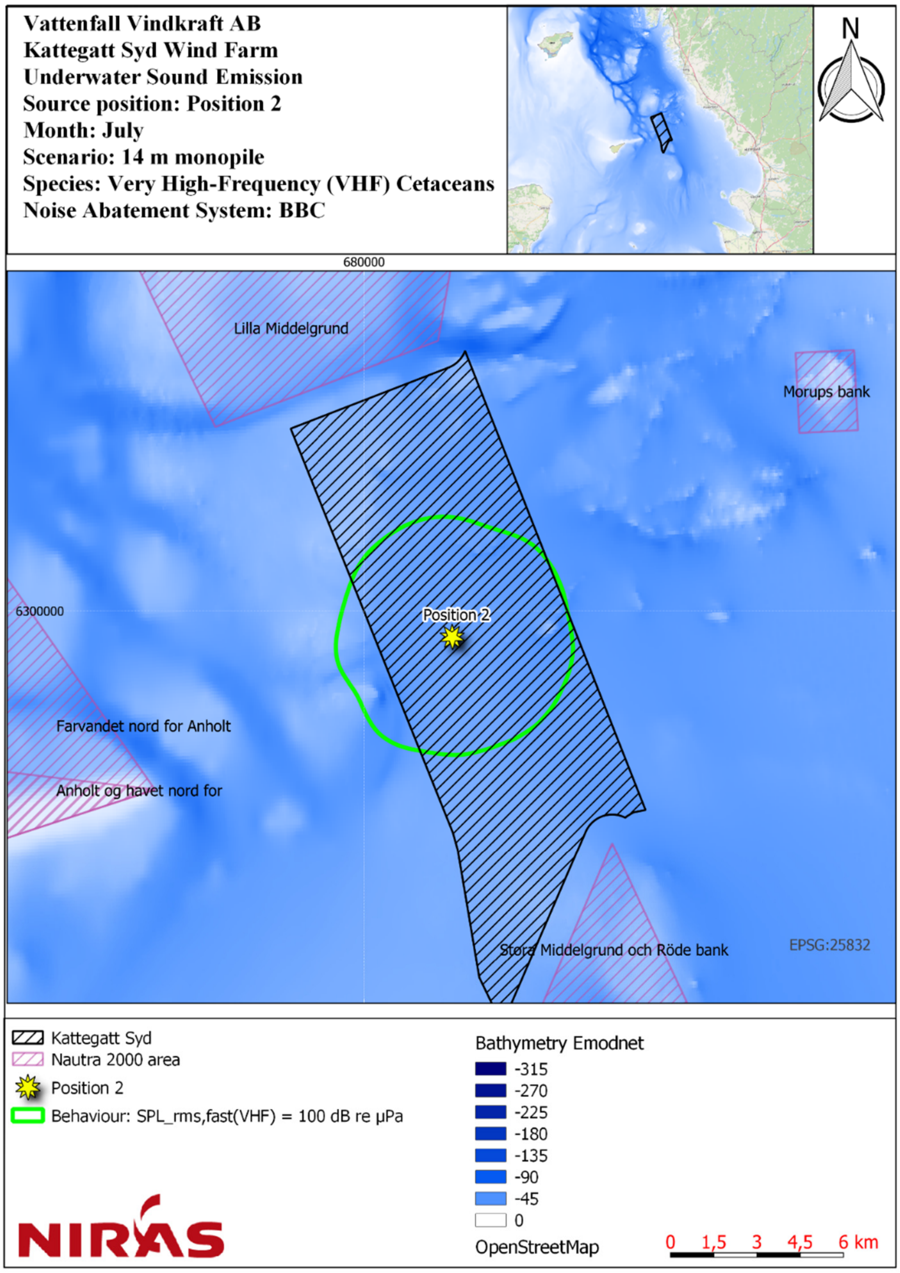


Figure 7.3. Area (green outline), wherein the behavioural disturbance threshold is exceeded during piling of each 14 m monopile installation, $SPL_{RMS\text{-}fast}$ (VHF-weighting) for July. Area is given mitigation with Big Bubble Curtains in place. The harbour porpoise behavioural threshold is used to define maximum disturbance of Natura 2000 sites following JNCC 2020. No Natura 2000 overlap is expected in July for a position within the middle part of the offshore windfarm site.

Seasonal average

For the Kattegatt Syd offshore windfarm site the only Natura 2000 sites that may be affected above the 20 % threshold is Stora Middelgrund & Röda Bank Natura 2000 site when piling in winter using BBC or DBBC + HSD noise abatement, or Lilla Middelgrund when using only BBC in winter (**Table 7.2**). Further, since there is a 1 km distance between the border of the windfarm area and the Natura 2000 sites, it is only the turbines within some closer range to the border that will cause for exceeding the 20 % JNCC threshold. For summer, none of the Natura 2000 sites are exposed above the 20 % threshold. In a winter worst-case scenario using BBC mitigation, the disturbance from each pile driving close to the border (1 km from the border) of these Natura 2000 sites will be above the JNCC-acceptable 20 % of its area (**Table 7.2**), unless more mitigation is added. To calculate the seasonal average for winter, the disturbance by construction activities in general must be estimated, as well as the ratio of days with piling to days without piling. The source level of ship noise is substantially lower than pile driving noise and thereby the predicted impact ranges are similarly smaller on days without piling, where the vessels are moving to a new position and preparing for piling there. Few good estimates of reaction thresholds or reaction distances to ship noise are available, the most direct one being from a visual observation study in the Strait of Istanbul (Bas, et al. 2017). The strait is heavily trafficked and the porpoises are exposed to vessels 50 % of their time, and are likely somewhat habituated to vessel noise. Nevertheless, in this study porpoises were observed to react to the presence of ships within a few hundred meters of the ships. If we, precautionary, set the disturbance range to 500 m, this means that the disturbed area around a ship is 0.8 km^2, however, since the border of the windfarm area is 1 km from the border of the Natura 2000 sites, there should be no effect inside the Natura 2000 sites, presuming all working vessels keep a 1 km distance to the Natura 2000 borders. Most of the time the vessels will be working further inside the investigation area, bringing the noise level down inside the Natura 2000 sites. The same goes for piling, which most of the time also will take place further inside the windfarm area. For the animals themselves, the effect of piling may last 24-72 h before they return (unmitigated) with a falling effect with range away from the pile driving site (Brandt, et al. 2011b). For noise abated pile driving, the duration of the displacement is shorter and was about 5 hours when using Big Bubble Curtains at DanTysk (Dähne, et al. 2017), and it is therefore important to asses if the return time is shorter or longer than the break between pilings, as the negative effect of pile driving may last beyond its cessation or break in activity and extend to more than one day depending on the use of and type of mitigation. In this assessment, only scenarios with noise abatement is assessed, and the effect is therefore assumed to be less than a day as observed for Dähne and colleagues.

In a worst case scenario for winter with BBC noise abatement, for pile driving every second day, the average disturbance will be the mean of 20 % (highest acceptable level on days with piling) and 0 % (expected disturbance inside the Natura 2000 site from the working vessels on days without piling), equal to maximum 10 % disturbance. This is for piling and working close to the border of the Natura 2000 site. In summer, or when using DBBC + HSD in winter, or when piling further inside the windfarm area, the disturbance will be less. It is therefore not expected that the 10 % JNCC threshold for evaluating the average disturbance per day across the duration of the construction phase, will be exceeded in the nearby Natura 2000 sites.

7.4 Disturbance from gravity based foundations

The main sources of disturbance from gravity based foundations are vessels employed with preparing the seabed and positioning the foundation. The noise from installation of gravity based foundations is therefore expected to create much lower source levels and disturb marine mammals in a much smaller area than piling by hammering will. The assessed disturbance in this assessment is therefore based on vessel noise and not the gravity foundations. The source level of ship noise is substantially lower than pile driving noise and are unlikely to cause neither PTS nor TTS. The impact from gravity based foundations will therefore be from disturbance of behavior and possibly masking during the period of preparing the seabed and placing the foundation. As described above, few good estimates of reaction thresholds or reaction distances to ship noise are available for harbor porpoises. The most relevant is from a visual observation study in the Strait of Istanbul (Bas, et al. 2017). The strait is heavily trafficked and porpoises are exposed to vessels 50

% of their time, and are likely somewhat habituated to vessel noise, yet they reacted to the presence of vessels within a few hundred meters of the ships. As for disturbance of Natura 2000 sites, we here, precautionary, set the disturbance range to 500 m, despite that porpoises in Kattegat also are used to vessel noise from the nearby shipping lanes, however not to the same degree as the porpoises in the Strait of Istanbul. For the installation of gravity based foundations, it is assessed that up to thirty vessels may be working at the same time in the area. This means that each vessel will have a working mode with a certain or changeable speed, direction and noise profile that the animals will need to take account of if they are in the area. Further, each vessel will have a disturbance radius of 0.5 km based on Bas, et al. 2017, or a disturbed area of 0.8 km^2. Assuming a worst case scenario of thirty vessels separated by more than 1 km and working simultaneously but with different modes, this means a total disturbed area of 24 km^2. In reality, this level of disturbance is likely overestimated, as many of the vessels, by the nature of the work they will be doing, will be close to each other and thereby have overlapping areas of impact, in turn reducing the total impacted area. Furthermore, not all vessels are likely to operate at full power and thereby maximum noise emission at the same time. Many ships will be idling (such as standby safety vessels), or even anchored, again meaning that the total disturbed area may be less than 30 times 0.8 km^2. The impact is therefore likely an over-estimated peak-impact and will serve for a precautionary assessment.

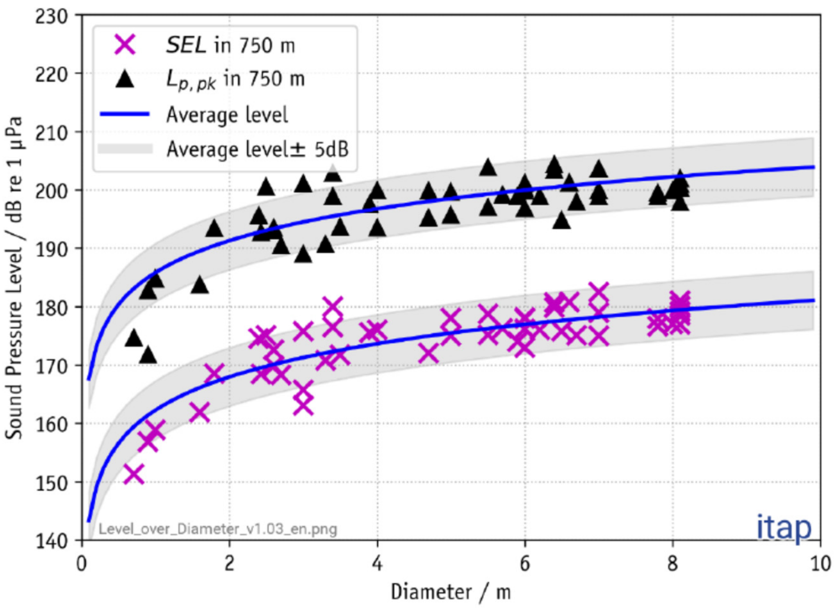
8 Assessment of impact from construction

The primary impact from construction is considered to be from the underwater noise generated from pile driving. In addition to this are much lower levels of underwater noise from ships and service boats (compared to the pile driving noise) which also constitutes the main noise source from installation of gravity based foundations. Vessel noise is incapable of inducing any injury or hearing loss and thus is only considered as a source of masking and behavioural disturbance.

8.1 Acoustic trauma

Peak pressures were not modelled for pile driving at Kattegatt Syd offshore windfarm site, as modelling this quantity is technically more demanding than modelling sound energy (SEL). However, based on a large number of measurements (Nehls and Bellmann 2016), the peak sound pressure level 750 m from the pile driving site can be estimated for a 14 m diameter pile. Extrapolating the upper curve on **Figure 8.1** to 14 m pile diameter gives an estimated peak sound pressure level of 209 dB re. 1 µPa. This should be held against the threshold for acoustic trauma (section 4.1) of 226 dB re. 1 µPa, 16 dB higher than the level at 750 m. A simple back-calculation, assuming spherical spreading loss (20 log r) shows that the threshold of 226 dB re. 1 µPa is exceeded within app. 120 m of the monopole when unabated, and exposure at this level is therefore not relevant for this assessment, as it only builds on scenarios with noise abatement. This extrapolation assumes that the monopile can be regarded as a point source, which is not the case (it is a very long cylinder) and will overestimate the sound pressures close to the source. Due to the noise abatement systems assumed in this report, impact from acoustic trauma is unrealistic and it is unlikely that any animal will be exposed to sound pressures close to the threshold for acoustic trauma. The impact of acoustic trauma from noise exposure during construction is thus assessed as **negligible**.

Figure 8.1. Measured sound exposure level (SEL_{SS}, crosses) and peak pressure levels (L_{Peak}, triangles) in a distance of 750 m from the monopile. From (Bellmann, et al. 2020).



Underwater explosions are considered capable of generating peak pressures and acoustic impulses sufficiently high to injure marine mammals. Such are not anticipated as part of the wind farm construction, although unexploded ordnance (UXO's) may be encountered everywhere in Kattegat and may require clearance by detonation on site. If such UXO clearance is required, it should be assessed separately and appropriate mitigation measures should be adopted to minimize the risk of injury to marine mammals.

8.2 Hearing loss

Pile driving is the only noise source during construction of the wind farm capable of inducing temporary or permanent hearing loss in marine mammals. Only sound propagation modelling with use of noise abatement with either BBC or HSD + DBBC were used, and the assessment only pertains to these results. It was assumed that both seals and porpoises would be deterred to safe distances (min. 25 m) (**Table 6.1**) by the presence of several vessels working close to the piling site, the air bubble noise from the bubble curtains, as well as soft start procedure. It was therefore assumed that no animals would be in within the zone of PTS of maximum 25 m at the onset of the soft start.

For **porpoises**, the cumulated exposure is reduced to levels exceeding the level required to elicit a temporary threshold shift (TTS) at a maximum of 90 m from the bubble curtain at position 1 and 3 in December (Table 6.1). For position 2 the range is 70 m in July. As the bubble curtains themselves also produce noise that are not familiar to porpoises and given the number of working vessels in the area, it is considered very rare that porpoises would be this close to the bubble curtains. Impacts on individuals are therefore expected to be very rare and with very small effects (no PTS, minute TTS), hearing loss is therefore considered unlikely to have any long-term consequences for the population, and the impact of pile driving with respect to hearing loss, assuming appropriate Best Available Technology of noise abatement, is considered **negligible**.

For **seals**, the cumulated exposure with application of noise abatement of either BBC or HSD + DBBC exceeds the TTS threshold at < 50 m range (Table 6.1). For the same reasons as for porpoises, it is considered very rare that seals would be this close to the bubble curtains, given all the vessels working in the area. The potential impact of pile driving with appropriate noise abatement for **harbour seals and grey seals** is therefore assessed to be **negligible**.

8.3 Behavioural disturbance

During the period of disturbance, foraging by animals in the impacted area will be reduced. The data available on temporal and spatial variation in presence of harbour porpoises in the Kattegatt Syd offshore Windfarm suggests that there may be similar quality habitats elsewhere, however since there likely will be an (small) increased number of animals in the adjacent areas, due to the displacement, the average foraging efficiency may decrease and the piling in this way affect a larger area.

8.3.1 Disturbance of porpoises by pile driving

In **Table 7.1** the area and percentage of the porpoise population impacted by pile driving noise was estimated. The area affected under worst case assumptions (December, only BBC noise abatement) indicates that porpoises are likely to be disturbed by the noise over an area of maximum app. 208 km^2, which amounts to < 1 % of the population of porpoises i.e. a relatively large area in southern Kattegat, but few animalsin rlation to the abundance of harbour porpoises in Kattegat. At the same time it is a period of about six months assuming that the piling of the 60 foundations takes place app. every second day. **Impact on the porpoise population** in Kattegat/Belt Seas under these conditions is assessed as **minor**.

If piling is carried out in December with use of BAT noise abatement (here HSD+DBBC), the impact is reduced to maximum 97 km^2 over a period of about six months assuming piling every second day. With this noise abatement the **impact on the porpoise population** is assessed as **minor**.

If construction is undertaken under conditions less favourable for long-range sound propagation (BEP) and with BAT noise abatement (here HSD+DBBC, or similar), the impacted area is reduced to around 19 - 26 km^2 (July) (reaction distances around 3-4 km), significantly reducing the affected number of porpoises from the southern Kattegat population. Under these conditions, the **impact on the porpoise population** by pile driving is assessed as **minor**.

Regardless of the type of noise abatement chosen, it is recommended that the impact on the porpoise population is monitored with a BACI study design (Before, After, Control, Impact) to evaluate the actual impact of the windfarm during its construction, as well as during operation.

8.3.2 Disturbance of seals by pile driving

As no generalised reaction threshold is available for seals, it is not possible to quantify the disturbance of seals by the pile driving noise. However, studies on reactions to pile driving noise suggest that seals react at similar distances as harbour porpoises do (Russell, et al. 2016). This is likely explained by seals' better hearing at low frequencies (compare **Figure 2 2** and **Figure 2 3**). It is therefore assessed, that seals react at distances comparable to porpoises, if not further away. In a precautionary way, the **impact on seals by pile driving noise abated by BBC is therefore assessed as minor**. If BAT is employed (HSD + DBBC) and assessed with measurements weighted by seal hearing, the reaction distances are reduced considerably. It is therefore assessed, that the **impact on seal populations by pile driving noise in July, with BAT noise abatement, is minor.**

8.3.3 Disturbance of porpoises from gravity based foundations

The area affected under worst-case assumptions (thirty vessels working simultaneously, none closer than 1 km to other vessels) indicate that porpoises could maximally be disturbed by the noise over an area covering 24 km^2. If the vessels are spread out and moving around, it may lead to a larger exclusion area. **Impact on the porpoise population** under these conditions is assessed as **minor,** as it amounts to app. 24 disturbed porpoises on any working day based on (Hammond, et al. 2017). In reality, it may be more individuals that are disturbed, because porpoises move around and naïve porpoise will arrive during the construction period. Nevertheless, it is a very small part of the population of about 42.000 porpoises in south Kattegat/Belt Seas (Hammond, et al. 2017), and the disturbance per se is unlikely to affect the population. The gravity foundation scenario is unlikely to be abated at the source, but it may be possible to reduce the amount of simultaneously working vessels within the windfarm site. Under such conditions with 4-5 simultaneously working vessels, the **impact on the porpoise population** by gravity base foundations is assessed to be **negligible** when considering the already present noise from the nearby shipping lanes.

8.3.4 Disturbance of seals from gravity based foundations

As no generalised reaction threshold is available for seals, it is not possible to quantify the disturbance to seals by the vessel noise from the instalment of foundations by gravitation. However, studies on reactions to pile driving noise suggest that seals react at similar distances as harbour porpoises do (Russell, et al. 2016). This is likely explained by seals' better hearing at low frequencies (compare Figure 2 2and Figure 2 3). On the other hand, it is generally believed that seals are more tolerable to noise than porpoises (see for example Mikkelsen, et al. 2017). In a precautionary way it is therefore assumed that seals react at distances comparable to porpoises, i.e. 500 m from the ships. **Impact on both the grey and harbour seal populations** under worst-case conditions (30 ships working at full power and dispersed throughout the construction site) is assessed as **minor**. This scenario is a worst-case peak exposure and under more realistic conditions with 4 or 5 vessels working simultaneously in the construction area, the **impact on the two seal populations by gravitation foundations is assessed to be negligible,** considering the ship noise already present in the area from the nearby shipping lanes.

8.4 Masking

Masking of other sounds by the pile driving noise is not very likely, as described in section 3.5. Masking of echolocation signals of porpoises is considered to be unlikely, due to the lack of overlap in frequency between noise and echolocation signals. Masking intensity is thus considered insignificant and hence impact of masking on **porpoises** is thus assessed as being **negligible**.

Harbour and grey seals use low frequency sounds in communication and the potential for masking is thus larger. However, mating only occurs close to breeding sites on the coast (Anholt, Hesselø and the Swedish archipelago), i.e. far from the wind farm area, where received levels of the pile driving noise is low. Furthermore, masking is only possible during pile driving. In a worst-case scenario (in the peak of the breeding season in June-August for harbour seals), with on average 4.5 hours of piling every second day, this would amount to masking in less than 10 % of the time. Potential masking intensity is thus assessed in a very precautionary manner as **medium** for the seals at the mating sites (it is not actually known whether pile driving noise can mask communication of mating calls). Because the breeding sites are beyond ranges at which masking can be expected the overall impact of masking from the pile driving noise with reduction in noise radiation from BBC on the Kattegat **harbour and grey seal populations** is thus assessed to be **negligible**. Reduction of radiated noise from the pile driving by HSD + DBBC noise abatement will reduce noise levels and thus reduce impact at the coast to **negligible** levels.

Noise from installing gravity based foundations could potentially mask seal communication sounds. However, in this area where vessel noise is always present from the two shipping lanes, additional masking would only be possible close to the ships, i.e. inside the construction site. As seals are known to communicate predominantly during the breeding period and close to the haul-out sites, the actual impact by masking from ship noise during construction is assessed as **negligible.**

8.5 Impact on Natura 2000 sites from piling

Listed in **Table 7.2** is the impact on the bordering Natura 2000 sites, with respect to the 20 % threshold. Impact is expressed as the fraction of the sites exposed to noise levels above the behavioural reaction threshold for porpoises. Impact is evaluated relative to the JNCC guidelines as acceptable (< 20 % disturbed area) or unacceptable (> 20 % disturbed area). The percent overlap with Natura 2000 sites is calculated from a distance of 1 km from the border of the Natura 2000 site, as all foundations will be placed minimum 1 km from the border of Natura 2000 sites.

Under worst case assumptions (December, position 1 and 3, BBC noise abatement) the set behavioural disturbance threshold is exceeded in Stora Middelgrund & Röda Bank (44 % overlap) and Lilla Middelgrund (29 % overlap) Natura 2000 sites. This means that parts of these sites will be exposed to noise levels exceeding the behavioural disturbance threshold of harbour porpoises and thereby exceeding the JNNC criterion where a maximum of 20 % of a Natura 2000 site may be impacted per piling day. **Impact on the Natura 2000 sites** under these conditions is therefore assessed as **unacceptable** according to the JNCC guidelines.

If piling is undertaken under conditions least favourable for long-range sound propagation, i.e. Best Environmental Practise (July) and with BAT noise abatement (HSD + DBBC or equivalent), none of the Natura 2000 sites are affected above the JNCC threshold, and **the impact is assessed as acceptable.**

8.6 Impacts on Natura 2000 sites from gravity based foundations

Under a peak worst-case condition up to thirty vessels may be working simultaneously to install gravitation foundations. The border of the windfarm area is 1 km from the border to the closest Natura 2000 site, therefore disturbance inside the Natura 2000 site is not expected. It is possible that vessels are passing through to work in the windfarm, and that will be temporary disturbances. **The peak impact on Natura 2000 sites from gravitation foundations is assessed as acceptable** as the disturbance will not exceed the 20 % threshold put forward by JNCC.

8.7 Cumulative impacts from construction of several windfarms

Several other offshore wind farms are planned in the eastern and central Kattegat, including Stora Middelgrund and the area between the Danish islands Anholt and Hesselø.

8.7.1 Impact on Natura 2000 sites

There is a potential for cumulative impact from simultaneous construction of these wind farms, should that occur. This is primarily relevant for wind farms potentially affecting the same Natura 2000 sites, as the contribution to disturbance from construction of both wind farms should be included in the comparison against the 10 % and 20 % limits to disturbed sites as stipulated by JNCC.

This, means that simultaneous pile driving at two wind farms impacting the same Natura 2000 site may mean that the cumulative impact exceeds the 20 % limit and even if installations are alternated, the average impact may exceed the 10 % limit across the season and or installation period. In case it is proposed to construct two adjacent wind farms (i.e. with overlapping areas of impact on Natura 2000 sites) within the same year, a thorough analysis of the combined impact should therefore be performed.

The cumulative impact on Natura 2000 sites from sequential construction of several wind farms in the eastern Kattegat **is assessed to be minor**, given that the impact of construction of the individual wind farms has been assessed to be **minor or less**.

8.7.2 Impact on the harbour porpoise and seal populations

As for the Natura 2000 sites there is a risk for cumulative impacts on the harbour porpoise, harbour- and grey seal populations in Kattegat. It is assessed that for sequential construction of several windfarms in south-eastern Kattegat, the impact on the three populations will be the same as assessed for the individual windfarms. In case it is proposed to construct two or more adjacent wind farms (i.e. with overlapping areas of impact) within the same year, a thorough analysis of the combined impact on the populations should be performed.

9 Noise from operating wind farms

Offshore wind turbines generate noise as the wings, gears and generator rotates. The moving gears in the gearbox is the primary source of the noise transmitted as vibrations down the turbine tower and radiated into the surrounding waters. Thus, the power density spectra of the underwater noise very commonly show that most of the energy is located at single frequencies, corresponding to the engagement frequency (and possibly harmonics) of the moving teeth on the gears (**Figure 9.1**).

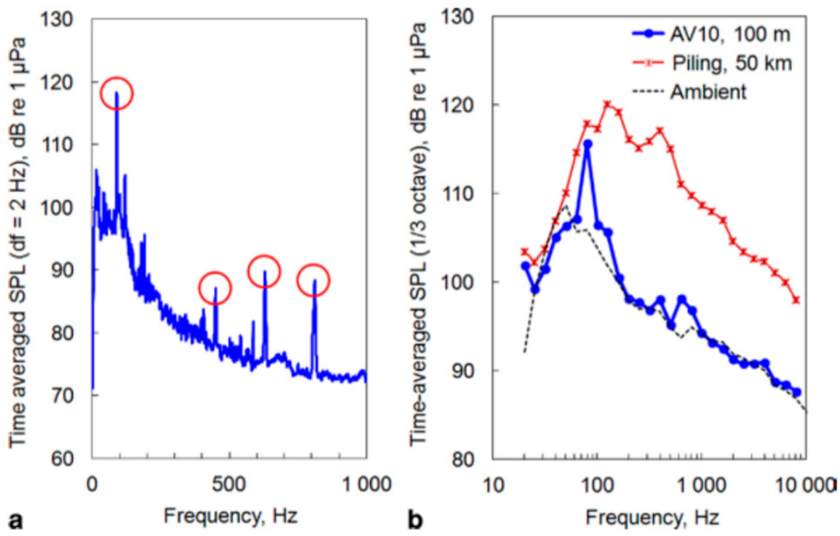
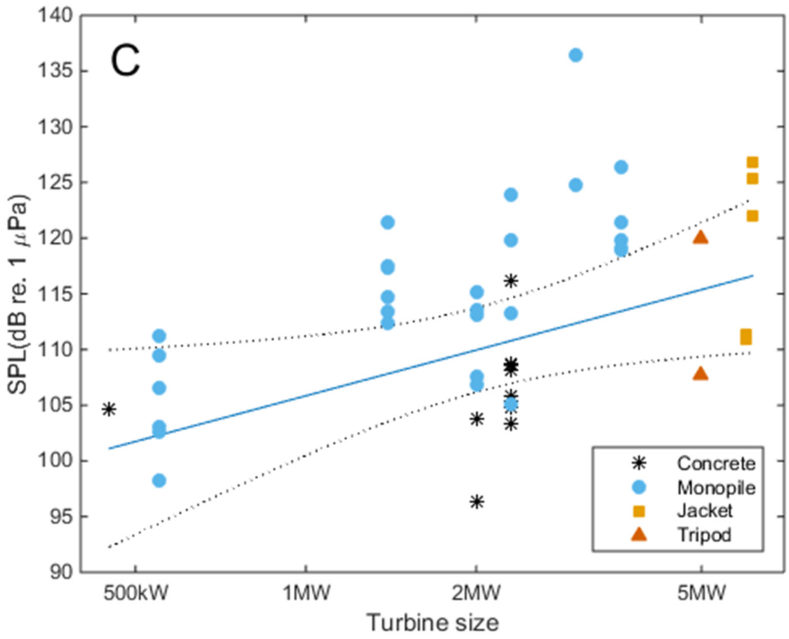


Figure 9.1. Operational noise measure.100 m from a 5 MW turbine at Alpha Ventus offshore wind farm. The turbine was operating at maximal power output. A) shows power density spectrum of the noise. Note the powerful component at 90 Hz and the harmonic overtones at 450 Hz, 630 Hz and 810 Hz. B) Third-octave spectrum of the same noise (blue), together with ambient noise (broken line), recorded at the same location and same wind speed, but before installation of the turbines, and noise from a distant pile driving (red). From Betke (2014)

Numerous recordings of underwater noise from operating turbines exists. A recent example is shown in **Figure 9.1**. and a compilation of measurements is shown in **Figure 9.2**. These recordings span a large range of turbine sizes, from 500 kW nominal power (Vindeby), to 6 MW (Thornton Bank), and reveal a statistically significant increase in radiated noise with size of the turbines (Tougaard, et al. 2020). The planned turbines for Kattegatt Syd is significantly larger (15 MW) and is therefore likely to more noisy than any farms measured to date. This is also anticipated in a recent paper comparing all previous available recordings from offshore windfarms (Stöber and Thomsen 2021). The authors concluded that “for larger size wind turbines, operational noise needs to be considered in sufficient detail as a part of the environmental impact assessment in the wind farm planning phase. In addition, further observations and modeling efforts are necessary to increase the accuracy of the estimates and resolve for further parameters like pile type and dimensions”. This makes fully sense given the much larger turbines planned in the 2020’es as compared to earlier days (see Tougaard et al. 2020 and Stöber and Thomsen 2021 for a comparison). As no recordings exists for windfarms of the size as planned for Kattegatt Syd, some caution is warranted with regards to effects of noise from the windfarm in operation.

Figure 9.2. Underwater noise recorded from a large number of different turbines. All levels were normalised to a recording distance of 100 m and wind speed of 10 m/s. From (Tougaard, et al. 2020).



Also the type of foundation could quite possibly affect the noise level, but data in **Figure 9.2** does not allow any conclusions on this question. The only turbine that really stands out is the small turbine at Utgrunden, Sweden (see Madsen, et al. 2006). The noise measured from this turbine was significantly louder than other turbines, especially at the higher frequencies. One possible explanation for this could be its placement on subsea bedrock, whereas all the other turbines are placed on soft bottom (Madsen, et al. 2006).

9.1 Ambient noise

The ambient noise in the wind farm area is dominated by the nearby deep-water shipping lane, route T, entering the Great Belt), and the additional route S, leading into the Sound. Median sound pressure levels in the 125 Hz third-octave band is shown as modelled data for July 2014 in **Figure 9.3**.

The shipping lanes were re-routed in summer 2020. The split between Route T and Route S has been moved from east of Totten, Anholt to a point north of Læsø, which means that route S now runs east of the proposed wind farm site and the Natura 2000 site. This change will no doubt affect the noise conditions, but unlikely to be of a magnitude affecting assessment of the impact of the wind turbines

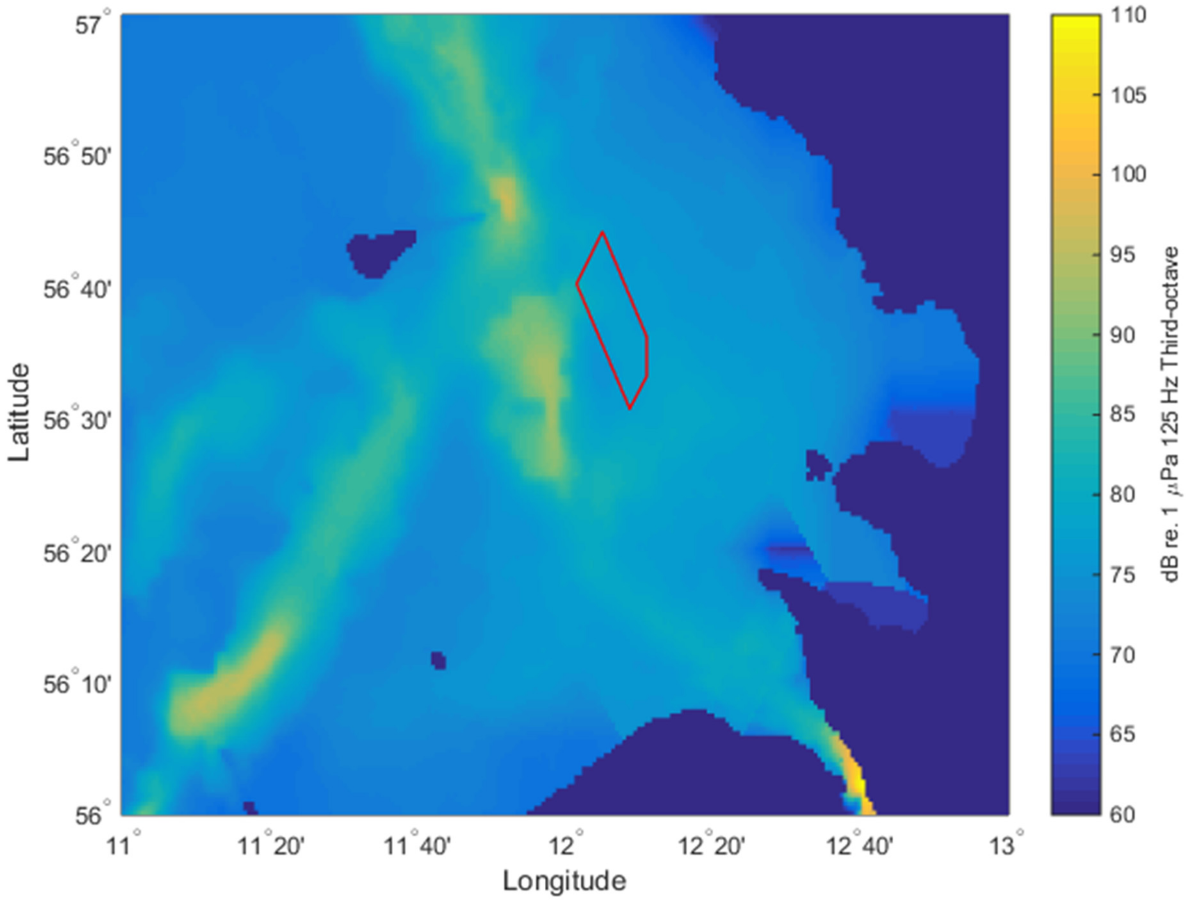


Figure 9.3. Modelled noise levels in the third-octave band centred at 125 Hz. The map shows the median noise level (L_{50}) for July 2014. Polygon shows outline of N2000 area Stora Middelgrund and Röda Bank. The shipping routes T and S running east of Anholt and into the Great Belt and the Sound, respectively, are visible as regions with elevated median noise levels. Source: EU-Life project BIAS (https://biasproject.wordpress.com/).

9.2 Cumulative noise from several turbines

Little information is available about the cumulative impact from several turbines in the same area. If two or more turbines produce noise at the same frequency and at the same sound pressure level, the two sounds can add and thus result in an increased sound pressure level. **Figure 9.4** shows an idealized example of this. The combined sound pressure level from two identical turbines is given as:

Equation 9.1

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

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

Only in the region roughly half-way between the turbines does the sum significantly exceed the sound pressure level of the closest turbine. Closer to one or the other turbine the contribution of the distant turbine to the sum is virtually zero. At most, the sum of the sound pressures from the two turbines can be 3 dB more than the noise form the individual turbines (exactly half way between them). Adding more turbines does not change much. If four identical turbines were considered, the combined sound pressure level at the exact centre between them would be 6 dB higher than the noise level of any of the individual turbines and as one moves away from the centre, the noise will be increasingly determined by the closest turbine. To achieve an additional 3 dB increase in sound pressure level, one would have to be at the exact centre between eight identical turbines, at which point the geometry is no longer consistent with the normal layout of wind farms.

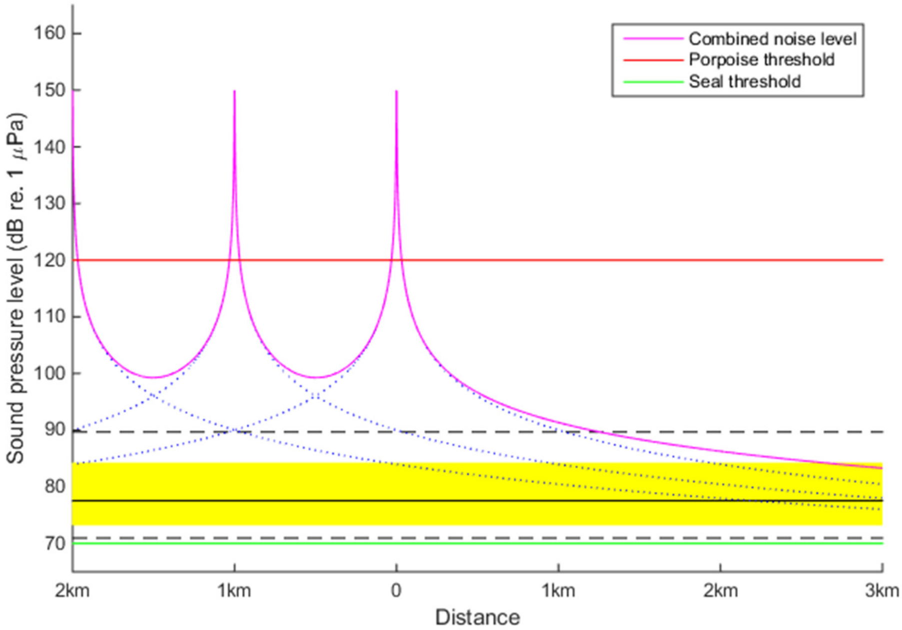


Figure 9.4. Idealized model of summation of noise from three identical turbines placed 1000 m apart. Each turbine is modelled as a point source with a spherical transmission loss (20 log r, dotted lines) and the combined noise level is found from **Equation 9.1**. (magenta line). The yellow band indicate the 25 % and 75 % exceedance levels of the ambient noise in the 125 Hz third octave band, modelled by the BIAS project inside the N2000 area; the solid line the median (L_{50}) and the stippled lines the 90 % and 10 % exceedance levels. Included are also the minimum hearing threshold for a harbour seal (Kastelein, et al. 2009, green line) and harbour porpoise (Kastelein, Hoek, Wensveen, et al. 2010, red line) estimated at 125 Hz.

Harbour porpoises have very poor hearing at the low frequencies of the turbine noise. No measurements are available at 100 Hz, but by extrapolation of the audiogram (**Figure 2 2**) a threshold of 120 dB re. 1 μPa was estimated. This threshold is so high that the turbine noise is expected to be inaudible to porpoises, unless they are very close to the turbine, within 100 m.

The situation is different for seals. Harbour seals (and presumably also grey seals) have good low-frequency hearing, well below the ambient noise levels between the two shipping lanes in southern Kattegat (**Figure 2 3**). Their ability to hear the turbine noise (and in the end be affected by it), is thus limited by the ambient noise rather than the hearing threshold. The simple model in **Figure 9.4** suggests that the turbine noise is audible to seals within the wind farm area and extending one or more kilometres out from the edge of the wind farm. Realizing that the simple spherical spreading model (20 log(r)) almost certainly does not apply to the turbine noise but only is used as a first approximation, means that these impact distances are very uncertain. The actual sound propagation loss could be larger (due to shallow-water high-pass filtering and Lloyd's mirror-effects), or smaller (due to cylindrical, rather than spherical spreading).

10 Assessment of impact from operation

10.1 Effect on abundance of porpoises

A few studies have looked at the effect of operating offshore wind farms on the abundance of porpoises inside the wind farm, compared to baseline measurements before construction began, however all of these studies pertains to much smaller turbines than expected for Kattegatt Syd. In an early study (Teilmann and Carstensen 2012) looked at abundance of porpoises (measured by passive acoustic monitoring) around the Nysted offshore wind farm (2.3 MW), the first large offshore wind farm established in the Baltic. This study showed a significant decrease in porpoise abundance during construction, followed by a gradual recovery during operation. The recovery to baseline levels were not reached several years after end of construction. This difference between pre-construction baseline and operation is unexplained and difficult to link unequivocally to an impact from the wind farm, because the baseline consisted of a few months only before the construction work began. It is therefore uncertain whether the baseline is representative or spuriously high in the monitoring year. Nevertheless, the Nysted offshore windfarm has not attracted porpoises when compared with reference stations.

Later Rødsand 2 was build, located in the Western Baltic Sea. Abundance of harbour porpoises were assessed by passive acoustic monitoring, where dataloggers (C-PODs), recorded the presence of porpoises through detection of their echolocation clicks (Teilmann, et al. 2012). The results from Rødsand 2 (Teilmann, et al. 2012) showed that in general there were more porpoises in the reference area than in the wind farm area, but that the ratio between the two areas was unaffected by the presence of the wind farm, i.e. the relative abundance of porpoises inside the wind farm area was unaffected by the presence of the turbines.

A later study in the Egmond aan Zee offshore wind farm (3 MW) off the Dutch North Sea coast showed a general and substantial increase in porpoise abundance from baseline before construction to operational period. This increase is consistent with other observations, supporting a long-term increase in porpoise abundance in the Dutch North Sea (Camphuysen, et al. 2008) and is as such unrelated to the wind farm. However, the relative increase in porpoise abundance inside the wind farm area was larger than in the reference areas, indicating that there were also more porpoises inside the wind farm relative to the outside, after the wind farm was put into operation.

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

To summarize there is a general lack of long term studies examining the effect of offshore windfarms covering the operation phase and comparing with reference areas and/or the same area before the installation of the windfarm.

This has become more prudent with the increase in size of the turbines and their emitted noise levels. Such studies should also aim at understanding what factors either deter or attract porpoises to windfarms. There is also an absence of studies examining the effect of the service vessels working within the wind farms on a daily or weekly basis. These vessels emit noise that is audible to harbour porpoises and may cause them to leave the area or change behaviour as was observed in the Bas, et al. (2017) study. The effect of these working vessels in individual windfarms may vary depending on type of and use of working vessels. It would overall be an advantage for the harbour porpoise population if the windfarm area was closed-off for fishing with nets as well as by trawling. The combined potential negative effects of an operational wind farm between Lilla Middelgrund and Stora Middelgrund & Röda Bank on the porpoise population in Kattegat is thus uncertain, but likely to be **negligible**.

10.2 Effect on abundance of seals

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

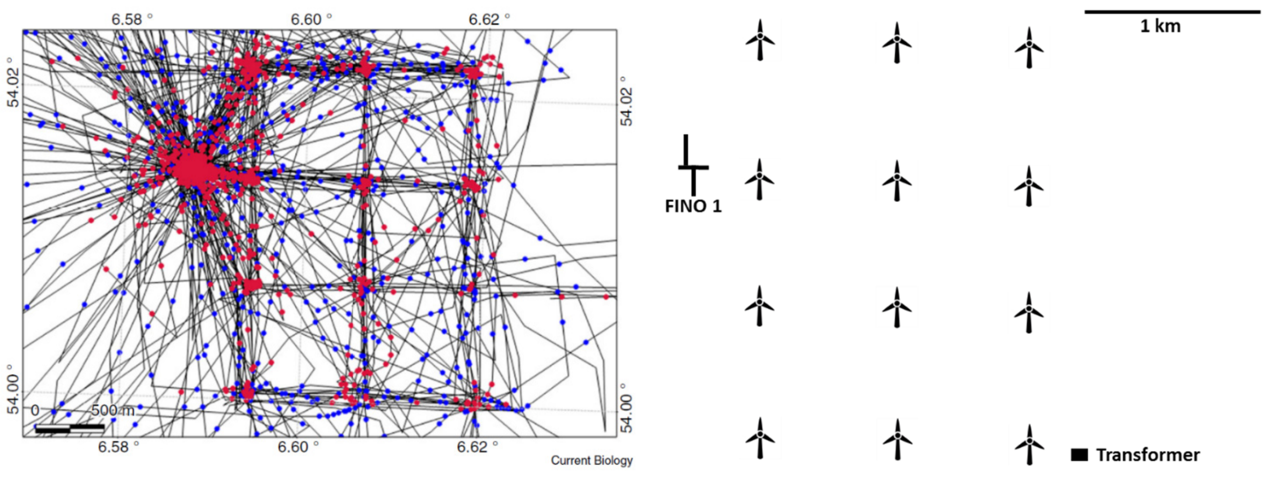


Figure 10.1. Tracks of a single harbour seal, tracked by GPS/satellite transmitter while swimming in and around the German offshore wind farm Alpha Ventus (outline shown on the right). It is evident that the seal actively seeks the turbine foundations, as well as the foundation of the research platform Fino 1 to the west of the wind farm. Partly redrawn from Russell, et al. (2014).

In contrast to this is a study from Rødsand in the Western Baltic (McConnell, et al. 2011). In this study, harbour seals were tagged with GPS trackers and their movement in and around the two nearby offshore wind farms Nysted and Rødsand II were studied. A statistical analysis convincingly showed that the seals completely ignored the turbine foundations: they were neither attracted, nor deterred from them, indicating that they did not disturb the seals but at the same time did not provide any attractive food items either.

Thus, despite the fact that the turbine noise is most likely audible to the seals, both within and beyond the wind farm (Figure 2 3), nothing in the available data suggests that the seals were deterred from the operating wind farm. This likely relates to the very low levels of noise, at maximum 20 dB above the ambient noise. The potential negative effect of an operational wind farm on seals is thus assessed as **negligible**.

10.3 Impact on Natura 2000 sites

The net impact of the operating turbines on the nearby Natura 2000 sites is likely to be **acceptable** as the noise is unlikely to affect > 20 % of the Natura 2000 site at any one day or more than 10 % on average over a season. Effects of the turbines themselves is most likely to be through underwater noise radiated from the turbine foundations. The levels of noise are expected to be low. However, service vessels working in the wind farm, likely on a daily or weekly basis can be heard by both seals and porpoises over km's, but the effect of service boats in wind farms have not been studied, and is here assumed to be in line with the Bas, et al. (2017) study showing an effect range of about 500 m for harbour porpoises (assumed also for seals). The effect of service vessels is therefore very unlikely to impact the surrounding Natura 2000 sites above the 20 % JNNC threshold and is assessed as **acceptable** according the JNCC guidelines. Over the season (Summer defined as April to September inclusive, winter as October to March inclusive), the threshold of an average of 10 % overlap is for the same reasons, not likely to be reached either, and the seasonal effect is therefore considered **acceptable**.

11 Assessment of impact from sediment spill

During construction of an offshore wind farm several actions causes stirring of the seabed with resuspension of the sediment. This resuspension is coined sediment spill and its potential for negative effects on marine mammals is assessed in this chapter. The potential sources of sediment spill are preparing the seabed for the installation, laying the cables, drilling for placing foundations, placing gravity foundations and installation of the offshore substation.

To quantify the impact on the environment from the sediment spill from these activities, NIRAS simulated the activities in a model for a representative period in time and space. They used a hydrodynamic model and a sediment model set up for the North Sea, Kattegat and the Baltic Sea to provide the background water level variations and current, to serve as input for the transport and sedimentation of the spilt sediment. The model results of the different scenarios for sediment spill and the report (NIRAS 2021) was made available for this assessment 29th March 2021.

Due to environmental restrictions other than marine mammals, most likely concern for spawning cod, the work causing sediment spills may only be carried out from 1st June to 30st November.

11.1 Drilling and gravity foundations

NIRAS has evaluated the geotechnical properties of the offshore Windfarm site and assessed that up to 15 % of the piles can be drilled to full depth, whereas the rest will be piled. Alternatively, the piles will be placed by gravity foundations. The drilling method was not known at the time NIRAS modelled the impact. The drill speed was assessed as 30 m^3/hr. For each pile drilled, it was estimated that up to 9,236 m^3 sediment would be pumped out in the water near the drill position for 60 m piles (Table 11.1). The drilled material is pumped to 2 m below the water surface about 10 m from the pile. For the monopiles assumed to be drilled, the spill is estimated to 100 %. For gravity foundations with a diameter of 60 m, the spill is estimated as maximum 29,568 m^3 for positions deeper than 30 m, as the spill is only 5 % (Table 11.2).

11.2 Installation of cables

In-field cables (Figure 11.1), connecting all the turbines to the offshore sub station, requires some preparation of the sea bed. For protection against anchors and fishing gear, the cables will be buried in the seabed. It is assessed by NIRAS that the cables will be buried by jetting. This methodology is at the same time the most conservative with regards to spill amounts, with 100% spill, and will thus serve as worst case scenario. For their modelling, it was assumed that all cables were jetted.

Export cables will connect the offshore substation to shore, which will also result in sediment spill, as they are buried in the seabed, and 100 % spill is expected. The same spill totalling 16,301 m^3 is expected regardless of method for placing the turbines and size of the turbines (**Table 11.1** and Table 11.2)

Table 11.1. The scenarios considered in NIRAS' modelled sediment spill analysis for piling. Copied from (NIRAS 2021).

Case			20/25MW MP		15MW MP	
MP	Layout	#	1		2	
	Nos, total	#	60		80	
	Water depth	m	<42m	>42m	<42m	>42m
	Nos	#	57	3	75	5
	Dia. at seabed	m	14	14	10	12
	Embedded depth	m	60	60	50	50
	Drill	%	15%	15%	15%	15%
	Nos to be drilled	#	9	0	11	1
	Vol., drilled/pos.	m3	9236	9236	3927	5655
	Spill	%	100%	100%	100%	100%
	Vol., spill	m3	83127	0	43197	5655
	MP, sum spill	**m3**	**83127**		**48852**	
Cable	Length	m	132075		149406	
	Burial depth	m	2		2	
	Width, trench	m	0.5		0.5	
	Spill	%	100%		100%	
	Vol. Spill	m3	132075		149406	
	Cable, sum spill	**m3**	**132075**		**149406**	
Export cable	Length (to boundary)	m	16301		16301	
	Burial depth	m	2		2	
	Width, trench	m	0.5		0.5	
	Spill	%	100%		100%	
	Vol. Spill	m3	16301		16301	
	Cable, sum spill	**m3**	**16301**		**16301**	
OSS	Length at seabed (100+2x10)	m	120		120	
	Width af seabed (80 + 2x10)	m	100		100	
	Embedded depth	m	5		5	
	Dredged	%	5%		5%	
	Nos to be dredged	#	1		1	
	Vol., drilled/pos.	m3	60000		60000	
	Vol., spill	m3	3000		3000	
	OSS GBS, sum spill	**m3**	**3000**		**3000**	
Total	**Gross, spill**	**m3**	**218202**		**201258**	

11.3 Installation of the offshore substation

For the modelling done by NIRAS, it was assumed that the offshore substation will be placed on a jacket foundation pinned to the seabed with five pins with dimensions as stated in **Table 11.1**. The sediment spill for each pin was estimated to 100 % amounting to a total of 7,854 m^3 sediment spill.

For the turbine foundations, three diameters at the level of the seabed have been modelled for piling / drilling; 10, 12 and 14 m, depending on the final layout of the windfarm. For gravity foundations, two diameters at the seabed have been assessed, namely 60 m and 70 m. It is clear, that the larger the diameter at the level of the seabed, the more extensive the sediment spill (**Table 11.1** and Table 11.2).

Table 11 2. The scenarios considered in NIRAS' modelled sediment spill analysis for gravity foundations. Copied from (NIRAS 2021).

Case		MW	20/25MW Gravity		15MW Gravity	
Gravity	Layout	#	1		2	
	Nos, total	#	60		80	
	Water depth	m	<30m	>30m	<30m	>30m
	Nos	#	5	55	8	72
	Dia. at seabed	m	70	70	60	70
	Excavation depth	m	2.5	2.5	2.5	2.5
	Dredged	%	100%	100%	100%	100%
	Nos to be dredged	#	5	55	8	72
	Vol., drilled/pos.	m3	10752	10752	8042	10752
	Spill	%	5%	5%	5%	5%
	Vol., spill	m3	2688	29568	3217	38708
	Gravity, sum spill	**m3**	**32256**		**41925**	
Cable	Length	m	132075		149406	
	Burial depth	m	2		2	
	Width, trench	m	0.5		0.5	
	Spill	%	100%		100%	
	Vol. Spill	m3	132075		149406	
	Cable, sum spill	**m3**	**132075**		**149406**	
Export cable	Length (to boundary)	m	16301		16301	
	Burial depth	m	2		2	
	Width, trench	m	0.5		0.5	
	Spill	%	100%		100%	
	Vol. Spill	m3	16301		16301	
	Cable, sum spill	**m3**	**16301**		**16301**	
OSS	Length at seabed (100+2x10)	m	120		120	
	Width af seabed (80 + 2x10)	m	100		100	
	Embedded depth	m	5		5	
	Dredged	%	5%		5%	
	Nos to be dredged	#	1		1	
	Vol., drilled/pos.	m3	60000		60000	
	Vol., spill	m3	3000		3000	
	OSS GBS, sum spill	**m3**	**3000**		**3000**	
Total	**Gross, spill**	**m3**	**167331**		**194331**	

11.4 Model of sediment spill

For the modelling of the sediment spill, NIRAS assumed four scenarios within the environmental temporal restrictions, narrowing the duration of the work to be performed between 1st June and 30st November. The scenarios were either based on piling and drilling or on gravity foundations. The scenarios were further built on a layout of either a 15 MW windfarm with 80 turbines, or a 20/25 MW layout windfarm with 60 turbines. In the other chapters of this EIA only the 15 MW layout has been assessed. Here, we show only worst case results, which is from modelling of the 20/25 MW layout to be drilled or piled down and the 15 MW layout to be built with gravity foundations. The assessment of impact on marine mammals is built on worst case results.

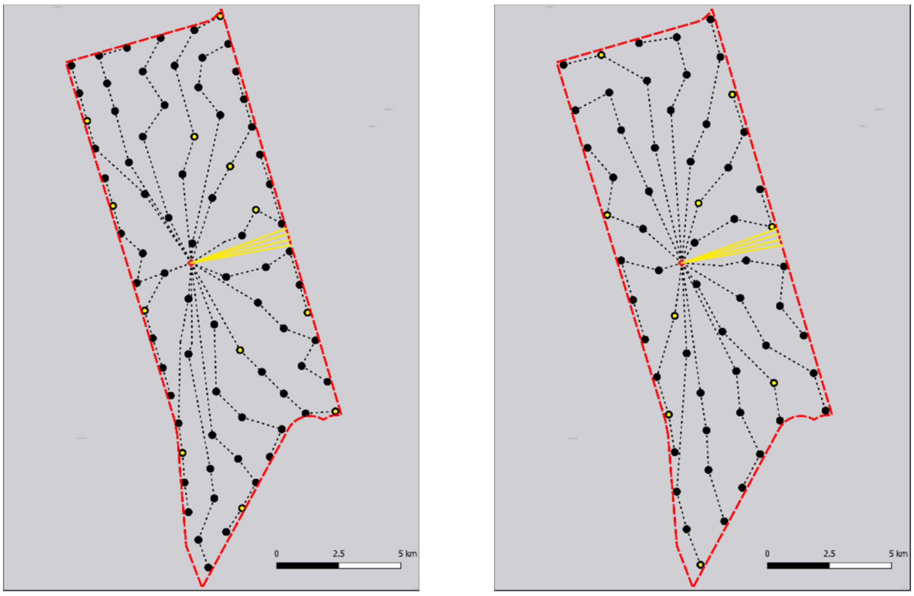


Figure 11.1. Possible layout of the 15 MW (left) and 20/25 MW (right) turbines. Yellow circles denote examples of drilling sites. Black circles sites with piling or gravity foundations. The red circle is the offshore subsea station and the yellow lines are the export cables. Copied from NIRAS (2021).

The modelling results are presented in the shape of duration of sediment concentrations above specific concentrations of sediment, in hectares (Table 11.3).

Table 11.3. Model output for the scenario of a 20 / 25 MW windfarm with 60 turbines piled or drilled down. The results are shown as concentration: hectares of sediment suspension for different concentrations with respect to duration. The windfarm area is 17,700 hectares. 100 ha = 1 km^2. 10 mg/L = 0.01 kg/m^3. The Copied from (NIRAS 2021).

Concen-tration	Duration												
	0.5 [hour]	1 [hour]	3 [hour]	6 [hour]	12 [hour]	1 [day]	2 [day]	1 [week]	2 [week]	3 [week]	4 [week]	5 [week]	6 [week]
2 mg/l	75525	64203	47489	37904	29176	20986	12449	3184	1041	465	172	62	23
10 mg/l	24431	20247	14549	10518	6188	2788	1064	178	37	8	1	0	0
25 mg/l	13482	10928	6578	3431	1430	533	217	12	0	0	0	0	0
50 mg/l	8849	6635	2406	1008	366	149	50	0	0	0	0	0	0
100 mg/l	4742	2513	646	187	61	10	0	0	0	0	0	0	0
500 mg/l	462	141	14	2	0	0	0	0	0	0	0	0	0
1000 mg/l	129	39	2	0	0	0	0	0	0	0	0	0	0

From **Table 11.3** it is clear that it is large areas that will be affected by the sediment spill and over long periods. For piling and drilling of a 20 / 25 MW windfarm (worst case for sediment spill), the construction phase is estimated as twenty weeks, assuming good weather and no delays, however it is unclear whether drilling and piling is performed simultaneously. Choosing gravity foundations instead for a 15 MW windfarm (worst case for gravity foundations) (Table 11.4), the construction is estimated to take thirty weeks, again assuming no delays.

Table 11.5 shows results from the same modelling, but here in the shape of sedimentation per hectares. Sedimentation will remain where it falls, and can be considered the result of the resuspension shown in Table 11.2 and Table 11.3.

Table 11.4. Model output for the scenario of a 15 MW windfarm with 60 turbines placed by gravity. The results are shown as concentration: hectares with a certain sediment resuspension for different concentrations with respect to duration. The wind-farm area is 17,700 hectares. 10 mg/L = 0.01 kg/m^3. 100 ha = 1 km^2. The table is copied from (NIRAS 2021).

Concen-tration	Duration												
	0.5 [hour]	1 [hour]	3 [hour]	6 [hour]	12 [hour]	1 [day]	2 [day]	1 [week]	2 [week]	3 [week]	4 [week]	5 [week]	6 [week]
2 mg/l	65276	55197	40913	32505	25007	17945	10817	2094	365	91	25	4	0
10 mg/l	21320	17800	13033	9164	4715	1637	416	15	2	0	0	0	0
25 mg/l	12182	9920	5499	2380	750	177	42	2	0	0	0	0	0
50 mg/l	7900	5780	1753	583	153	40	9	0	0	0	0	0	0
100 mg/l	4116	2027	411	103	28	8	1	0	0	0	0	0	0
500 mg/l	348	105	9	3	0	0	0	0	0	0	0	0	0
1000 mg/l	89	28	3	0	0	0	0	0	0	0	0	0	0

Table 11.5. Model output for the scenario of a 15 MW windfarm with 60 turbines piled or drilled down. The results are shown as maximum sedimentation in mm per hectares.

Sedimentation										
>1 [mm]	>2 [mm]	>5 [mm]	>10 [mm]	>15 [mm]	>20 [mm]	>25 [mm]	>30 [mm]	>35 [mm]	>40 [mm]	>50 [mm]
9940	5770	1426	279	107	61	41	27	20	17	11

Table 11.6. Model output for the scenario of a 15 MW windfarm with 60 turbines placed by gravity. The results are shown as maximum sedimentation in mm per hectares.

Sedimentation										
>1 [mm]	>2 [mm]	>5 [mm]	>10 [mm]	>15 [mm]	>20 [mm]	>25 [mm]	>30 [mm]	>35 [mm]	>40 [mm]	>50 [mm]
9554	5668	1380	286	99	48	26	16	10	6	3

11.5 Impact on marine mammals

Harbour porpoises forage by means of echolocation and therefore primarily depend on acoustic cues and accurate hearing for reception of relevant cues from the environment, for example echoes from prey species (Wisniewska, et al. 2012). However, given that the drill is working from a large vessel emitting noise, it is very likely that porpoises are scared away from the core area with the most turbid water. However, porpoises return when the noise disappears and may be exposed to lower concentrations of suspended sediment within days after the drilling or placement by gravity foundations (Table 11.2 and Table 11.3). Given that the overall habitat of the harbour porpoise in other parts of the world also includes estuaries with heavy tide and thus suspended bottom material, it is assessed that the **sensitivity** of harbour porpoises to sediment spills is **low**. It assessed that **the impact of sediment spills on the harbour porpoise population in southern Kattegat**, as modelled by NIRAS, despite its extensive coverage in time and space, is **negligible.**

Seals forage by means of their vibrissae (Hyvärinen 1989), as well as by vision when light is available. Effect of turbidity on vision was tested on harbour seals and showed that visual acuity decreased rapidly with turbidity, even at low levels (Weiffen, et al. 2006) thus negatively affecting hunting by vision. Despite of this, seals forage and thrive in the Wadden Sea where the turbidity is high, however it is unclear whether they only forage in the deeper and narrow passages, where the water may be more clear One reason for this is the ability of seals to forage by means of their vibrissae. The vibrissae is used to follow the flow changes in the water from moving prey (Miersch, et al. 2011). The **sensitivity** of both harbour and grey seals to sedimentation is assessed as **low**. The impact from sedimentation during construction of the offshore wind farm at Kattegatt Syd is therefore assessed as **negligible** for seals of both species.

12 Conclusion

Construction and operation of an offshore wind farm in the Kattegatt Syd offshore windfarm site has been assessed with respect to impacts on marine mammals. The conclusions with respect to abundance of marine mammals, their sensitivity to impact and assessment of impact during construction and operation are summarized below.

12.1 Abundance and sensitivity of marine mammals

- Harbour porpoises are abundant and the population is in favourable conservation status.

- Harbour seals are abundant in the area and the population is in favourable conservation status.

- Grey seals are found in low numbers in the area. The population is growing, but assessed as being in a non-favourable conservation status, due to the small population size.

- Noise from pile driving is likely to constitute the single most disturbing factor for both seals and porpoises.

12.2 Impact from construction

- Sound propagating properties of the water is the most important factor determining the extent of impact zones around the construction site. Worst case conditions are with an upward refracting sound speed profile, typical for winter months, whereas conditions in spring and summer are less favourable for long-range propagation and hence results in smaller impact ranges.

- Position of the pile driving site within the proposed wind farm area had only a smaller influence on the impact ranges.

- Use of powerful noise abatement measures, such as a combination of Hydro Sound Dampeners and Double Big Bubble Curtains or equivalent to reduce emitted noise levels during pile driving is likely to have a considerable effect on impact ranges and to be able to prevent permanent hearing loss in both seals and porpoises.

- Behavioural disturbance from pile driving of both porpoises and seals are likely to occur at ranges up to about 8 km with use of Big Bubble Curtains under worst case conditions (December). For both seals and porpoises, this impact of construction is assessed to be **minor** as it affects a very small part of the population.

- By restricting pile driving to Best Environmental Practise, i.e. periods of the year with sound propagation properties less favourable for long-range propagation (i.e. not in winter months with a pronounced stratification of the water column with less saline water flowing out of the Baltic overlaying more saline waters from the North Sea at the bottom) in combination with the use of Best Available Technology in terms of noise abatement systems (e.g. HSD+DBBC or equivalent), the impact on seal and porpoise populations by construction can be reduced to **minor**.

- The impact of masking by noise from piling and or vessels used for positioning of gravity based foundations, drilling and preparing the sea bed is assessed to be **negligible** for harbour porpoises as the noise is at frequencies much below their echolocation.

- The impact of masking by noise from piling and or vessels used for positioning of gravity based foundations, drilling and preparing the sea bed is assessed to be **negligible** for seals, as they primarily used communication during the mating season close to their haul-outs, and there are no haul-outs close to the offshore windfarm site.

- The worst impact from gravity based foundations is assessed to pertain to vessel noise and is assessed to be **negligible** for both seal species and porpoises.

- Sediment spill during construction is temporally and spatially extensive, however since none of the three marine mammal species depends on visual cues for survival, the impact of sedimentation during construction is assessed as **negligible**.

12.3 Impact on Natura 2000 sites

- The assessment is based on modelling of pile driving noise. Positions for the modelling was in the middle and in the periphery in either end of the windfarm site to allow calculation of maximum overlap with Natura 2000 sites. The border of the windfarm site is 1 km from the border of the Natura 2000 sites. The overlaps calculated are therefore worst case scenarios for the peripheral turbine locations.

- Pile driving in winter with a noise abatement system of Big Bubble Curtains is likely to exceed the behavioural reaction threshold for harbour porpoises within 29 % of the Lilla Middelgrund Natura 2000 site and up to 45 % of the Stora Middelgrund & Röda Bank, Natura 2000 site, and thereby exceeding the threshold of maximum disturbance of 20 % of a Natura 2000 site put forward by JNCC. The impact on the Natura 2000 sites during construction in winter months with Big Bubble Curtain noise abatement is according to the JNCC guidelines assessed **unacceptable.**

- The impact of construction on Natura 2000 sites in periods of the year with sound propagation properties less favourable for long-range propagation such as July (Best Environmental Practise), and with the use of Best Available Technology noise abatement (Hydro Sound Dampeners and Double Big Bubble Curtains or similar), is for Lilla Middelgrund Natura 2000 site reduced to 2.8 % and is assessed according to the JNCC guidelines to be **acceptable.**

- Use of Best Available Technology for noise abatement, i.e. at the time of writing a system combining Hydro Sound Dampeners and Double Big Bubble Curtains, combined with Best Environmental Practise of choosing a period with sound propagation properties least favourable for long-range propagation such as July, is likely to reduce the impacted area of

Stora Middelgrund & Röda Bank to 5.3 %. According to the JNCC guidelines this impact is assessed as **acceptable**.

- None of the other nearby Natura 2000 areas are expected to be affected by the pile driving with the use of either Big Bubble Curtains or a combination of Hydro Sound Dampeners and Double Big Bubble Curtains or equivalent noise abatement. The effect on these areas is therefore **negligible**.

12.4 Impact from operation

- There are very few studies available to evaluate the long term effect of a wind farm in operation on neither harbour porpoises or seals. The effects observed in other windfarms range from an increased number of porpoises likely due to banning of trawling inside the windfarm, to a reduced number of animals in the windfarm compared with reference stations. The long-term impact of the Kattegatt Syd wind farm in operation is thus assessed as **negligible,** however with some uncertainty. It would be an advantage for harbour porpoise, harbour seal and grey seal populations, if the windfarm area would be closed for all fishing activities.

13 References

Akamatsu T, Dietz R, Miller LA, Naito Y, Siebert U, Teilmann J, Tougaard J, Wang D, Wang K. (2352 co-authors). 2007. Comparison of echolocation behavior between coastal oceanic and riverine porpoises. Deep-Sea Research Part II 54:290-297.

Andersson MH, Andersson S, Ahlsén J, Andersson BL, Hammar J, Persson LKG, Pihl J, Sigray P, Wirkström A. 2016. A framework for regulating underwater noise during pile driving. A technical Vindval report. In. Stockholm, Sweden.

Bailey H, Senior B, Simmons D, Rusin J, Picken G, Thompson PM. (3129 co-authors). 2010. Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals. Marine Pollution Bulletin 60:888-897.

Bas AA, Christiansen F, Amaha Ozturk A, Ozturk B, McIntosh C. 2017. The effects of marine traffic on the behaviour of Black Sea harbour porpoises (*Phocoena phocoena relicta*) within the Istanbul Strait, Turkey. PLoS ONE 12:e0172970.

Bellmann MA, Brinkmann J, May A, Wendt T, Gerlach S, Remmers P. 2020. Underwater noise during the impulse pile-driving procedure: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values. Report to the Federal Maritime and Hydrographic Agency. In. Oldenburg, Germany.

Bellmann MA, Schuckenbrock J, Gündert S, Müller M, Holst H, Remmers P. 2017. Is There a State-of-the-Art to Reduce Pile-Driving Noise? In. Wind Energy and Wildlife Interactions. p. 161-172.

Betke K. 2014. Underwater construction and operational noise at alpha ventus. In. Ecological Research at the Offshore Windfarm alpha ventus. Wiesbaden: Springer Fachmedien. p. 171-180.

Blackwell SB, Lawson JW, Williams MT. (2132 co-authors). 2004. Tolerance by ringed seals (*Phoca hispida*) to impact pipe-driving and construction sounds at an oil production island. Journal of the Acoustical Society of America 115:2346-2357.

Bloomfield P. 1976. Fourier analysis of time series: an introduction. New York: John Wiley and Sons.

Brandt MJ, Diederichs A, Betke K, Nehls G. (3148 co-authors). 2011a. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series 421:205-216.

Brandt MJ, Diederichs A, Betke K, Nehls G. 2011b. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. Marine Ecology Progress Series 421:205-216.

Brandt MJ, Dragon AC, Diederichs A, Bellmann MA, Wahl V, Piper W, Nabe-Nielsen J, Nehls G. 2018. Disturbance of harbour porpoises during construction of the first seven offshore wind farms in Germany. Marine Ecology Progress Series 596:213-232.

Brandt MJ, Höschle C, Diederichs A, Betke K, Matuschek R, Witte S, Nehls G. (3414 co-authors). 2012. Far-reaching effects of a seal scarer on harbour porpoises, *Phocoena phocoena*. Aquatic Conservation: Marine and Freshwater Ecosystems 23:222-232.

Bröker K, Gailey G, Muir J, Racca R. 2015. Monitoring and impact mitigation during a 4D seismic survey near a population of gray whales off Sakhalin Island, Russia. Endangered Species Research 28:187-208.

Camphuysen CJ, Smeenk C, Addink M, van Grouw H, Jansen OE. (2983 co-authors). 2008. Cetaceans stranded in the Netherlands from 1998 to 2007. Lutra 51:87-122.

Carlén I, Thomas L, Carlström J, Amundin M, Teilmann J, Tregenza N, Tougaard J, Koblitz JC, Sveegaard S, Wennerberg D, et al. 2018. Basin-scale distribution of harbour porpoises in the Baltic Sea provides basis for effective conservation actions. Biological Conservation 226:42-53.

Dietz R, Galatius A, Mikkelsen L, Nabe-Nielsen J, Riget F, Schack HB, Skov H, Sveegaard S, Teilmann J, Thomsen F. 2015. Marine mammals - Investigations and preparation of environmental impact assessment for Kriegers Flak Offshore Wind Farm. In: Energinet.dk. p. 208.

Dietz R, Teilmann J, Andersen SM, Rigét F, Olsen MT. 2012. Movements and site fidelity of harbour seals (Phoca vitulina) in Kattegat, Denmark, with implications for the epidemiology of the phocine distemper virus. ICES Journal of Marine Science: Journal du Conseil 70:186-195.

Dähne M, Gilles A, Lucke K, Peschko V, Adler S, Krügel K, Sundermeyer J, Siebert U. (3418 co-authors). 2013. Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany. Environmental Research Letters 8:025002.

Dähne M, Tougaard J, Carstensen J, Rose A, Nabe-Nielsen J. 2017. Bubble curtains attenuate noise from offshore wind farm construction and reduce temporary habitat loss for harbour porpoises. Marine Ecology Progress Series 580:221-237.

Edrén SME, Wisz MS, Teilmann J, Dietz R, Söderkvist J. (3499 co-authors). 2010. Modelling spatial patterns in harbour porpoise satellite telemetry data using maximum entropy. Ecography.

Ellison WT, Southall BL, Clark CW, Frankel AS. (3359 co-authors). 2012. A new context-based approach to assess marine mammal behavioral responses to antropogenic sounds. Conservation Biology 26:21-28.

Erbe C, Reichmuth C, Cunningham K, Lucke K, Dooling R. 2016. Communication masking in marine mammals: A review and research strategy. Marine Pollution Bulletin 103:15-38.

Finneran JJ. 2015. Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. The Journal of the Acoustical Society of America 138:1702-1726.

Finneran JJ, Carder DA, Schlundt CE, Dear RL. 2010. Temporary threshold shift in a bottlenose dolphin (*Tursiops truncatus*) exposed to intermittent tones. The Journal of the Acoustical Society of America 127:3267-3272.

Finneran JJ, Dear R, Carder DA, Ridgway SH. (2367 co-authors). 2003. Auditory and behavioral responses of California sea lions (*Zalophus californianus*) to single underwater impulses from an arc-gap transducer. Journal of the Acoustical Society of America 114:1667-1677.

Galatius A, Kinze CC, Teilmann J. (3420 co-authors). 2012. Population structure of harbour porpoises in the Baltic region: evidence of separation based on geometric morphometric comparisons. JMBA 92:1669-1676.

Gallon SL, Sparling CE, Georges JY, Fedak MA, Biuw M, Thompson D. 2007. How fast does a seal swim? Variations in swimming behaviour under differing foraging conditions. J Exp Biol 210:3285-3294.

German Federal Ministry for the Environment and Nuclear Safety. 2013. Konzept für den Schutz der Schweinswale vor Schallbelastungen bei der Errichtung von Offshore-Windparks in der deutschen Nordsee (Schallschutzkonzept). https://www.bfn.de/fileadmin/BfN/awz/Dokumente/schallschutzkonzept_BMU.pdf (accessed 2017/03/10). In.

Haelters J, Dulière V, Vigin L, Degraer S. 2015. Towards a numerical model to simulate the observed displacement of harbour porpoises Phocoena phocoena due to pile driving in Belgian waters. Hydrobiologia 756:105-116.

Hammond PS, Berggren P, Benke H, Borchers DL, Collet A, Heide-Jørgensen M-P, Heimlich S, Hiby AR, Leopold MF, Øien N. (2082 co-authors). 2002. Abundance of harbour porpoise and other cetaceans in the North Sea and adjacent waters. J.Appl.Ecol. 39:361-376.

Hammond PS, Lacey C, Gilles A, Viquerat S, Börjesson P, Herr H, Macleod K, Ridoux V, Santos MB, Scheidat M, et al. 2017. Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys. In: SCANS III.

Hammond PS, Macleod K, Berggren P, Borchers DL, Burt L, Canadas A, Desportes G, Donovan GP, Gilles A, Gillespie D, et al. (3433 co-authors). 2013. Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management. Biological Conservation 164:107-122.

Hansen JW, Høgslund S. 2019. Marine områder 2018. NOVANA. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 156 s. - Videnskabelig rapport fra DCE nr. 355. In.

Hansen JWr. 2018. Marine områder 2016. NOVANA. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 140 s. - Videnskabelig rapport fra DCE - Nationalt Center for Miljø og Energi nr. 253 http://dce2.au.dk/pub/SR253.pdf. In.

Hermannsen L, Mikkelsen L, Tougaard J. 2015. Review: Effects of seal scarers on harbour porpoises. Research note from DCE - Danish Centre for Environment and Energy. In. Roskilde, Denmark: Aarhus University.

Houser DS, Yost W, Burkard R, Finneran JJ, Reichmuth C, Mulsow J. 2017. A review of the history, development and application of auditory weighting functions in humans and marine mammals. The Journal of the Acoustical Society of America 141:1371-1413.

Hyvärinen H. (274 co-authors). 1989. Diving in darkness: whiskers as sense organs of the ringed seal (*Phoca hispida saimensis*). Journal of Zoology 218:663-678.

ICES. 2020. Working Group on Marine Mammal Ecology (WGMME). ICES Scientific Reports 2:85.

Jepsen PU. 2005. Forvaltningsplan for spættet sæl (Phoca vitulina) og gråsæl (*Halichoerus grypus*) i Danmark. Miljøministeriet, Skov- og Naturstyrelsen. In.

JNCC. 2020a. Background to the advice on noise management within harbour porpoise SACs in England, Wales and Northern Ireland. In.

JNCC. 2020b. Guidance for assessing the significance of noise disturbance against Conservation Objectives of harbour porpoise SACs. In: JNCC.

JNCC. 2020c. Guidance for assessing the significance of noise disturbance against Conservation Objectives of harbour porpoise SACs. (England, Wales & Northern Ireland). In.

Johnston DW. (2677 co-authors). 2002. The effect of acoustic harassment devices in harbour porpoises (*Phocoena phocoena*) in the Bay of Fundy, Canada. Biol.Conserv. 108:113-118.

Kastak D, Mulsow J, Ghoul A, Reichmuth C. (2816 co-authors). 2008. Noise-induced permanent threshold shift in a harbor seal. The Journal of the Acoustical Society of America 123:2986-2986.

Kastelein RA, Gransier R, Hoek L. (3498 co-authors). 2013. Comparative temporary threshold shifts in a harbor porpoise and harbor seal, and severe shift in a seal (L). Journal of the Acoustical Society of America 134:13-16.

Kastelein RA, Gransier R, Hoek L, Rambags M. (3491 co-authors). 2013. Hearing frequency thresholds of a harbor porpoise (*Phocoena phocoena*) temporarily affected by a continuous 1.5 kHz tone. Journal of the Acoustical Society of America 134:2286-2292.

Kastelein RA, Gransier R, Marijt MAT, Hoek L. 2015. Hearing frequency thresholds of harbor porpoises (*Phocoena phocoena*) temporarily affected by played back offshore pile driving sounds. Journal of the Acoustical Society of America 137:556-564.

Kastelein RA, Helder-Hoek L, Covi J, Gransier R. 2016. Pile driving playback sounds and temporary threshold shift in harbor porpoises (Phocoena phocoena): Effect of exposure duration. J Acoust Soc Am 139:2842.

Kastelein RA, Hoek L, de Jong CAF, Wensveen PJ. (3228 co-authors). 2010. The effect of signal duration on the underwater detection thresholds of a harbor porpoise (*Phocoena phocoena*) for single frequency-modulated tonal signals between 0.25 and 160 kHz. Journal of the Acoustical Society of America 128:3211-3222.

Kastelein RA, Hoek L, Gransier R, Rambags M, Clayes N. (3559 co-authors). 2014. Effect of level, duration, and inter-pulse interval of 1-2kHz sonar signal exposures on harbor porpoise hearing. Journal of the Acoustical Society of America 136:412-422.

Kastelein RA, Hoek L, Wensveen PJ, Terhune JM, de Jong CAF. 2010. The effect of signal duration on the underwater hearing thresholds of two harbor seals (*Phoca vitulina*) for single tonal signals between 0.2 and 40 kHz. Journal of the Acoustical Society of America 127:1135-1145.

Kastelein RA, Steen N, Gransier R, Wensveen PJ, de Jong CAF. (3502 co-authors). 2012. Threshold received sound pressure levels of single 1-2 kHz and 6-7 kHz up-sweeps and down-sweeps causing startle responses in a harbor porpoise (*Phocoena phocoena*). Journal of the Acoustical Society of America 131:2325-2333.

Kastelein RA, Van de Voorde S, Jennings N. 2018. Swimming Speed of a Harbor Porpoise (Phocoena phocoena) During Playbacks of Offshore Pile Driving Sounds. Aquatic Mammals 44:92-99.

Kastelein RA, Wensveen PJ, Hoek L, Verboom WC, Terhune JM. 2009. Underwater detection of tonal signals between 0.125 and 100 kHz by harbor seals (*Phoca vitulina*). Journal of the Acoustical Society of America 125:1222-1229.

Kinze CC. (1964 co-authors). 1990. Marsvinet i danske farvande - udbredelse, yngleforekomst og trusler. Fauna och Flora 85:114-121.

Kinze CC, Thøstesen CB, Olsen MT. 2018. Cetacean stranding records along the Danish coastline: records for the period 2008-2017 and a comparative review. Lutra 61:87-105.

Koschinski S, Lüdemann K. 2020. Noise mitigation for the construction of increasingly large offshore wind turbines. Technical options for complying with noise limits. In.

Kujawa SG, Liberman MC. (3474 co-authors). 2009. Adding Insult to Injury: Cochlear Nerve Degeneration after "Temporary" Noise-Induced Hearing Loss. The Journal of Neuroscience 29:14077-14085.

Kyhn LA, Tougaard J, Beedholm K, Jensen FH, Ashe E, Williams R, Madsen PT. (3535 co-authors). 2013. Clicking in a Killer Whale Habitat: Narrow-Band, High-Frequency Biosonar Clicks of Harbour Porpoise (*Phocoena phocoena*) and Dall's Porpoise (*Phocoenoides dalli*). PlosOne 8:e63763.

Kyhn LA, Tougaard J, Thomas L, Duve LR, Steinback J, Amundin M, Deportes G, Teilmann J. (3219 co-authors). 2011. From echolocation clicks to animal density - acoustic sampling of harbour porpoises with static dataloggers. Journal of the Acoustical Society of America 131:550-560.

Lance RM, Capehart B, Kadro O, Bass CR. 2015. Human injury criteria for underwater blasts. PLoS ONE 10:e0143485.

Linnenschmidt M, Teilmann J, Akamatsu T, Dietz R, Miller LA. 2013. Biosonar, dive, and foraging activity of satellite tracked harbor porpoises (Phocoena phocoena). Marine Mammal Science 29:E77-E97.

Lockyer C. 2003. Harbour porpoises (Phocoena phocoena) in the North Atlantic: Biological parameters. NAMMCO Sci. Publ.:71-90.

Lockyer C, Morris R. 1987. Observations on diving behaviour and swimming speeds in a wild juvenile *Tursiops truncatus*. Aquatic Mammals 13:31-35.

Lucke K, Siebert U, Lepper PA, Blanchet M-A. (2926 co-authors). 2009. Temporary shift in masked hearing thresholds in a harbor porpoise (*Phocoena phocoena*) after exposure to seismic airgun stimuli. Journal of the Acoustical Society of America 125:4060-4070.

Madsen PT, Carder DA, Beedholm K, Ridgway SH. (2277 co-authors). 2005. Porpoise clicks from a sperm whale nose - convergent evolution of 130 kHz pulses in toothed whale sonars? Bioacoustics 15:195-306.

Madsen PT, Wahlberg M, Tougaard J, Lucke K, Tyack PL. (2162 co-authors). 2006. Wind turbine underwater noise and marine mammals: Implications of current knowledge and data needs. Marine Ecology Progress Series 309:279-295.

McConnell BJ, Lonergan M, Dietz R. 2011. Interactions between seals and offshore wind farms. Draft report to the Crown Estate. In. St. Andrews.

Miersch L, Hanke W, Wieskotten S, Hanke FD, Oeffner J, Leder A, Brede M, Witte M, Dehnhardt G. 2011. Flow sensing by pinniped whiskers. Philosophical Transactions of the Royal Society B: Biological Sciences 366:3077-3084.

Mikkelsen L, Hermannsen L, Beedholm K, Madsen PT, Tougaard J. 2017. Simulated seal scarer sounds scare porpoises, but not seals: species-specific responses to 12 kHz deterrence sounds. Royal Society Open Science 4:170286.

Mikkelsen L, Hermannsen L, Tougaard J. 2015. Effect of seal scarers on seals. Literature review for the Danish Energy Agency. In. Roskilde: Aarhus University, DCE. p. 19.

Moeslund JE, Nygaard B, Ejrnæs R, Bell N, Bruun LD, Bygebjerg R, Carl H, Damgaard J, Dylmer E, Elmeros M, et al. 2019. Den danske rødliste 2019. In. Aarhus.

Møhl B. (2108 co-authors). 1968. Auditory sensitivity of the common seal in air and water. J.Aud.Res 8:27-38.

Møhl B. 1981. A discussion of noise generated by icebreaking LNG carriers. In: Peterson NM, editor. The question of sound from icebreaker operations. Proceedings of a Workshop 23 and 24 February 1981. Toronto: Arctic Pilot Project. p. 206-209.

Møhl B. (13 co-authors). 1967. Seal Ears. Science 157:99.

Møhl B, Andersen S. (653 co-authors). 1973. Echolocation: high-frequency component in the click of the harbour porpoise (*Phocoena ph. L.*). Journal of the Acoustical Society of America 54:1368-1372.

Nabe-Nielsen J, van Beest FM, Grimm V, Sibly RM, Teilmann J, Thompson PM. 2018. Predicting the impacts of anthropogenic disturbances on marine populations. Conservation Letters.

Nachtigall PE, Supin AY. (3560 co-authors). 2014. Conditioned hearing sensitivity reduction in a bottlenose dolphin (*Tursiops truncatus*). The Journal of Experimental Biology 217:2806-2813.

National Marine Fisheries Service. 2016. Technical guidance for assessing the effects of anthropogenic sound on marine mammal hearing underwater acoustic thresholds for onset of permanent and temporary threshold shifts. NOAA Technical Memorandum NMFS-OPR-55. In. Silver Spring, MD. p. 178.

National Research Council. 2003. Ocean noise and marine mammals. Washington, D.C.: The National Academies Press.

Nehls G, Bellmann M. 2016. Weiterentwicklung und Erprobung des „Großen Blasenschleiers“ zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten Förderkennzeichen 0325645A / B / C / D. In. Husum, Germany.

NIRAS. 2021. Kattegatt Syd - Sweden. Sediment Dispersal Installation Activities. In: NIRAS. p. 71.

Olesiuk PF, Nichol LM, Sowden MJ, Ford JKB. (2678 co-authors). 2002. Effect of the sound generated by an acoustic harassment device on the relative abundance and distribution of harbor porpoises (*Phocoena phocoena*) in Retreat Passage, British Columbia. Marine Mammal Science 18:843-862.

Olsen MT, Andersen LW, Dietz R, Teilmann J, Harkonen T, Siegismund HR. 2014. Integrating genetic data and population viability analyses for the identification of harbour seal (*Phoca vitulina*) populations and management units. Molecular Ecology 23:815-831.

Otani S, Naito Y, Kato A. (3346 co-authors). 2000. Diving behaviour and swimming speed of a free-ranging harbor porpoise, *Phocoena phocoena*. Marine Mammal Science 16:811-814.

Popov VV, Supin AY, Wang D, Wang K, Dong L, Wang S. (3257 co-authors). 2011. Noise-induced temporary threshold shift and recovery in Yangtze finless porpoises *Neophocaena phocaenoides asiaorientalis*. Journal of the Acoustical Society of America 130:574-584.

Reichmuth C, Ghoul A, Sills JM, Rouse A, Southall BL. 2016. Low-frequency temporary threshold shift not observed in spotted or ringed seals exposed to single air gun impulses. J Acoust Soc Am 140:2646.

Reichmuth C, Holt M, Mulsow J, Sills J, Southall B. 2013. Comparative assessment of amphibious hearing in pinnipeds. Journal of Comparative Physiology A 199:491-507.

Russell DF, Brasseur SMJM, Thompson D, Hastie GD, Janik VM, Aarts G, McClintock BT, Matthiopoulos J, Moss SEW, McConnell BJ. (3569 co-authors). 2014. Marine mammals trace anthropogenic structures at sea. Current Biology 24:R638-R639.

Russell DJF, Hastie GD, Thompson D, Janik VM, Hammond PS, Scott-Hayward LAS, Matthiopoulos J, Jones EL, McConnell BJ. 2016. Avoidance of wind farms by harbour seals is limited to pile driving activities. Journal of Applied Ecology:1-11.

Ryan AF, Kujawa SG, Hammill T, Le Prell C, Kil J. 2016. Temporary and permanent noise-induced threshold shifts: A review of basic and clinical observations. Otol Neurotol 37:e271-275.

Sabinsky PF, Larsen ON, Wahlberg M, Tougaard J. 2017. Temporal and spatial variation in harbor seal (*Phoca vitulina* L.) roar calls from southern Scandinavia. The Journal of the Acoustical Society of America 141:1824-1834.

Scheidat M, Tougaard J, Brasseur S, Carstensen J, Petel TvP, Teilmann J, Reijnders P. (3229 co-authors). 2011. Harbour porpoises (*Phocoena phocoena*) and wind farms: a case study in the Dutch North Sea. Environmental Research Letters 6:025102.

Skjellerup P, Maxon CM, Tarpgaard E, Thomsen F, Schack HB, Tougaard J, Teilmann J, Madsen KN, Mikaelsen MA, Heilskov NF. 2015. Marine mammals and underwater noise in relation to pile driving - report of working group. In: Energinet.dk. p. 20.

Skjellerup P, Tougaard J. 2016. Marine mammals and underwater noise in relation to pile driving - Revision of assessment. . In. Fredericia, Denmark: Energinet.dk. p. 8.

SLU Artdatabanken. 2020. Rödlistade arter i Sverige 2020. In. Uppsala.

Southall BL, Bowles AE, Ellison WT, Finneran JJ, Gentry RL, Greene CR, Kastak D, Ketten DR, Miller JH, Nachtigall PE, et al. (2673 co-authors). 2007. Marine Mammal Noise Exposure Criteria. Aquatic Mammals 33:411-414.

Southall BL, Finneran JJ, Reichmuth C, Nachtigall PE, Ketten DR, Bowles AE, Ellison WT, Nowacek DP, Tyack PL. 2019. Marine Mammal Noise Exposure Criteria: Updated Scientific Recommendations for Residual Hearing Effects. Aquatic Mammals 45:125-232.

Stöber U, Thomsen F. 2021. How could operational underwater sound from future offshore wind turbines impact marine life? The Journal of the Acoustical Society of America 149:1791-1795.

Sveegaard S, Balle JD, Kyhn L, Larsen J, Mohn C, Teilmann J, Nabe-Nielsen J. 2017. Monthly variation in fine-scale distribution of harbour porpoises at St. Middelgrund reef. Technical Report from DCE – Danish Centre for Environment and Energy No. 97. . In. p. 34.

Sveegaard S, Galatius A, Dietz R, Kyhn L, Koblitz JC, Amundin M, Nabe-Nielsen J, Sinding M-HS, Andersen LW, Teilmann J. 2015. Defining management units for cetaceans by combining genetics, morphology, acoustics and satellite tracking. Global Ecology and Conservation 3:839-850.

Sveegaard S, Nabe-Nielsen J, Teilmann J. 2018a. Marsvins udbredelse og status for de marine habitatområder i danske farvande. In. Videnskabelig rapport: Aarhus Universitet, DCE - Nationalt Center for Miljø og Energi. p. 36.

Sveegaard S, Nabe-Nielsen J, Teilmann J. 2018b. Marsvins udbredelse og status for de marine habitatområder i danske farvande. Aarhus Universitet, DCE – Nationalt Center for Miljø og Energi, 36 s. - Videnskabelig rapport nr. 284.

Sveegaard S, Teilmann J, Tougaard J, Dietz R, Mouritsen H, Desportes G, Siebert U. (3099 co-authors). 2011. High density areas for harbor porpoises (*Phocoena phocoena*) identified by satellite tracking. Marine Mammal Science 27:230-246.

Teilmann J. (1966 co-authors). 2003. Influence of sea state on density estimates of harbour porpoises (*Phocoena phocoena*). Journal of Cetacean Research and Management 5:85-92.

Teilmann J, Carstensen J. (3567 co-authors). 2012. Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic—evidence of slow

recovery. Environmental Research Letters 7:45101.

Teilmann J, Larsen F, Desportes G. (2866 co-authors). 2007. Time allocation and diving behaviour of harbour porpoises (*Phocoena phocoena*) in Danish and adjacent waters. Journal of Cetacean Research and Management 9:201-210.

Teilmann J, Sveegaard S, Dietz R, Petersen IK, Berggren P, Desportes G. 2008. High density areas for harbour porpoises in Danish waters. NERI Technical Report No. 657. In. Roskilde. p. 84.

Teilmann J, Tougaard J, Carstensen J. 2012. Effects on harbour porpoises from Rødsand 2 offshore wind farm. In. Roskilde, Denmark.

Terhune JM. (3386 co-authors). 1988. Detection thresholds of a harbor seal to repeated underwater high-frequency, short duration sinusoidal pulses. Canadian Journal of Zoology 66:1578-1582.

Todd VLG. 2016. Mitigation of underwater anthropogenic noise and marine mammals: the ‘death of a thousand’ cuts and/or mundane adjustment? Marine Pollution Bulletin 102:1-3.

Tougaard J, Beedholm K. 2019. Practical implementation of auditory time and frequency weighting in marine bioacoustics. Applied Acoustics 145:137-143.

Tougaard J, Buckland ST, Robinson SP, Southall B. 2013. An analysis of potential broad-scale impacts on harbour porpoise from proposed pile driving activities in the North Sea. Report of an expert group convened under the Habitats and Wild Birds Directive – Marine Evidence Group MB0138. 38pp. In.

Tougaard J, Carstensen J, Teilmann J, Skov H, Rasmussen P. 2009. Pile driving zone of responsiveness extends beyond 20 km for harbor porpoises (Phocoena phocoena (L.)). Journal of the Acoustical Society of America 126:11-14.

Tougaard J, Dähne M. 2017. Why is auditory frequency weighting so important in regulation of underwater noise? Journal of the Acoustical Society of America 142:EL415-EL420.

Tougaard J, Hermannsen L, Madsen PT. 2020. How loud is the underwater noise from operating offshore wind turbines? The Journal of the Acoustical Society of America 148:2885-2893.

Tougaard J, Kyhn LA, Amundin M, Wennerberg D, Bordin C. 2012. Behavioral reactions of harbor porpoise to pile-driving noise. In: Popper AN, Hawkins AD, editors. Effects of Noise on Aquatic Life. New York: Springer. p. 277-280.

Tougaard J, Mikaelsen M. 2020. Effects of larger turbines for the offshore wind farm at Krieger's Flak, Sweden. Addendum with revised and extended assessment of impact on marine mammals. Aarhus University, DCE – Danish Centre for Environment and Energy, 32 pp. Scientific Report No. 366. In.

Tougaard J, Mikaelsen MA. 2018. Effects of larger turbines for the offshore wind farm at Krieger's Flak, Sweden. Assessment of impact on marine mammals. Aarhus University, DCE – Danish Centre for Environment and Energy, 112 pp. Scientific Report No. 286. . In.

Tougaard J, Teilmann J, Tougaard S. (2518 co-authors). 2008. Harbour seal spatial distribution estimated from Argos satellite telemetry - overcoming positioning errors. Endangered Species Research **4**:113-122.

Tougaard J, Wright AJ, Madsen PT. (3597 co-authors). 2015. Cetacean noise criteria revisited in the light of proposed exposure limits for harbour porpoises. Marine Pollution Bulletin 90:196-208.

Van Parijs SM, Kovacs KM, Lydersen C. (2410 co-authors). 2001. Spatial and temporal distribution of vocalising male bearded seals - implications for male mating strategies. Behaviour 138:805-922.

Viquerat S, Herr H, Gilles A, Peschko V, Siebert U, Sveegaard S, Teilmann J. 2014. Abundance of harbour porpoises (Phocoena phocoena) in the western Baltic, Belt Seas and Kattegat. Marine Biology 161:745-754.

Weiffen M, Möller B, Mauck B, Dehnhardt G. 2006. Effect of water turbidity on the visual acuity of harbor seals (Phoca vitulina). Vision Res 46:1777-1783.

Welch PD. (3343 co-authors). 1967. The use of fast fourier transform for the estimation of power spectra: A method based on time averaging over short, modified periodograms. IEEE Transactions on Audio Electroacoustics AU-15:70-73.

Wiemann A, Andersen L, Berggren P, Siebert U, Benke H, Teilmann J, Lockyer C, Pawliczka I, Skora K, Roos A, et al. (3419 co-authors). 2010. Mitochondrial Control Region and microsatellite analyses on harbour porpoise (Phocoena phocoena) unravel population differentiation in the Baltic Sea and adjacent waters. Conserv Genet 11:195-211.

Williams R, Noren DP. 2009. Swimming speed, respiration rate, and estimated cost of transport in adult killer whales. Marine Mammal Science 25:327-350.

Wisniewska DM, Johnson M, Beedholm K, Wahlberg M, Madsen PT. 2012. Acoustic gaze adjustments during active target selection in echolocating porpoises. The Journal of Experimental Biology 215:4358-4373.

Wisniewska DM, Johnson M, Teilmann J, Rojano-Donate L, Shearer J, Sveegaard S, Miller LA, Siebert U, Madsen PT. 2016. Ultra-High Foraging Rates of Harbor Porpoises Make Them Vulnerable to Anthropogenic Disturbance. Current Biology 26:1441-1446.

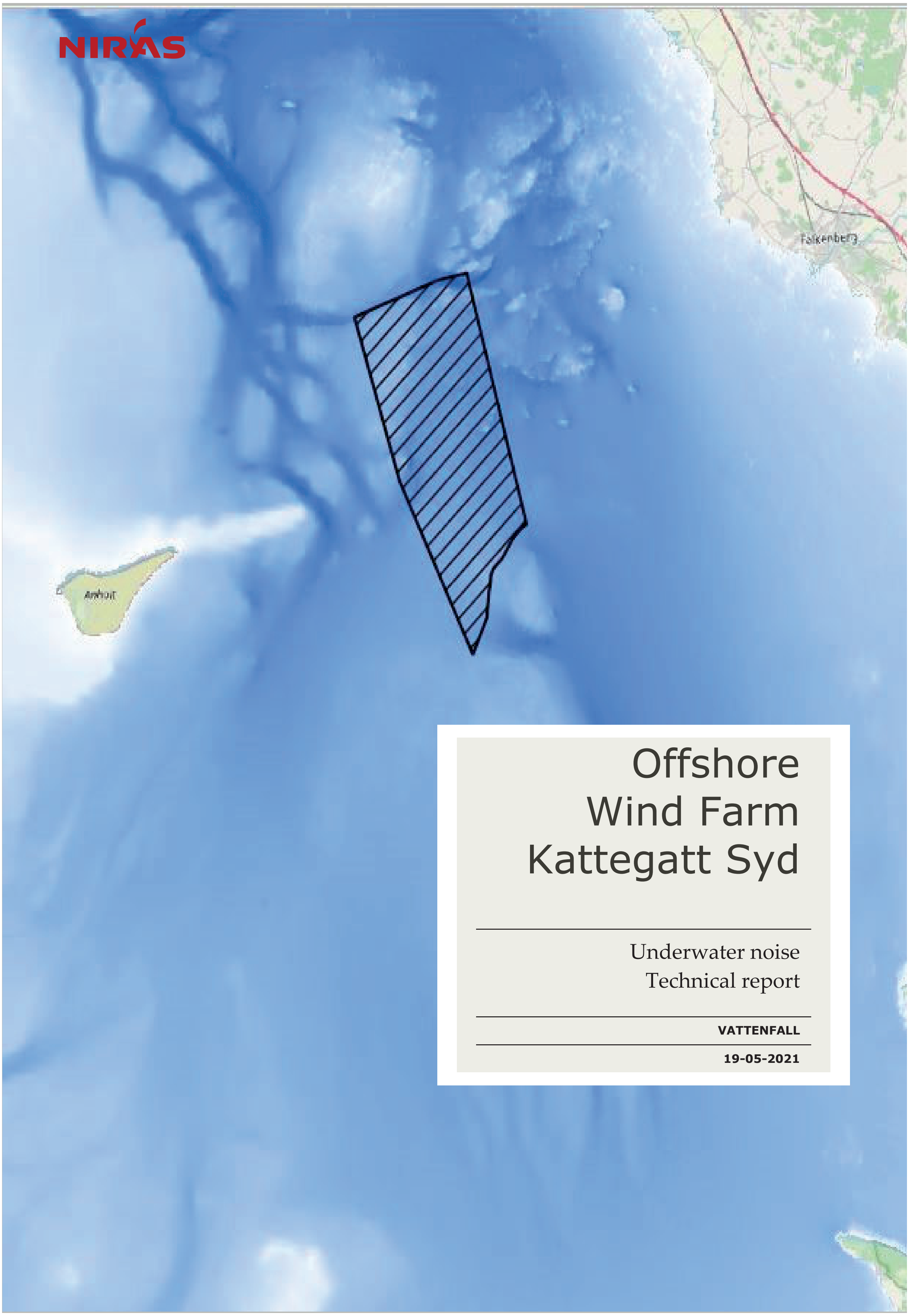
Wisniewska DM, Johnson M, Teilmann J, Siebert U, Galatius A, Dietz R, Madsen PT. 2018. High rates of vessel noise disrupt foraging in wild harbour porpoises (*Phocoena phocoena*). Proceedings of the Royal Society B: Biological Sciences 285.

Yelverton JT, Richmond DR, Fletcher ER, Jones RK. 1973. Safe distances from underwater explosions for mammals and birds. In. Albuquerque, New Mexico.

Appendix 1 Sound propagation modelling

This appendix was written by NIRAS for Vattenfall Vind AB. It has been delivered directly to Vattenfall, but is included here to provide the full background for the included modelling and its results.

NIRAS



Offshore Wind Farm Kattegatt Syd

Underwater noise
Technical report

VATTENFALL

19-05-2021

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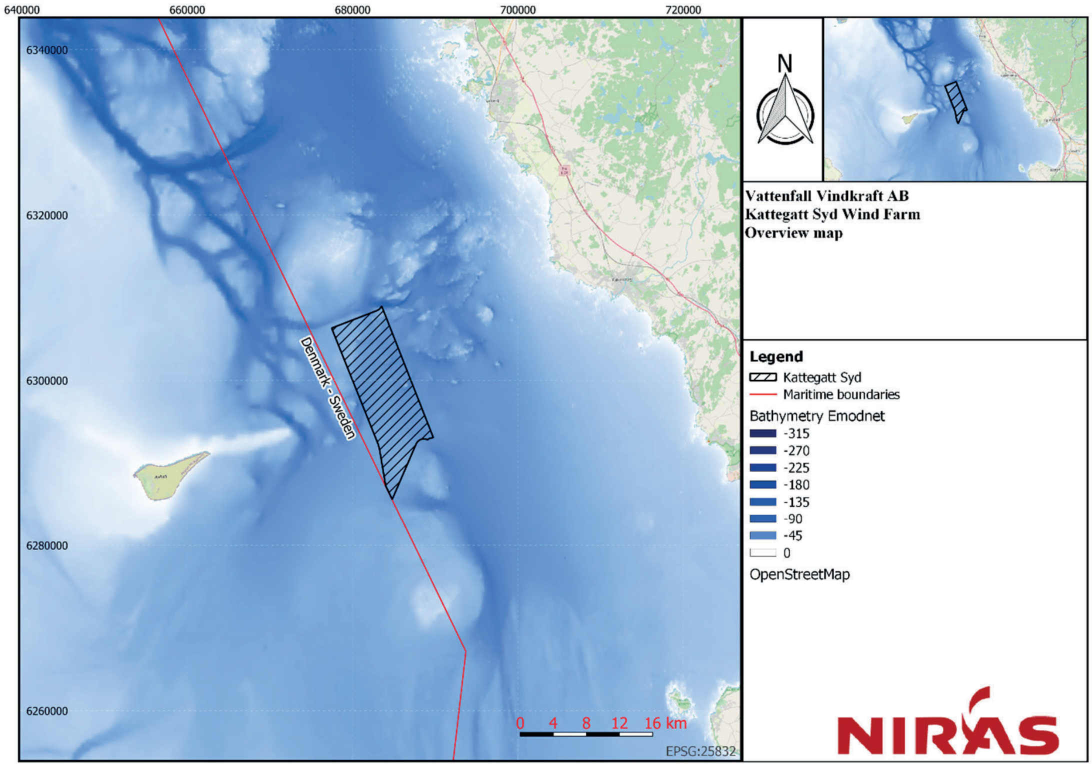
List of abbreviations

Full name	Abbreviation
Sound Exposure Level	SEL
Cumulative Sound Exposure Level	SEL_{C24h}
Sound Pressure Level	SPL
Permanent Threshold Shift	PTS
Temporary Threshold Shift	TTS
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
IHC Noise Mitigation Screen	IHC-NMS
World Ocean Atlas 2018	WOA18
Normal modes	NM
Parabolic Equation	PE

1 Introduction

This report documents underwater sound propagation modelling in connection with the application for the installation of wind turbine foundations at Kattegatt Syd offshore wind farm (OWF). Kattegatt Syd OWF is located in the Swedish part of Kattegatt, see Figure 1.1. The wind farm site is located near the Danish EEZ indicated by the red line in Figure 1.1.

Figure 1.1: Overview of Kattegatt Syd offshore wind farm site and surrounding area.



The project includes installation of up to 60 wind turbines on monopile foundations up to 14 m diameter, installed using impact pile driving, which, from an underwater noise perspective, carries the risk of negatively impacting nearby marine mammals. In order to reduce this impact, a number of mitigating measures are included in the underwater noise calculations.

The report documents impact ranges for all relevant threshold levels outlined in chapter 3.

2 Purpose

The purpose of this report is to document the underwater sound propagation modelling carried out for the installation of wind turbine foundations at Kattegatt Syd offshore wind farm, as well as to calculate impact distances to relevant thresholds for marine mammals.

3 Background

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.

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 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.

$$\mathrm{SPL_{RMS}} = 20 * \log_{10}\left(\sqrt{\left(\frac{1}{\mathrm{T}}\right)\int_{\mathrm{T}} \mathrm{p(t)^2}}\right) \quad [\mathrm{dB\ re.\ 1\mu Pa}]$$ 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 sound pressure level 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 (Jakob Tougaard, 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.

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

Where $\mathrm{T_0}$ is 1 second, 0 is the starting time and T is end time of the noise event, p is the pressure, and $\mathrm{p_0}$ is the reference sound pressure which is $1\ \mathrm{\mu Pa}$. 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).

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

3.1.3 Fleeing behavior 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 Temporary Threshold Shift (TTS) and

Permanent Threshold Shift (PTS) caused by underwater noise on marine mammals, $\mathrm{SEL}_{\mathrm{C},<\mathrm{duration}>}$ is used to describe the noise dose received by the receptors. It is therefore important to include the behaviour of marine mammals in the calculation of $\mathrm{SEL}_{\mathrm{C},<\mathrm{duration}>}$. 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 $\mathrm{SEL}_{\mathrm{C},<\mathrm{duration}>}$ has already been done by (Energistyrelsen, 2016), for the Danish guidelines for pile driving activities, as given by Equation 4. Here, the duration is fixed to 24h to represent the daily $\mathrm{SEL}_{\mathrm{C}}$. If multiple foundations are installed in the same 24 hour window, they all have to be included in the calculation.

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

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
- $\mathrm{SEL}_{\mathrm{Max}}$ 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.

The calculation model presented in Equation 4, is used throughout the report for all calculations of $\mathrm{SEL}_{\mathrm{C},<\mathrm{duration}>}$. Furthermore, the Danish approach of looking at all installations occurring within a 24 hour period is adopted, and $\mathrm{SEL}_{\mathrm{C24h}}$ is therefore used for the remainder of this report.

3.2 Underwater noise impact criteria

Guidance or threshold values for regulating underwater noise during construction of offshore wind farms (pile driving) have been developed by several different countries and international organizations. There are different approaches in the different countries when it comes to estimating impacts from pile driving on marine mammals. The project area is located in Swedish waters, and Sweden does not have established guidelines for impact pile driving. A more thorough description of guidelines and threshold values relevant for the impact assessment is provided in chapter 3. The thresholds are briefly described in the following, and the reader is referred to the impact assessment report for a more in depth description.

3.2.1 Frequency weighted threshold levels

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, taking the hearing sensitivity of each species into account when estimating the impact of a given noise source. Hearing group classification is updated in (Southall, et al., 2019), and is used throughout the remainder of this report to describe the different hearing groups.

In NOAA (April 2018) the marine mammal species, are divided into four hearing groups in regards to their frequency specific hearing sensitivities, with group labels according to (Southall, et al., 2019): 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. More details about the hearing groups and their frequency sensitivities are given in section 3.2.2. The hearing group weighted threshold criteria, can be seen in Table 3.1.

Table 3.1: 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.

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]
Very High-Frequency Cetaceans	Harbour porpoise	1.5	153	173	140	155	100
Phocid Pinniped	Harbour seal	1.5	181	201	170	185	-
"-" Threshold is not calculated for this hearing group. *: frequency weighted level							

In addition to the PTS and TTS thresholds, it is also proposed, in section XX, to consider the behavioural impact on harbour porpoise, through the single pulse criteria $\mathrm{SPL}_{\mathrm{RMS-fast,VHF}} = 100\ dB\ re.\,1\mu Pa$. No behavioural impact threshold for harbour seal is considered because of lack of knowledge.

3.2.1.1 Threshold distance representation

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

As such, threshold distances for PTS and TTS describe the minimum distance from the source, a marine mammal must at least be, 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 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.

3.2.2 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.

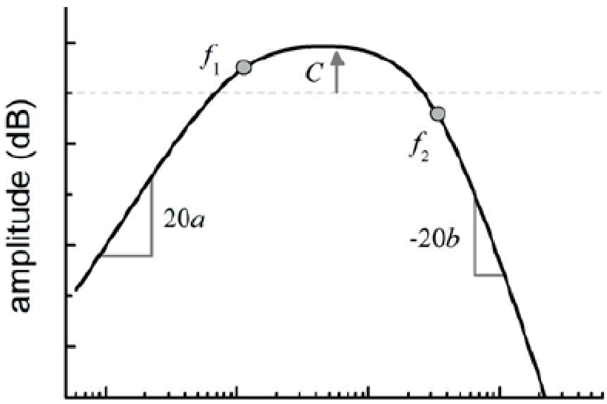
$$W(f) = C + 10 * \log_{10}\left(\frac{\left(\frac{f}{f_1}\right)^{2*a}}{\left[1+\left(\frac{f}{f_1}\right)^2\right]^a * \left[1+\left(\frac{f}{f_2}\right)^2\right]^b}\right) \text{ [dB]} \qquad \text{Equation 5}$$

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].



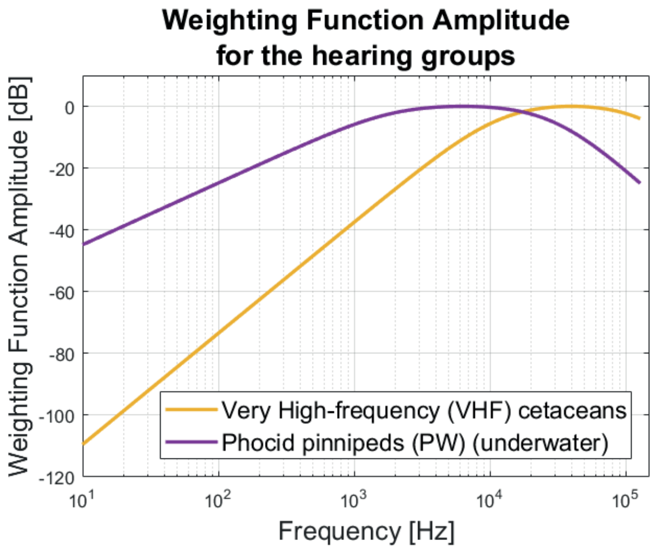
The parameters in Equation 5 are defined for the four hearing groups and the values are presented in Table 3.2.

Table 3.2: Parameters for the weighting function for the four different hearing groups *(NOAA, April 2018)*, *(Southall, et al., 2019)*.

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 in Table 3.2 into Equation 5, the following spectra is obtain for the hearing groups.

Figure 3.2: The weighting functions for all the marine mammal hearing groups in (NOAA, April 2018).



4 Source modelling methodology

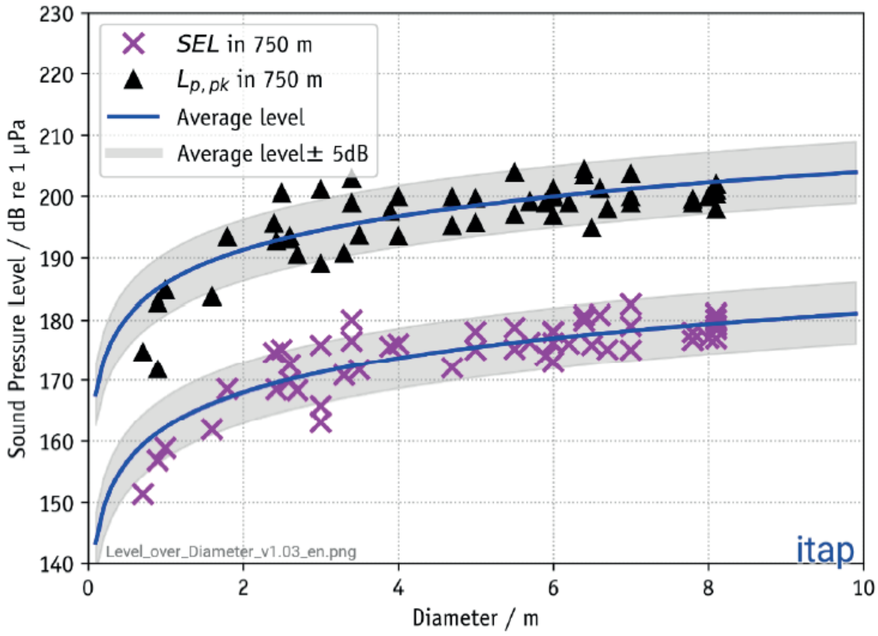
Impact pile driving activities are required for the installation of monopile foundations. Such activities are expected to produce underwater sound levels that can potentially have an impact on marine mammals.

To estimate the impact on marine mammals, 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.

4.1 Pile driving source level

The best available knowledge on the relationship between pile size and 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 summary of measured sound levels at 750 m distance as a function of pile size. This is shown in Figure 4.1. The measurements are all normalized to 750 m distance from the pile.

Figure 4.1: Relationship between measured SPL and SEL levels at 750 m distance, and pile size [Bellmann, et al., August 2020]



Examining Figure 4.1, 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 a underwater sound transmission model, the source level at 1 m distance must 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 measurements at real sites.

From Figure 4.1 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 gray shaded areas in Figure 4.1. 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 warrant 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.

4.1.1 Uncertainties in determining source level

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

4.1.1.1 Soil resistance

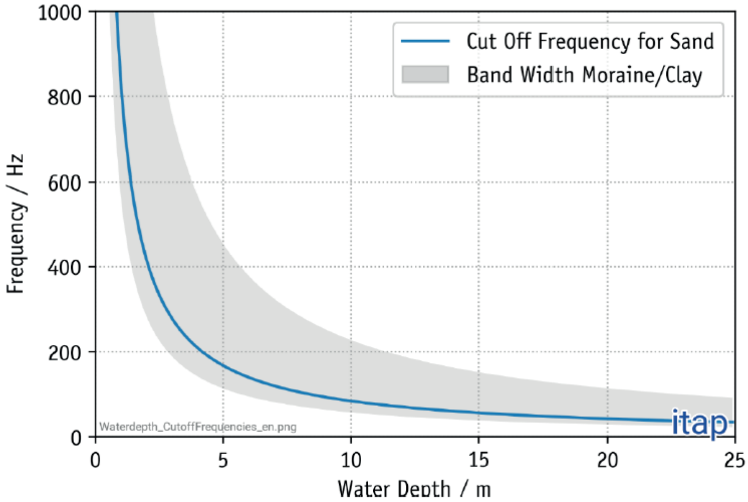
To install the foundation, the piles have to be driven into the seabed. To be able to do this the predominant soil resistance has to be overcome. In general, the larger the soil resistance, the higher the blow energy required, which in turn increases the noise output (Bellmann, et al., August 2020).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

4.1.1.2 Water depth

The water depth, in shallow water, can also influence the noise emission. When the water depth decreases the cut-off frequency increases, which can be seen in Figure 4.2. 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 is dependent on, not only the water depth, but also the upper sediment type of the sea-bed.

Figure 4.2: Cut off frequency and its dependency on sediment type and water depth [Bellmann, et al., August 2020].

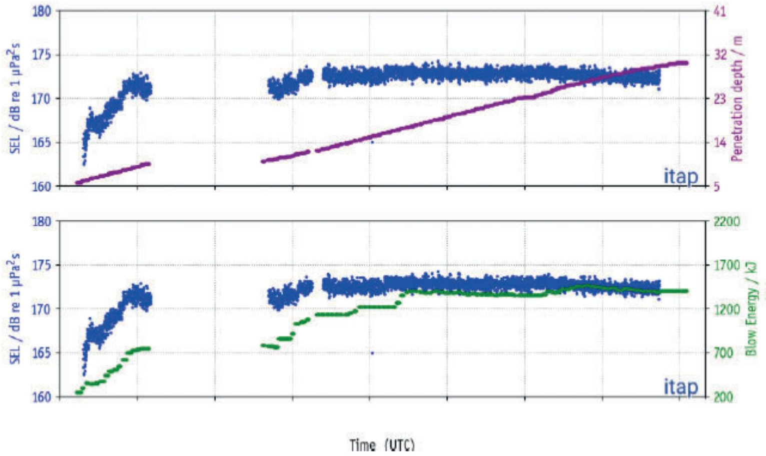


4.1.1.3 Hammer energy

An increase in hammer energy applied to a pile, will transfer more energy into the pile and therefore also results in a higher noise emission. In Figure 4.3, 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 4.3: Relationship between SEL versus penetration depths and blow energy [Bellmann, et al., August 2020].



4.1.1.4 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).

Using a large impact hammer with a heavy falling mass at 50-60% of its full capacity, will for acoustic reason 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).

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).

4.1.1.5 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.

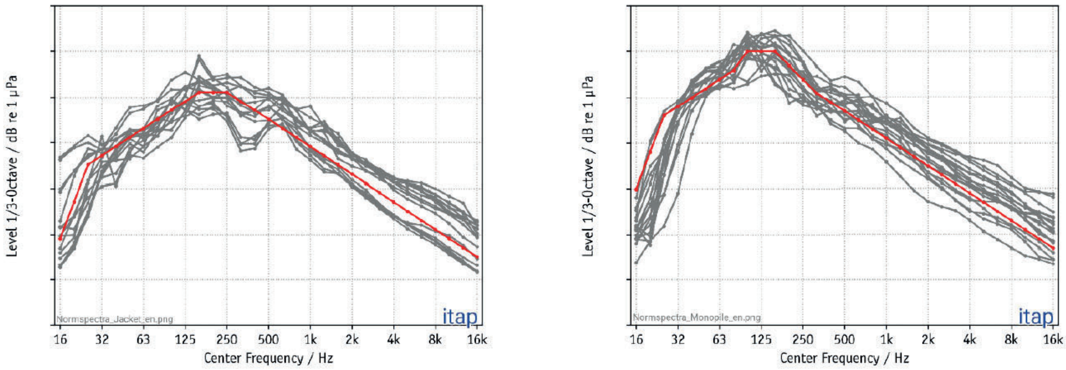
Above water level piling automatically means that part of the pile is in contact with the entire water depth, and thus has a large radiating area. For below water level piling, this is not the case, as parts of the water column might no longer be occupied by the pile, but rather the hammer. For this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

4.2 Pile driving frequency spectrum

Due to the natural variations of measured frequency content, Figure 4.4 (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.

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).

Figure 4.4: 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 4.4 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 4.4 is showing the pile driving frequency spectrum (grey lines) measured at 750m 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 of monopiles for the measured spectrums.

4.3 Pile driving source mitigation

As foundation structures become larger and more knowledge come to light about marine mammal hearing, the more unlikely it is that the projects can comply with local regulation without mitigating the noise emission.

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 NAS, 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 can mitigate some of this noise as it is partly reintroduced to the water column after a few metres. Big Bubble Curtain 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 Big Bubble Curtain 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 transmission. This system was used for example at the German wind park Riffgat. Noise mitigation was assessed to be around 16-18 dB (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 consist 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, 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 a perfect seal.

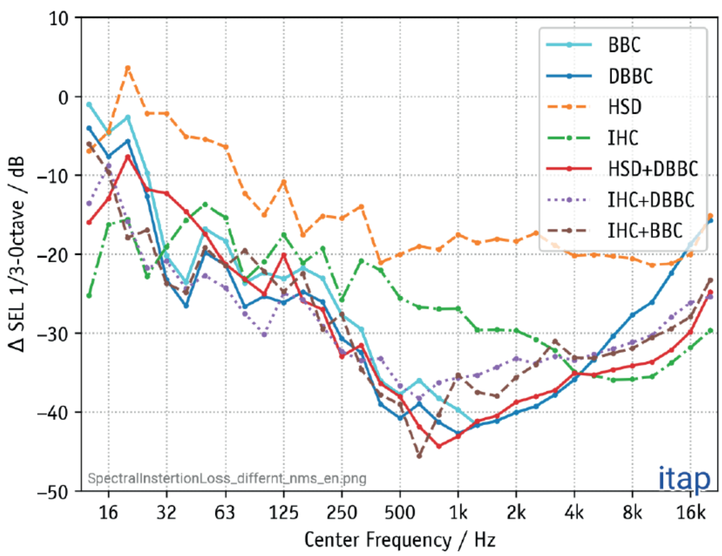
For commercially available and proven NAS, a summary of achieved mitigation levels throughout completed installations is given in (Bellmann, et al., August 2020), as shown in Figure 4.5. It must, however, be noted that the reported broadband mitigation, $\Delta\mathrm{SEL}$ is given for a flat frequency 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 4.2, are far from a flat octave band spectra, 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 4.6, 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 offshore wind farm installed, new knowledge and often better solutions become available.

Figure 4.5: Achieved noise reduction on completed projects using different NAS, [Bellmann, et al., August 2020].

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 4.6: Frequency dependent noise reduction for Noise Abatement Systems, [Bellmann, et al., August 2020].



5 Underwater noise modelling scenarios

The details of the different project scenarios are outlined below, based on information received by Vattenfall for the foundation installation process.

Based on the knowledge presented in chapter 4, a source model is proposed for the 14 m monopile scenario. The source model assumes the use of an NAS equal to either the BBC NAS or the HSD-DBBC NAS, documented in section 4.3. This, as a consequence of the extremely high unmitigated source levels, which makes it unlikely that installation without an effective NAS will be allowed. Both BBC NAS and HSD-DBBC NAS has been used in previous projects, primarily at German offshore wind farms. BBC is one of the best tested available NAS currently commercially available (Bellmann, et al., August 2020).

In the following, the foundation scenario considered in this project is described in detail, followed by an evaluation of which source positions are necessary to model.

5.1 Scenario 1: 14 m monopile

In Scenario 1, turbines are installed on a 14 m monopile foundation, which is a single hollow steel pipe. 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 per foundation		1	
Impact hammer energy		6000 kJ	
Pile Diameter		14 m	
Noise Abatement System Applied		Big Bubble Curtain (BBC) HSD-DBBC	
Total number of strikes pr. pile		10350	
Pile driving procedure			
Name	Number of strikes	% of maximum hammer energy	Time interval between strikes [s]
Soft start	150	10%	4
Ramp-up	75 75 75 75	20% 40% 60% 80%	4
Full power	9900	100%	2

5.1.1 Pile driving source level and spectrum, scenario 1

In section 5.1 the technical specification and the pile driving procedures are stated for scenario 1. By applying the knowledge presented in section 4.1 and 4.2, regarding source level and source frequency spectrum, the unmitigated and unweighted SEL at 750 m was derived to be: $\mathrm{SEL}_{@750\mathrm{m}} = 184.3\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$. Back-calculating this level to 1 m, results in $\mathrm{SEL}_{@1\mathrm{m}} = 227.7\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$.

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 $\mathrm{SEL}_{@1m} = 229.7\ \mathrm{dB\ re.\ 1\ \mu Pa^2 s}$. The source level is presented in all relevant metrics and combinations between frequency weighting and source levels unmitigated, with BBC NAS, and with HSD-DBBC NAS in Table 5.2 for reference.

Table 5.2: Source Level for 14 m monopile, with and without weighting and mitigation.

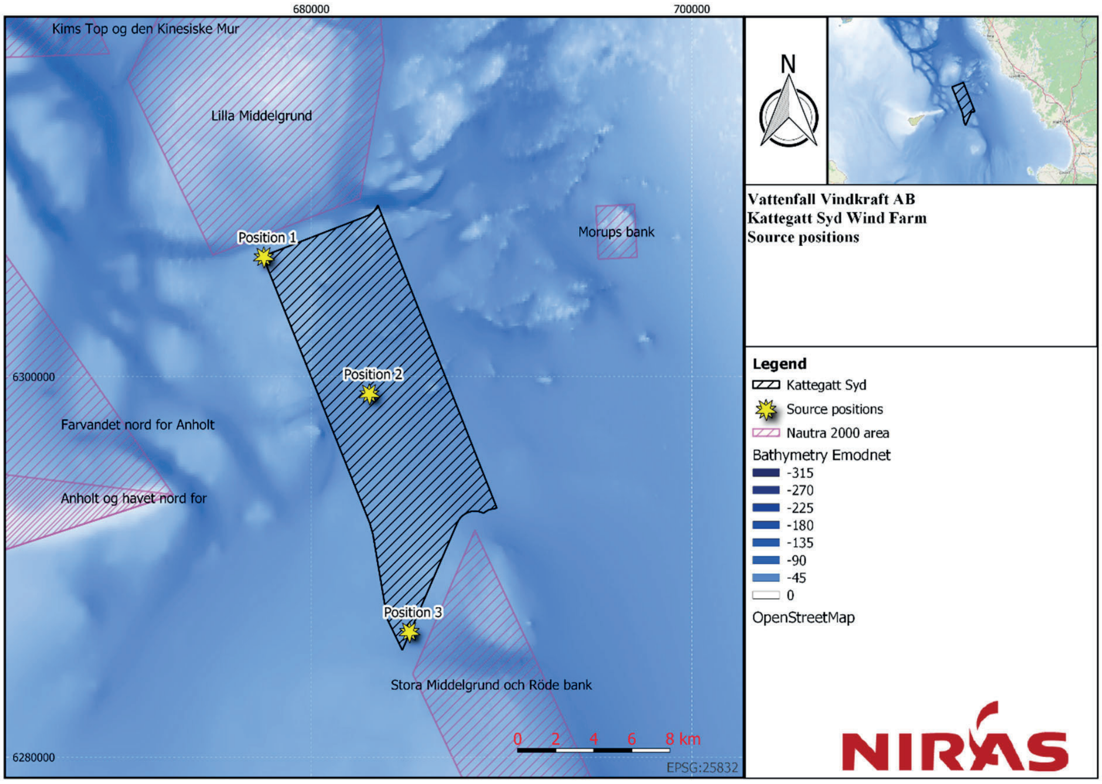
Frequency weighting	Source level ($\mathrm{SEL}_{@1m}$) [dB re. 1μPa²s]		
	Unmitigated	With Big Bubble Curtain (BBC)	With Hydro Sound Damper Double Big Bubble Curtain (HSD-DBBC)
Unweighted	229.7 dB	210.3 dB	209.1 dB
VHF Cetaceans	183.6 dB	159.9 dB	151.6 dB
Phocid Pinniped	208.5 dB	184.0 dB	182.1 dB

5.2 Source positions

It was chosen to carry out underwater sound propagation modelling for installations at three different source positions, representing different representative worst case locations within the wind farm site, from an underwater sound propagation perspective. The three positions are shown in Figure 5.1. The site is evaluated in three parts, with an equal area three part split from northwest-southeast with a single representative worst-case position within each area. These source positions were chosen from their location relative to maximum expected sound propagation, and in relation to the nearby Natura 2000 areas.

The northern part of the site borders on the Natura 2000 area "Lilla Middelgrund". The representative worst case locations is Position 1, which is placed in the northernmost corner 1 km from the Natura 2000 area. In the northern part the top sediment layer type is varying, as is the bathymetry. The position is chosen in order to represent the worst case scenario with regards to sound propagation into the Natura 2000 area. Position 2 is located in the middle of the site, since there is little variation in the top sediment and bathymetry and is therefore representative position for a large part of the wind farm site. The southern area of the site borders on the Natura 2000 area "Stora Middelgrund". There is also little variation in the top sediment and bathymetry, and the location for Position 3 is therefore primarily chosen as representative worst case with regards to the Natura 2000 area, at a distance of 1 km between source and Natura 2000.

Figure 5.1: Source positions chosen for sound propagation modelling.



There is no final layout for the wind farm at this stage of the process, and it has also not been decided whether more than one foundation will be installed per day. The sound propagation modelling, carried out in this report assumes a single pile installation within any 24 hour period, and the results therefore reflect this.

6 Underwater sound propagation modelling methodology

This chapter provides a brief overview of underwater sound propagation theory and the software program used in the modelling, followed by a description of the inputs used for the propagation model. This includes environmental and source input parameters.

The chapter concludes with documentation of the sound propagation modelling results in both graphic representation, and in numerical form.

6.1 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. The interested reader is referred to (Jensen, et al., 2011) chapter 1, for a more detailed and thorough explanation of underwater sound propagation theory.

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 the sound being able to travel far with very low sound transmission 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 Kattegatt, Skagerrak and the Baltic Sea, an estuary-like region with melted freshwater on top, and salty sea 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.

In the North Sea, a gradual shift in sound speed profile from near-iso speed in the winter, to downward refracting in the summer is observed based on temperature and salinity readings throughout the year. The readings comes 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 more rough 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 propagation 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 dependent on chemical conditions of the water column. This parameter has been approximated by Equation 7 (Jensen, et al., 2011):

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

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

6.2 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 6.1, an overview of the application range of the different sound propagation models is shown.

Table 6.1: 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	

6.3 Underwater sound modelling software

NIRAS uses the underwater noise modelling software: dBSea version 2.3.1, 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.

6.4 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.

6.4.1 Bathymetry

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

Figure 6.1 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 (SDB) 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).

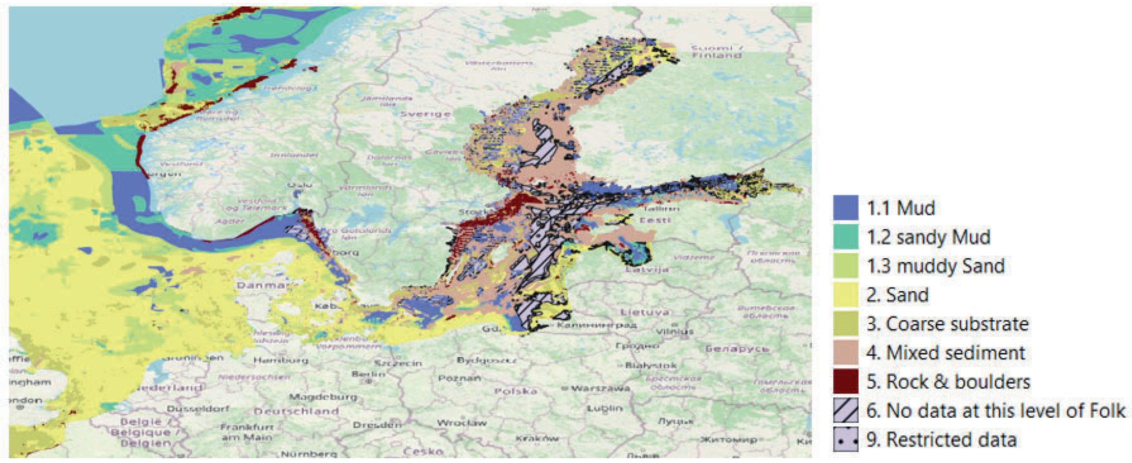
Figure 6.1: Bathymetry map over European waters from Emodnet, where light blue indicates shallow waters and dark blue indicates deeper waters. [EMODnet, 2021].

6.4.2 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 6.2.

Figure 6.2: A section of the seabed substrate map, (Folk 7) [EMODnet, 2021].



6.4.3 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.

6.5 dBSea settings and environmental parameters in the project

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

6.5.1 dBSea settings

For this project, the dBSea settings listed in Table 6.2 were used.

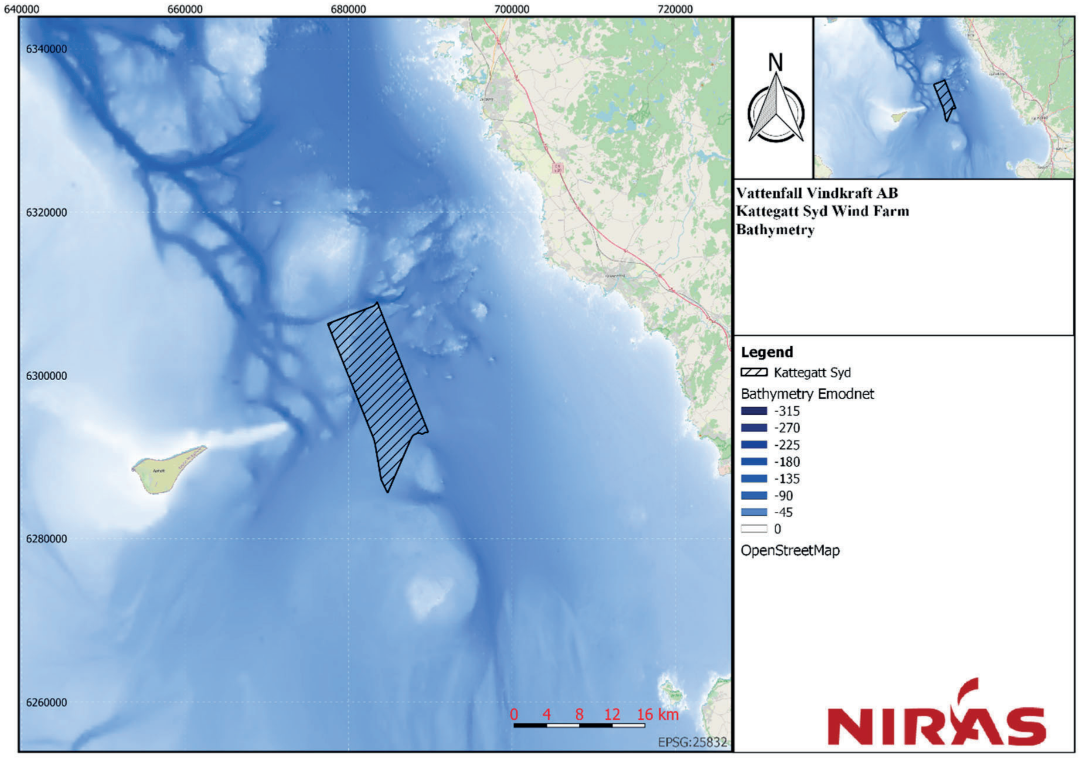
Table 6.2: dBSea Settings

Technical Specification		
Octave bands		1/1 octave bands
Grid resolution (range x depth)		50 m x 1 m
Number of transects		180 (2°)
Sound Propagation Model Settings		
Model	Start frequency band	End frequency band
dBSeaModes (Normal Modes)	16 Hz	1 kHz
dBSeaRay (Ray tracing)	2 kHz	16 kHz
"-" indicates that there is no procedure in this category		

6.5.2 Bathymetry

The bathymetry implemented for this project, is shown in Figure 6.3, and includes the wind farm site and around 20 km to each side (extracted from the bathymetry map in section 6.4.1). In this area the bathymetry range from a depth of 127 m, indicated by the darker colours, to a height of 3 m, indicated by the lighter colours.

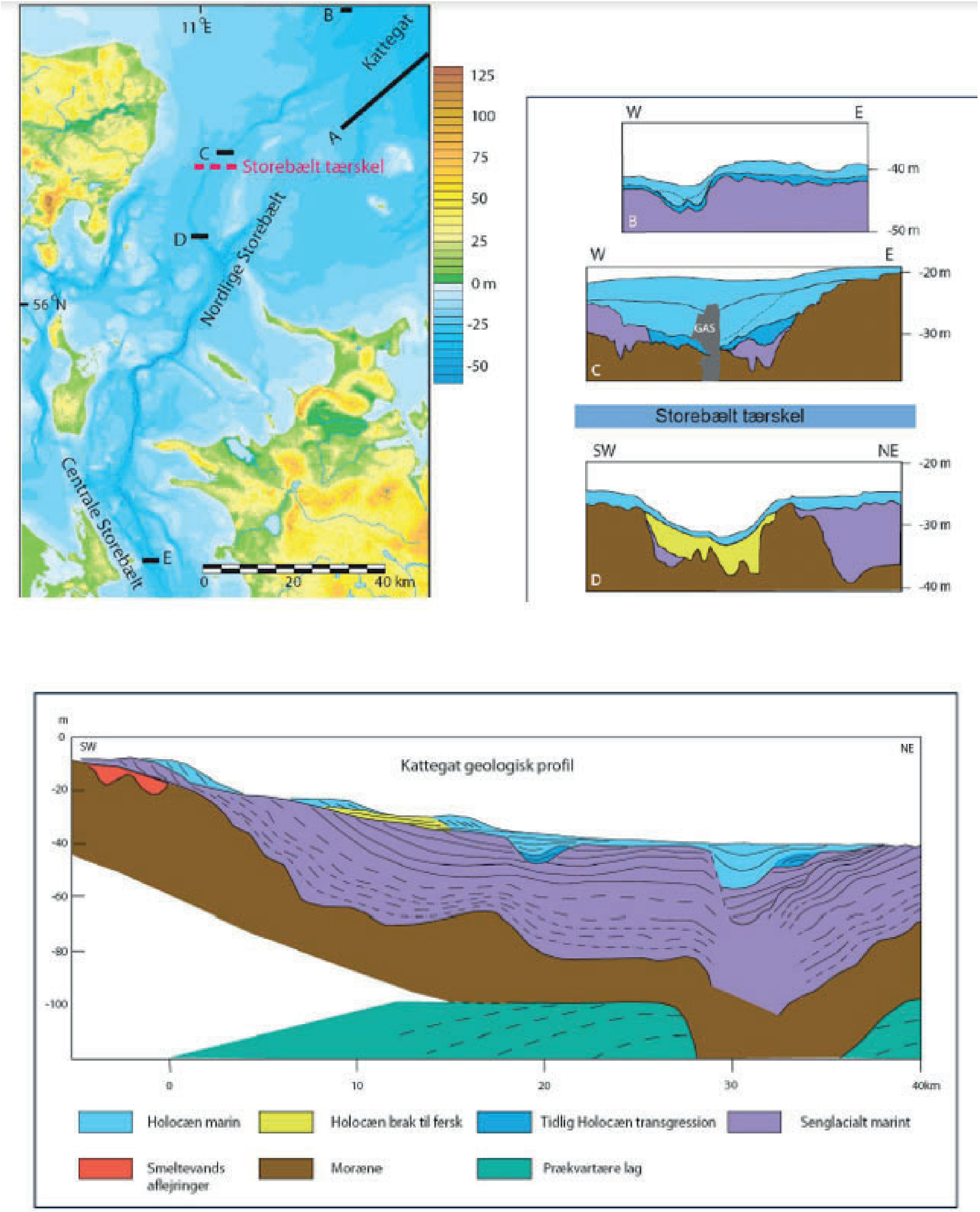
Figure 6.3: Bathymetry map for Kattegatt Syd project area and surroundings.



6.5.3 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. For the project site, (Nielsen, et al., 2011), provided information on local layer depths through sediment profiles, see Figure 6.4. These profiles are from seismic survey transects obtained near the project area, and are therefore included in the sediment model layer composition.

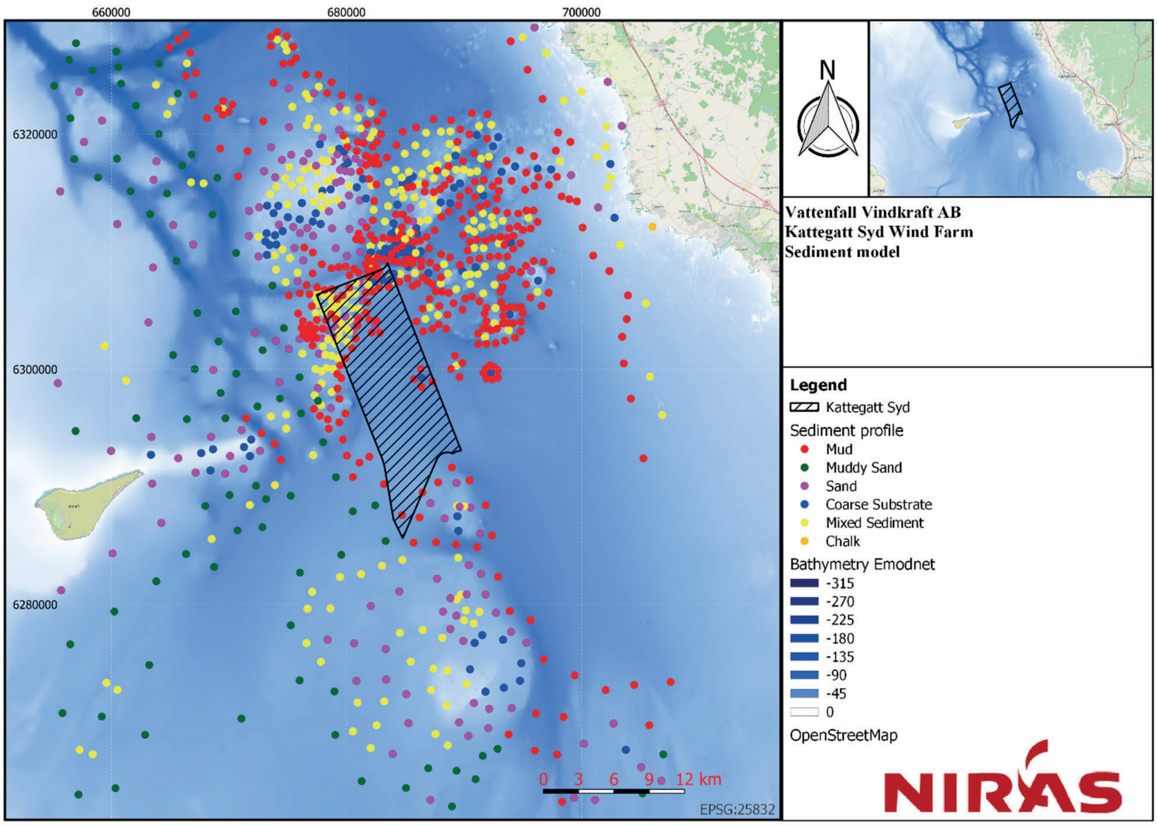
Figure 6.4: Interpreted geological sediment profiles from [Nielsen, 2011].



To be able to make a detailed model that takes the seabed substrate into account as well as the varying bathymetry, a 960 point sediment model was made. Figure 6.5 shows the distribution of the sediments points with the corresponding seabed sediment from Folk 7 (EMODnet, 2021).

The sediment model uses the information from the seabed substrate map to determine the top layer type, while the literature was used to determine average thickness at the different positions. Below the top layer, literature indicates a thick layer of mixed gravelly, muddy sediment and an equally thick layer of moraine. Below that chalk.

Figure 6.5: Sediment model for Kattegatt Syd project area and surroundings.



6.5.4 Sound speed profile

Figure 6.6 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. Empty plots thus illustrate where landmass is present and a sound speed profile therefore is not available.

Examining Figure 6.6, this would indicate March as the worst case month and June as the best case. Vattenfall has informed that piling will not take place between January – May, both months included. Re-examining Figure 6.6 to represent only June – December, the worst case month would be December. Sound propagation in December would be applicable for the period from early fall – end of December, however is likely to overestimate the sound emission during early – late fall. For the summer months of June – August, the month of July is considered representative.

Based on the indicated time periods for foundation installation, it was agreed with Vattenfall to model the northern and southern positions (1 and 3), for both July and December, and for position 2 in the middle, only July. In Figure 6.7 the sound speed profiles for December and July shown.

Figure 6.6: Sound speed profiles for Kattegatt Syd project area.

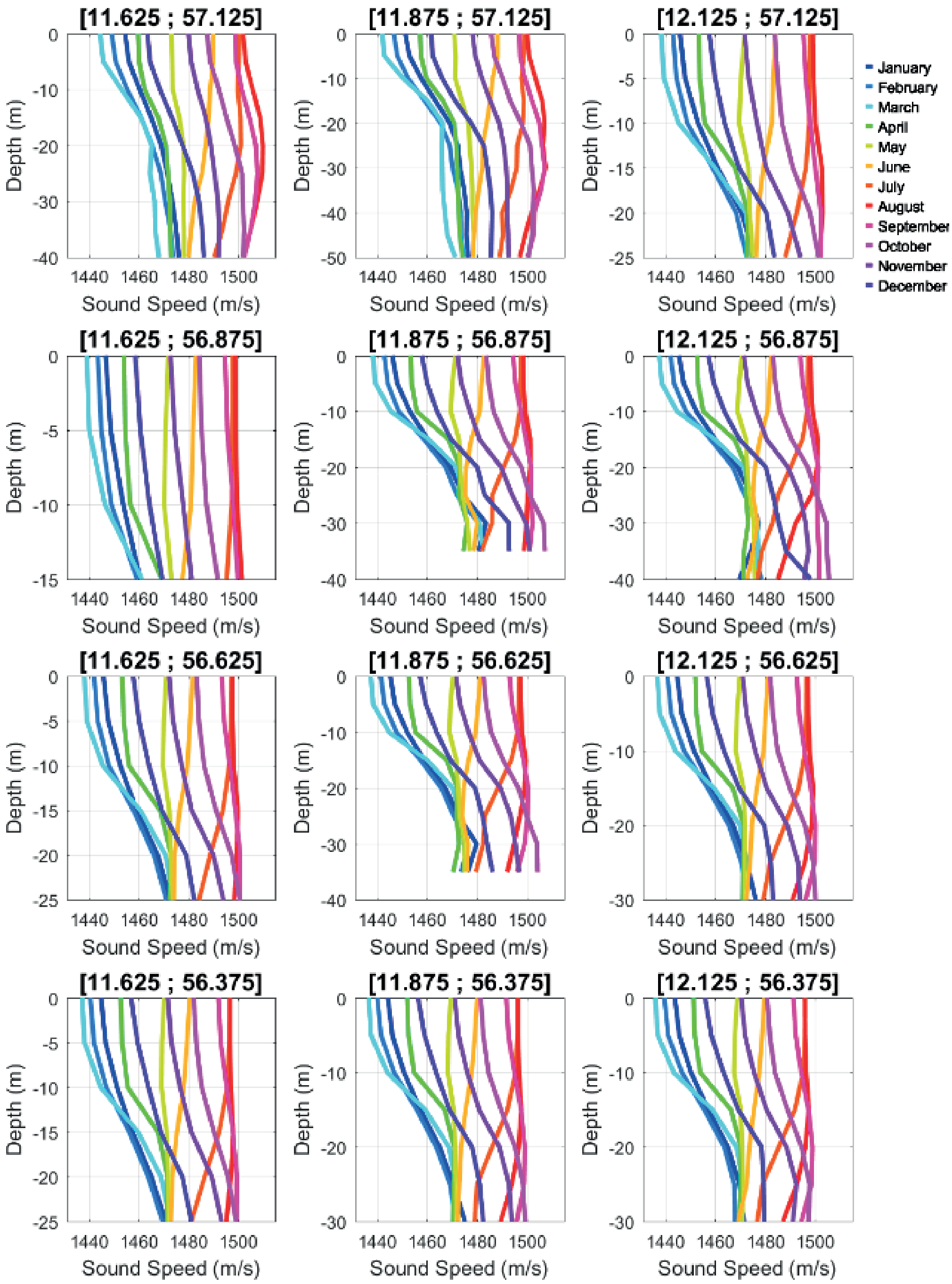
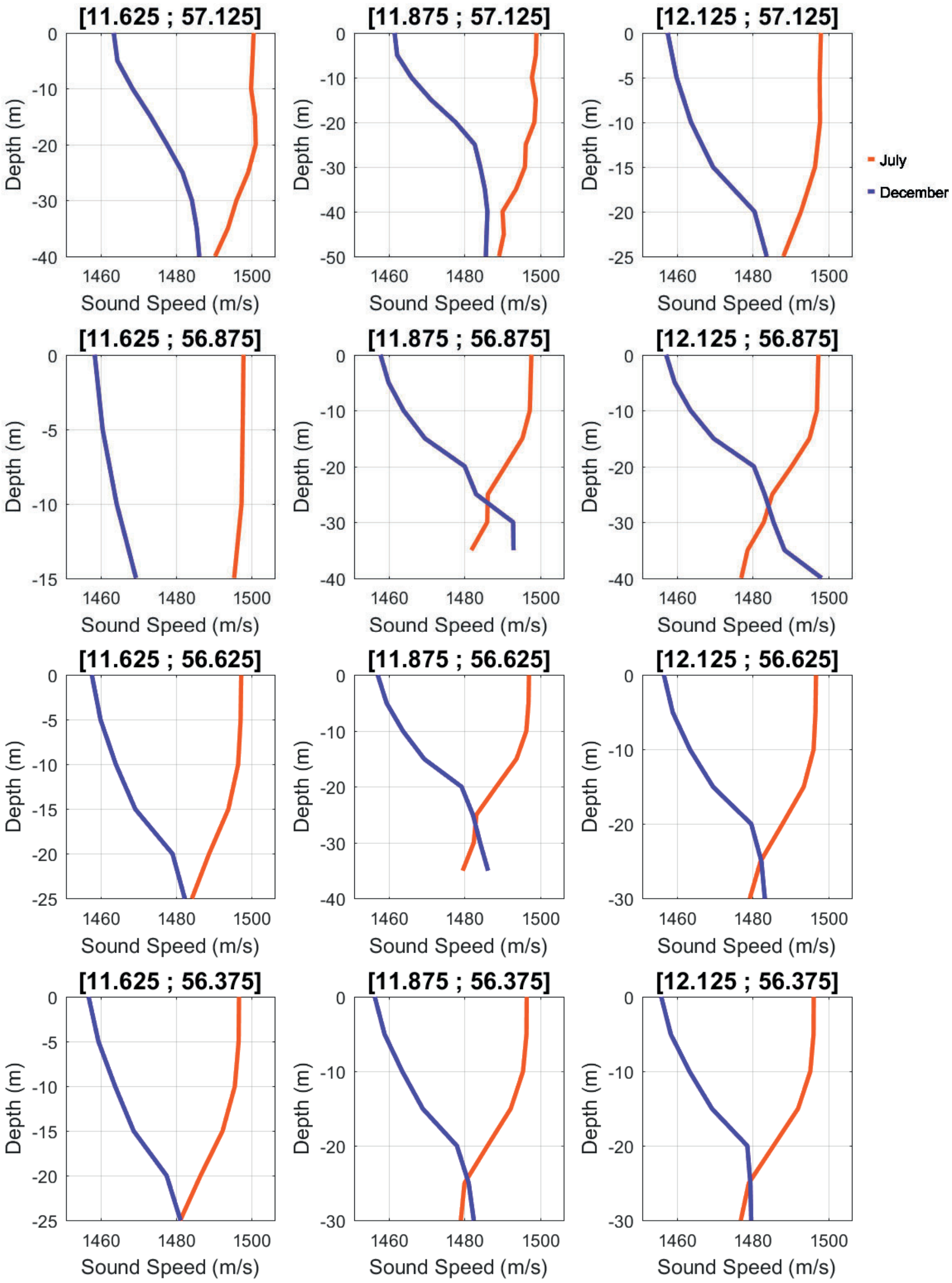


Figure 6.7: Sound speed profile for the worst case months for the two different time frames in the project area of Kattegatt Syd.



7 Results

Calculations were carried out for the source model based on installation of a 14 m monopile with either a BBC NAS or HSD-DBBC NAS applied, at the three chosen positions. Table 7.1 presents all impact thresholds in numerical form for marine mammals. In addition to the numerical results, noise contour maps for harbour porpoise behaviour are shown in Figure 7.2 - Figure 7.6 when BBC is applied and Figure 7.7 - Figure 7.11 when HSD-DBBC is applied.

Table 7.1: Resulting threshold impact distances for marine mammals.

Hearing group	Representative species	Fleeing speed [m/s]	Position	Month	Mitigation	Distance to impact threshold [m]		
						SEL_{C24h}*		$SPL_{RMS-fast}$*
						TTS	PTS	Behaviour
Very High-Frequency Cetaceans	Harbour porpoise	1.5	Position 1	December	BBC	90	< 25	7950
			Position 1	December	HSD-DBBC	< 50	< 25	5550
			Position 1	July	BBC	60	< 25	3700
			Position 1	July	HSD-DBBC	< 50	< 25	2600
			Position 2	July	BBC	70	< 25	4250
			Position 2	July	HSD-DBBC	< 50	< 25	2950
			Position 3	December	BBC	90	< 25	8350
			Position 3	December	HSD-DBBC	< 50	< 25	5700
			Position 3	July	BBC	60	< 25	4000
			Position 3	July	HSD-DBBC	< 50	< 25	2750
Phocid Pinniped	Harbour seal		Position 1	December	BBC	< 50	< 25	-
			Position 1	December	HSD-DBBC	< 50	< 25	-
			Position 1	July	BBC	< 50	< 25	-
			Position 1	July	HSD-DBBC	< 50	< 25	-
			Position 2	July	BBC	< 50	< 25	-
			Position 2	July	HSD-DBBC	< 50	< 25	-
			Position 3	December	BBC	< 50	< 25	-
			Position 3	December	HSD-DBBC	< 50	< 25	-
			Position 3	July	BBC	< 50	< 25	-
			Position 3	July	HSD-DBBC	< 50	< 25	-
"-" Threshold is not obtained for this species. * Threshold level is frequency weighted								

As previously mentioned, threshold distances for PTS and TTS describe the minimum distance from the source, a marine mammal must at least be deterred to, 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.

A way to describe the noise impact in a measurable metric, is through a frequency weighted single strike SEL value at 750 m distance, $SEL_{SS@750m,VHF}$. This metric describes the maximum allowed noise level from any pile strike, measured at 750 m distance from the pile. For the worst case scenario of December, where the sound propagates the furthest, and applying the best NAS, HSD-DBBC, the value is:

$$\boldsymbol{SEL_{SS,VHF} = 110.7\ dB\ re.1\ \mu Pa^2 s.}$$

In addition to the impact distance results in Table 7.1, worst case area of effect has also been calculated. This is given as the total area affected by noise over the behaviour threshold limits in Table 7.2.

Table 7.2: Area affected for impact threshold criteria for harbour porpoise (TTS and behaviour)

Position	Month	Mitigation	Area of threshold effect for harbour porpoise [km^2]	
			Behaviour [$SPL_{RMS-fast,VHF}$]	TTS [$SEL_{C24h,VHF}$]
Position 1	December	BBC	187	< 0,1
	July		37	< 0,1
Position 2	July		53	< 0,1
Position 3	December		208	< 0,1
	July		40	< 0,1
Position 1	December	HSD-DBBC	89	< 0,1
	July		19	< 0,1
Position 2	July		26	< 0,1
Position 3	December		97	< 0,1
	July		21	< 0,1

Calculations determining the worst-case overlap with nearby Natura 2000 sites have also been carried out, based on the behaviour noise contours for the positions closest to each site. For the “Lilla Middelgrund” (SE), position 1 noise emission was used, while position 3 was used for “Stora Middelgrund” (SE). As the layout of the OWF has not yet been determined, the presented overlap areas should be considered only as a worst case scenario, as it is not certain whether a turbine will be placed in that specific location. Figure 7.1 shows the five Natura 2000 sites near the project area, however only three are appointed for marine mammals, and are therefore relevant with regards to underwater noise.: 1) Lilla Middelgrund (SE), 2) Anholt og havet nord for (DK), 3) Stora Middelgrund och Röde bar (SE). For these three Natura 2000 sites, the worst case overlap is given in Table 7.3 and Table 7.4, when using BBC NAS and HSD-DBBC NAS respectively. Noise contour maps with overlap into Natura 2000 sites, indicated by the shaded area, for harbour porpoise behaviour are shown in Figure A.1-Figure A.8 in Appendix 1 for position 1 and position 3.

Figure 7.1: Overview map of the nearby Natura 2000 sites

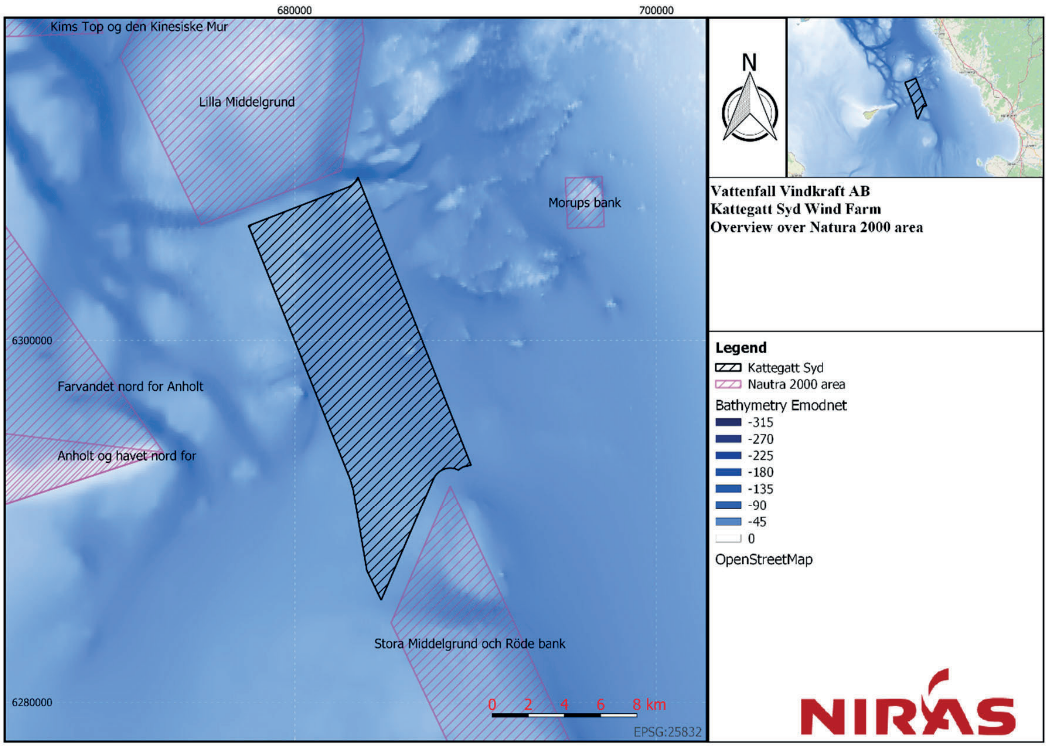


Table 7.3: Overlap with Natura 2000 sites (worst case for any location within the site further from the Natura 2000 site than 1 km impact distance for marine mammals).

Natura 2000 site	Natura 2000 site total area [km²]	Overlap of harbour porpoise behaviour impact with Natura 2000 site, using BBC [km²]		Overlap of harbour porpoise behaviour impact with Natura 2000 site, using BBC [%]	
		December	July	December	July
Lilla Middelgrund	178	52	11	29.2%	6.2%
Anholt og havet nord for	134	0	0	0	0
Stora Middelgrund och Röde bank	114	50	12	43.9%	10.5%

Table 7.4: Overlap with Natura 2000 sites (worst case for any location within the site further from the Natura 2000 site than 1 km impact distance for marine mammals).

Natura 2000 site	Natura 2000 site total area [km^2]	Overlap of harbour porpoise behaviour impact with Natura 2000 site, using HSD-DBBC [km^2]		Overlap of harbour porpoise behaviour impact with Natura 2000 site, using HSD-DBBC [%]	
		December	July	December	July
Lilla Middelgrund	178	27	5	15.2%	2.8%
Anholt og havet nord for	134	0	0	0	0
Stora Middelgrund och Röde bank	114	31	6	27.2%	5.3%

One of the criteria, as described in section above, is that an overlap of avoidance behaviour threshold with any Natura 2000 site must not exceed 20% for any one pile installation. From Table 7.3, it is seen that for the BBC NAS, this threshold is exceeded at both Lilla Middelgrund and Stora Middelgrund for the month of December. For the month of May, the overlap is less than 20 %. As listed in Table 7.4, using an HSD-DBBC NAS instead, will reduce the impacted areas, and for Lilla Middelgrund, the 20% maximum overlap is no longer exceeded.

For Stora Middelgrund, however, the 20 % is still exceeded with an overlap of 27.2 % during December, whereas for July only a 5.3 % overlap occurs. For the months in between July and December, the overlap in %, will gradually change, however it is not possible to determine where the exact time of a 20 % overlap will occur. This is primarily due to the fact, that while calculations are based on best available historical data, the actual conditions during installation are unknown. Depending on weather conditions up to, and during, installation, the sound propagation both regionally and locally can vary significantly.

Further calculations show, that in order to comply with a 20 % maximum exceedance area, additional mitigation effect of $\Delta SPL_{VHF} = 2\ dB\ re. 1\ \mu Pa$ would have to be applied. This metric implies, that the additional mitigation effect to be achieved must be related to the VHF-frequency weighting function, and is in addition to the already included mitigation effect of the HSD-DBBC NAS.

It is possible to express the combined mitigation requirement for each position and month as a single value SEL that must not be exceeded at 750 m distance, in order to comply with an overlap of maximum 20% with the nearby Natura 2000 area for the harbour porpoise behaviour metric: $SPL_{RMS,fast(VHF)} = 100\ dB\ re. 1\ \mu Pa$. The values are only valid for the months modelled, however will be useable, albeit conservative, for any month with a higher sound transmission loss, as discussed in section 6.5.4. The 750 m SEL threshold values are shown in Table 7.5, for the different positions and months modelled. It is important to notice, that the allowed noise level at 750 m increases for foundation positions further from the Natura 2000 site, than the modelled position.

Table 7.5: Sound Exposure Level ($SEL_{SS,VHF,750m}$) from a single pile strike using maximum hammer energy for each of the modelled scenarios near Natura 2000 sites, so that no more than 20 % of the specific Natura 2000 is exposed to noise beyond the behaviour threshold for harbour porpoise.

Hearing group	Representative species	Natura 2000 site	Month	Position	Sound Exposure Level, at 750 m
					$SEL_{SS@750m,VHF}\ [dB\ re. 1\mu Pa^2 s]$
	Harbour porpoise	Lilla Middelgrund	December	1	112.0 dB

Hearing group	Repre-sentative species	Natura 2000 site	Month	Position	Sound Exposure Level, at 750 m
					$SEL_{SS@750m,VHF}$ $[dB\ re.\ 1\mu Pa^2 s]$
Very High-Fre-quency Ceta-ceans			July	1	124.5 dB
		Stora Mid-delgrund	December	3	108.7 dB
			July	3	120.0 dB

A noise contour map showing the theoretical avoidance behaviour threshold distance and overlap with HSD-DBBC and additional source mitigation, is shown in Appendix 1, for position 3 in

Figure A. 9.

An alternative to applying extra mitigation, would be increasing the distance between pile driving activities and the border to Stora Middelgrund Natura 2000 area to 2 km, which would reduce the overlap to 20%.

Figure 7.2: Noise contour map for position 1, showing impact distance for behaviour in December with VHF-weighting and BBC.

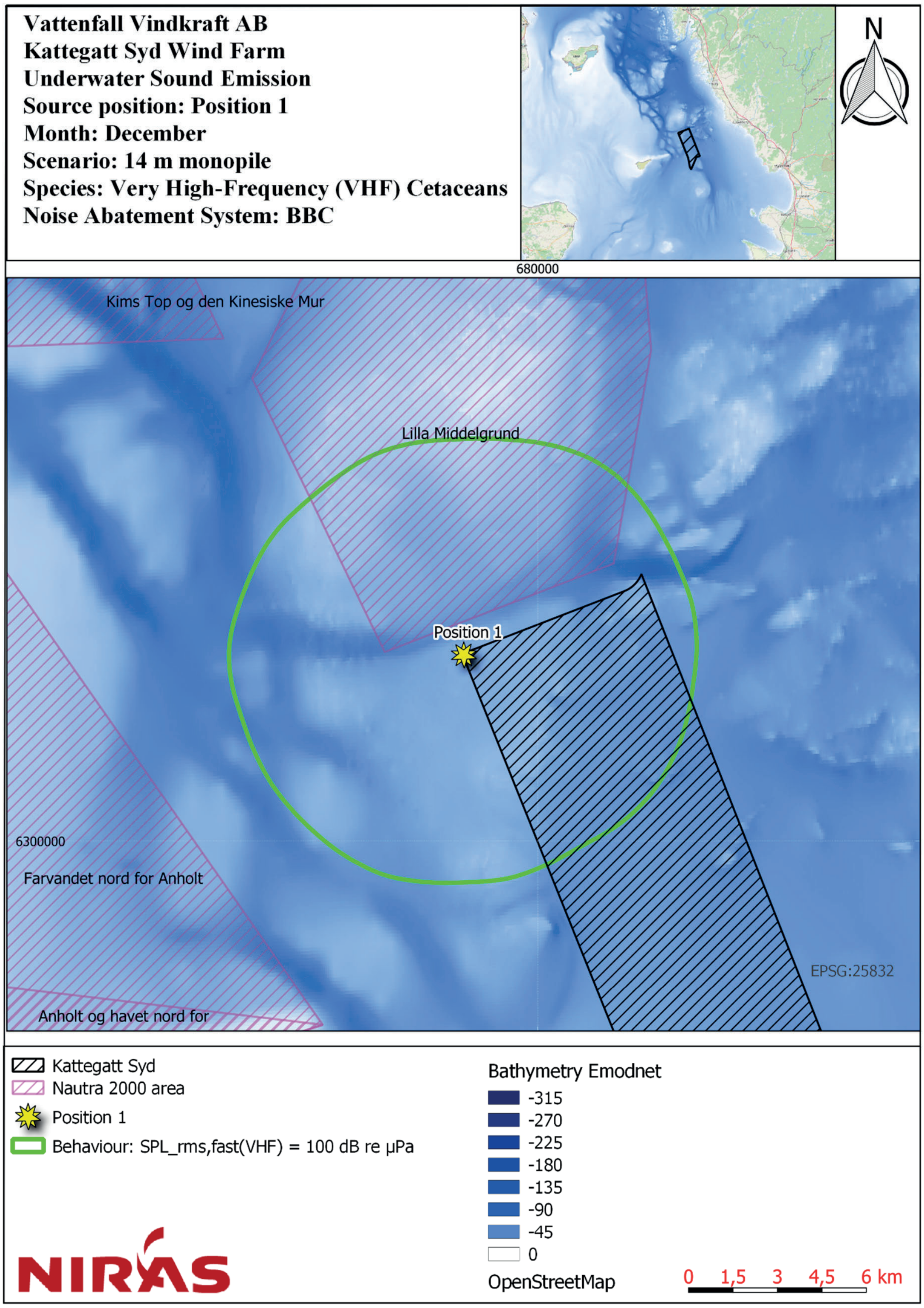


Figure 7.3: Noise contour map for position 1, showing impact distance for behaviour in July with VHF-weighting and BBC.

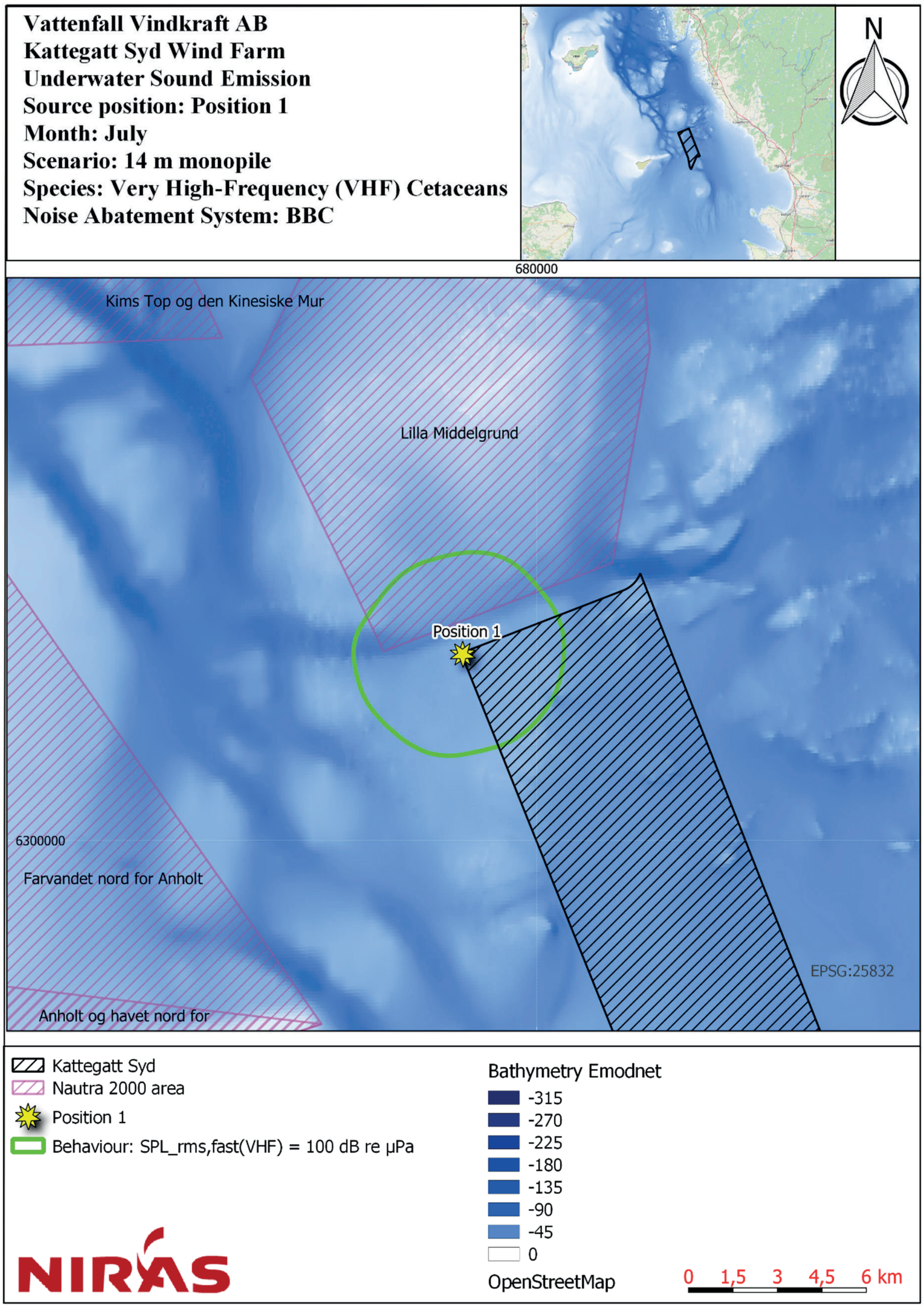


Figure 7.4: Noise contour map for position 2, showing impact distance for behaviour in July with VHF-weighting and BBC.

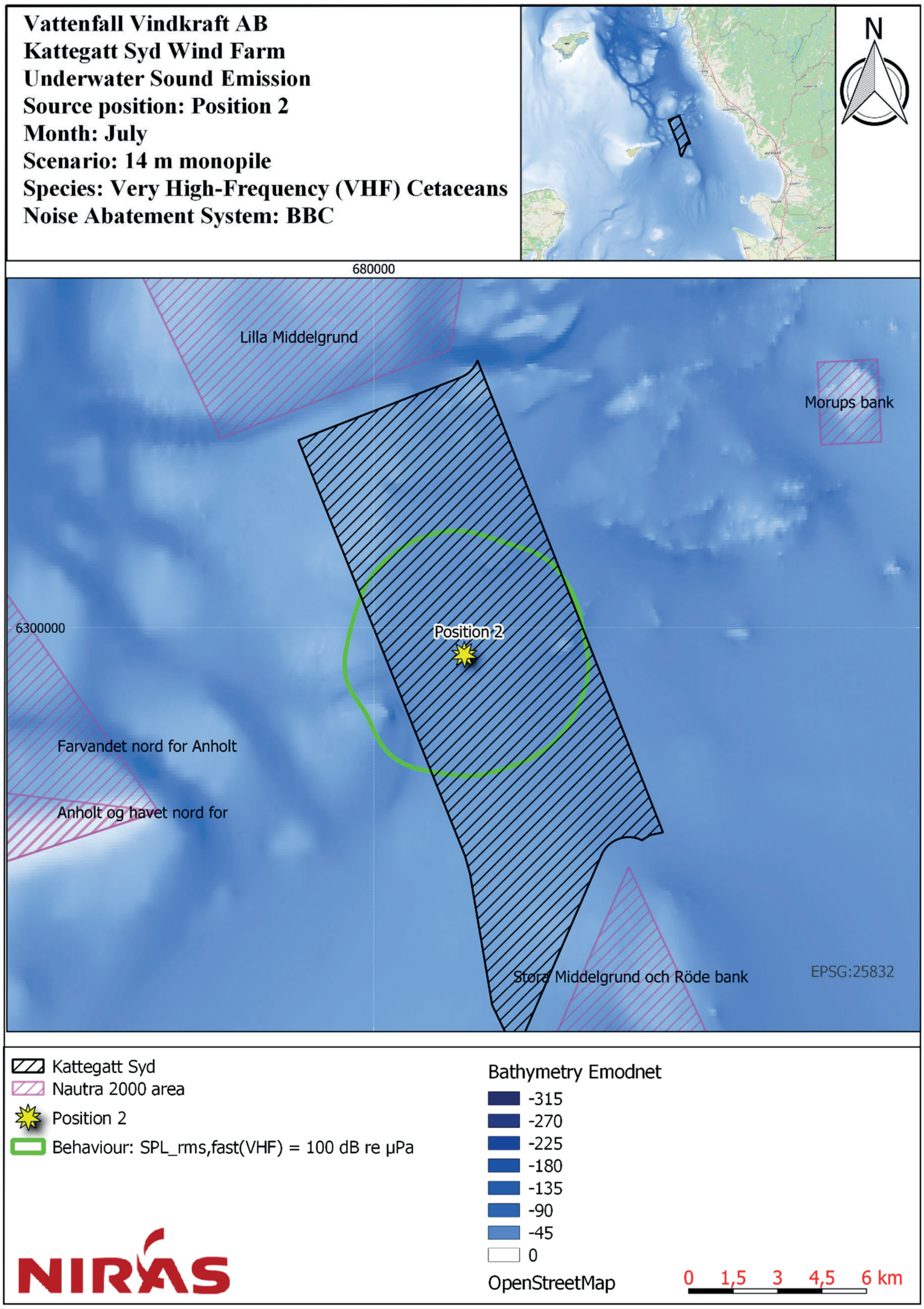


Figure 7.5: Noise contour map for position 3, showing impact distance for behaviour in December with VHF-weighting and BBC.

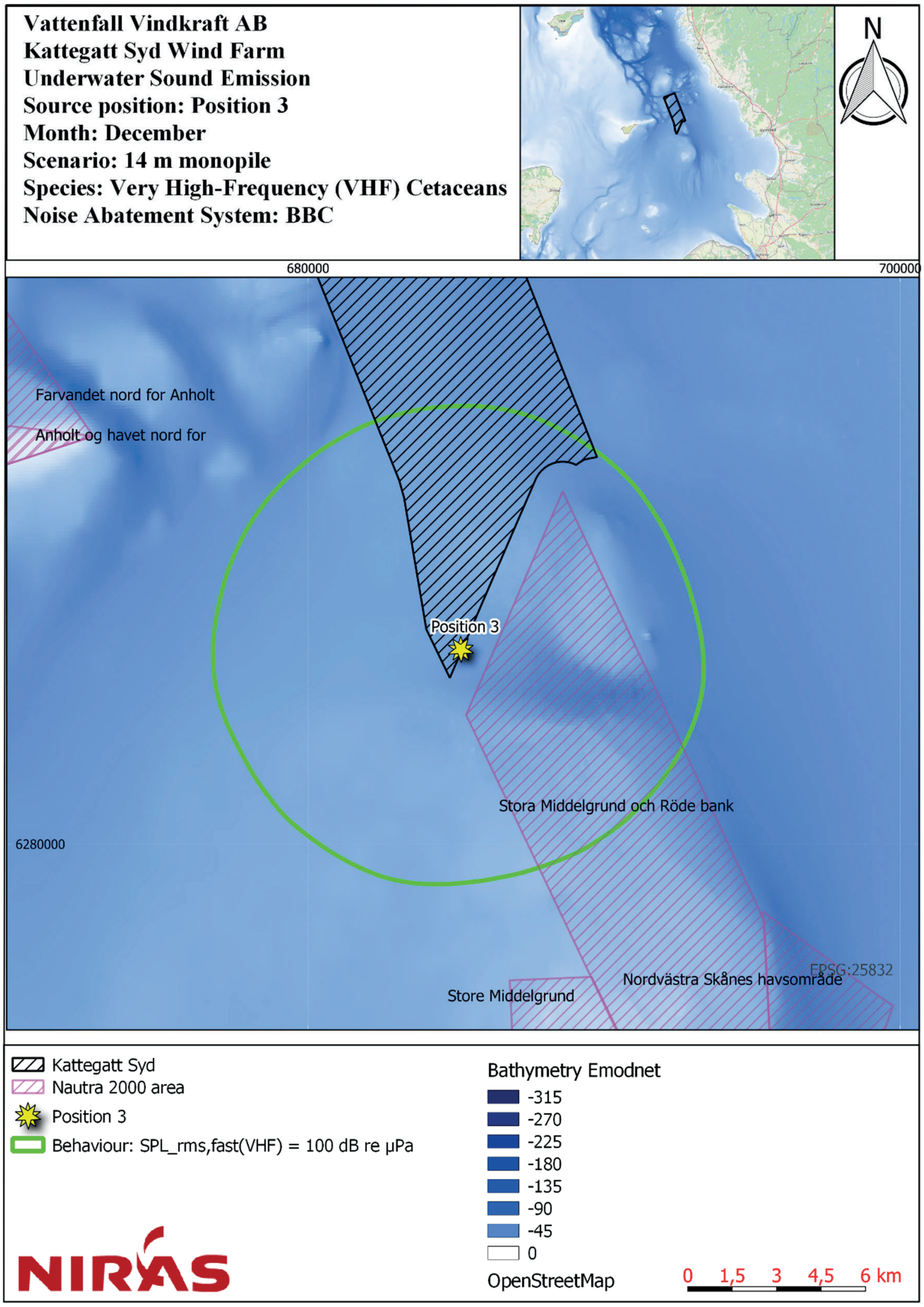


Figure 7.6: Noise contour map for position 3, showing impact distance for behaviour in July with VHF-weighting and BBC.

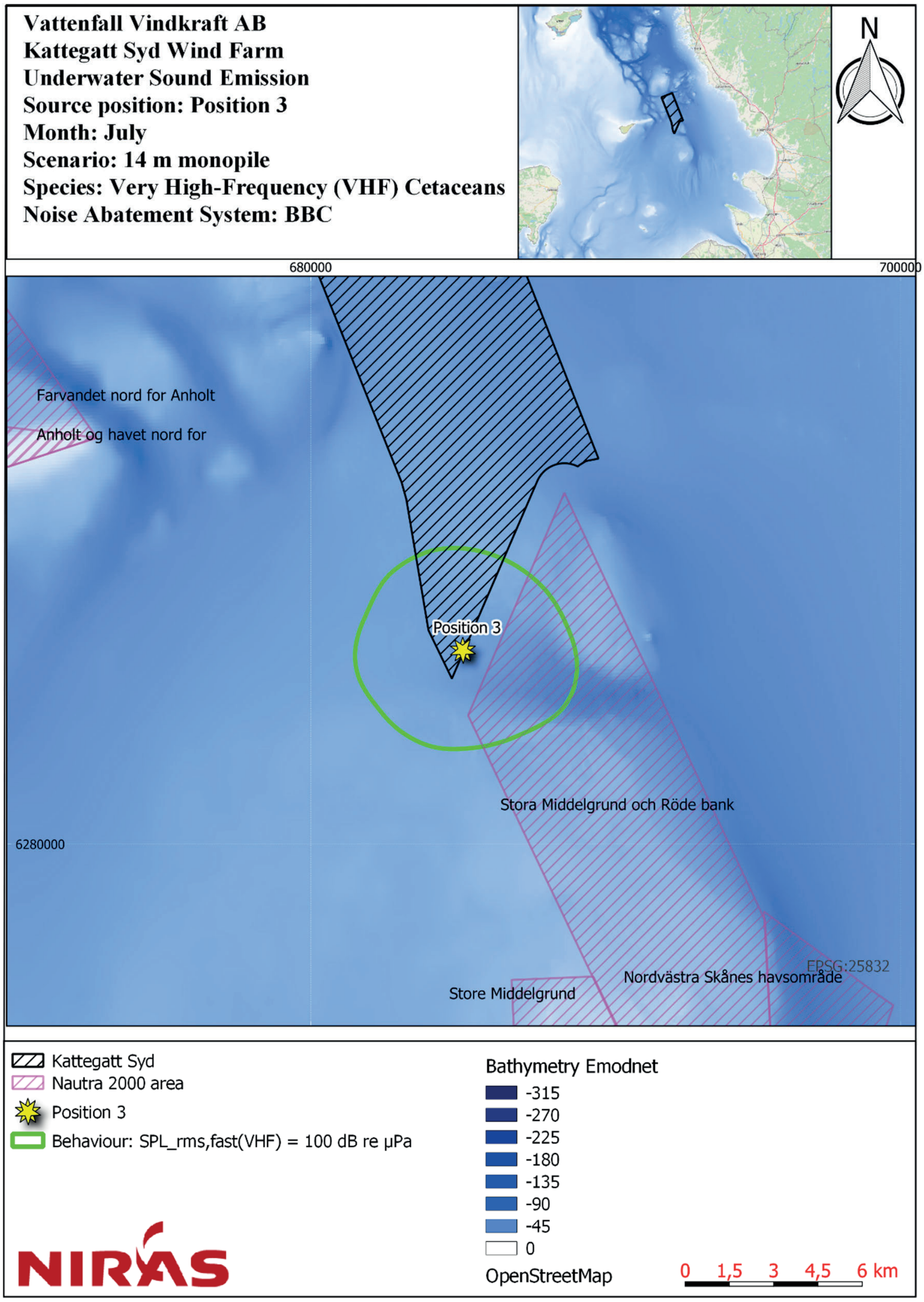


Figure 7.7: Noise contour map for position 1, showing impact distance for behaviour in December with VHF-weighting and HSD-DBBC.

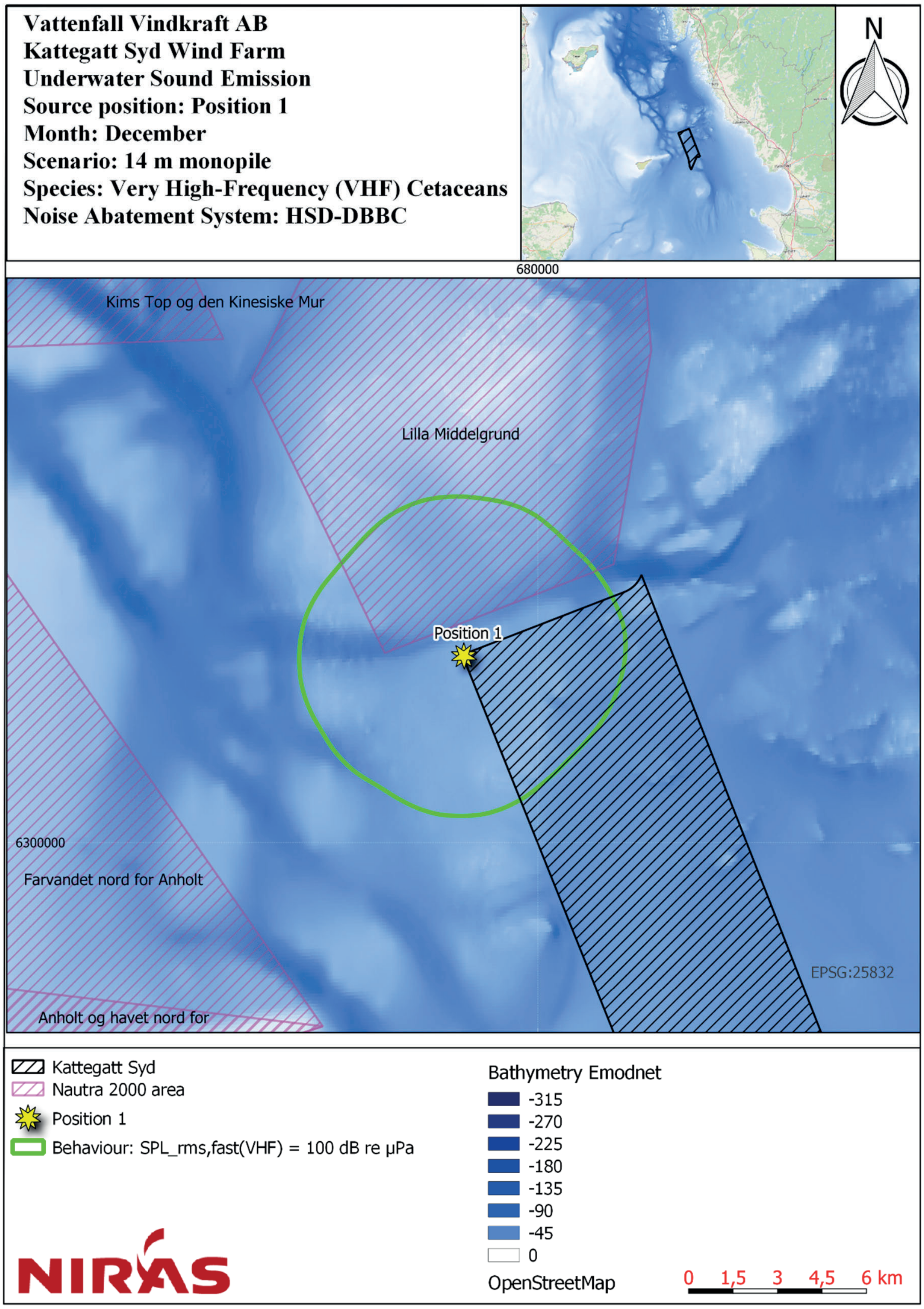


Figure 7.8: Noise contour map for position 1, showing impact distance for behaviour in July with VHF-weighting and HSD-DBBC.

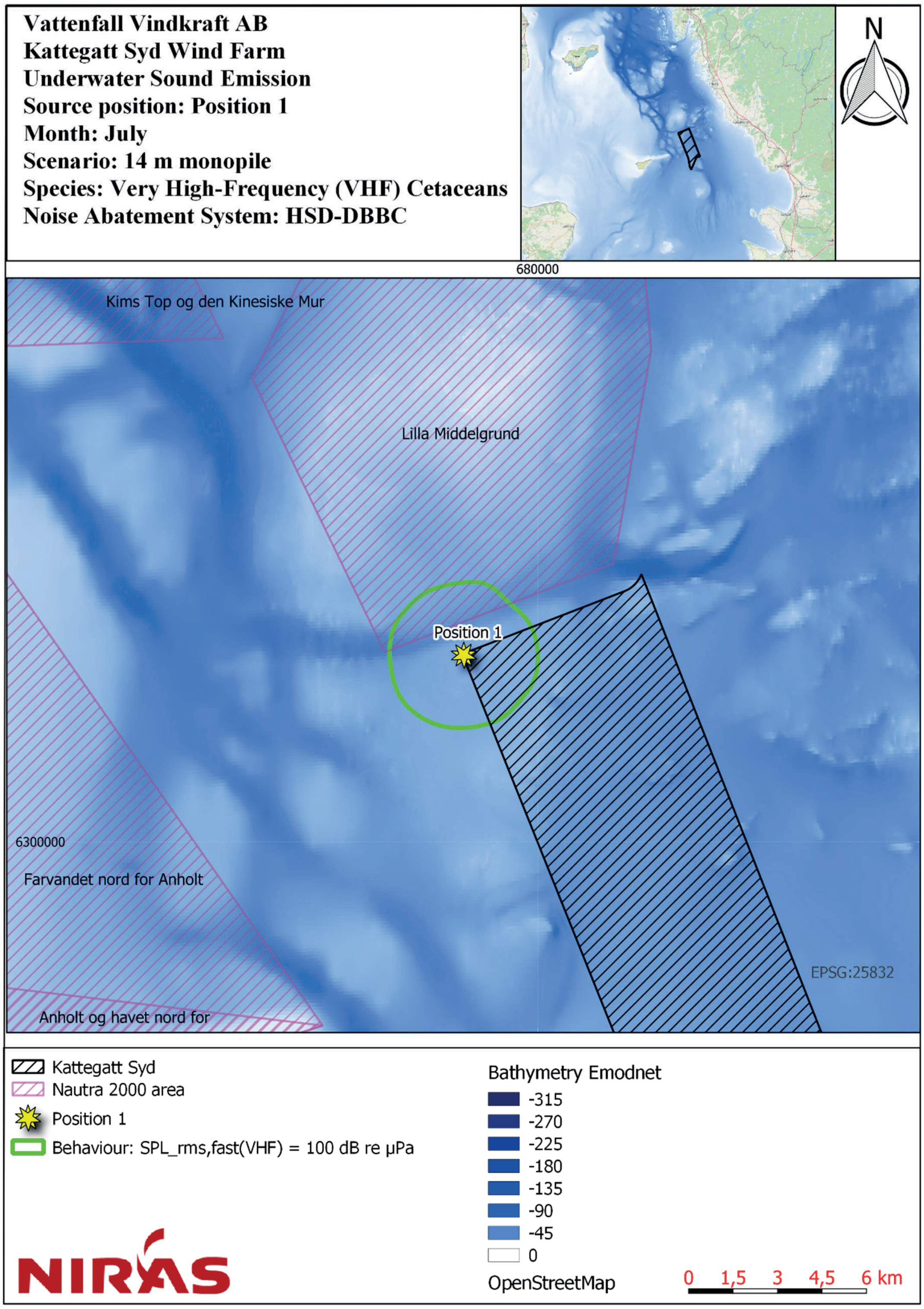


Figure 7.9: Noise contour map for position 2, showing impact distance for behaviour in July with VHF-weighting and HSD-DBBC.

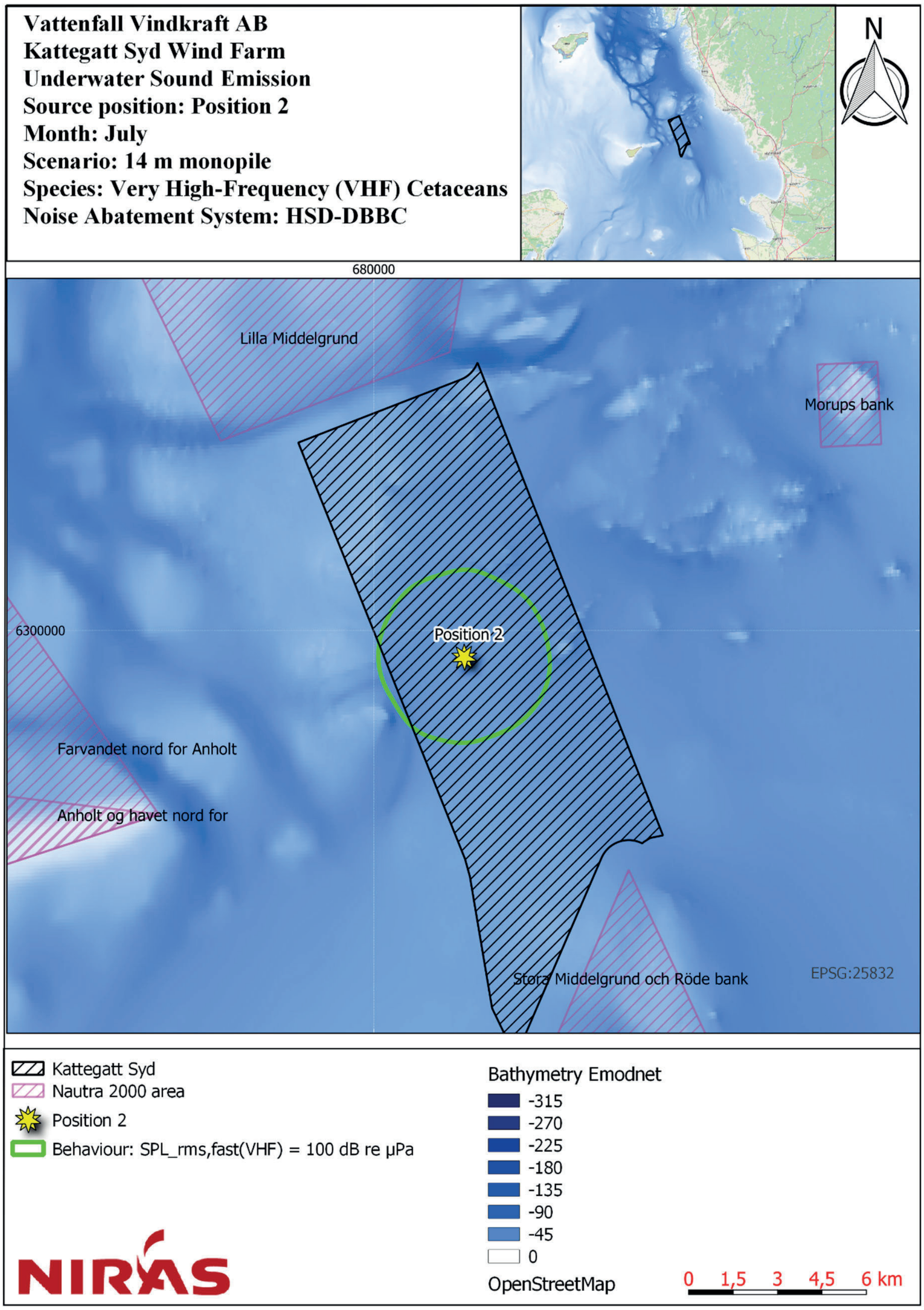

Vattenfall Vindkraft AB
Kattegatt Syd Wind Farm
Underwater Sound Emission
Source position: Position 2
Month: July
Scenario: 14 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
6300000
Lilla Middelgrund
Morups bank
Position 2
Farvandet nord for Anholt
Anholt og havet nord for
Stora Middelgrund och Röde bank
EPSG:25832
Kattegatt Syd
Nautra 2000 area
Position 2
Behaviour: SPL_rms,fast(VHF) = 100 dB re µPa
Bathymetry Emodnet
-315
-270
-225
-180
-135
-90
-45
0
OpenStreetMap
0 1,5 3 4,5 6 km

Figure 7.10: Noise contour map for position 3, showing impact distance for behaviour in December with VHF-weighting and HSD-DBBC.

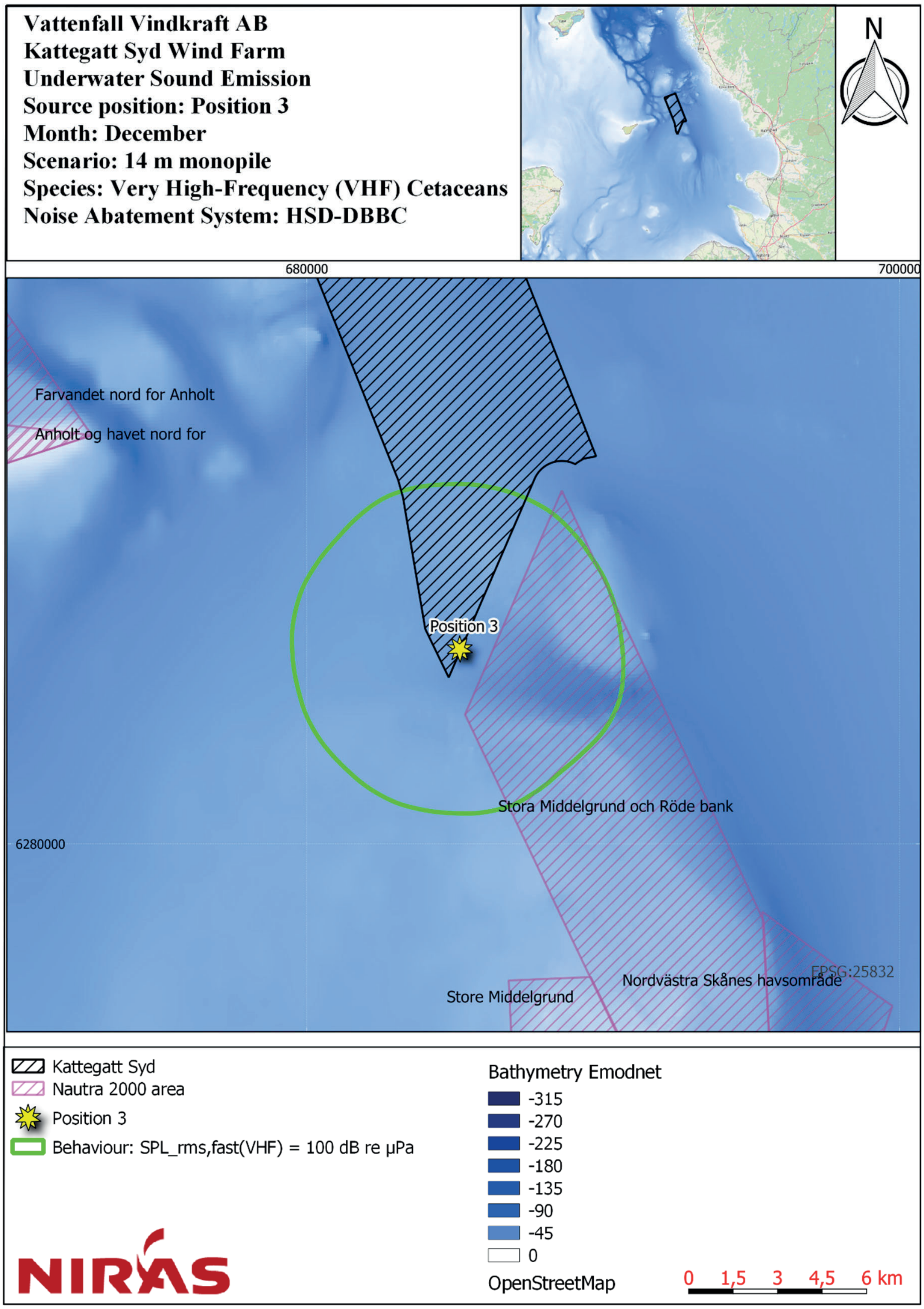
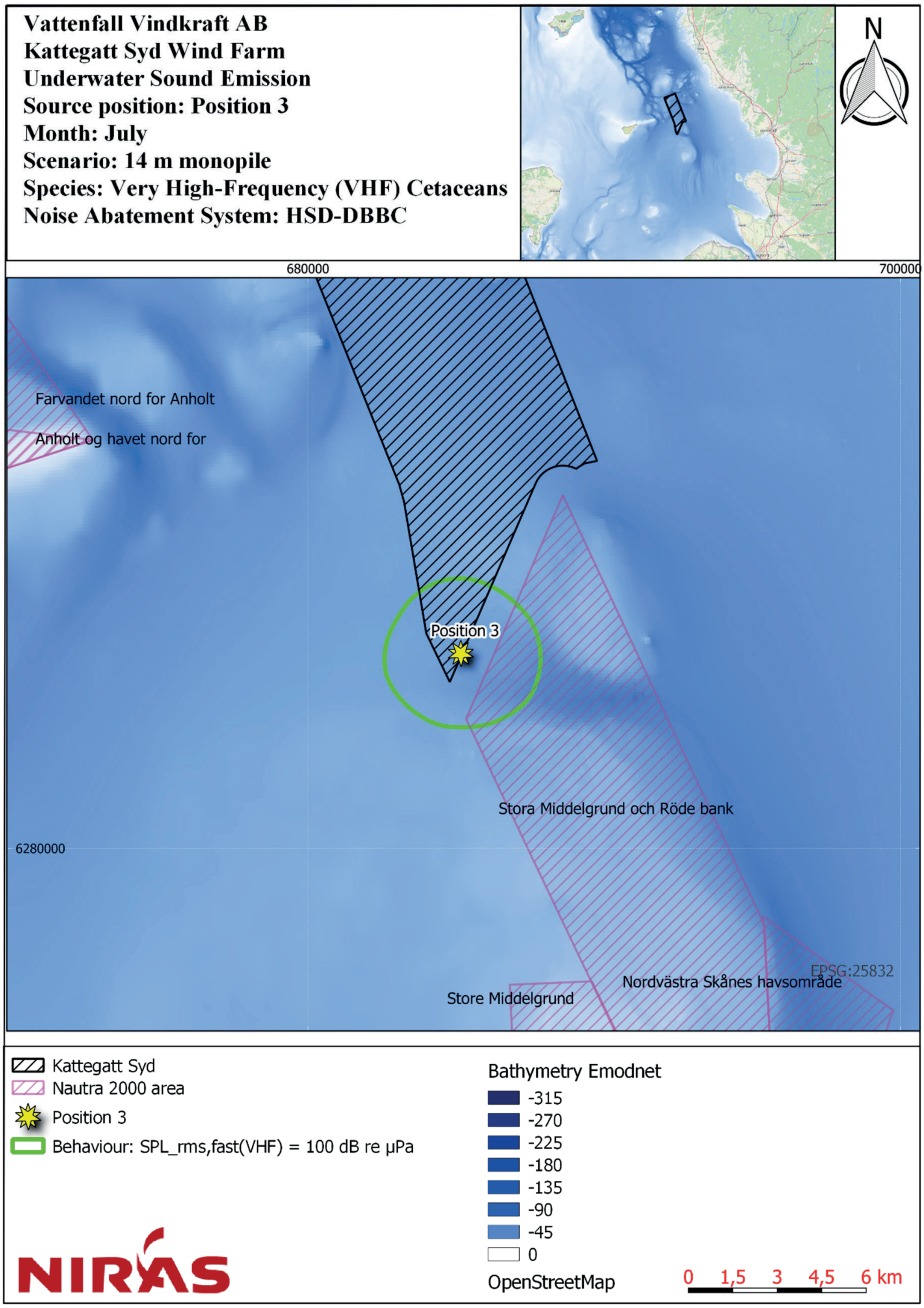


Figure 7.11: Noise contour map for position 3, showing impact distance for behaviour in July with VHF-weighting and HSD-DBBC.



8 Conclusion

Sound propagation modelling results show, that PTS is unlikely to occur for harbour porpoise located further than 25 m away from the source at the onset of piling activities, regardless of position, installation time, and which NAS is applied. TTS is unlikely to occur in harbour porpoise located further than 90 m from the source at onset of piling when using a HSD-DBBC NAS, and 50 m when using a BBC NAS.

Avoidance behaviour effects are likely to occur for harbour porpoise located within an 8.4 km radius of the installation for the part of the installation where 100% hammer energy is applied, when installation occurs in the winter months and with the BBC NAS, and within a 5.7 km radius when the HSD-DBBC NAS is applied. For installation in the summer months, the behaviour radius for the BBC NAS is limited to 4.3 km, and 3.0 km with the HSD-DBBC. For lower hammer energies, such as during soft start and ramp up, the distance will be shorter.

For seal, calculations showed that PTS is unlikely to occur within animals located further than 25 m from piling at the onset of piling activities, and for TTS further than 50 m, regardless of position, installation time, and which NAS is applied.

Calculation of overlapping areas, showed a harbour porpoise behaviour threshold exceedance zone of up to 208 km^2 for the winter months using a BBC NAS, reduced to a maximum of 97 km^2 when using a HSD-DBBC NAS. For the summer months, the corresponding areas were calculated to 53 km^2 and 26 km^2, for BBC and HSD-DBBC NAS respectively.

It was also found, that the worst-case harbour porpoise behaviour threshold exceedance zone within the "Lilla Middelgrund" Natura 2000 site in December month amounted to 52 km^2, or 29.2% of the Natura 2000 site area, with BBC NAS applied, and up to 27 km^2, or 15.2% with the HSD-DBBC NAS. For the "Stora Middelgrund" Natura 2000 site, corresponding worst-case overlap was found to be 50 km^2, or 43.9% of the Natura 2000 site area with the BBC NAS, and up to 31 km^2, or 27.2% of the Natura 2000 site area with the HSD-DBBC NAS. For installation in the summer months the worst-case harbour porpoise behaviour threshold exceedance zone within the "Lilla Middelgrund" Natura 2000 site is limited to 11 km^2, or 6.2% of the Natura 2000 area, with BBC NAS applied. This is reduced to 5 km^2, or 2.8% with the HSD-DBBC NAS. For the "Stora Middelgrund" Natura 2000 site, corresponding worst-case overlap was found to be 12 km^2, or 10.5% of the Natura 2000 site area with the BBC NAS, and up to 6 km^2, or 5.3% of the Natura 2000 site area with the HSD-DBBC NAS.

For a maximum 20% exceedance area within any of the Natura 2000 sites, the HSD-DBBC NAS is sufficient towards the Lilla Middelgrund site, while an extra mitigation effect of $\Delta SPL_{VHF} = 2\ dB\ re. 1\ \mu Pa$ in addition to HSD-DBBC NAS would be required towards the Stora Middelgrund site. Alternatively for the Stora Middelgrund site, a 2 km distance between any pile installation and the Natura 2000 border would also achieve a maximum of 20% overlap.

9 References

Adegbulugbe, O., Jung, S. & Kampmann, R., 2019. *Task 1 Report: Literature Review of Pile Driving System, Evaluation of Glass Fiber Reinforced Polymer (GFRP) Spirals in Corrosion Resistant Concrete Piles,* s.l.: Florida Department of Transportation.

Bellmann, M. A. et al., August 2020. *Underwater noise during percussive pile driving: Influencing factors on pile-driving noise and technical possibilities to comply with noise mitigation values,* Oldenburg, Germany: ITAP.

Diederichs, A. et al., 2014. *Entwicklung und Erprobung des Großen Blasenschleiers zur Minderung der Hydroschallemissionen bei Offshore-Rammarbeiten. P. 240. BioConsult.* s.l.:s.n.

EMODnet, 2021. [Online]
Available at: https://www.emodnet-bathymetry.eu/data-products
[Accessed 2021].

Energistyrelsen, 2016. *Guideline for underwater noise - installation of impact-driven piles,* København: ens.dk.

Erbe, C., 2011. *Underwater Acoustics: Noise and the Effects on Marine Mammals.* s.l.:jasco.

Jacobsen, F. & Juhl, P. M., 2013. FUGA. In: *Fundamentals of General Linear Acoustics.* s.l.:Wiley, p. 285.

Jakob Tougaard, K. B., 2018. *Practical implementation of auditory time and frequency weighting in marine bioacoustics.* s.l.:Department of Bioscience, Aarhus University, Denmark.

Jensen, F. B., Kuperman, W. A., Porter, M. B. & Schmidt, H., 2011. *Computational Ocean Acoustics, 2nd edition.* s.l.:Springer.

Koschinski S et al., L. K., 2013. *Development of Noise Mitigation Measures in Offshore Wind Farm Construction,* Nehmten and Hamburg, Germany, 6 February 2013: Federal Agency for Nature Conservation (Bundesamt für Naturschutz, BfN).

Martin, B., Morris, C. & O'Neill, C., 2019. *Sound exposure level as a metric for analyzing and managing underwater.* s.l.:s.n.

Nielsen, B. et al., 2011. *Marin råstof- og naturtypekortlægning i Kattegat og vestlige Østersø.* s.l.:s.n.

NOAA, 2019. *WORLD OCEAN ATLAS 2018 (WOA18).* [Online].

NOAA, April 2018. *Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0), NOAA Technical Memorandum NMFS-OPR-59,* Silver Spring, MD 20910, USA: National Marine Fisheries Service.

Porter, M., 2011. *The BELLHOP Manual and User's Guide: PRELIMINARY DRAFT.* s.l.:Heat, Light and Sound Research Inc. La Jolla, CA, USA.

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

Thiele, R., 2002. *Propagation loss values for the North Sea. Handout Fachgespräch: Offshore-Windmillssound emissions and marine mammals., 15.01.2002. pp.,* s.l.: s.n.

Tsouvalas, A., 2020. *Underwater Noise Emission Due to Offshore Pile.* s.l.:s.n.

Verfuß, T., 2014. *Noise mitigation systems and low-noise installation technologies..* ISBN: 978-3-658-02461-1: 10.1007/978-3-658-02462-8_16..

Wang, L. et al., 2014. *Review of Underwater Acoustic Propagation Models.* s.l.:s.n.

Appendix 1 – Affected area

Figure A.1: Noise contour map for position 1, showing impact distance for behaviour in December with VHF-weighting and BBC, together with the affected Natura 2000 area.

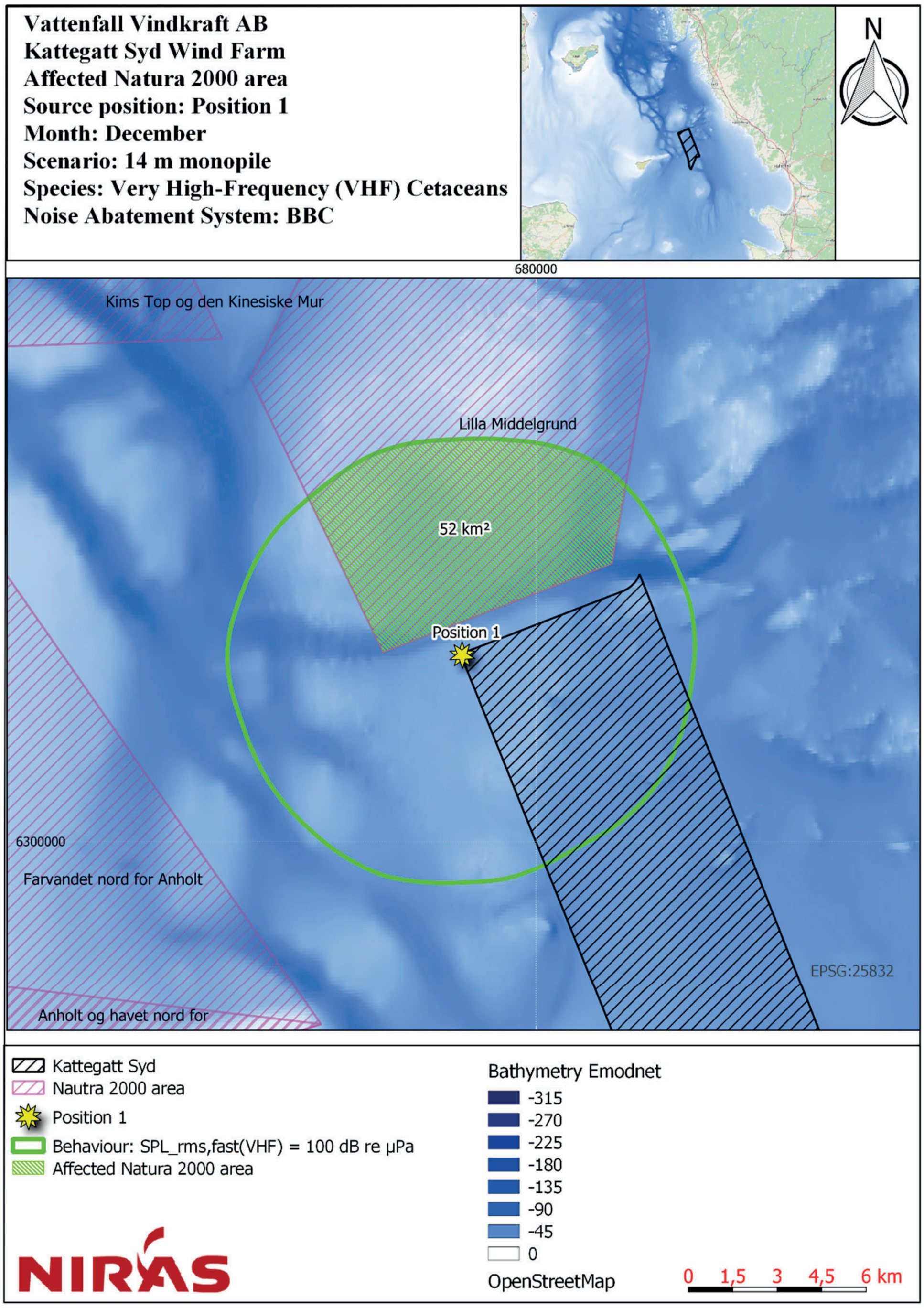


Figure A.2: Noise contour map for position 1, showing impact distance for behaviour in July with VHF-weighting and BBC, together with the affected Natura 2000 area.

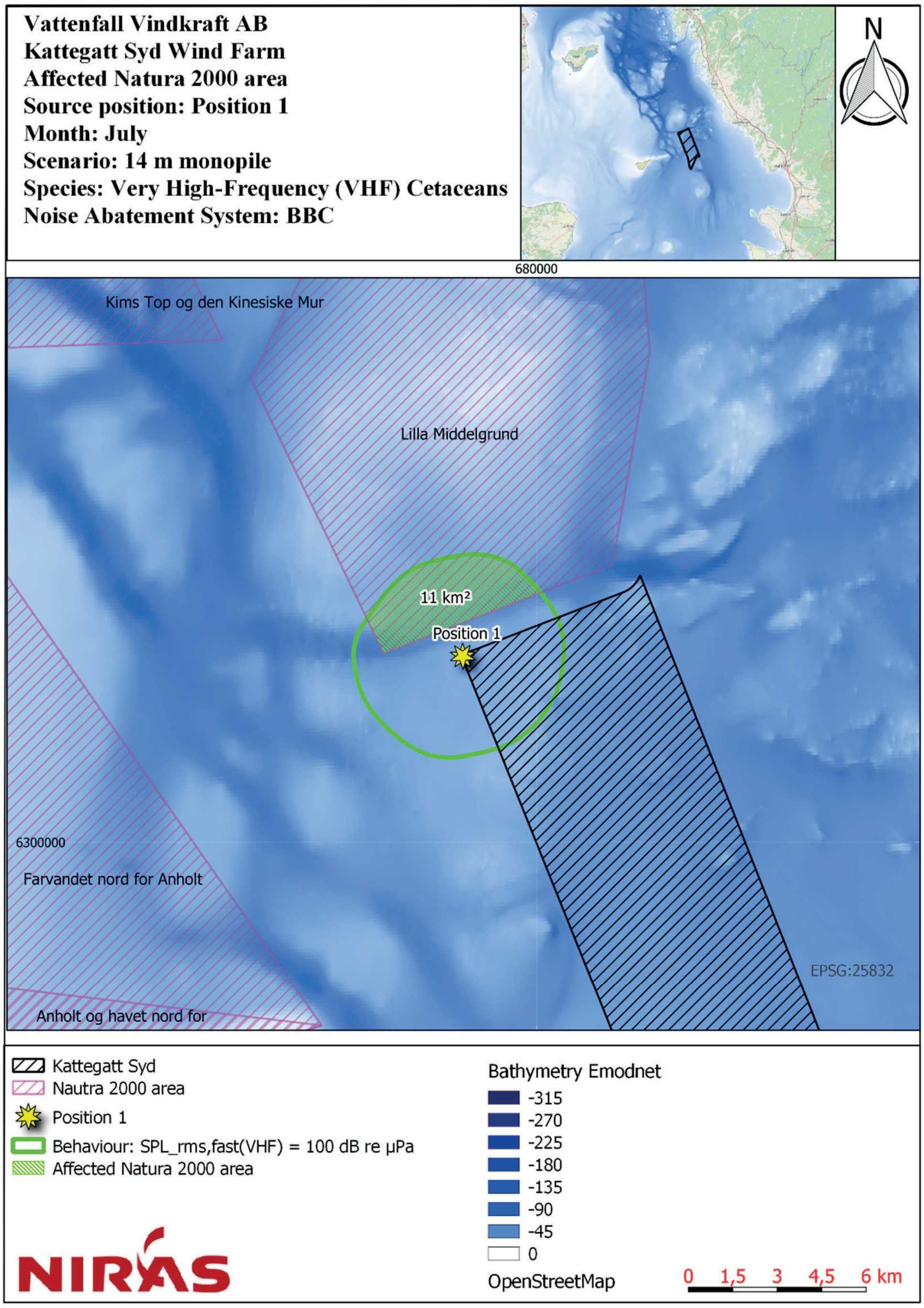


Figure A.3: Noise contour map for position 3, showing impact distance for behaviour in December with VHF-weighting and BBC, together with the affected Natura 2000 area.

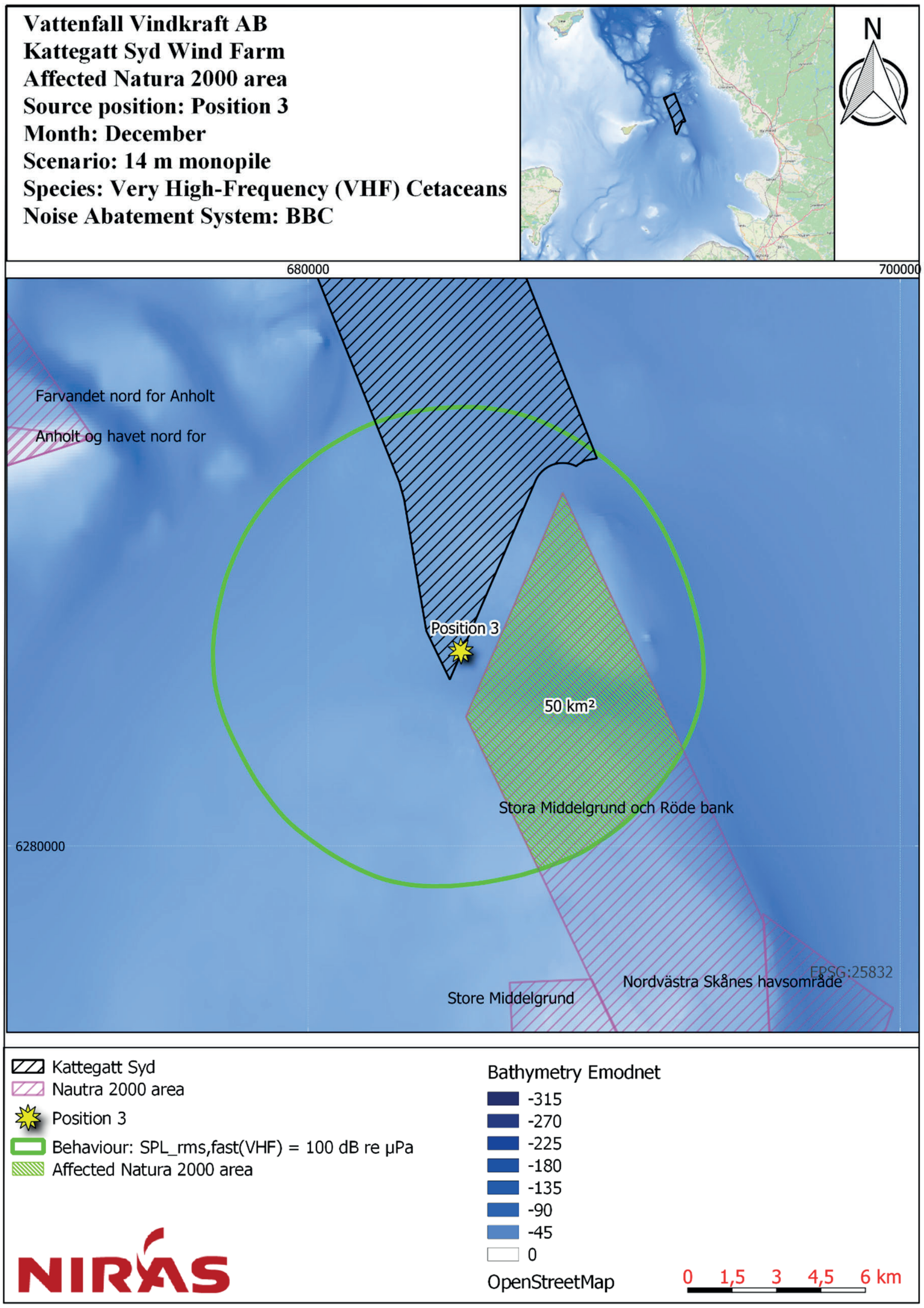


Figure A.4: Noise contour map for position 3, showing impact distance for behaviour in July with VHF-weighting and BBC, together with the affected Natura 2000 area.

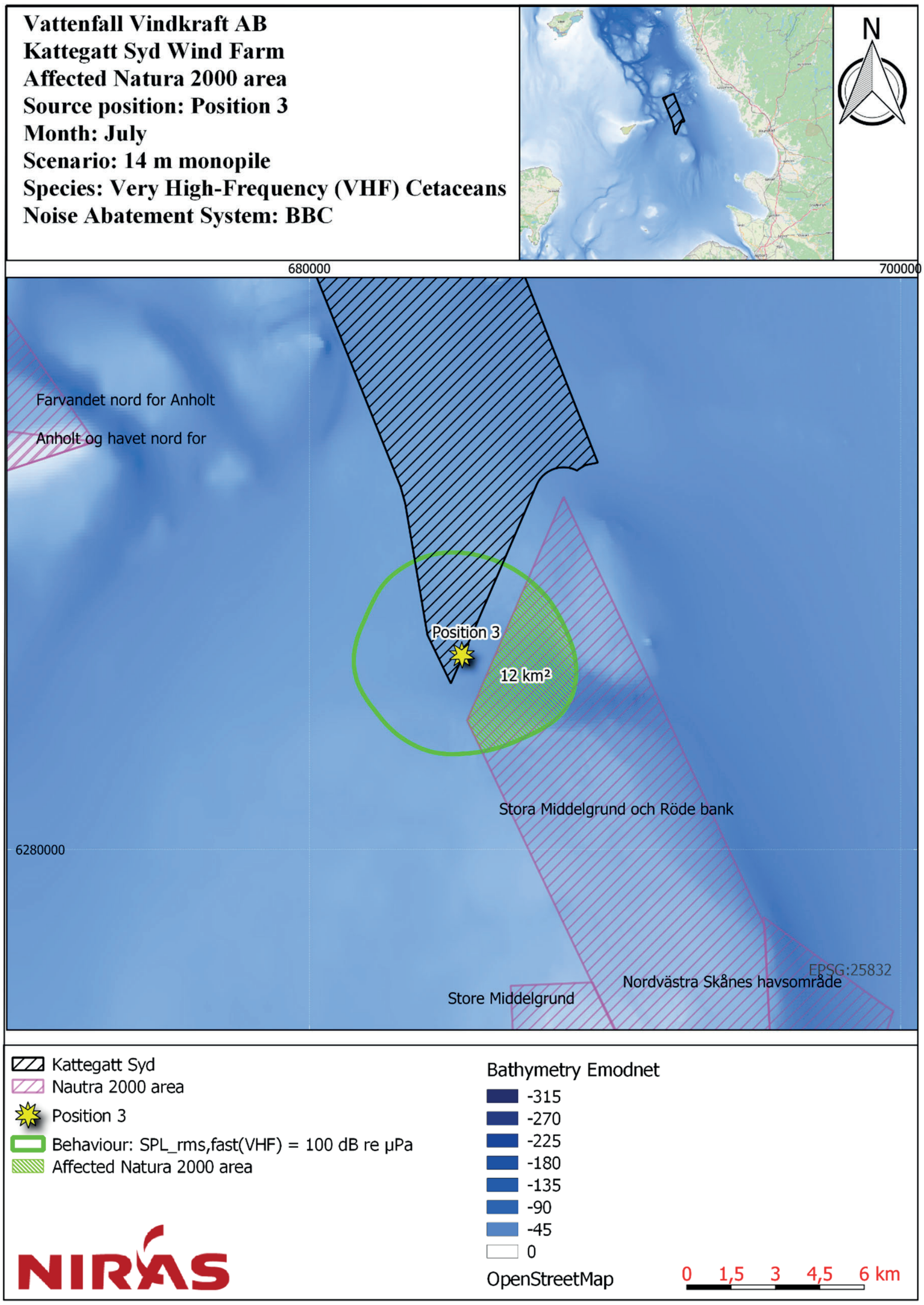


Figure A.5: Noise contour map for position 1, showing impact distance for behaviour in December with VHF-weighting and HSD-DBBC, together with the affected Natura 2000 area.

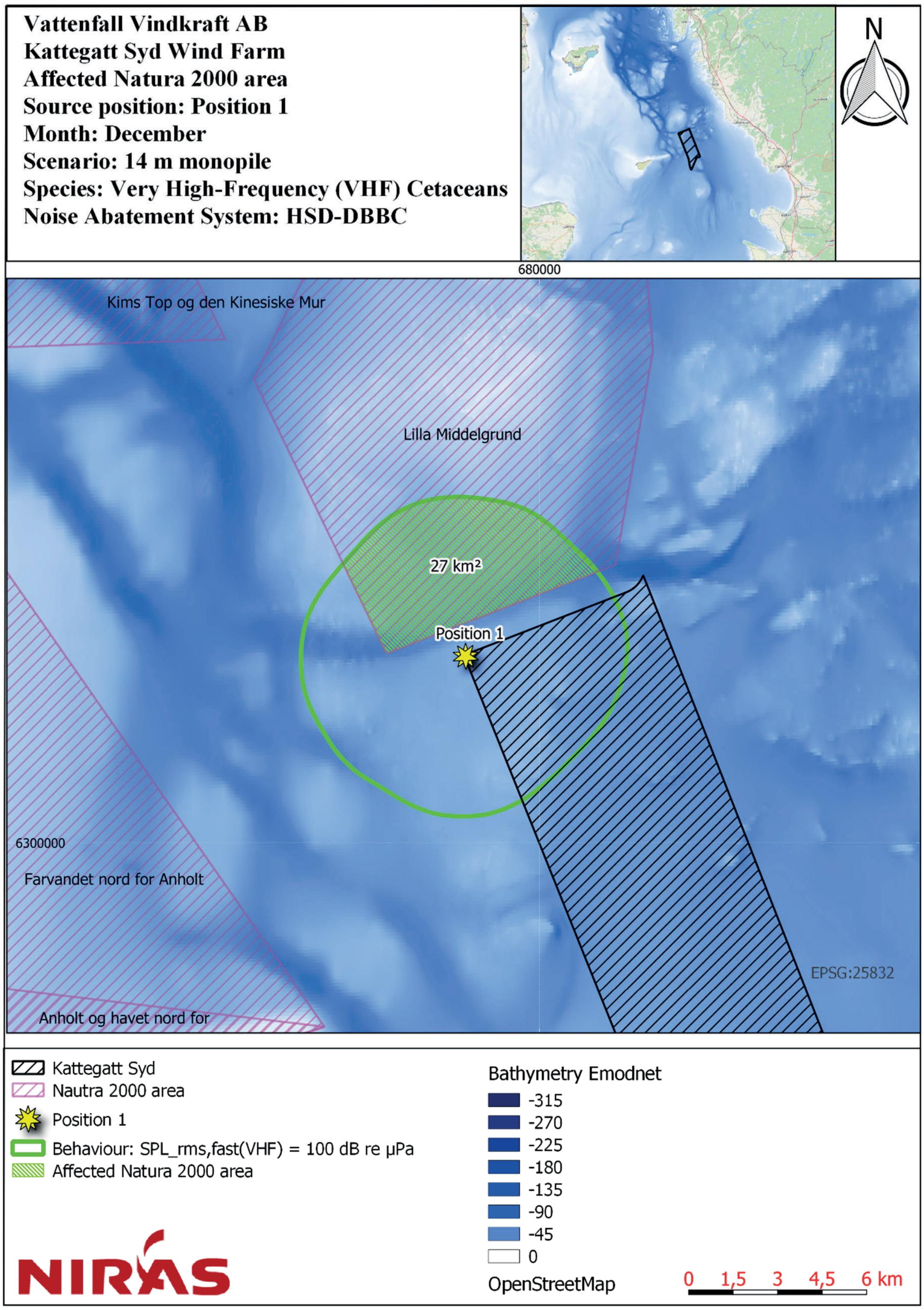


Figure A.6: Noise contour map for position 1, showing impact distance for behaviour in July with VHF-weighting and HSD-DBBC, together with the affected Natura 2000 area.

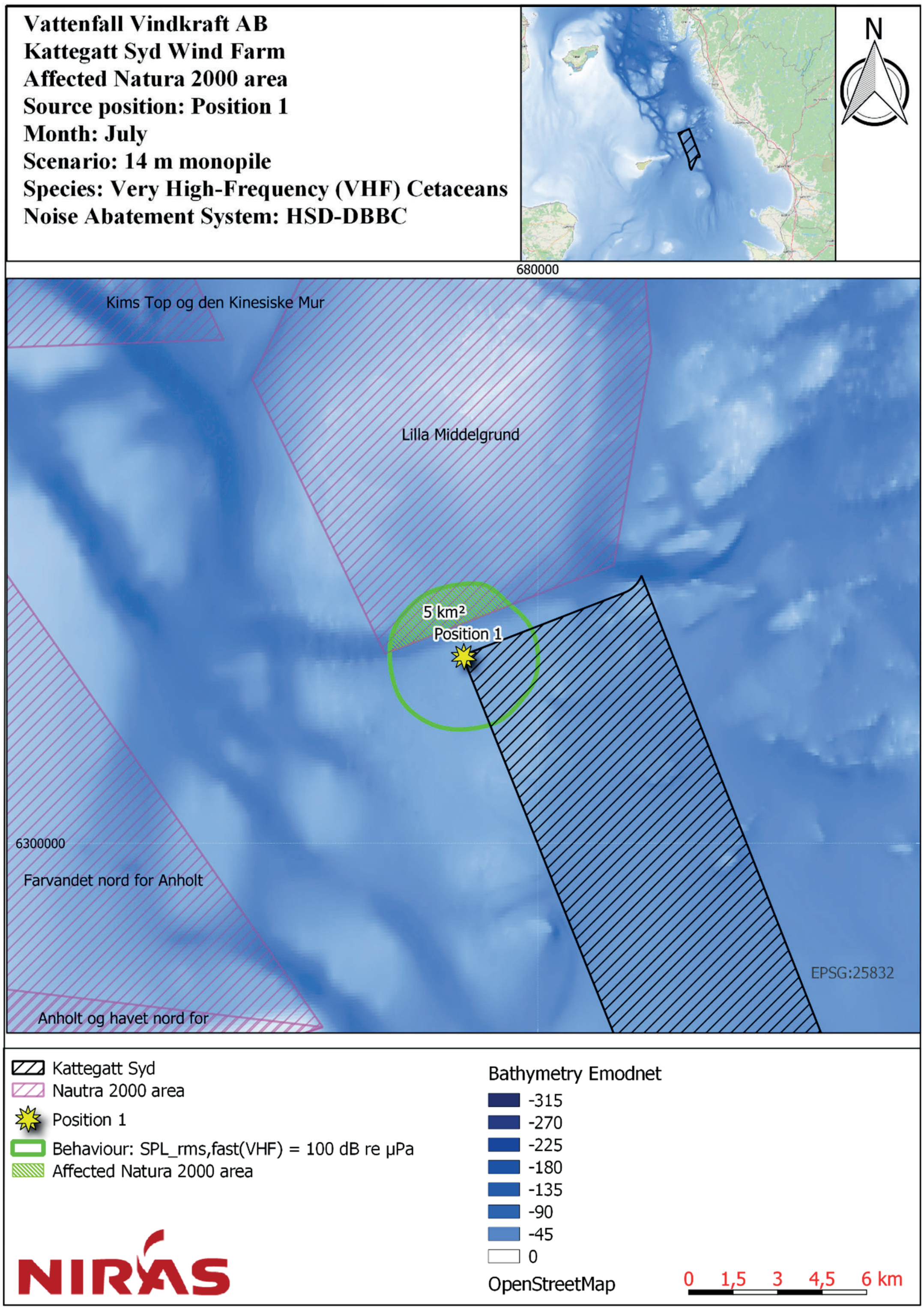


Figure A.7: Noise contour map for position 3, showing impact distance for behaviour in December with VHF-weighting and HSD-DBBC, together with the affected Natura 2000 area.

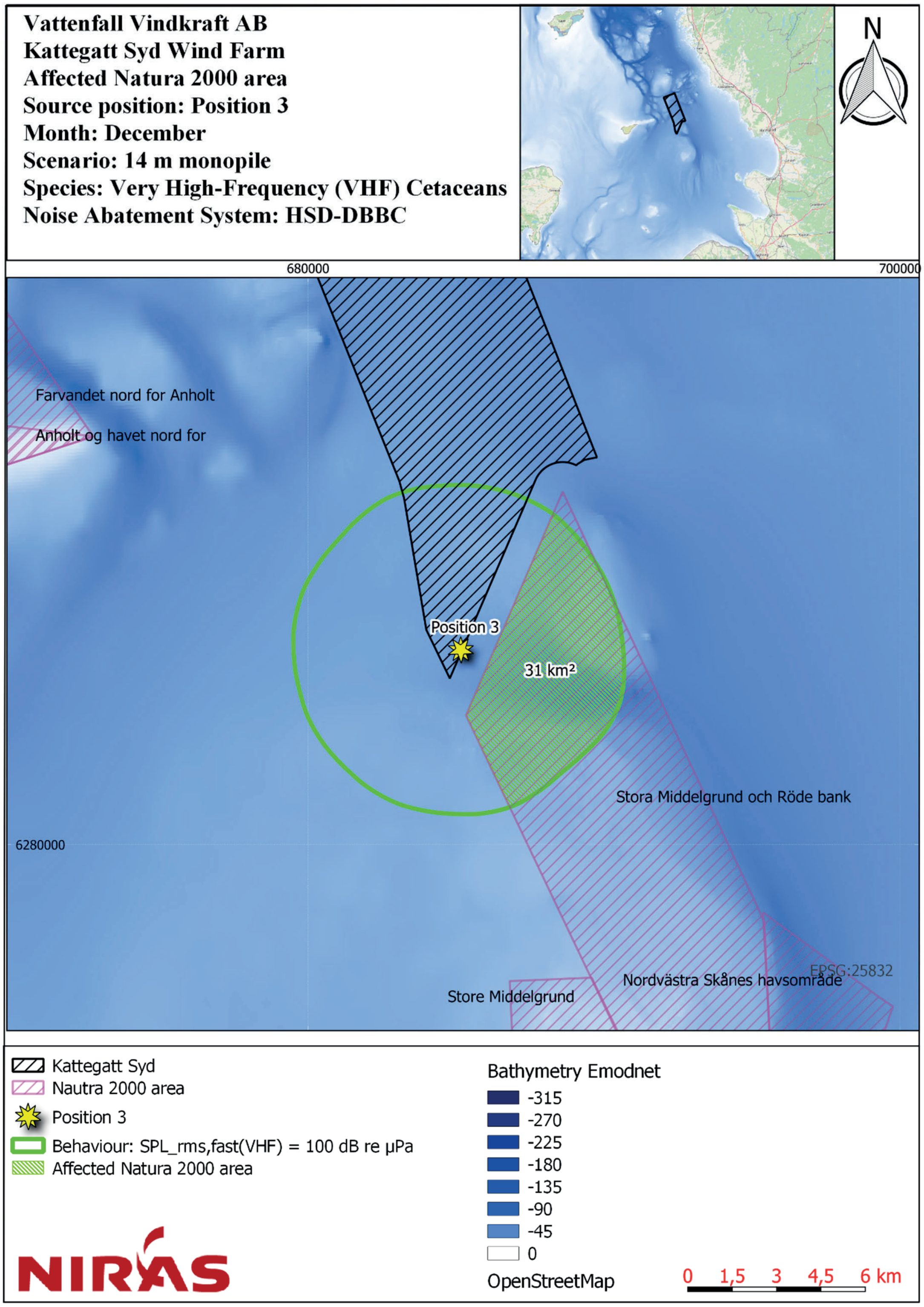


Figure A.8: Noise contour map for position 3, showing impact distance for behaviour in July with VHF-weighting and HSD-DBBC, together with the affected Natura 2000 area.

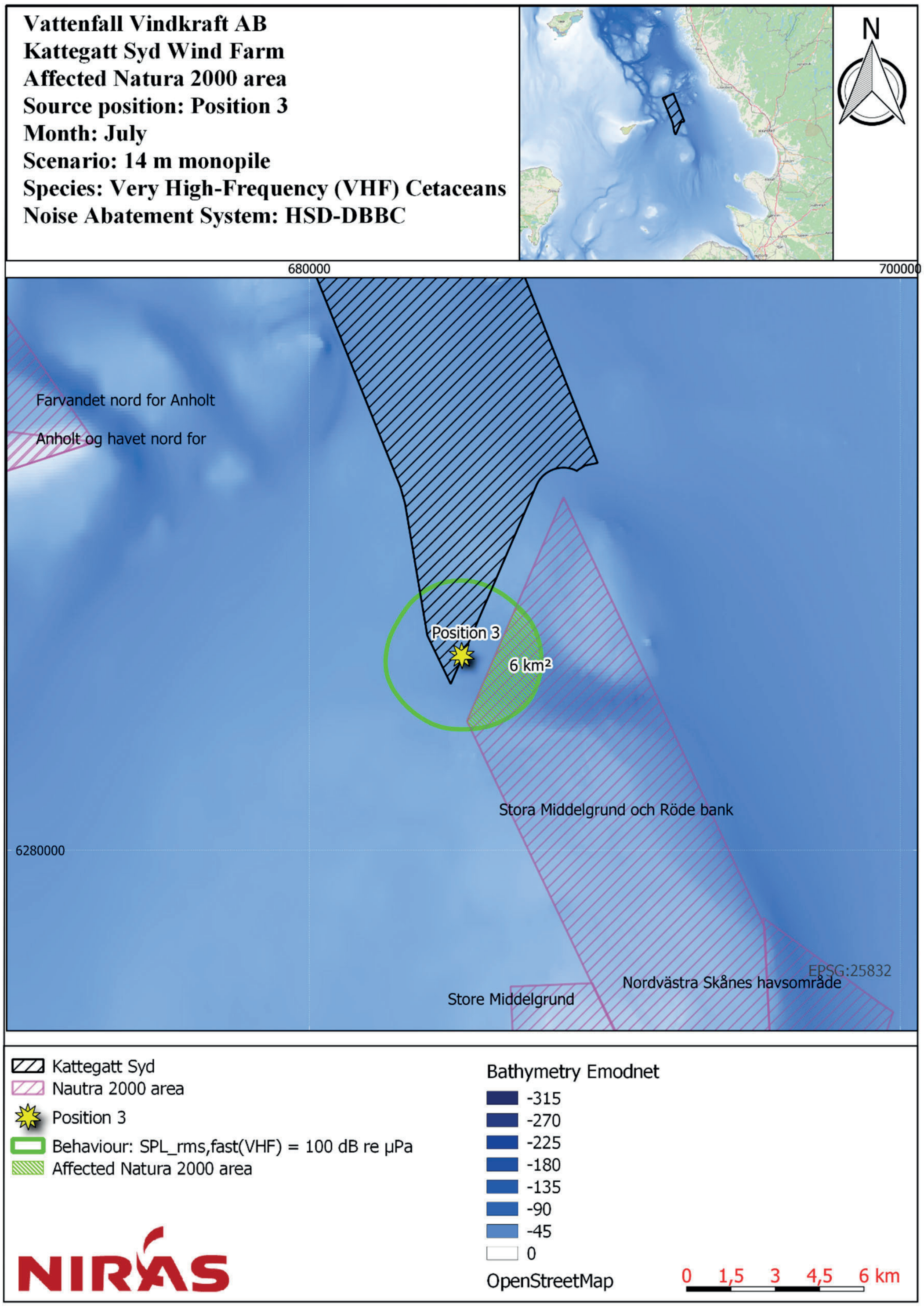
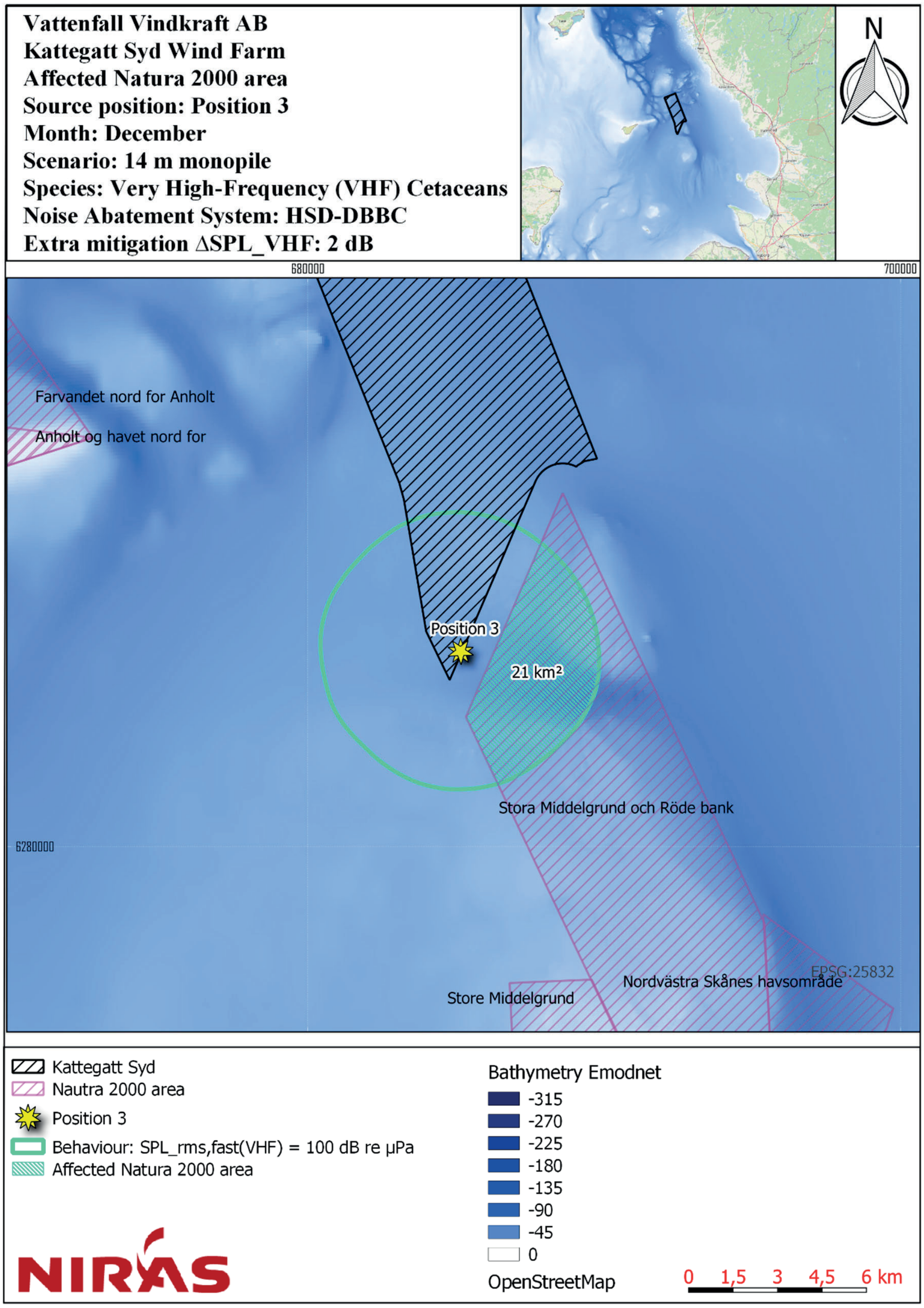


Figure A. 9: Noise contour map for position 3, showing impact distance for behaviour in December with VHF-weighting and HSD-DBBC and additional 2 dB mitigation (ΔSPL_{VHF}), together with the affected Natura 2000 area.



KATTEGATT SYD OFFSHORE WIND FARM

Effects of pile driving, gravity foundations and sediment spill on marine mammals

Construction and operation of an offshore wind farm between the two Swedish Natura 2000 sites Lilla Middelgrund and Stora Middelgrund & Röda Bank has been assessed with respect to potential impacts on marine mammals from underwater noise and sediment spill. Underwater noise is assumed the main source of potential impact from construction, in particular percussive piling of turbine foundations. Impact was modelled for July and December by estimating the cumulated sound exposure for marine mammals near the construction site and by assessing disturbance to animals in time and space. Construction in December is predicted to result in significantly larger affected areas than construction in July due to differences in hydrography and hence sound propagation properties. Impact was assessed with noise abatement in shape of Big Bubble Curtains (BBC), as well as with best available technology (BAP) noise abatement with hydro sound dampeners (HSD) and Double Big Bubble Curtains (DBBC). With BBC noise abatement 29 % and 44 % of the Lilla Middelgrund and Stora Middelgrund & Röda Bank, respectively, will be exposed to noise levels above the reaction threshold for harbour porpoises. With the use of HSD + DBBC noise abatement in Summer, this effect can be reduced to 2.8 % and 5.3 %, respectively for the two Natura 2000 sites. With such mitigation measures in place, the construction is not considered to have long-term impacts on the abundance or population development of marine mammals in the area. Likewise, the operation of the wind farm is considered to be without significant long-term impact on marine mammals.

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