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Effects of underwater noise on marine mammals during the installation phase

Scientific Report from DCE – Danish Centre for Environment and Energy No. 409 2021

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Data sheet

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Abstract: Construction and operation of an offshore wind farm in the Swedish Natura 2000 site Stora Middelgrund & Röde 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 February and May 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 February is predicted to result in significantly larger affected areas than construction in May due to differences in hydrography and hence sound propagation properties. Without noise abatement, 100 % of the Natura 2000 site will be exposed to noise levels above the reaction threshold for harbour porpoises and marine mammals are at risk of acquiring partial, but permanent loss of hearing. Provided best available technology for noise abatement is used, exemplified by the double Big Bubble Curtain in combination with the use of hydro sound dampeners, the risk of hearing loss is removed and the behavioural disturbance reduced significantly. If additional noise abatement of up to 11 dB is provided, the impact on the Natura 2000 sites is reduced to less than 20 % and then assessed as acceptable according to JNCC guidelines. With such mitigation measures, the construction is not considered to have long-term impact 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 areas

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Contents

Preface

This report was commissioned by Vattenfall Stora Middelgrund Vind AB. It contains assessment of potential impact on marine mammals from construction of an offshore wind farm on Stora Middelgrund, Swedish Kattegat. NIRAS contributed with appendix 1 and 2 and commented on the main text as part of the quality assurance procedure. Conclusions with respect to impact on animals remain the sole responsibility of DCE. The assessment of impact is largely based on methodology also used for a similar assessment for an offshore wind farm on Swedish Kriegers Flak. Description of methodology and background information is therefore largely identical to the report on the Kriegers Flak offshore wind farm, updated wherever relevant. Incorporated in this report are also replies to statements from the Swedish Authorities ("remisyttrande") regarding the project at Kriegers Flak. This has been done to align the two assessments as much as possible with respect to methodology. There are important differences between the two areas and projects and direct comparison of conclusions between the two are not always appropriate. A key difference between the two locations is the conservation status of harbour porpoises, as Stora Middelgrund is located in the core habitat of the Danish Belt Sea population. This population is considered in favourable conservation status, whereas Kriegers Flak is located in an area also frequented by the critically endangered Baltic Proper population. This difference in conservation status is central for conclusions regarding assessed impact.

Vattenfall Stora Middelgrund Vind AB was given the opportunity to comment on a late 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 on the Swedish part of Stora Middelgrund in the Natura 2000 site Stora Middelgrund & Röde 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 around Stora Middelgrund. In the southern part of Kattegat these porpoises belong to the Danish Belt Seas population, which is assessed on national red lists as Least Concern.

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, whereas the grey seal appears in low numbers and is red-listed as Vulnerable.

Sensitivity to impact

Underwater noise is likely to be the main source of impact on marine mammals from windfarm construction, but the impact of sediment spill is also assessed in this report. 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.

As none of the three marine mammal species depend on visual cues for foraging or survival, the sensitivity of the extensive sediment spill from construction of the offshore wind farm, is assessed as **negligible**.

Various mitigation measures 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, or shifting to gravity foundations where possible.

Magnitude of impact on harbour porpoises and seals was assessed for sediment spill, as well as for effects of underwater noise from installation of piles by either gravity or piling with hammers. The assessed effects were from 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 (15 m diameter, 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 areas, within one of which the offshore windfarm is intended built. 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).

Impact magnitude from construction

For the noise exposure assessment, modelling was performed for two positions (on a shallow part and a deeper part of the proposed windfarm area) and two months (February and May). The two months were picked to represent the most extreme hydrographical conditions with respect to sound propagation, with February being the worst (upward-refracting conditions) and May the most favourable (downward-refracting conditions). Modelling was performed for two different monopile diameters: 12 and 15 m. The 15 m diameter monopile was used in impact modelling, representing the worst-case scenario.

A further dichotomy was introduced, by modelling pile driving with and without best available technology for noise abatement, currently 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. However, because unabated piling is unlikely to be permitted inside the Natura 2000 site, only abated scenarios are assessed with respect to marine mammals. Some calculations for unabated scenarios are however shown for comparison.

Assessment of impact:

- It is considered unlikely that marine mammals will be exposed to sound pressures able to inflict acute injury (acoustic trauma).

- The risk of inflicting permanent hearing loss can be eliminated by using best available technology and best environmental practice, which in this case is pile driving in May with the HSD-DBBC system. The impact on seals and porpoises through hearing loss is then 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 unabated pile driving in February, 61 % of the porpoise population in the South-Eastern Kattegat is predicted to be exposed to sound pressures above the behavioural reaction threshold, amounting to an exposed area of 10,647 km^2, and this impact is assessed as **major**.

- With use of best available technology and best environmental practice, which is pile driving in May (due to larger transmission loss), with the HSD-DBBC noise abatement system, it is assessed that only <1 % of the porpoise population, equal to an area of max 37 km^2, depending on pile diameter, will be exposed to noise levels above the behavioural reaction threshold. 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 abated pile driving noise or noise from installation of gravity foundations will be capable of masking sounds relevant to porpoises e.g. during prey capture or intraspecific communication 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. The communication is especially important during the mating season near haul-outs. Given the favourable conservation status of the population of harbour seals, the overall impact of masking from the abated pile driving noise is assessed to be **negligible**.

- As none of the three marine mammal species depend on visual cues for foraging or survival, the impact of the extensive sediment spill from construction of the offshore wind farm, is assessed as **negligible**.

Impact from operation

Based on studies of effects from existing offshore wind farms in operation, no negative effects of the wind farm is predicted on seals and porpoises 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**.

Impact on Natura 2000 sites

As no national guidelines exists on restriction of underwater noise inside Natura 2000 sites, the impact is evaluated on the basis on the JNCC guidelines from 2020.

The Natura 2000 sites Stora Middelgrund & Röde Bank, together with adjacent or nearby seven sites: Skånes Nordvästvatten, Lilla Middelgrund, Store Middelgrund (DK), Fladen, Balgö, Anholt, and Gilleleje Flak and Tragten could be affected by construction of the offshore windfarm. Under worst case conditions, which is unabated pile driving in February, all eight areas would be affected by exposure to noise levels well above the behavioural reaction thresholds for porpoises.

Application of *Best Available Technology* to the pile driving, which would be noise abatement, such as double Big Bubble Curtains and hydro sound dampeners, and piling during a period with a downward refracting sound speed profile (*Best Environmental Practice*) will reduce the emitted noise considerably. This would reduce the fraction of the Natura 2000 site Stora Middelgrund & Röde Bank (in which the wind farm is located) exposed above the behavioural reaction threshold to between 18-27 % for 15 m piles. The impact is assessed to be **unacceptable** according to the JNCC guidelines, because the **impacted area exceeds 20 % of the Natura 200 site**. The same applies to the neighbouring Natura 2000 site Store Middelgrund (DK).

The impact on the combined Store Middelgrund and Stora Middegrund & Röde Bank Natura 2000 sites under application of Best Available Technology and Best Environmental Practice and **with an additional mitigation** amounting to up to 11 dB extra abatement, depending on location, will reduce affected area to below the 20 % threshold put forward by JNCC and is therefore assessed to be **acceptable**. The same applies to the six more distant Natura 2000 sites.

It is assessed likely that under worst-case conditions vessel noise from installation of gravity foundations will affect up to 17 % of the combined area of the two Store Middelgrund and Stora Middelgrund & Röde Bank Natura 2000 sites, which is assessed as **acceptable**.

1 Background

Vattenfall Stora Middelgrund Vind AB proposes establishing an offshore wind farm on the Swedish part of Stora Middelgrund, Kattegat. 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, as these effects are likely to dominate overall impact completely. This would change if alternatives to monopile foundations, such as gravity-based foundations, were selected for the current project. In that case, an updated assessment is required, which would include also the other construction activities besides installation of the foundations. An exception is the sediment resuspension that may occur during installation of cables in the seabed. Effects of such sediment spill on marine mammals is therefore also assessed in this report.

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, such as common dolphin, white-beaked dolphin and fin whale. These are not treated in this assessment.

The harbour porpoise is the most common Danish cetacean and is present throughout Danish waters. It is listed in annex II and IV of the EU Habitats Directive (92/43/EEC), annex II of the Bern convention, annex 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). Of these legislations, the EU Habitats Directive is currently the most important European legislative mechanism for addressing the conservation of wildlife and habitats. It 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. Since the harbour porpoise is listed in both appendix II and IV, it 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).

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

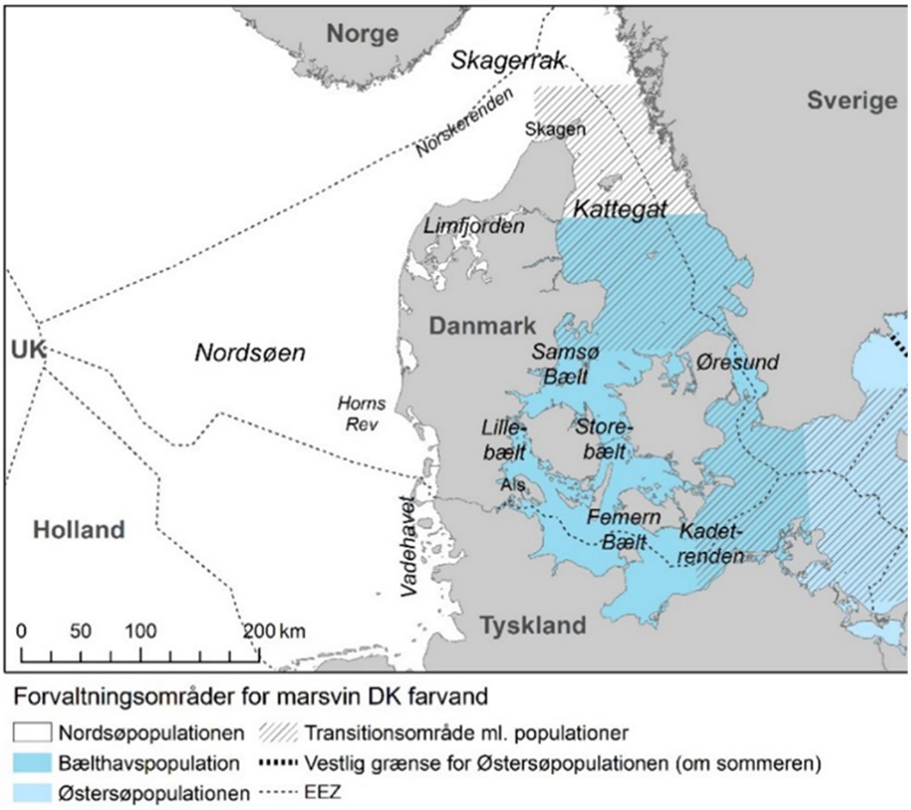


Figure 1.1. Map of management areas for the three populations of harbour porpoises. The North Sea population (white) overlaps with the Belt Seas population (dark blue) in southern Kattegat (hatched area).

The marine territories of Denmark and Sweden are inhabited by three different populations of harbour porpoises: The North Sea, Belt Sea and Baltic Proper population. Management units have been suggested for the Belt Sea population (Wiemann, et al. 2010; Galatius, et al. 2012; Sveegaard, et al. 2015) *(*Figure 1.1) and the Baltic Proper population (Carlén, et al. 2018). The population inhabiting the Stora Middelgrund area belongs to the Belt Sea Population. The management area of the Belt Sea population covers the Belt Sea, the Sound, southern Kattegat and the western Baltic Sea. 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 in these waters (Sveegaard, et al. 2011) and in Denmark Special Areas of Conservation have been appointed where the density is highest (Sveegaard, et al. 2011). One of these Natura 2000 sites, No.193, comprises a 2,094 ha area around Stora Middelgrund within Danish Waters (Figure 1.2). Two other Natura 2000 sites have been appointed for harbour porpoises nearby: Kims Top and the Chinese Wall and Anholt (please see figure 1.2), however these are waiting for approval by the EU.

Within the Swedish Waters a joint Natura 2000 site is appointed for harbour porpoises for Stora Middelgrund & Röde Bank(SE0510186). It is an area of 11,410 ha. To the southeast of here, there is a very large area 'Nordvästra Skånes havsområde' (SE0420360) of 134240.8 ha also appointed for harbour porpoises (Figure 1.2).

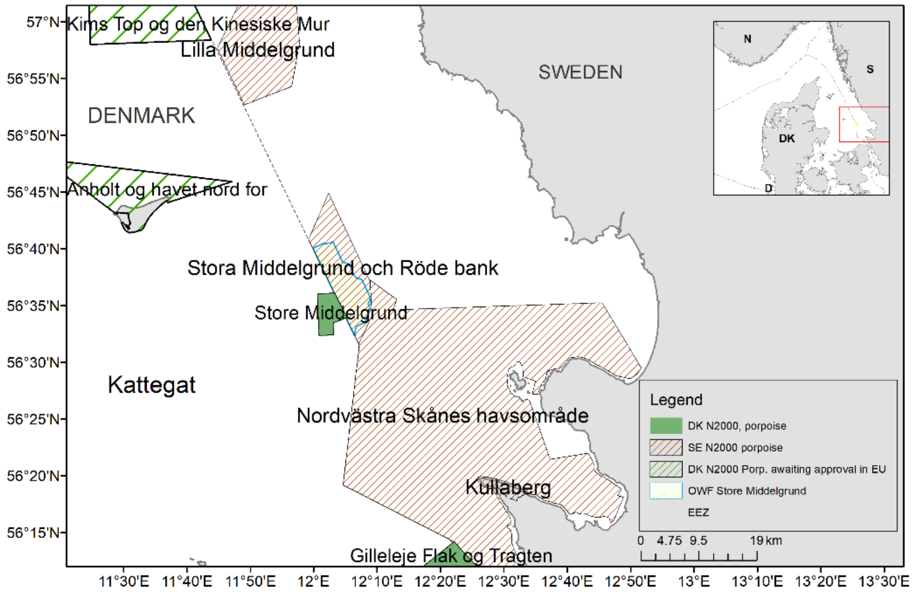


Figure 1.2. Map of Swedish and Danish Natura 2000 sites appointed for harbour porpoises near Stora Middelgrund. Another two N2000 areas have been appointed in Denmark for harbour porpoise, but are awaiting approval by the EU. The offshore wind farm is also shown with blue outline.

1.2.1 Distribution

The distribution of harbour porpoises is relatively well known in southern Kattegat, the Sound and Great Belt as the Belt Sea population has been surveyed with multiple methods during the last three decades. By 'well known' is meant that the overall importance of the area to porpoises is considered robust and suitable as a basis for this EIA. However, the temporal resolution of data from the actual wind farm area is coarse. The large-scale SCANS surveys I-III covered this area with aerial and boat-based surveys three times (Hammond, et al. 2002; Hammond, et al. 2013; Hammond, et al. 2017). Since the 1990-ties, multiple projects have equipped porpoises with satellite transmitters to inform about their distribution and movements (Synthesized by Edrén, et al. 2010; Sveegaard, et al. 2011; Sveegaard, et al. 2018) (Figure 1.3).

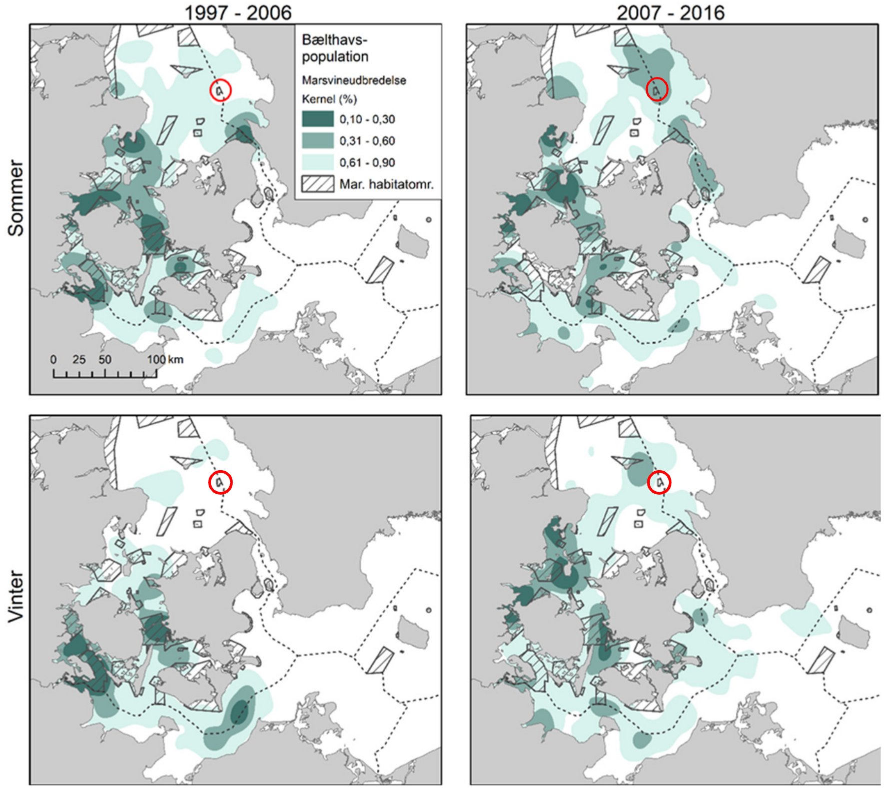


Figure 1.3. Distribution of satellite tracked harbour porpoises in the Belt Sea management area analysed as kernel densities (the darker the colour, the higher the density) in two ten-year periods in summer (April-September) and winter (October-March). The Kernel categories are defined as high (contains 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 Store Middelgrund Natura 2000 site can be seen close to the border to Sweden in red circle. 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), however Stora Middelgrund is not covered herein. In the light of increased bycatch near Stora Middelgrund a special study was conducted from February 2016 to January 2017 to examine when and where porpoises were present near Stora Middelgrund. The joint information from these different studies (except the study at Stora Middelgrund) was analysed by Sveegaard, et al. (2018), which led to an update of the MaxEnt habitat suitability model of preferred habitat for porpoises (Figure 1.5).

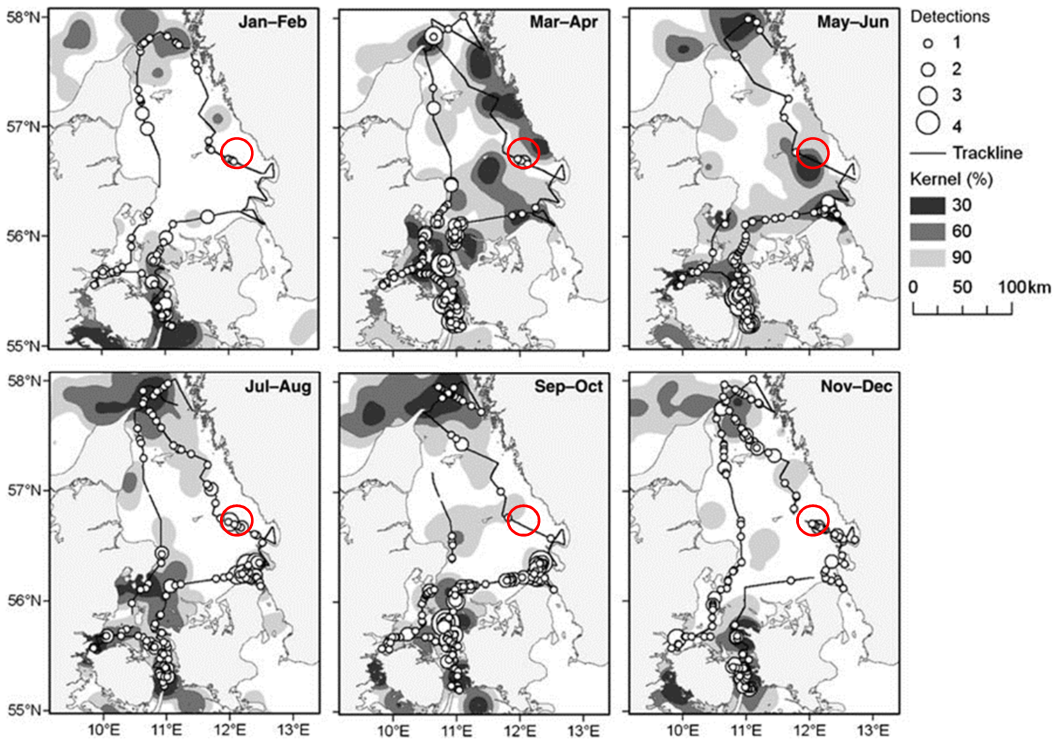


Figure 1.4. The distribution of detections of harbour porpoises (white dots) during six acoustic ship surveys conducted in 2007. The size of the dots corresponds to the number of detections per kilometre. The survey track line is shown in black. The underlying kernel-density, percentage-volume contours were generated from satellite-tracked 64 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 Stora Middelgrund 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.

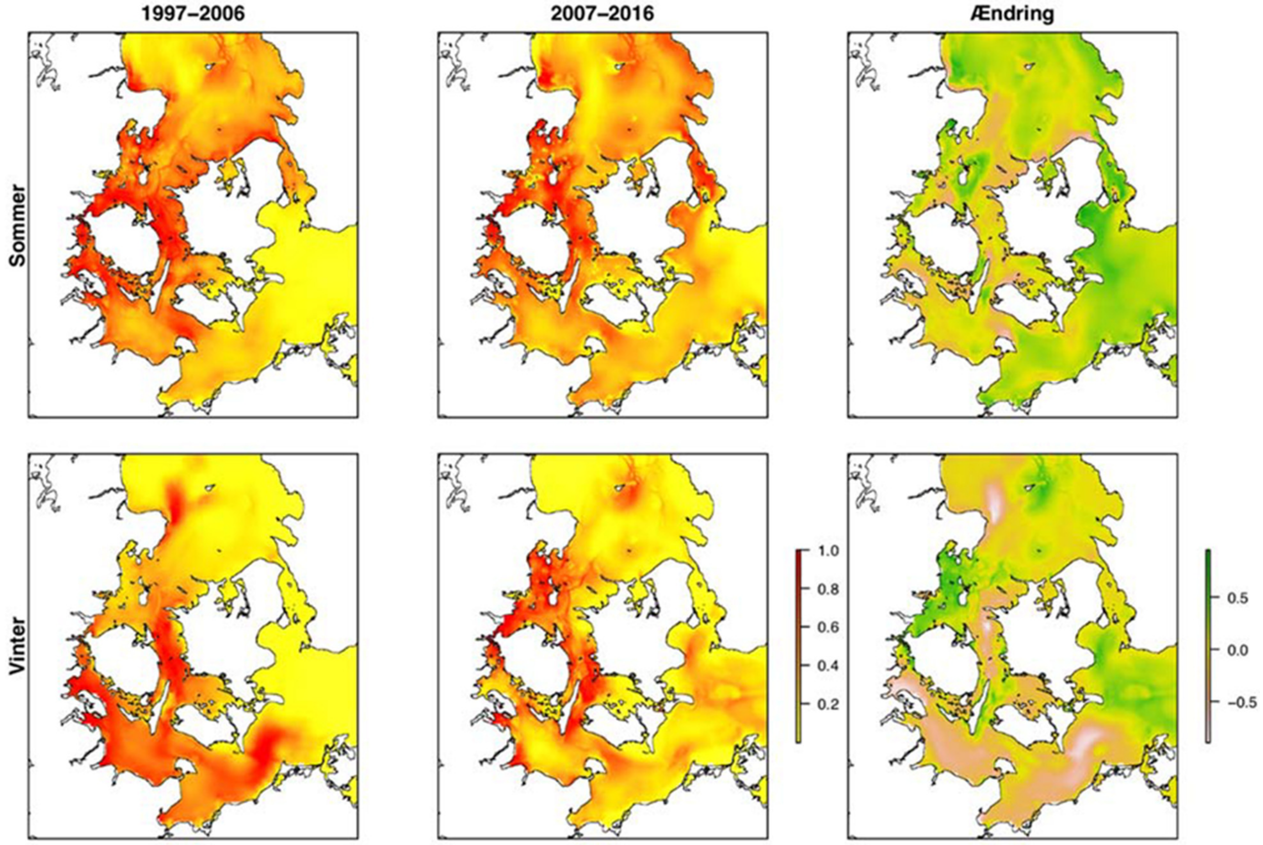
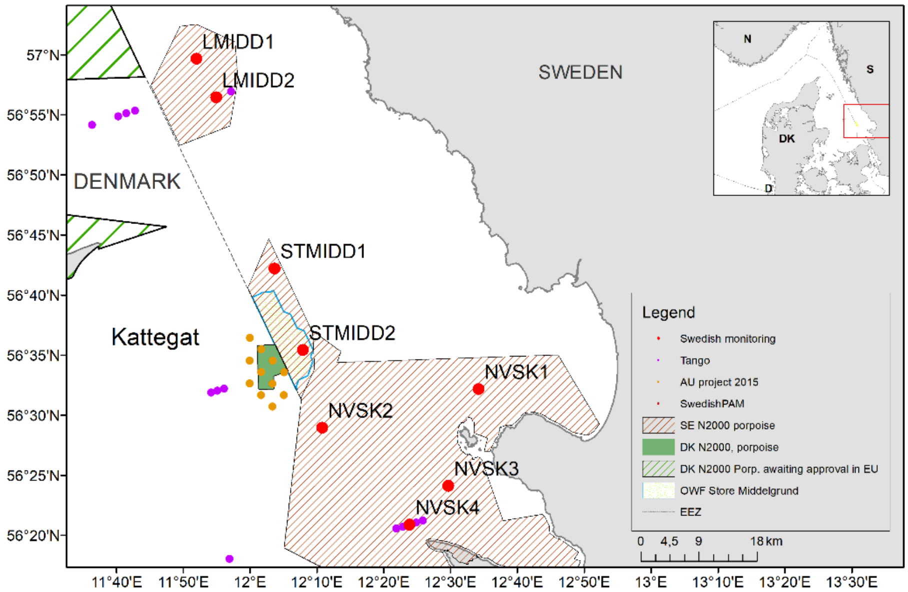


Figure 1.5. Suitable harbour porpoise habitats in the Belt Sea management area modelled with MaxEnt model for two 10-yr periods; summer and winter. Red signifies most suitable habitat. The right panel shows changes from the first to the second period, where green signifies the areas that have become 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. Figure and text from Sveegaard, et al. (2018).

In Sweden, passive acoustic monitoring of harbour porpoises in appointed Natura 2000 sites (Figure 1.2) began in spring 2019 and two stations are located near Stora Middelgrund reef (Figure 1.6) in the Swedish Stora Middelgrund Natura 2000 site. These data are public domain and have been included below. In general data from Denmark and Sweden points to Stora Middelgrund reef being an area of high density of harbour porpoises confirmed by both visual and acoustic surveys (Sveegaard, et al. 2011; Sveegaard, et al. 2018), as well as by passive acoustic monitoring in dedicated studies at the Stora Middelgrund reef in Denmark (Sveegaard, et al. 2017) (Figure 1.7).

Figure 1.6. Map of present and previous PAM stations near the proposed Stora Middelgrund off-shore wind farm. Presently there is one Swedish monitoring station within the wind farm area active from 2019. TANGO stations running from 2019-2021 is a joint Danish/Swedish study. Eleven Danish PAM locations were active in 2015 (Sveegaard, et al. 2017).



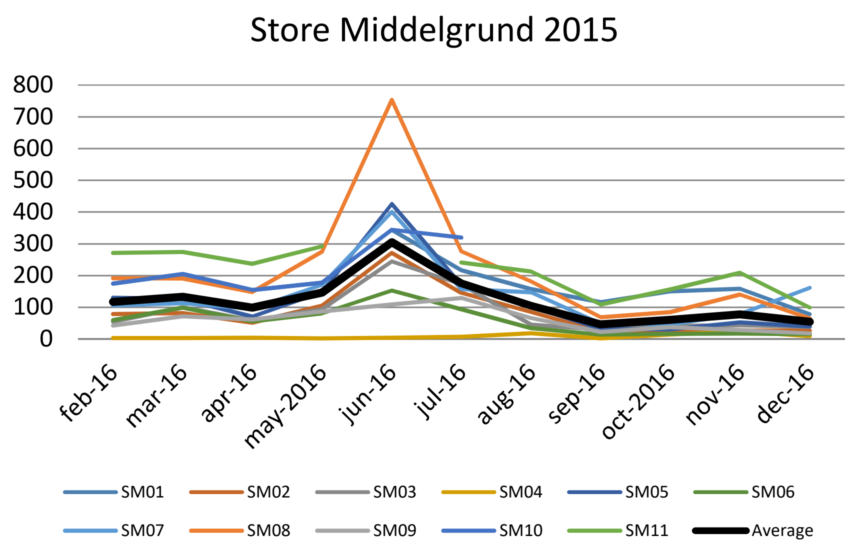
1.2.2 Yearly pattern in presence at Stora Middelgrund

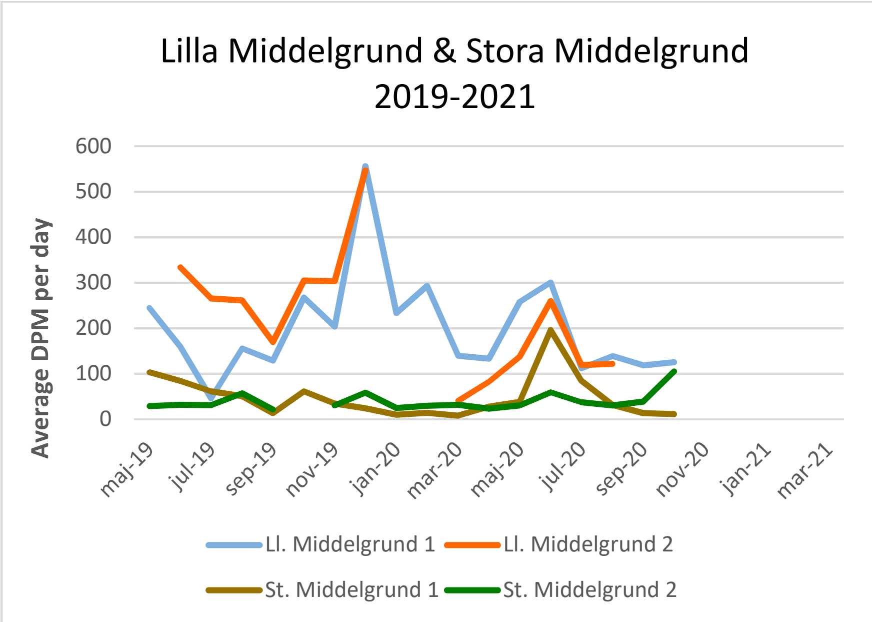
Harbour porpoises move around throughout the year and their temporal presence and abundance is important to consider in relation to establishment of an offshore Windfarm such as at Stora Middelgrund. Porpoise calves are entirely dependent on their mother during their first ten months of life, where they are nursed and slowly learn to forage independently (Lockyer 2003; Teilmann, et al. 2007, Camphuysen and Kropp 2011). 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 these waters, which is interpreted as the period where calves from the previous year begin to separate form their mother and, naïve as they are, therefore are especially prone to end as 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.

There are three independent studies providing data on yearly presence of harbour porpoises at Stora Middelgrund. 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 Stora Middelgrund being most important for harbour porpoises during summer months.

- In 2007 towed acoustic array data was collected close to Stora Middelgrund (see the red circles of Figure 1.4) every second month (Figure 1.4) (Sveegaard, et al. 2011). The data showed several peaks in presence at St. Middelgrund: 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 / at Stora Middelgrund during the summer period. However, it should be kept in mind that the resolution of the method is not very high, and it is therefore not possible to resolve detailed distribution of porpoises on and around Stora Middelgrund.
- Aarhus University conducted a study at the Danish 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 1.7) (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 was also modelled against a suit of environmental variables to test, which described porpoise presence best. The modelling was based on the PAM data and it did not identify a single or a few parameters as more important. Model examples of four different months are shown in Figure 1.88. 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 Swedish Stora Middelgrund & Röde BankNatura 2000 site (Figure 1.6) since spring 2019 (Figure 1.7). There is a small peak in presence during June-July at the two stations at Stora Middelgrund. Generally, the mean number of detection positive minutes per month were up to tenfold as high on some of the Danish monitoring stations on Store Middelgrund, as on the Swedish part covered (Figure 1.7). The reason for this is unclear and may relate to underlying factors affecting porpoise presence such as distribution of prey in the covered years or some physical differences between the covered sites affecting the presence of suitable prey. The huge variance between the eleven monitored stations points to the latter. The data was analysed in the exact same fashion and all dataloggers had been recently calibrated. Looking at all the Swedish monitoring stations in Kattegat (Figure 1.9), the average number of detection positive minutes was higher at stations closer to the coast than at Stora Middelgrund.

Figure 1.7. Detection positive minutes per month for PAM stations at or near Stora Middelgrund offshore wind farm area. **Top**: Danish data from a project conducted in 2016 at Store Middelgrund. **Bottom**: Swedish data collected in 2019 at three monitoring stations located within/near the Swedish Natura 2000 site Stora Middelgrund & Röde Bank(See figure 1.6). Notice that number of minutes with porpoises per day vary a lot between the Danish and Swedish part of Stora/Store Middelgrund. The Swedish Stations have only been monitored since Spring 2019. Data made available from Havs- and Vattenmyndigheden All available Swedish monitoring data downloaded from Sharkweb.





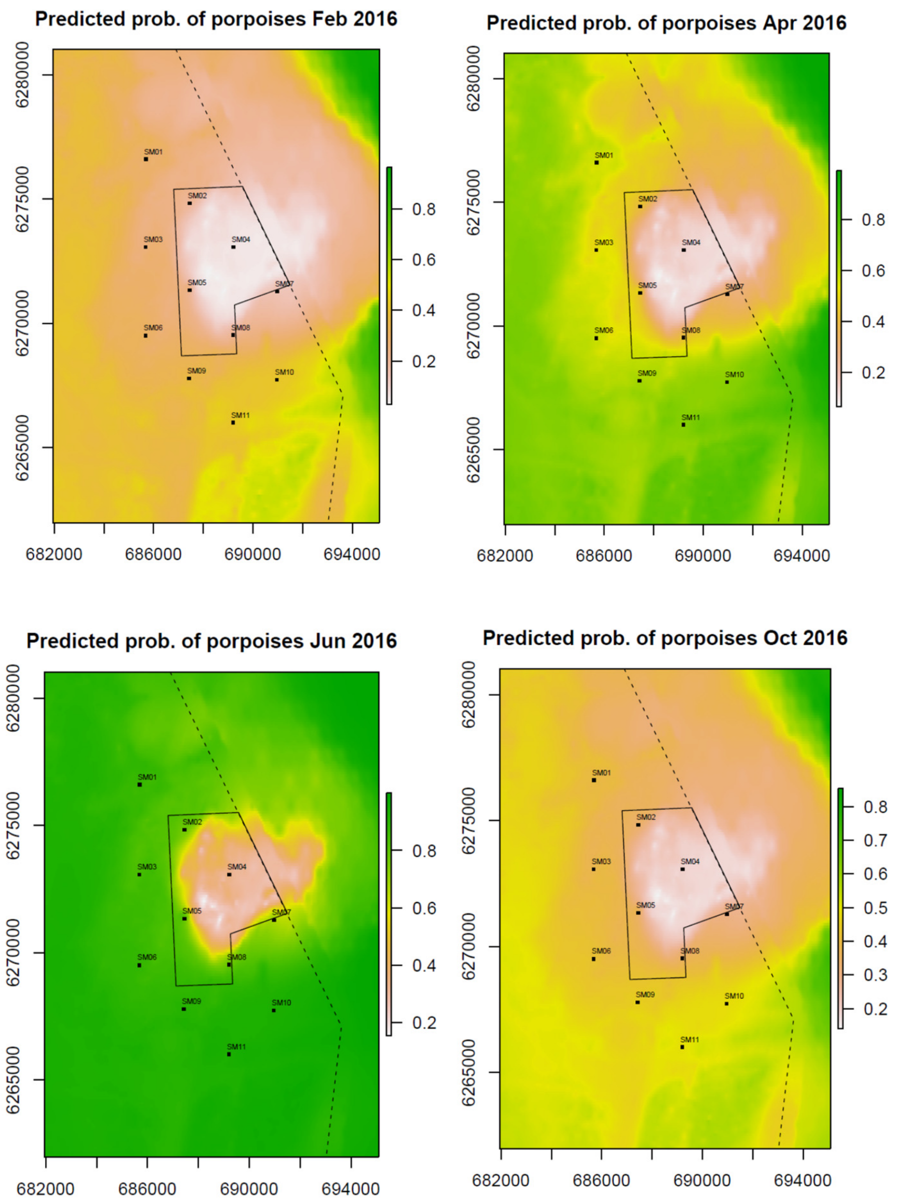
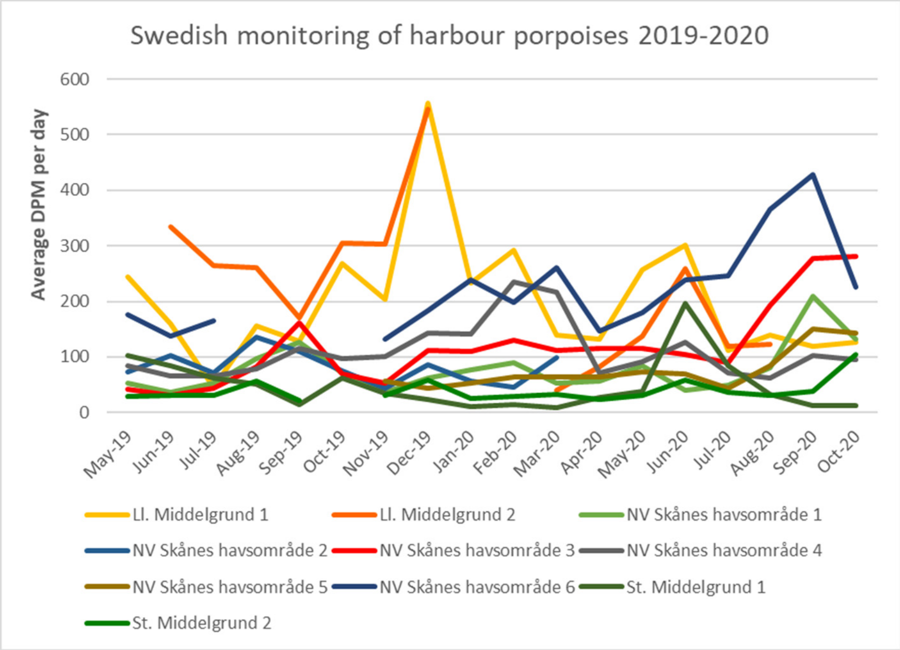


Figure 1.8. Results of a local habitat suitability model for harbour porpoises at Stora Middelgrund during four different months. Green is highest probability of porpoise presence and white is lowest. June is the month with highest probability of presence over the study year 2016. The model included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

Figure 1.9. Mean number of Detection Positive Minutes per month at all Swedish monitoring stations relatively close to Stora Middelgrund. The two Stora Middelgrund stations are shown in dark green. Monitoring began in spring 2019. See station positions in figure 1.6. Data made available from Havs- and Vattenmyndigheden All available Swedish monitoring data downloaded from Sharkweb.



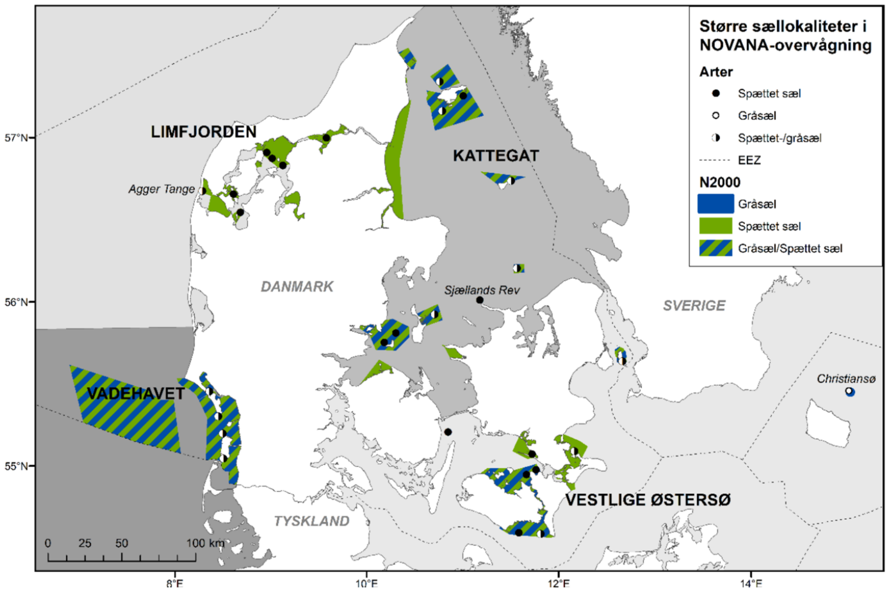
1.2.3 Conclusion on seasonal presence and vulnerability

In conclusion from the above: Three independent studies show that the Stora Middelgrund reef is important for harbour porpoises especially during summer months May to August, overlapping entirely with the calving period. However, due to breeding season and nursing behaviour, porpoises are considered vulnerable to disturbances all year.

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 in both Sweden and Denmark (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). Hunting has been abandoned since 1976 (Jepsen 2005), although a limited number of licences for regulation due to conflicts with fisheries are given annually with app. 30-40 harbour seals shot per year. Seal hunting is allowed in Sweden with permission from the Swedish Environmental Protection Agency (Naturvårdsverket). Special areas of conservation have been appointed for the protection of the harbour seal in Denmark and Sweden (Figure 1.10). Several important Danish haul out sites, also outside Natura 2000 areas, are further protected from any disturbance (some only during the breeding and moulting seasons) as national wildlife 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 Stora Middelgrund belong, is shared with Sweden. In 2018 it was estimated to consist of 6300 individuals in the Danish part of Kattegat alone (Hansen and Høgslund 2019).



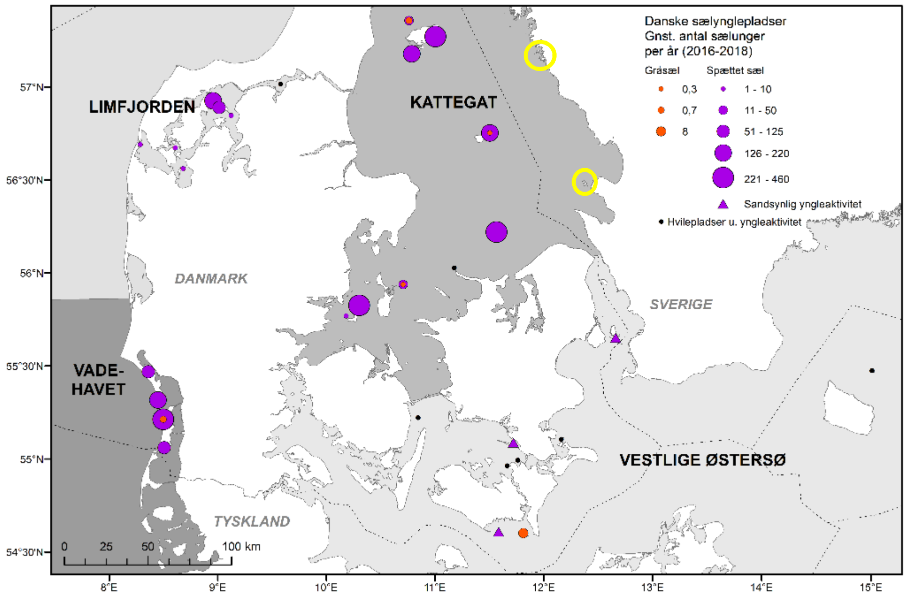


Figure 1.10. Top: Map of Natura 2000 sites appointed for harbour and grey seals. The grey colours signify the four management areas for harbour seals. Bottom: Map of breeding sites in Danish Waters. Number of pups (average over three years, 2016-2018) is shown as purple circles. There are two relevant 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 and around the Stora Middelgrund reef. These data were used to build a habitat suitability model based on environmental variables and location and size of haul out sites (please see https://niva.brage.unit.no/niva-xmlui/handle/11250/2678968). The output of the model is shown in Figure 1.11 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 built almost entirely on yearlings and sub adult seals, which means that it may not be truly representative for adult seals. From the data, however, it appears very likely that harbour seals spent significant time at or near Stora Middelgrund reef.

1.3.2 Yearly pattern in presence at Stora Middelgrund

The data from Anholt collected in 2005, 2006 and 2008 (Dietz, et al. 2012) and in 2014 (not published) was all from 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 summer months. The information about distribution of harbour seals is not extensive and assessments relying on fine-scale patterns in the distribution maps should be interpreted with caution. This applies even more to the temporal trends in abundance, where the important breeding period in summer is largely absent from the data.

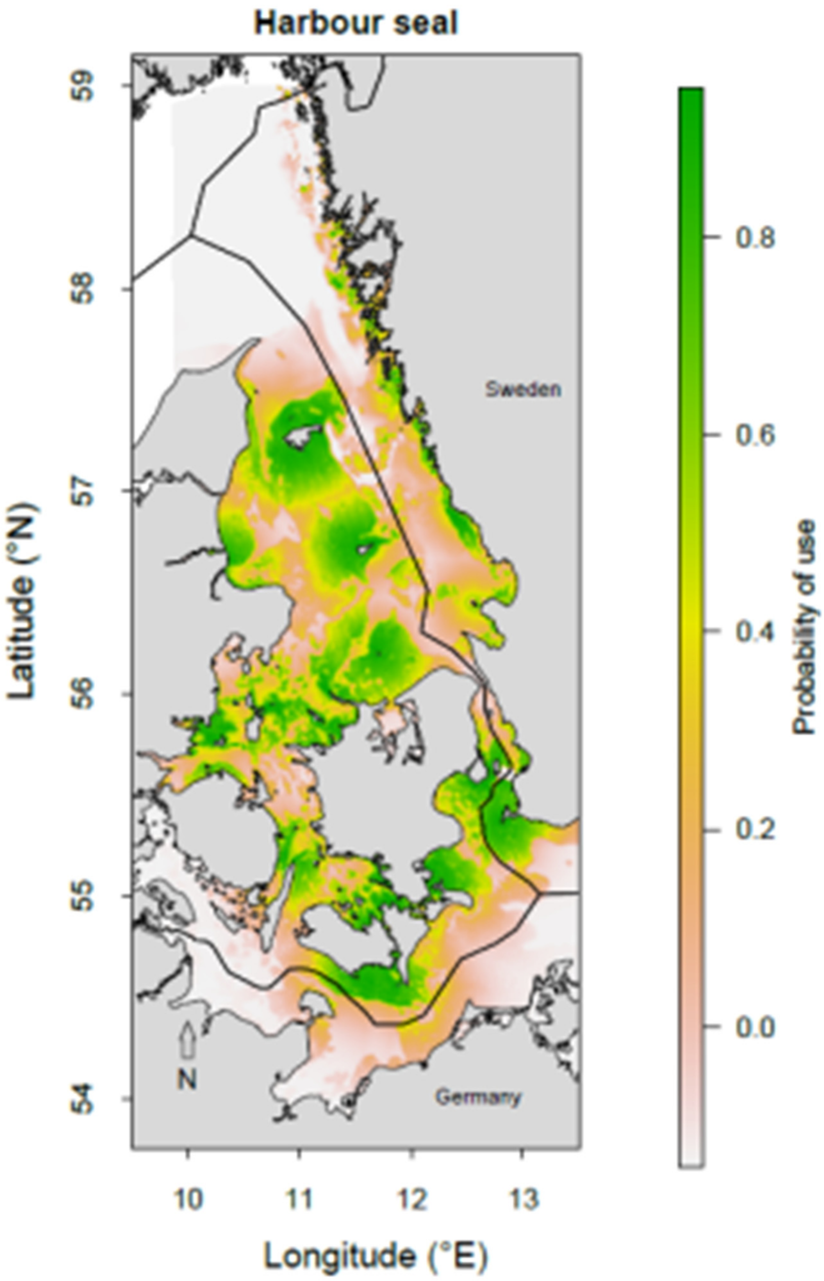


Figure 1.11. Habitat suitability for harbour seals modelled from satellite tracked harbour seals tagged at Anholt (Dietz, et al. 2012) and Rødsand. High suitability means high likelihood of encountering seals when the seal population is healthy. Modelling performed by Floris van Beest (Aarhus University). Unpublished.

1.3.3 Conclusion on seasonal presence and vulnerability

There is too little data and from too few age classes of harbour seals to judge the temporal importance of Stora Middelgrund reef. Harbour seals are 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 at Stora Middelgrund, harbour seals are considered equally vulnerable to disturbances from underwater noise throughout the year.

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

The grey seal was exterminated from Danish and West Swedish waters in the beginning of the 20th century by hunting. The population is now increasing, but only for immigrating adults. A very small number of grey seal pups are born in Danish Waters inside Skagen, with hardly any reported from Kattegat: Since surveillance began in 2011: Six born at Borfeld near Læsø, three at Anholt and one born at Bosserne near Samsø.

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). Hunting was abolished in Denmark in 1976 and Denmark mainly near Bornholm, 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. 40 grey seals may be shot per year in Denmark (Jepsen 2005), mainly near Bornholm, but few are also shot around Zealand. Grey seal hunting is allowed in Sweden with permission from the Swedish Environmental Protection Agency (Naturvårdsverket) and several hundred seals are shoot per year in the Baltic proper. Special areas of conservation have been appointed for the protection of the grey seal in Denmark and Sweden. As for harbour seals, a number of grey seal haul sites are further protected as national wildlife reserves.

1.4.1 Distribution

No data exist on grey seal distribution in Kattegat, except for presence at the haul-out sites. In Kattegat, the population is increasing (but 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 at Stora Middelgrund

There is not enough data to evaluate the importance of Stora Middelgrund 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 Stora Middelgrund reef. Grey seals are 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 at Stora Middelgrund reef, grey seals are considered equally vulnerable to disturbances from underwater noise throughout the year.

1.5 Other marine mammal species

Fin whale, humpback whale, white-beaked dolphin, common dolphin, striped dolphin and bottlenose dolphin are occasionally observed in Kattegat. 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

Sweden has appointed numerous Natura 2000 sites for harbour porpoises, harbour and grey seals (Figure 1.2 and Table 1.1) relevant for Stora Middelgrund offshore wind farm. Stora Middelgrund & Röde Bank(SE0510186) (Natura 2000 site, in which Stora Middelgrund offshore wind farm is projected) and the large area to the southeast of here, the Northwestern Marine Area of Skåne (Nordvästra Skånes havsområde, SE0420360) are the closest Natura 2000 sites. To the north are Lille Middelgrund (SE0510126) and Fladen (SE0510127) N2000 sites.

Within Danish Waters, the closest Natura 2000 site appointed for harbour porpoises is at Stora Middelgrund (#169) and to the south Gilleleje Flak and the Sound (# 171). Two new Natura 2000 areas have been appointed nearby, "Anholt and the sea north heroff" 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 1.2).

Table 1.1. List of Natura 2000 areas in Swedish and Danish Waters in Kattegat. Notice that the area "Anholt and sea to the north" is not yet confirmed by the EU.

Natura 2000 sites	Distance to wind farm	Designation species
Stora Middelgrund och Röda Bank	0 km	Harbour porpoise
Store Middelgrund, DK	0 km	Harbour porpoise
Nordvästra Skånes havsområde	0 km	Harbour porpoise, grey and harbour seals
Anholt and sea	18 km	Harbour porpoise
Lilla Middelgrund	26 km	Harbour porpoise
Gilleleje Flak og Tragten	38 km	Harbour porpoise
Balgö	49 km	Harbour porpoise, grey and harbour seals
Fladen	50 km	Harbour porpoise

The suggested Stora Middelgrund offshore windfarm site is placed within the Swedish Natura 2000 site Stora Middelgrund & Röda Bank. This area is characterized by typical banks of southern Kattegat. It consists of two banks made of 'gravel, sand, shell gravel, mussel beds and finer fractions where some fields of stones and ridges of boulderstone is spread over the banks'. The area is diverse and so are the fish and invertebrate fauna living there. The area is an important spawning ground as well as it is important for growing fish for most of the fish species found in Kattegat. It holds a diverse fauna of invertebrates. Especially important are its mussel beds consisting of *Modiolus modiolus (*https://skyddadnatur.naturvardsverket.se/*)*.

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. This background is provided 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

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

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

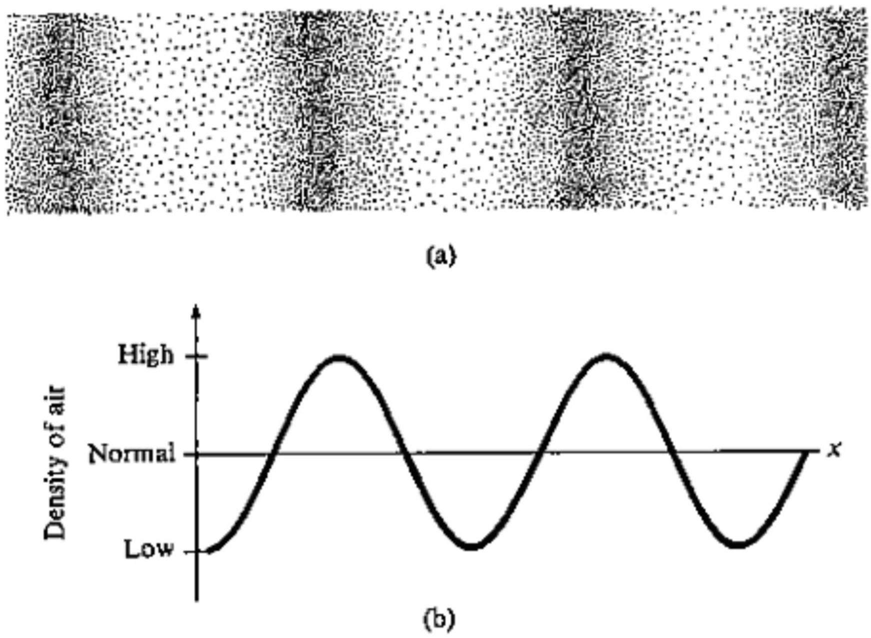


Figure 2.1. Illustration of the air density in a propagating sound wave The line marked 'normal' corresponds to the ambient (barometric) pressure of the surrounding air or water.

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]:

Equation 2.2

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

[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.

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. 1µPa^{2}s. 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 / m^2 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 µPa^{2}s) 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 µPa^2 / 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

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

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

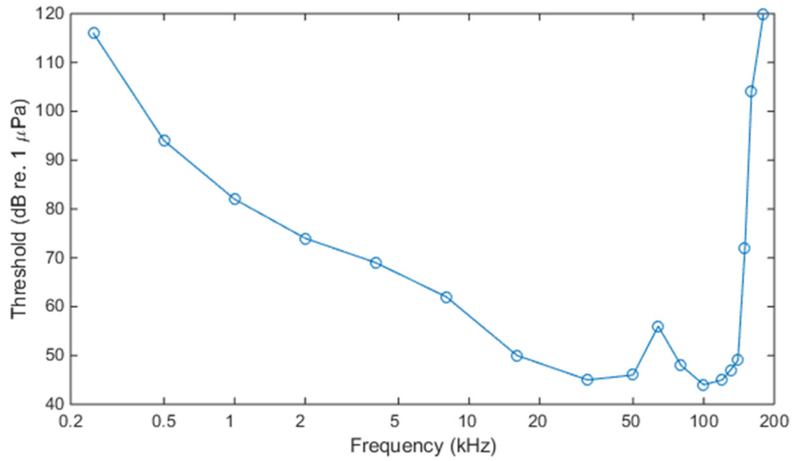
Marine mammals rely heavily on underwater hearing for orientation, prey capture and communication underwater. Consequently, they have very good underwater hearing and are sensitive to noise, as a disturbing factor and, if sufficiently loud, also by directly inflicting injury to the animals. The most 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.

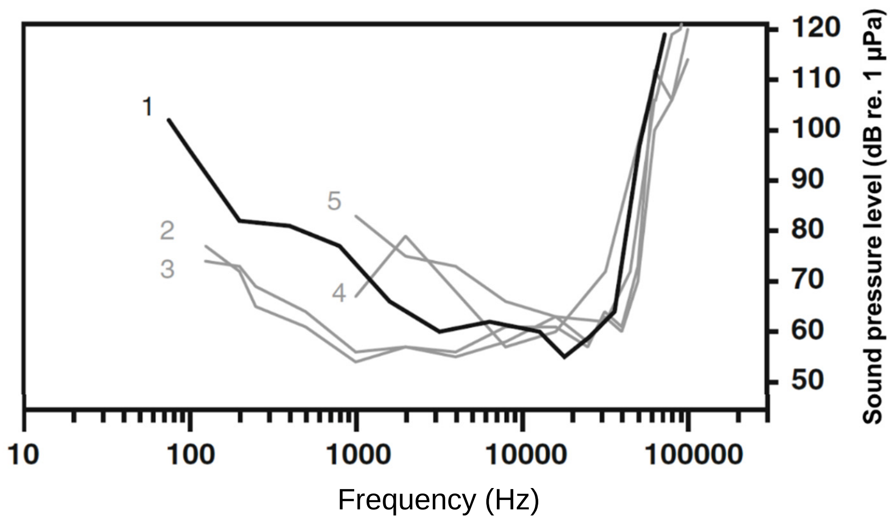
Figure 2.2. Audiogram for harbour porpoise, adapted from Kastelein, Hoek, de Jong, et al. (2010). The audiogram shows the hearing threshold, i.e. the minimum audible level as a function of frequency. Best sensitivity (lowest threshold) is in the range 10-160 kHz.



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 pile driving, not considered relevant in 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).

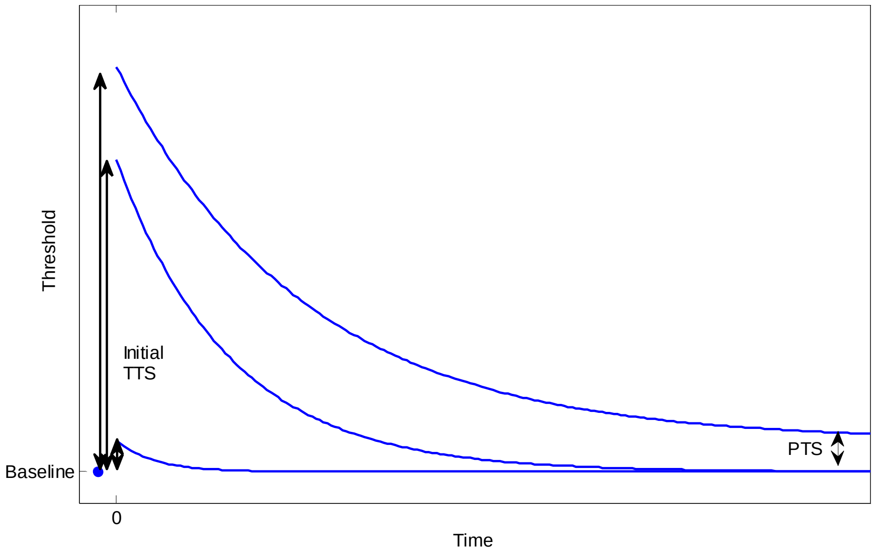
3.3 Noise induced hearing loss

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.

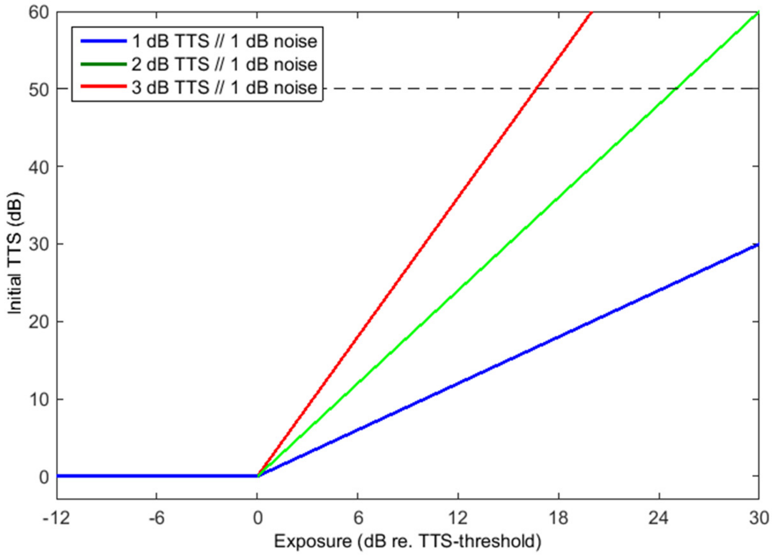


Figure 3.2. Schematic illustration of the growth of initial TTS with increasing noise exposure. Three different slopes are indicated. Note that the real curves are not necessarily linear. Broken line indicate threshold for inducing PTS, assumed in this figure to be at 50 dB initial TTS. From Skjellerup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

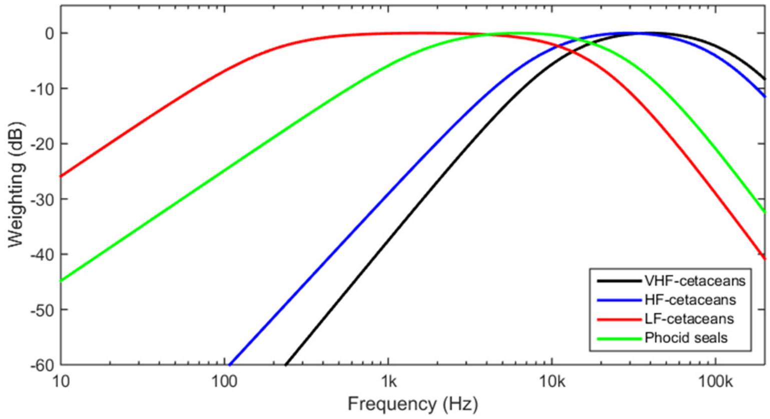


Figure 3.3. Frequency weighting curves proposed by National Marine Fisheries Service (2016) and Southall, et al. (2019).

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.

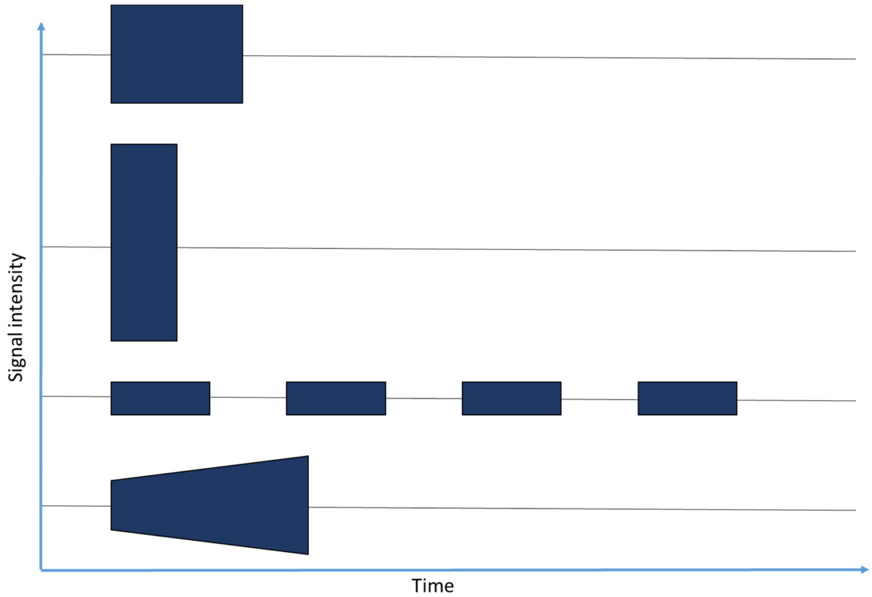


Figure 3.4. The equal energy hypothesis implies that all four examples of signals shown to the right have the same ability to induce TTS, as they are of equal energy (the areas of the four signals are the same).

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.

3.3.5 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

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

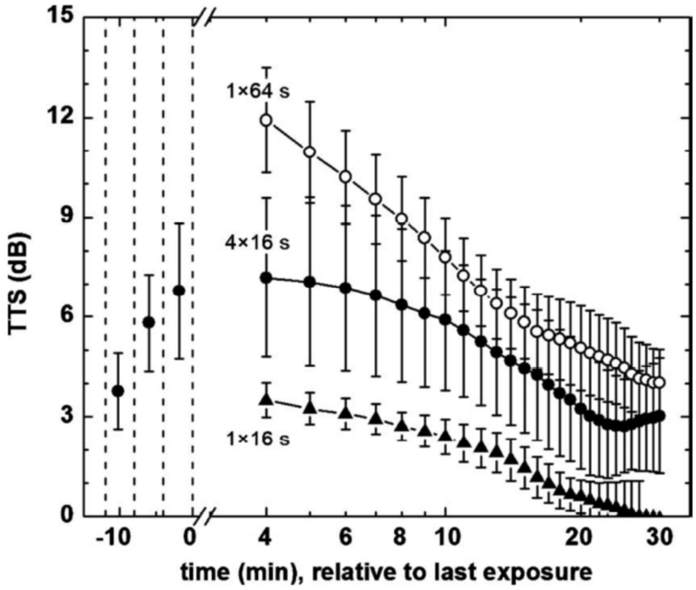
dolphins and beluga whales. This has changed dramatically and harbour porpoise is now one of the best-studied species when it comes to TTS. See Finneran (2015) and Tougaard, et al. (2015) for recent reviews.

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 μPa^2s (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 μPa^2s, 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 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.

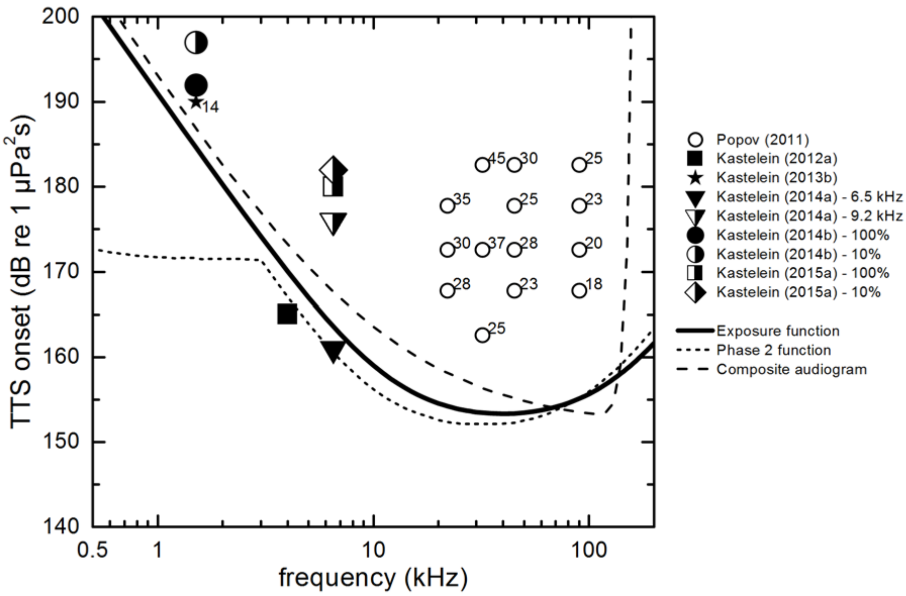
[4] There is some variation in this threshold, depending on authors and values between 152 and 155 can be found in different sources. The variation is due to different definitions of TTS-threshold, ranging from lowest level where a threshold elevation, no matter how small, can be reliably detected, to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

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.

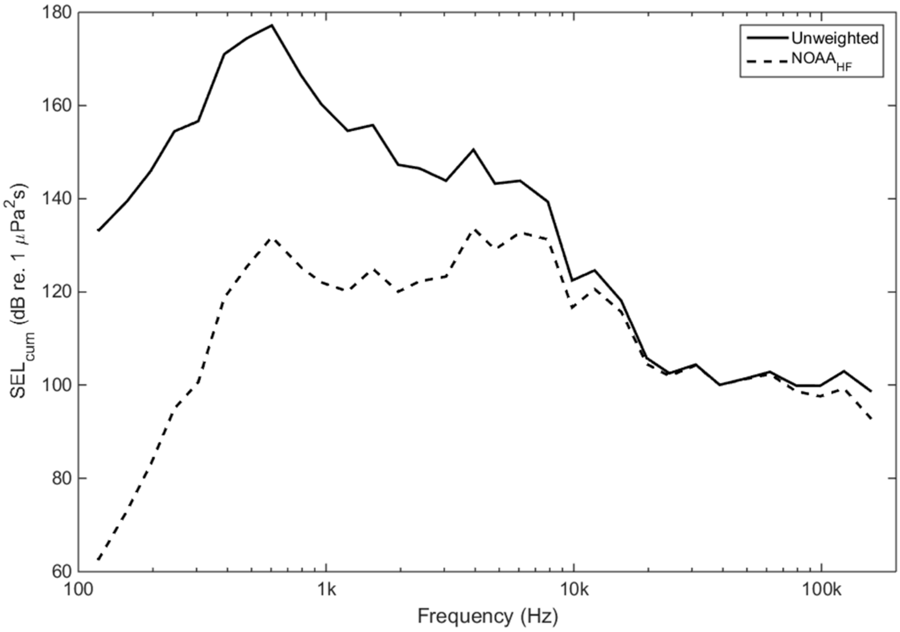


Figure 3.7. Third-octave spectrum of the stimulus used by Kastelein, et al. (2015), adjusted to a total SELcum of 180 dB re. 1 µPa²s (solid line) and the same spectrum weighted with the HF-cetacean weighting function of National Marine Fisheries Service (2016). Modified from Tougaard and Dähne (2017).

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

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 s tone at 4.1 kHz at a total SEL of 202 dB re. 1 µPa²s. 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 µPa²s (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.

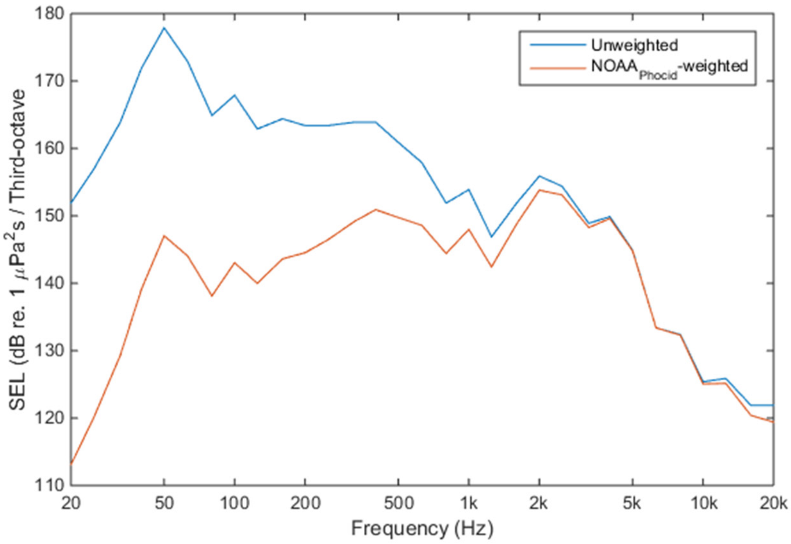
Table 3.2. Weighted thresholds for TTS and PTS in phocid seals. From National Marine Fisheries Service (2016).

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 µPa²s (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 $\text{NOAA}_{\text{phocid}}$-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).

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.

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).



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).

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.

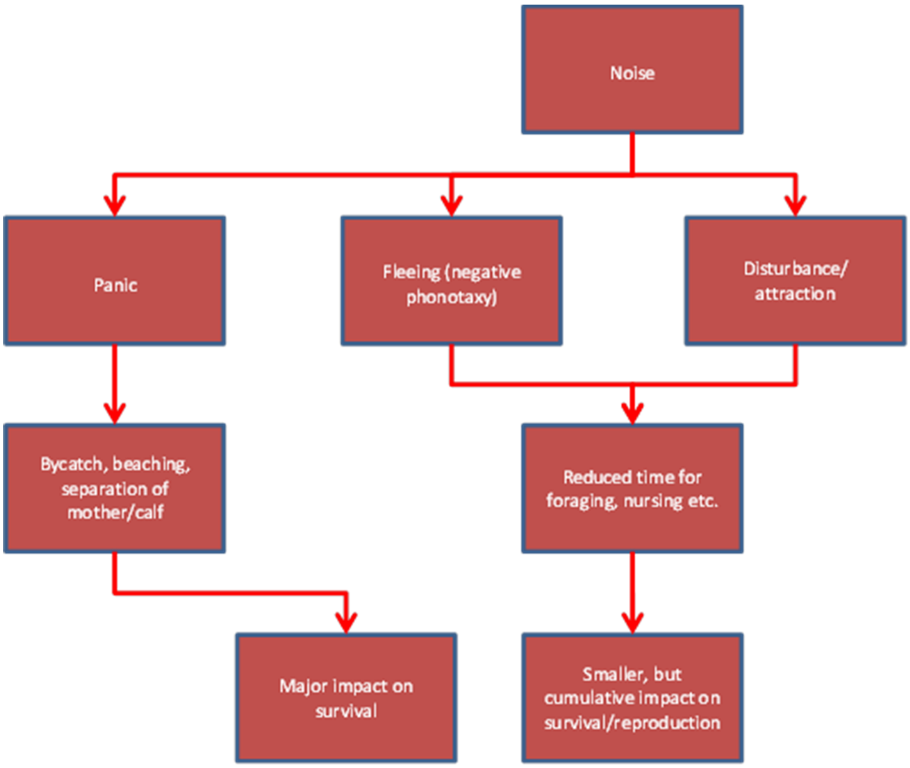


Figure 3.9. Schematic illustration of mechanisms by which noise-induced changes to behaviour can lead to effects on short-term and long-term survival and reproduction (fitness) in marine mammals. From Skjellerup et al. (2015).

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. 2011; 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.

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. 2011; 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 μPa^2s, 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).

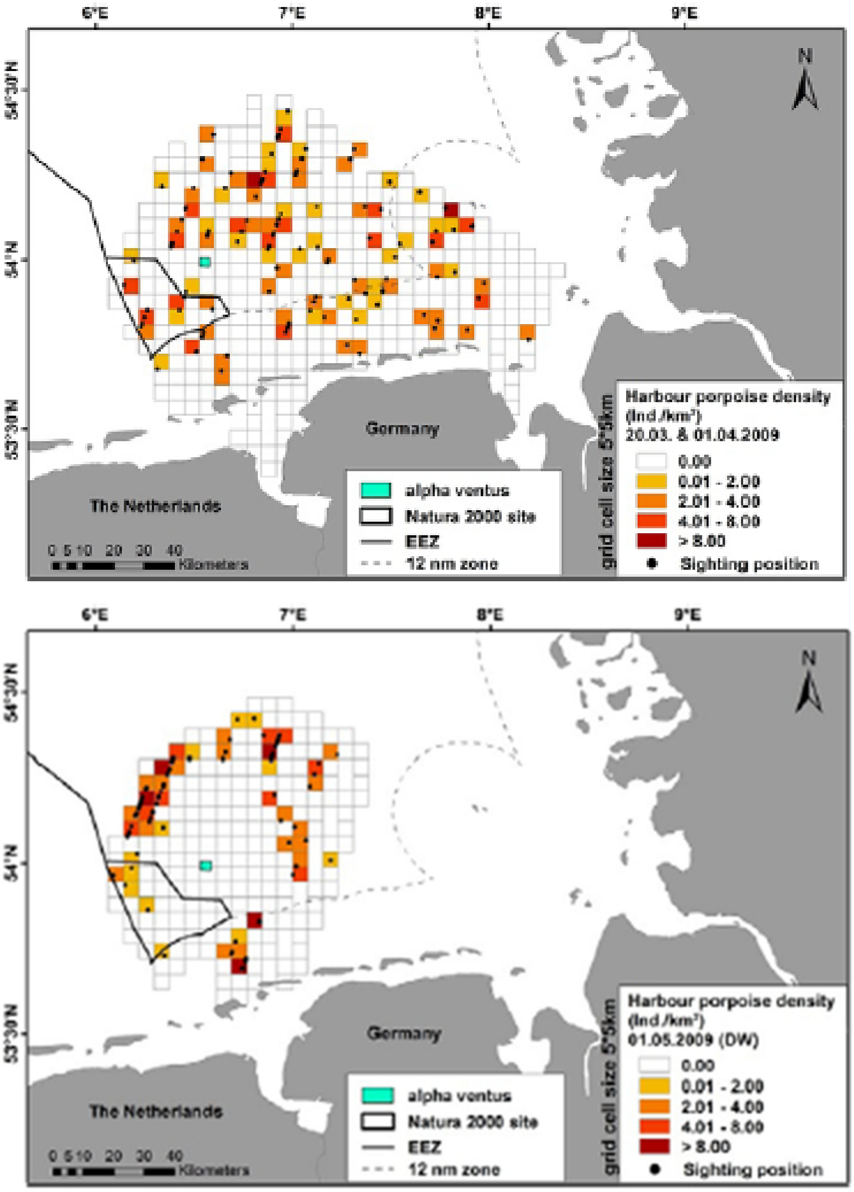


Figure 3.10. Porpoises observed from aerial survey before (top) and during (bottom) pile driving at the German offshore wind farm Alpha Ventus. The blue square indicates the position of pile driving operation. From Dähne, et al. (2013).

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 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

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

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 1.11), 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 4, 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

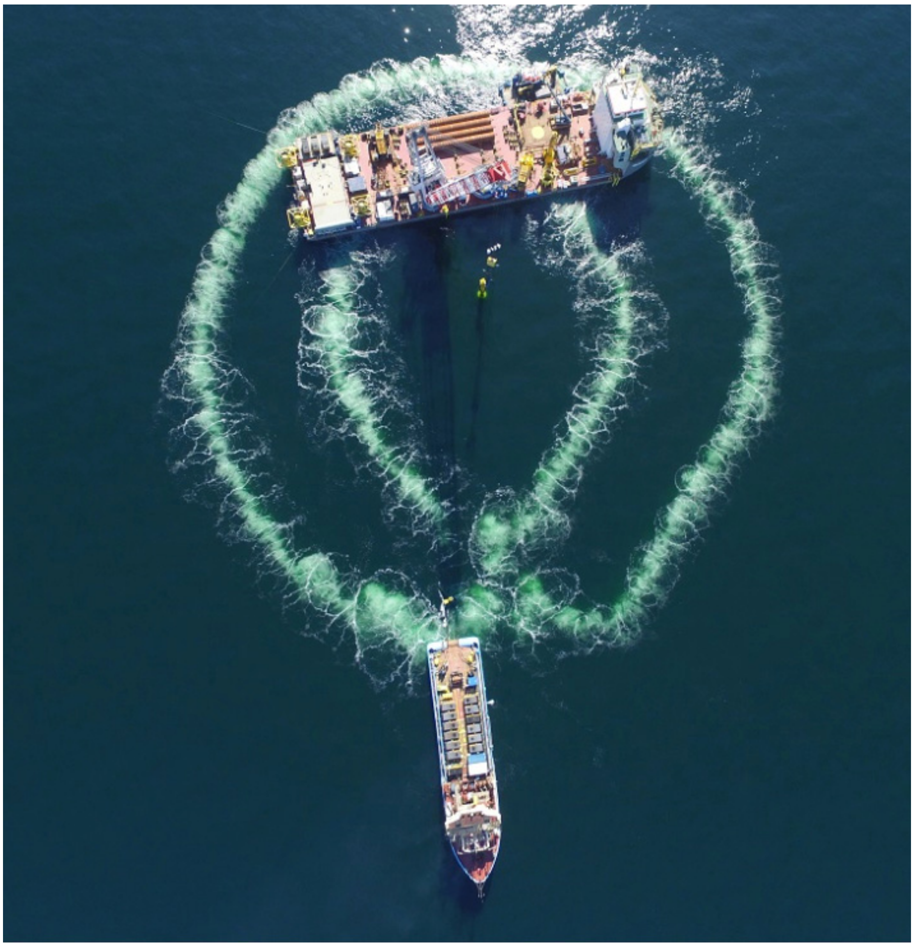


Figure 3.11. Example of active bubble curtain (double Big Bubble Curtain) deployed around the jack-up platform used for pile driving. Air bubbles are visible in the surface as the white ring. The ship in the front is used for deployment and recovery of the hose system and contains the very large compressors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

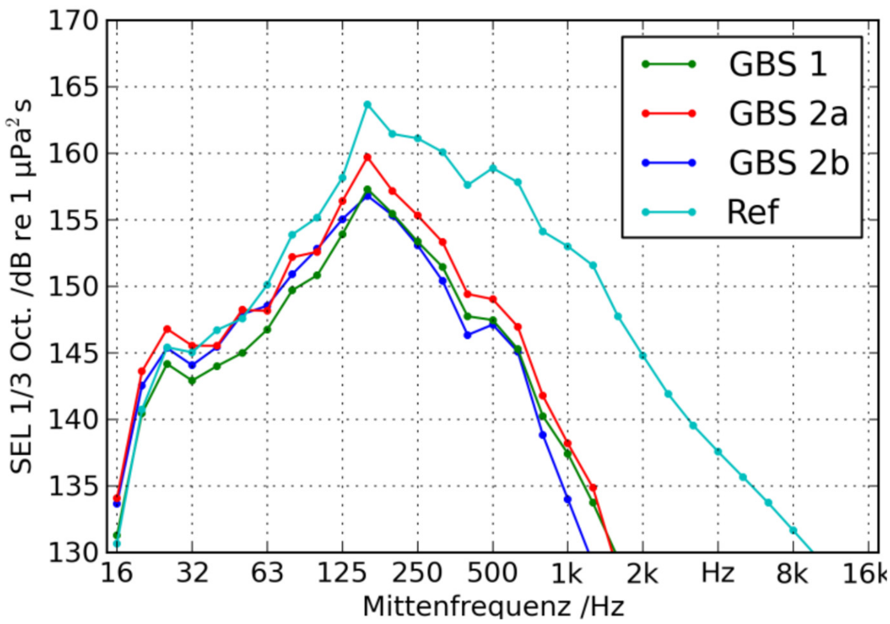


Figure 3.12. Median third-octave band spectra of pile driving noise measured 750 m from pile driving at the GlobalTech 1 offshore wind farm (tripod foundations). Spectra are shown without bubble curtain (Ref) and three different configurations of the bubble curtain. From Nehls and Bellmann (2016).

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.

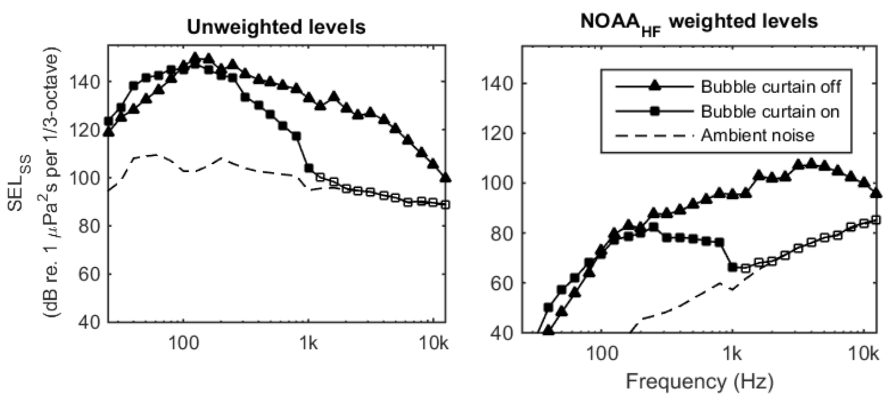


Figure 3.13. Effect of applying the VHF-cetacean weighting curve of Southall, et al. (2019), which is identical to NOAA$_{HF}$ (National Marine Fisheries Service 2016), to spectra of pile driving noise (6 m diameter monopile) with and without a double bubble curtain. Open symbols indicate levels dominated 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.

4 Assessment methodology and criteria

This assessment evaluates impact on the two largest populations of marine mammals in the area: harbour 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, however always with the use of present best available technology noise abatement (Hydro sound Dampeners + Double Big Bubble Curtains):

- Worst sound propagation conditions (bathymetry and hydrography)
- Worst location of foundation, based on sound propagation conditions in relation to Natura 2000 areas
- Worst case foundation type and installation procedure (hammer energy and number of strikes required to complete piling)

Additional construction scenarios are included. These are identical to the worst-case scenario, except that construction is done under more favourable sound transmission conditions, in more favourable positions, or both. The combined scenario is included as an example of the best environmental practise and best available technology for reducing impact of pile driving. As an alternative to pile driving, 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.

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 (few days), but insignificant impact on individual animals, no long-term consequences for the population.
Minor	Possible short-term duration of impact, with 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 with disturbance of significant part of available habitat. 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 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 population 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 population of harbour porpoises in the Baltic Proper. Here, any impact on an animal considered to have significant impact on the survival and reproductive success of that individual, must be considered a significant impact on the population as a whole.

Criteria and assessment methodology for the four different types of impacts are 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. Intuitively, as PTS is graded, there should be a lower level, below which the hearing loss is so small that it is without long-term consequences for the animal. This is supported by the observation that also dolphins seem to experience natural, age-related hearing loss (presybycusis; Ridgway and Carder 1997; Houser and Finneran 2006; Li, et al. 2013). Large hearing losses, however, will inevitably affect the ability of the animal to carry out its normal range of behaviours and hence cause a decrease in fitness. Although this may not directly lead to the death of the individual, it may reduce the life span and reproductive success of the animal.

TTS and PTS primarily affects hearing around and immediately above the frequency range of the fatiguing noise. In a study with playback of pile driving sounds to harbour porpoises, the TTS developed at 4 kHz and 8 kHz, but not at 16 kHz or 128 kHz (Kastelein, et al. 2015). 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), the impact of permanent low-frequency hearing loss could potentially be larger in seals than in porpoises.

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. The overall effect of inducing small amounts of TTS in porpoises as a consequence of pile driving is thus assessed to be insignificant for the long-term survival and reproduction of the animal, and thus in turn also without any effects at the level of the population. 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 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. Thus, noise exposure resulting in less than 40 dB of TTS is considered to have insignificant consequences for the survival, reproduction and energetic budget of both porpoises and seals. 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. In line with recommendations of 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 the onset of more than one occasion. It could happen, but with very low likelihood. 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), 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 µPa^{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 with and without the use of noise abatement techniques.

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.

Table 4.3. Criteria for assessing intensity of behavioural disturbance from pile driving noise.

Impact magnitude	Criteria/conditions
Negligible	Number of animals affected is insignificant and/or disturbances very short (such as startle responses), without any significant effect on the time budget of animals. The total impact on the habitat is therefore insignificant.
Minor	Disturbance of small parts of the available habitat over short periods, unlikely to affect the available habitat and hence energy budget of animals significantly.
Moderate	Significant disturbance of considerable parts of the available habitat and/or over extended time periods, effectively reducing the available habitat and hence 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 4.1. 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
Insignificant	Lack of overlap in frequency between masking noise and sounds potentially masked and/or noise only rarely above natural ambient at location of animals.
Small	Overlap in frequency between masking noise and sounds potentially masked, but noise only above natural ambient at location of animals for short periods.
Medium	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.
Large	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

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. EU member states are required to protect these habitat areas from 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. These 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 the harbour porpoise, 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 habitat area and they certainly do not rely on the habitat area for day-to-day survival in the same way as a reef-dwelling fish relies on the reef, for example. In other words, disturbance of animals inside a habitat area 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 as the original area. The only difference is that the affected animals will end up spending less time in the habitat area and more time in the adjacent areas, compared to the undisturbed situation. The adjacent areas must be presumed to be less favourable than the habitat area (almost by definition, as the habitat areas should be the most important areas to the species), which, everything else being equal, should mean that displacement from the habitat area 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 Stora Middelgrund 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 $L_{eq-125ms}$ 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 Stora Middelgrund OWF the relevant area is interpreted as the combined area of the Swedish Natura 2000 site Stora Middelgrund & Röde Bankand the Danish Natura 2000 site Store Middelgrund. The two Natura 2000 sites are adjacent, relate to the same physical structure (Stora Middelgrund), and they are separated because of a national border. From an ecological point of view, it therefore does not make sense to treat the two Natura 2000 areas separately. Besides of this joint area, impact is assessed for the large Natura 2000 site 'Nordvästra Skånes havsområde' that is situated just south of Stora Middelgrund.

"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 areas 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 combined Store & Stora Middelgrund Natura 2000 sites {Mikaelsen, 2021 #1142} and the 'Nordvästra Skånes havsområde' Natura 2000 site, considering monopile installation of 12 m and 15 m monopiles for 2 locations within the Stora Middelgrund site located in Kattegat. The calculations were done for two months, February and May, representing worst and best 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.

4.6 Impacts from gravitation foundations

Due to the location within the Stora Middelgrund & Röde Bank Natura 2000 site and proximity to several others, 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 sea bed and to position the piles. Therefore, in this assessment, vessel noise is the noise source considered in terms of potential impacts on marine mammals.

4.6.1 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;

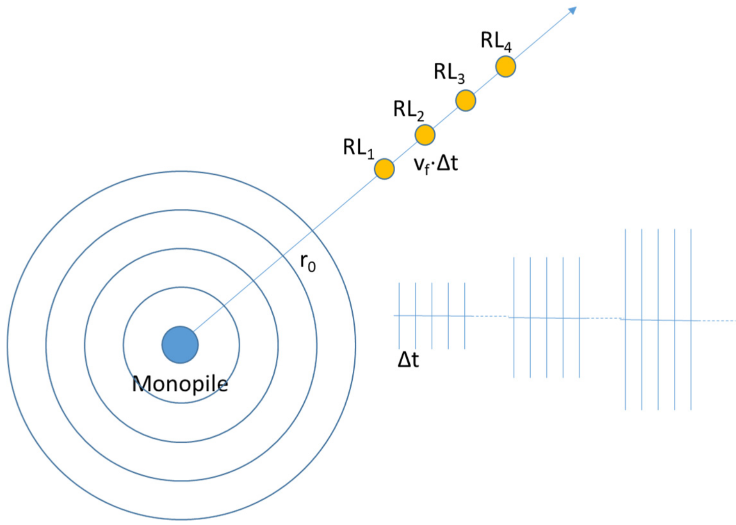
< 10 % = acceptable

> 10 % = unacceptable.

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. 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

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

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

$$E_i = SL_i - TL(r_i)$$

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

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.

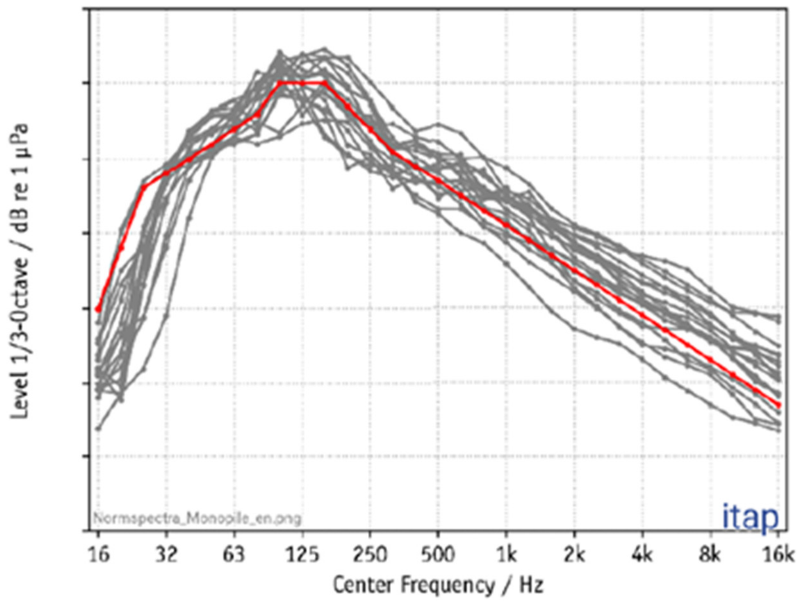
Equation 5.4 $$SL_i = SL_{max} + 10\log_{10}\frac{S_i}{100\%}$$

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 two different monopile diameters: 12 and 15 m. Source levels and spectra were estimated and extrapolated from recordings from a number of pile drivings in the North Sea, as described in Tougaard and Mikaelsen (2018). The 15 m diameter monopile is considered to represent a worst case scenario and this scenario was retained for the impact modelling. Maximum hammer energy was set to 5000 kJ per strike. 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 227.4 dB re. 1 μPa^2s, also estimated from Bellmann et al. 2020s by extrapolating the relationship between pile diameter and source level (figure 1 in Bellmann, et al. 2017). As an illustration of a piling scenario where mitigation in the form of a reduction in radiated noise is employed, a propagation model was also conducted with a source spectrum and level estimated to be representative of piling with a noise abatement system of hydro sound dampeners and double big bubble curtains in place.

Figure 5.2. Idealized pile driving frequency spectrum (red) used for modelling of sound transmission from 15 m monopile. Source: (Bellmann, et al. 2020).



5.4 Pile driving scenario

The following sequence of hammer energy (S_i in **Equation 5.4**) was used for 12 and 15 m monopiles:

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 and strike rate of 30 / min.

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

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 (February and May). The methodology is described in Appendix 1 Sound propagation modelling.

All modelled maps for combinations of two pile driving positions (on the shallow part of reef and in the deep part), two seasons (February and May), and three different frequency weightings (unweighted, VHF-cetacean and Phocid seals) are shown in Appendix 2.

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 $\mu Pa^2 s$ 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 to 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. 2011; Dähne, et al. 2013) and all are consistent with porpoises moving out to distances of tens of kms 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.

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 6 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 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 the present noise abatement system (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. 2011; 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 windfarm within the Stora Middelgrund & Röde Bank Natura 2000 site, and proximity to several others. 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 transmission loss model was combined with the assumptions about initial deterrence distance (r_0) (i.e. distance at first piling exposure) and flee speed into the cumulated exposure model.

Figure 6.1 shows an example of results of the exposure modelling. All scenarios modelled are shown in Appendix 2.

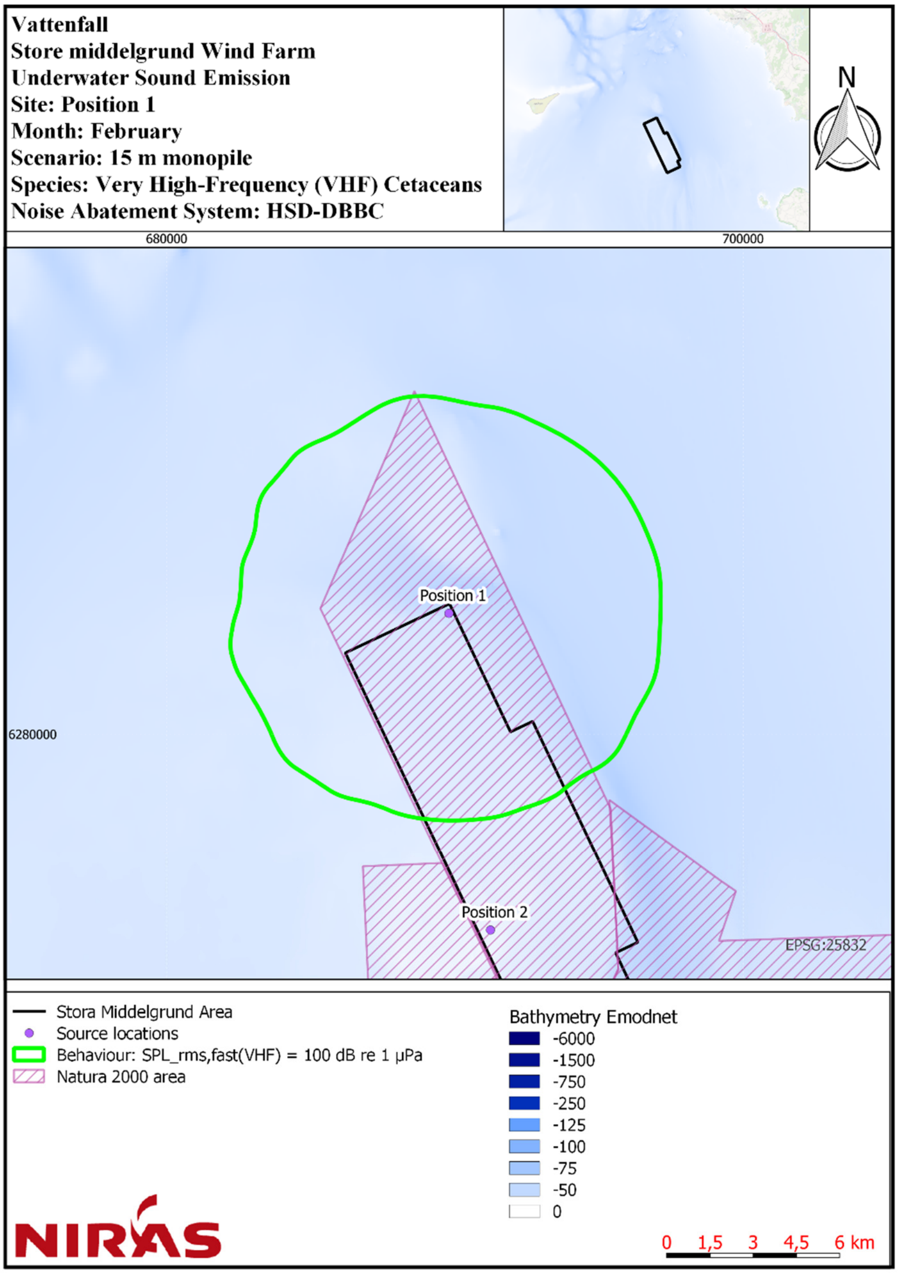


Figure 6.1. Example from the exposure modelling: position 1 in February with noise mitigation system of HSD+ DBBC. This is a worst case scenario – see Figure 7.2. The green line denotes the behavioural threshold for harbor porpoises.

Table 6.1. Threshold impact distances for 12 m and 15 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 HSD+DBBC. See app. 1 for further explanations of underlying assumptions.

Hearing Group	Pile size [m]	Position and month	Distance to impact threshold		
			$SEL_{C24,weighting}$		$SPL_{RMS,fast,VHF}$
			TTS [m]	PTS [m]	Behaviour [m]
Very High frequency Cetaceans	12	Position 1 February	<50	< 25	6450
		Position 1 May	<50	< 25	4200
		Position 2 February	<50	< 25	6050
		Position 2 May	75	< 25	2750
Phocid Pinniped		Position 1 February	< 50	< 25	-
		Position 1 May	< 50	< 25	-
		Position 2 February	< 50	< 25	-
		Position 2 May	< 50	< 25	-
Very High frequency Cetaceans	15	Position 1 February	75	< 25	7650
		Position 1 May	<50	< 25	4700
		Position 2 February	50	< 25	6950
		Position 2 May	100	< 25	3300
Phocid Pinniped		Position 1 February	< 50	< 25	-
		Position 1 May	< 50	< 25	-
		Position 2 February	< 50	< 25	-
		Position 2 May	< 50	< 25	-

Final impact thresholds for all modelled scenarios are shown in table 6.1. A number of conclusions are evident from the numbers:

- The difference between the months of February and May is considerable with respect to behaviour, with 2-3 km difference in behavioural threshold for porpoises and presumable the same for seals (not specifically assessed for seals as no threshold for behaviour exists) with May being the best month in terms of the size of the disturbed area.

- There is little difference between the two turbine positions (1 and 2, respectively, when all other factors are kept identical), however in May position 2 results in a smaller disturbed area.

- The effect of increasing foundation diameter is consistent, but not large, compared to the effect of noise abatement and time of year.

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 the noise. 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 a habitat suitablity model for harbour porpoises based on MaxEnt modelling of satellite tracked porpoises and environmental parameters (Sveegaard, et al. 2018) shown in Figure 7.1.

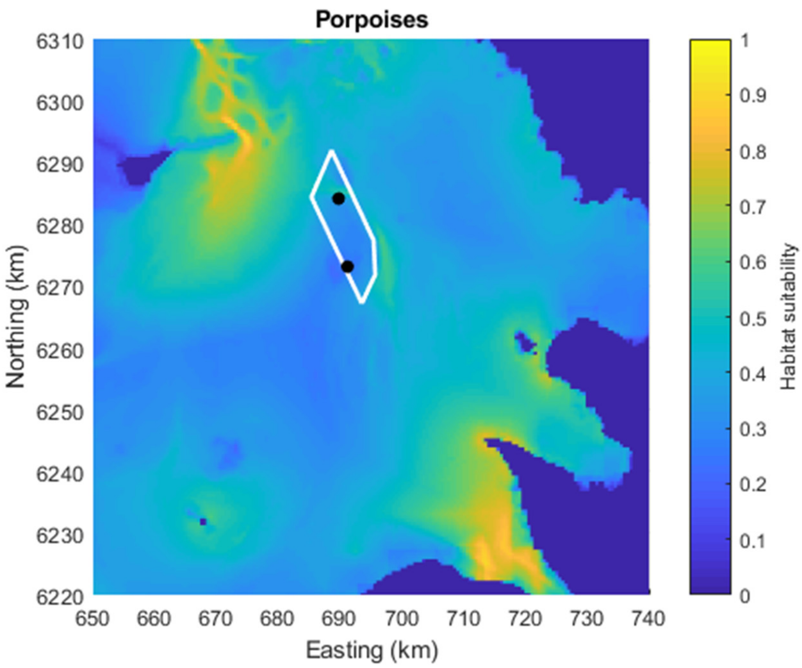


Figure 7.1. Habitat suitability models for porpoises, summer 2007-2016 (see section 1.2.1, Figure 1.5). The scale represents the relative likelihood of the habitat being suitable for porpoises based on MaxEnt modelling of satellite tracked porpoises and environmental parameters. Map from (Sveegaard, et al. 2018)

There are pros and cons of using both mean density and the modelled density surface in assessments. The mean density cannot, by definition, capture local variation in densities and will therefore result in underestimated numbers of affected animals if the exposed area is important to the animals (or vice versa, if the area is not important). Ideally, the modelled density surfance will capture this variation and allow for a better estimate of the number of impacted animals. However, spatial models, such as the habitat suitability model in Figure 7.2 do not reflect all details of the distribution accurately. This is due to several reasons, the most important one, besides too little observational data, is that co-variates are often environmental drivers (depth, sediment, hydrography etc.) for the real determining factor – prey availability. Spatial habitat suitability models are therefore to be interpreted with caution and small scale features should never be trusted. This is evident in the density surface in Figure 7.2, which clearly fails to capture the importance of Stora

Middelgrund for porpoises. This must be kept in mind when interpreting the results and estimates should *not* be understood as accurate figures, but indications of orders of magnitude.

With this in mind, the habitat suitability model was used to overlay with the noise propagation maps to estimate the exposed area, weighted according to porpoise hearing, respectively.

7.1 Modelled exposure of porpoises

$SPL_{RMSfast,VHF}$, weighted with the porpoise audiogram (VHF-weighting (Southall, et al. 2019)) was modelled (see Appendix 1 Sound propagation modelling) 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 is in February at position 1, which is shown in Figure 6.1. This worst case scenario was based on a 15 m diameter pile and 7000 kJ hammer energy.

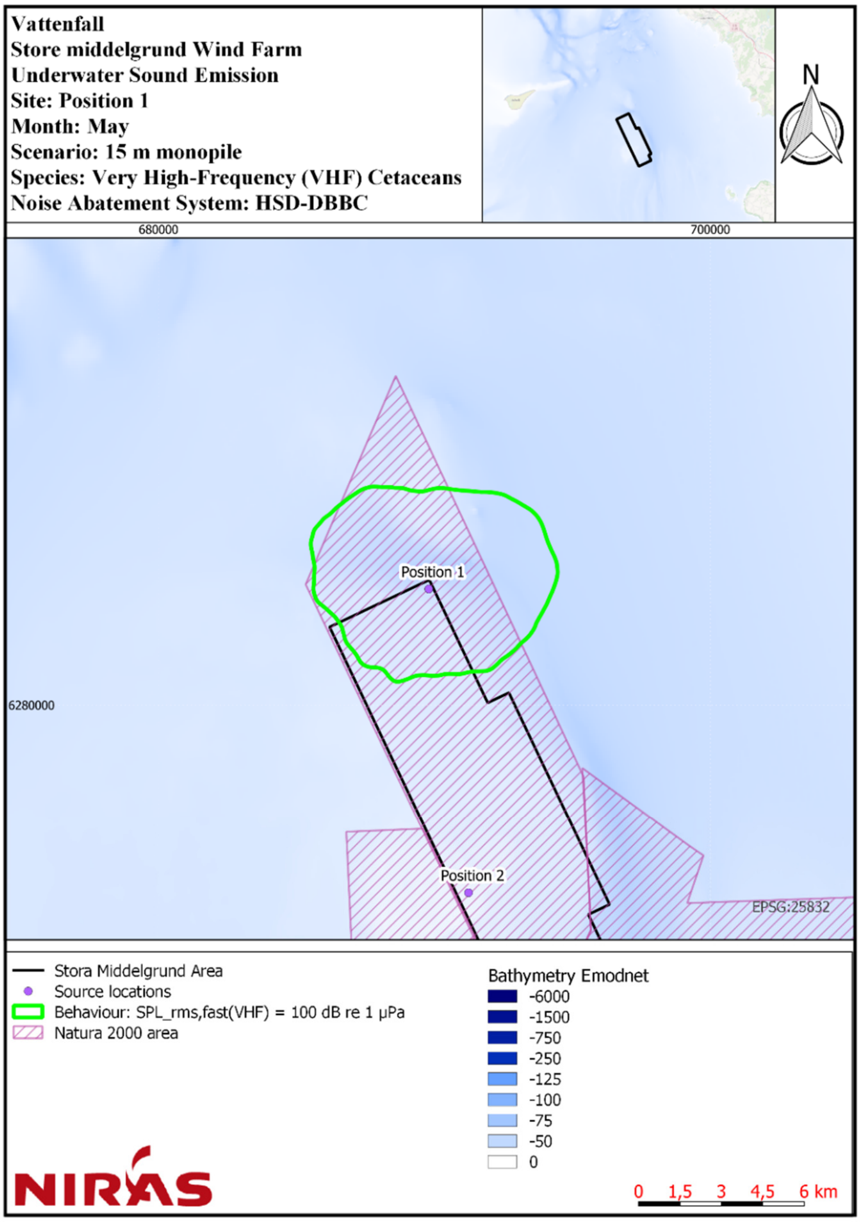


Figure 7.2. Example from the exposure modelling: position 1 in May with noise mitigation system of HSD+ DBBC. This is a best case scenario – see Figure 6.1 to compare with a worst case scenario for the same position. The green line denotes the behavioural threshold for harbor porpoises.

By comparing Figure 6.1 with Figure 7.2 the mitigating effect of selecting a time of year where sound propagation properties are less favourable for long-range transmission, are evident and is caused by a complete mixing of the water column in February, which leads to less favourable conditions for long-range sound propagation (iso-velocity, or downward-refracting conditions). The difference between worst case (February) and best case (May) is a factor 2. The difference between position 1 and 2 is insignificant compared to the differences caused by the sound propagation conditions. Worst case scenario is also calculated for 15 m piles without abatement to show effect of the HSD + DBBC noise abatement system (Table 7. 1).

Table 7. 1. Disturbance of porpoises from pile driving, expressed as area where modelled pile driving noise level is above the reaction threshold. Right column show the area weighted by the porpoise habitat suitability, taken from the model in Figure 7.1. Affected area without the use of proper abatement is shown only for the worst case scenario with 15 m piles.

Pile size	Position	Month	Noise Abatement System	Total area affected by noise above behaviour threshold [km^2]	% porpoises affected
12 m	1	February	HSD-DBBC	65	< 1
		May	HSD-DBBC	32	< 1
	2	February	HSD-DBBC	70	< 1
		May	HSD-DBBC	19	< 1
15 m	1	February	None	10,647	59
			HSD-DBBC	72	1
		May	None	2,140	16
			HSD-DBBC	37	< 1
	2	February	None	10,362	61
			HSD-DBBC	77	< 1
		May	None	2,187	15
			HSD-DBBC	24	< 1

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 2.3), 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 areas

In the lack of national guidelines for disturbance of Natura 2000 sites, 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 4.5 above).

Based on the definitions listed in chapter 4.5, NIRAS calculated disturbance percentages for the two combined Natura 2000 sites Store Middelgrund and Stora Middelgrund & Röde Bank (Mikaelsen, 2021) considering monopile installation of 12 and 15 m monopiles for two locations within the Stora Middelgrund site. The calculations were done for two months, February and May, representing worst and best cases scenarios, respectively, with regards to sound propagation conditions. The two sites are evaluated as one since they have been appointed for the same environmental feature and the same species.

Listed in table 7.2 is the estimated disturbed fraction of the two most impacted Natura 2000 sites in south-eastern Kattegat (see Table 1.1 for a list of Natura 2000 sites nearby). 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. Adoption of Best Available Technology (HSD + DBBC) and Best Environmental Practice (pile driving in May) reduces the impact to affecting primarily Stora Middelgrund & Röde Bank and the Danish Store Middelgrund Natura 2000 sites. For no other Natura 2000 sites is the limit of 20 % disturbed area exceeded.

A result from February at position 2 is shown in figure 7.3. The figure shows that the underwater piling noise after appropriate filtering by the VHF audiogram of harbour porpoises (Southall, et al. 2019) exceeds the behavioural threshold of harbour porpoises in an area corresponding to 57 % of the combined Store Middelgrund and Stora Middelgrund & Röde Bank Natura 2000 sites. In order to reduce the impact to be below the recommended maximum 20 % disturbed area of a Natura 2000 site requires additional mitigation (X dB (VHF frequency weighted), $\Delta SPL(VHF) = X\ dB\ re. 1\ \mu Pa$, on top of the currently best BAT applied here. The amount of additional mitigation in dBs are shown in Table 7.2. This is in addition to the already applied HSD+DBBC.

For the example at position 2 in February, the noise level has to be decreased by an additional 10 dB (VHF frequency weighted), $\Delta SPL(VHF) = 10\ dB\ re. 1\ \mu Pa$ (Table 7.2). This is in addition to the already applied HSD+DBBC NAS, or similar.

With the additional source mitigation applied, the overlap between pile driving and Natura 2000 sites is reduced to below the recommended 20 % disturbed area, as shown in Table 7.2.

Table 7.2. Fraction of the combined Natura 2000 sites Store Middelgrund and Stora Middelgrund & Röde Bank exposed to noise levels above the behavioural reaction threshold for porpoises, modelled with use of Best Available Technology (BAT), i.e. HSD+DBBC in February and May. The combined area of the Natura 2000 site of 135 km^2 is used for calculation of the overlap in %. The overlap assumes the use of a Noise Abatement System equal in effect to the HSD+DBBC. Also shown is the additional source mitigation require to be below the threshold of maximum 20 % affected Natura 2000 site. The listed additional source mitigation requirements are therefore in addition to the already included effect of the HSD+DBBC, or similar.

Pile size	Position	Month	Noise Abatement System	Total area affected by noise above behaviour threshold [km^2]	% Natura 2000 site affected
12 m	1	Feb	HSD-DBBC	65	48.1 %
			HSD-DBBC+$\Delta SEL_{VHF} = 9\ dB$	26	19.3 %
		May	HSD-DBBC	32	23.7 %
			HSD-DBBC+$\Delta SEL_{VHF} = 2\ dB$	26	19.3 %
	2	Feb	HSD-DBBC	70	51,9%
			HSD-DBBC+$\Delta SEL_{VHF} = 8\ dB$	25	18.5 %
		May	HSD-DBBC	19	14.1 %
			HSD-DBBC+$\Delta SEL_{VHF} = 0\ dB$	"	"
15 m	1	Feb	HSD-DBBC	72	53,3%
			HSD-DBBC+$\Delta SEL_{VHF} = 11\ dB$	26	19.3 %
		May	HSD-DBBC	37	27,4%
			HSD-DBBC+$\Delta SEL_{VHF} = 4\ dB$	26	19.3 %
	2	Feb	HSD-DBBC	77	57,0%
			HSD-DBBC+$\Delta SEL_{VHF} = 10\ dB$	25	18.5 %
		May	HSD-DBBC	24	17.8 %
			HSD-DBBC+$\Delta SEL_{VHF} = 0\ dB$	"	"

The expected disturbance from piling and overlap with Natura 2000 sites for May of a 15 m pile is presented in figure 7.4. The model results show that the disturbed area is significantly smaller than in February, 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 15 m monopile installation, $SPL_{RMS-fast}$ (VHF-weighting) for February. Area is assumimg mitigation with HSD+DBBC noise abatement system in place. The harbour porpoise behavioural threshold is used to define maximum disturbance of Natura 2000 sites following JNCC 2020. Overlay with nearby Natura 2000 sites are shown. Store Middelgrund (DK) and Stora Middelgrund & Röde Bank are combined for the assessment.

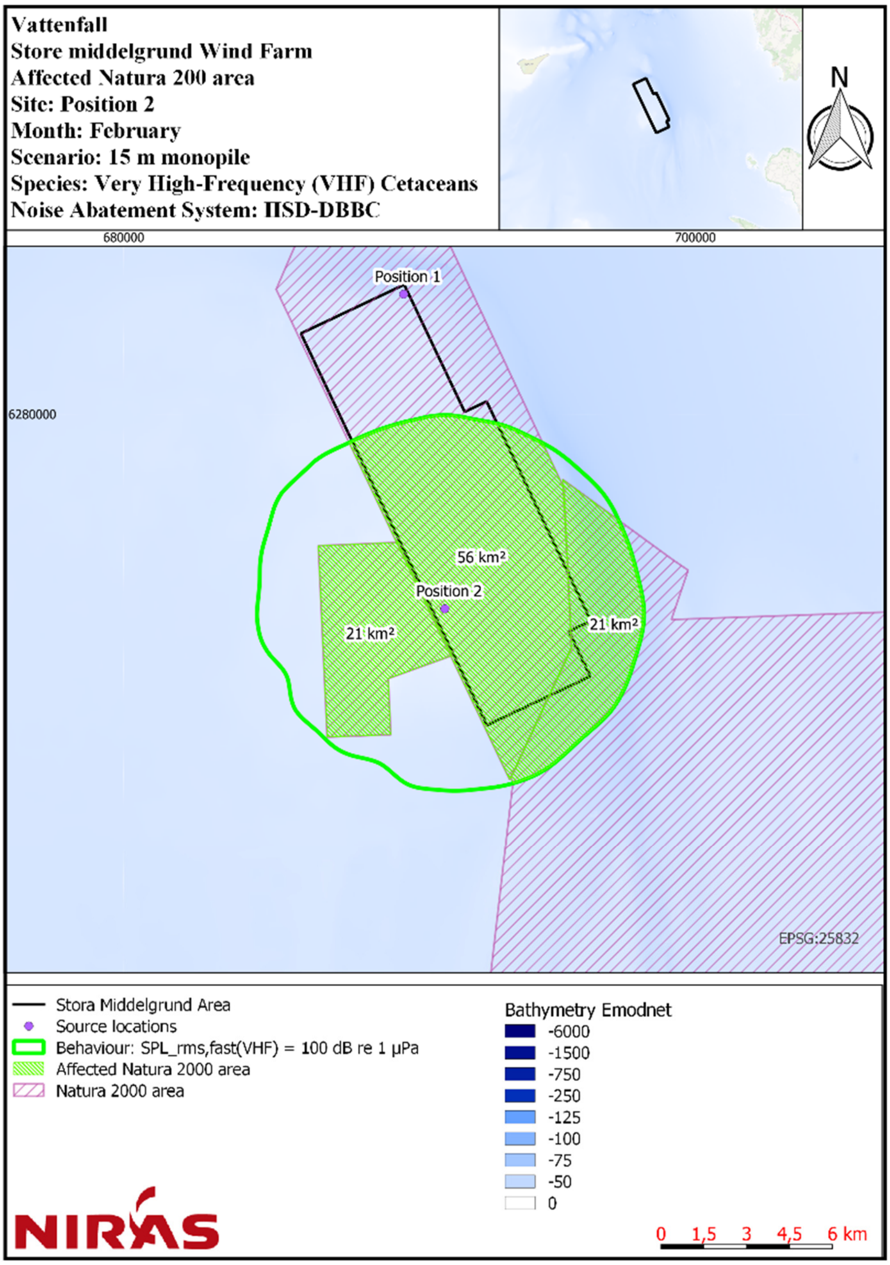
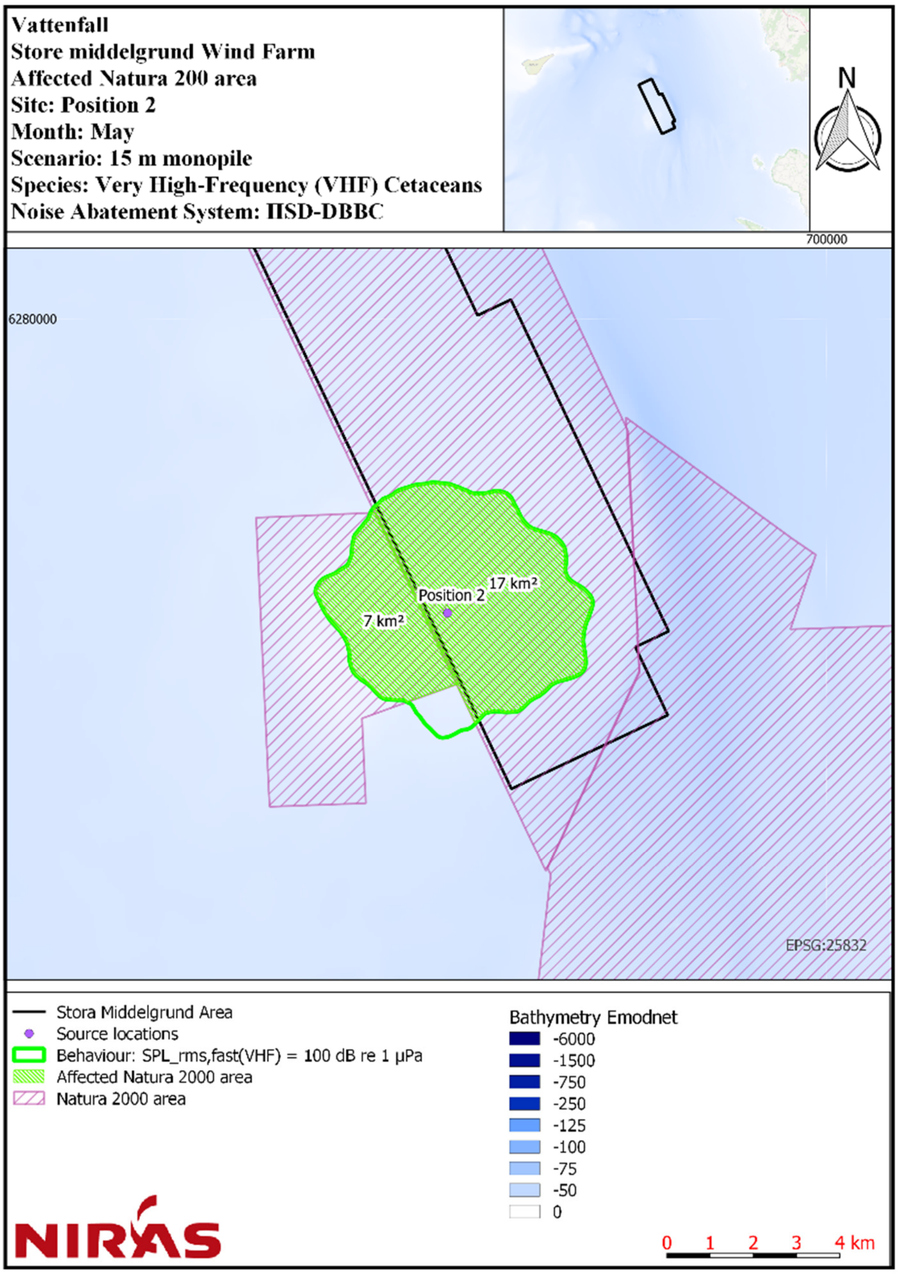


Figure 7.4. Area (green outline), wherein the behavioural disturbance threshold is exceeded during piling of each 15 m monopile installation, $SPL_{RMS\text{-}fast}$ (VHF-weighting) for May. Area is given mitigation with HSD+DBBC noise abatement system in place. The harbour porpoise behavioural threshold is used to define maximum disturbance of Natura 2000 sites following JNCC 2020. Overlay with nearby Natura 2000 sites are shown. Store Middelgrund (DK) and Stora Middelgrund & Röde Bank are combined for the assessment.



In May for a 15 m pile the behavioural disturbance threshold is exceeded in 27,4 % of the combined Natura 2000 sites (figure 7.4) with proper use of the presently best available mitigation (Bellmann, et al. 2020) in the shape of a combined Noise Abatement System (NAS) consisting of Hydro Sound Dampeners (HSD) and a Double Big Bubble Curtain (DBBC). This means that the noise level has to be decreased with an additional 4 dB mitigation (VHF frequency weighted), $\Delta SPL(VHF) = 4\, dB\, re.1\, \mu Pa$ (Table 7.2) in order for the disturbance to remain below the maximum 20 % disturbed area following the JNCC criteria. This is in addition to the already applied HSD+DBBC NAS.

If the piling is to take place in the autumn, the sound propagation probabilities are expected to fall somewhere in between the best and worst case scenarios presented here, which means that the additionally required mitigation for 15 m piles would be in the range of $\Delta SPL(VHF) = 7 - 9\, dB\, re.1\, \mu Pa$, in addition to the already applied HSD+DBBC noise abatement system in order to remain below the 20 % disturbed area. For 12 m piles the extra requirement for noise abatement is $\Delta SPL(VHF) = 5 - 7\ dB\ re. 1\ \mu Pa$.

Seasonal average

In a worst-case scenario, the disturbance of each pile driving is kept at exactly 20 % of the Natura 2000 sites. To calculate the seasonal average, 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. 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 each ship is 0.8 km^2, or 0.6 % of the total areas of the Natura 2000 sites (21.5 km^2 + 114 km^2). Furthermore, we assume that three ships are always present in the Natura 2000 site during construction, and that they are more than 1 km apart, in which case the total disturbed fraction of the Natura 2000 sites amounts to 1.7 %. This is likely grossly overestimated, but it will serve for a precautionary assessment of the average disturbance.

If pile driving takes place every second day, the average disturbance will be the mean of 20 % (highest acceptable level on days with piling) and 1.7 % (disturbance from the ships on days without piling), equal to 10.9 %. In this calculation, we assume that the ships are within the area disturbed by pile driving on days with pile driving, and therefore is included in the 20 %. The disturbed fraction with piling every other day is above the acceptable average disturbance, but it is also unlikely that construction will be so efficient that piling from first to last foundation will occur without a single break longer than 1 day. The average disturbance is given by

$$Disturbed\ fraction = \frac{0.2 \cdot N_{piling} + 0.017 \cdot N_{no\ piling}}{N_{piling} + N_{no\ piling}}$$

where N_{piling} and $N_{no\ piling}$ are number of days with and without pile driving, respectively.

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. 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. For the installation of gravity base 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 23.6 km^2, which amounts to 17.4 % of the combined Natura 2000 sites Store Middelgrund og Stora Middelgrund & Röde Bank (21.5 km^2 + 114 km^2). In reality, this level of disturbance is likely grossly 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 will be less than 30 times 0.8 km^2. The impact is therefore an over-estimated peak-impact and will serve for a precautionary assessment.

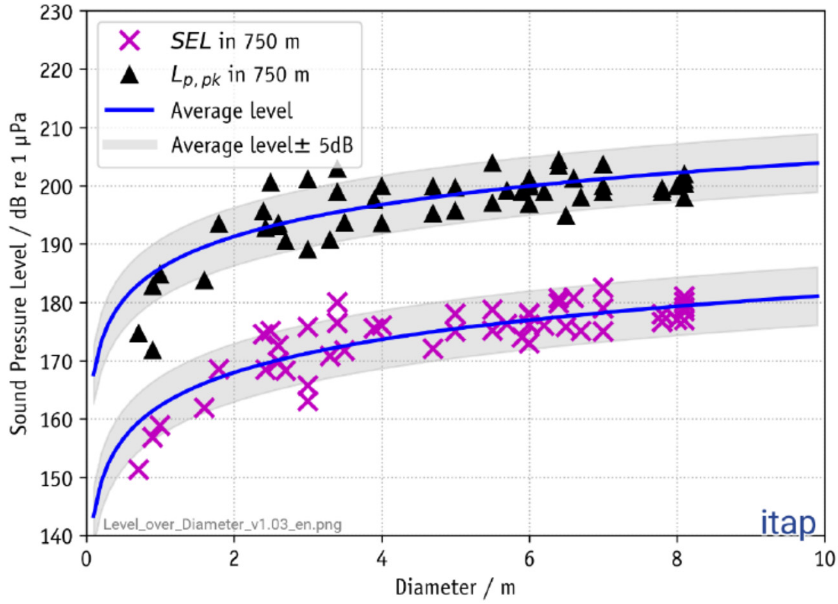
8 Assessment of impact from construction

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 from gravity foundation. 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 Stora Middelgrund, 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 15 m diameter pile. Extrapolating the upper curve on Figure 8.1 to 15 m pile diameter gives an estimated peak sound pressure level of 210 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 120 m of the monopile. 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. Furthermore as no animals, neither seals, nor porpoises, are expected to be within 500 m, due to the deterrence effect of the vessels used for piling and abatement, as well as the soft start procedure, 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).



Only one activity is considered capable of generating peak pressures and acoustic impulses sufficiently high to injure marine mammals and this is underwater explosions. 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. Sound propagation modelling with noise abatement (HSD + DBBC) were used. It was assumed that both seals and porpoises would be deterred to safe distances (min. 25 m) by the presence of several vessels working close to the piling site, for piling and abating the piling noise, respectively. It was therefore assumed that no animals would be in within the zone of TTS or PTS at the onset of the soft start.

8.2.1 Piling without noise abatement technology

Due to the location of the potential offshore windfarm inside the Stora Middelgrund & Röde Bank Natura 2000 site, only scenarios with best available technology using hydrosound dampeners and double big bubble curtains has been assessed.

8.2.2 Piling with hydro sound dampeners and double Big Bubble Curtains

Use of HSD + DBBC, with the noise abatement capabilities assumed in the model (see Appendix 1 Sound propagation modelling) reduces the cumulated noise exposures of seals and porpoises to very low levels and reduces the PTS threshold range to below max. 25 m (Table 6.1), and is thus unlikely to induce any permanent hearing loss in neither seals, nor porpoises.

For **porpoises**, the cumulated exposure is reduced to levels exceeding the level required to elicit temporary threshold shift (TTS) at a maximum of 100 m at position 2 in May for 15 m piles and 75 m for 12 m piles (Table 6.1). Otherwise, the range for eliciting TTS is below 50 m in May for both 12 m and 15 m piles. In February, the range is below 50 m for both pile sizes except at position 1, where it is 75 m for 15 m piles. As the impact on individuals from hearing loss therefore is expected to occur very close to the piling site and it is expected that animals will be scared out of this zone by the vessels, impact on hearing is unlikely to have any long-term consequences for the population. The impact of pile driving with appropriate best available technology noise abatement, is considered **negligible** with respect to hearing.

For **seals**, the cumulated exposure with application of HSD + DBBC does not exceed the TTS threshold (Table 3.2) and the range of potential PTS is thus assessed as below 25 m. The range of potential TTS is maximum 50 m for both months and positions. It is assessed unlikely that seals will remain this close to the piling site when piling begins due to the presence of several vessels in proximity to the piling site. The potential impact of pile driving with appropriate noise abatement on the hearing of **harbour seals and grey seals** is therefore assessed to be **negligible**.

8.3 Behavioural disturbance

Pile driving without use of bubble curtains is known to cause disturbance of seals and porpoises out to at least 20 km from the pile driving site, with the effect lasting up to 24 hours (see section 0) after termination of the piling. This means for example that during this period foraging by the animals in the impacted area, which is of considerable size, will be reduced. Very little data is available on temporal and spatial variation in presence of harbor porpoises at Stora Middelgrund and adjacent waters. This means that there is insufficient knowledge to judge whether porpoises displaced from Stora Middelgrund during piling are able to forage in similar quality habitats elsewhere. 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 impacted by pile driving noise was estimated for porpoises. It is not considered a viable option to pile without noise abatement inside the Natura 2000 site, however the area affected under worst case assumptions without noise abatement is shown for illustration (February, 15 m pile) and indicate that porpoises are likely to be disturbed by the noise over a very large area, affecting a substantial part of the south-eastern Kattegat and the local population of porpoises. **Impact on the porpoise population** under these conditions is therefore assessed as **major**.

If construction is undertaken under conditions less favourable for long-range sound propagation (BEP) (here May) and with BAP noise abatement (here HSD+DBBC), the impacted area is reduced to around 37 km^2 (15 m pile) or 32 km^2 (12 m pile) (reaction distances around 2.7-4.7 km depending on piling site), significantly reducing the affected number of porpoises from the Kattegat population with several orders of magnitude. (This impacted area can be reduced even further if additional abatement is used (Table 7.2)). Under these conditions, the **impact on the porpoise population by pile driving is assessed to be minor**.

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 to 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 unabated pile driving in February is therefore assessed as major**. The BAT employed is very effective also when assessed with measurements weighted by seal hearing and is likely to reduce reaction distances considerably. It is therefore assessed that the **impact on seal populations by pile driving noise in May, with appropriate noise abatement, is minor.**

8.3.3 Disturbance of porpoises from gravity base 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 17 km^2. **Impact on the porpoise population** under these conditions is assessed as **minor**. This scenario is unlikely to be abated at the source, but it is likely possible to reduce the amount of simultaneously working vessels within the Stora Middelgrund offshore 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 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 2.2 and 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 grey and harbour seal populations** under worst-case conditions (30 ships working at full power and dispersed throughout the construction site) these conditions is assessed as **minor**. This scenario is a worst-case peak exposure and under more typical conditions, with 4 or 5 vessels working simultaneously in the construction site, 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 precautious 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). Given the favourable conservation status of the population of harbour seals, **the overall impact of masking from the pile driving noise with reduction in noise radiation on seal populations is thus assessed to be minor**. Reduction of radiated noise from the pile driving by additional noise abatement (Table 7.2) will reduce noise levels and thus reduce impact at the coast to **negligible** levels.

Noise from installing gravity base 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 areas from piling

Listed in Table 7.2 is the impact on the combined Store Middelgrund and Stora Middelgrund & Röde Bank Natura 2000 sites, where the impact approaches or exceeds the 20 % threshold depending on scenario. Impact is expressed as the fraction of the sites exposed to noise levels above the behavioural reaction threshold for porpoises.

Under worst case assumptions with no noise abatement in February (considered an unlikely scenario within the Natura 2000 site), the entire Stora Middelgrund & Röde Bank, Fladen, Nordvästra Skånes havsområde, Lilla Middelgrund and Store Middelgrund (DK), as well as more than 60 % of Anholt, Balgö, and Gilleleje Flak Tragten Natura 2000 sites would be exposed to noise levels well 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 day. **Impact on the Natura 2000 sites under these conditions is therefore assessed as unacceptable**.

If piling is undertaken under conditions least favourable for long-range sound propagation (May) and with BAT noise abatement (HSD + DBBC), only the Store Middelgrund (DK) and Stora Middelgrund & Röde Bank Natura 2000 sites are impacted to a noticeable degree. The impacted fraction of the combined Store Middelgrund (DK) and Stora Middelgrund & Röde Bank Natura 2000 site is then reduced to 18-27 % of the area, depending on position of the piling site within the wind farm area (see Table 7.2). More important, however, is that most of the area will be exposed to noise levels only slightly exceeding the behavioural threshold. **The impact on Stora Middelgrund & Röde Bank is therefore assessed to be unacceptable**, as temporary displacement of animals is expected, but no long-term effects on the area or population is anticipated. The same applies to the neighbouring Natura 2000 area **Store Middelgrund DK.** The impact on the two combined Natura 2000 sites may be reduced to **acceptable**, provided the noise level can be reduced with additional noise abatement (on top of the HSD+DBBC abatement system) at the source as given in Table 7.2 in order to reduce the impacted area to below 20 %, as stipulated in the JNCC guidelines.

Across the season (winter or summer), the impact is likely to exceed the 10 % JNCC threshold, unless there are several breaks in piling of more than one day duration. If piling is planned carried out every second day, and the 20 % threshold is exceeded for single days, the 10 % average disturbance threshold will also be exceeded. If piling remains at the 20 % threshold for individual days, and there are only single days in between with vessels working in the area, the 10 % threshold will also be exceeded across the season, in both cases the disturbance of the Natura 2000 site is assessed as **unacceptable**. To remain below the average of 10 % disturbance across the season, a well-thought schedule should be prepared.

Depending on the location of the pile driving, also the nearby area **Skånes Nordvästvatten (13,424 km²)** will be affected in up to 1.6 % of the area in February with BAT noise abatement in place. **Impact** on this area under best case conditions BAT and BEP is assessed to be **acceptable,** according to the JNCC guidelines**.** With addition of extra noise abatement (on top of the HSD+DBBC abatement system) as given in Table 7.2, the impact on Skånes Nordvästvatten Natura 2000 site can be further reduced. Since the disturbance on single days is much below the 20 % threshold, the 10 % threshold will not be exceeded and the seasonal disturbance of area Skånes Nordvästvatten is assessed as **acceptable** according to the JNCC threshold.

If piling takes place every second day and with the above conditions of BAT, BEP and additional noise abatement, the seasonal disturbance threshold with a maximum average of 10 % disturbance per day across a season, will be exceeded, if all single days reach the maximum 20 % disturbance threshold. Under these conditions, the seasonal disturbance is assessed as **unacceptable**. With longer breaks in piling, the average percent disturbance per day will decrease, and if a schedule can be prepared in order not to exceed the 10 % threshold, the disturbance can be assessed as **acceptable** according to the JNCC guidelines.

The impact on the more distant Natura 2000 areas **Balgö, Fladen, Anholt, Lilla Middelgrund and Gilleleje Flak & Tragten** under BAT and BEP best case conditions is assessed as **acceptable**.

8.6 Impacts on Natura 2000 sites from gravity base foundations

Under a peak worst-case condition up to thirty vessels may be working simultaneously to install gravitation foundations. In this case it is assessed that ship noise will affect 17.4 % of the combined Store Middelgrund and Stora Middelgrund & Röde Bank Natura 2000 sites, which is below the 20 % threshold set by JNCC (JNCC 2020c). **The peak impact on Natura 2000 sites from gravitation foundations is therefore assessed to be acceptable.** The assessed scenario is likely to represent an atypical worst-case peak impact. A more typical impact from only 4 or 5 ships working in the construction area will impact less than 2 % of the Natura 2000 sites in which case the impact is assessed as **acceptable**.

8.7 Cumulative impacts from construction of several windfarms

Several other offshore wind farms are planned in the eastern and central Kattegat, including the area north of Stora Middelgrund and the area between the Danish islands Anholt and Hesselø. 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 area stipulated by JNCC. This very likely means that simultaneous pile driving on two wind farms impacting the same Natura 2000 site will mean that the cumulative impact exceeds the 20 % limit and even if installations are alternated, the average impact may exceed the 10 % limit. In case it is proposed to construct two adjacent wind farms (i.e. with overlapping areas of impact) within the same year, a thorough analysis of the combined impact of both should therefore be performed.

The cumulative impact 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.

9 Noise from operational wind farms

Offshore wind turbines generate noise as the wings, gears and generator rotates. The moving gears in the gearbox is the primary source of the noise transmitted as vibrations down the turbine tower and radiated into the surrounding waters. Thus, the power density spectra of the underwater noise very commonly 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).

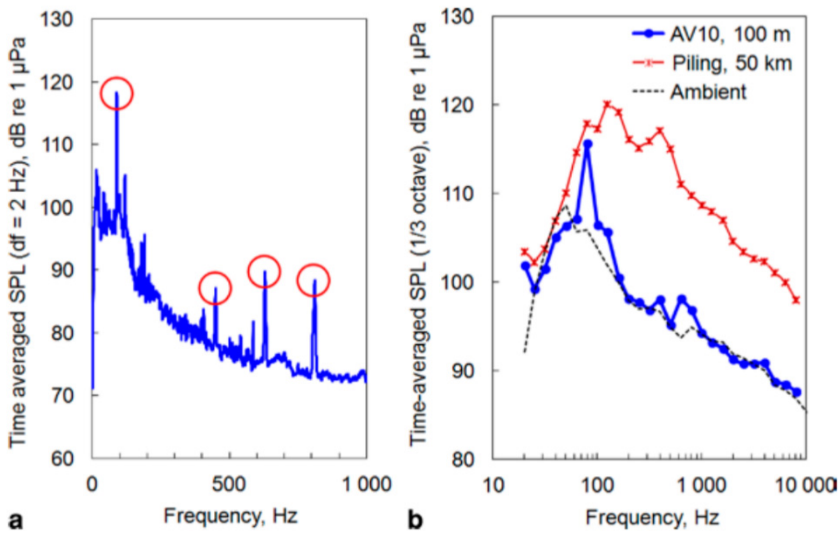


Figure 9.1. Operational noise measured 100 m from a 5 MW turbine at Alpha Ventus offshore wind farm. The turbine was operating at maximal power output. A) shows power density spectrum of the noise. Note the powerful component at 90 Hz and the harmonic overtones at 450 Hz, 630 Hz and 810 Hz. B) Third-octave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

Numerous recordings of underwater noise from operating turbines exists. A recent 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. in press).

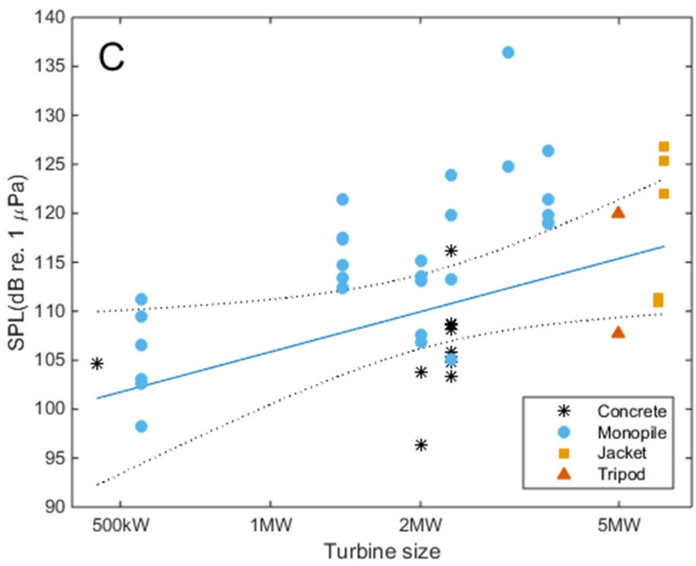


Figure 9.2. Underwater noise recorded from a large number of different turbines. All levels were normalised to a recording distance of 100 m and wind speed of 10 m/s. From Tougaard et al. (in press).

The type of foundation could quite possibly affect the noise levels too, but the 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 and on Stora Middelgrund 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 N2000 area. 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.

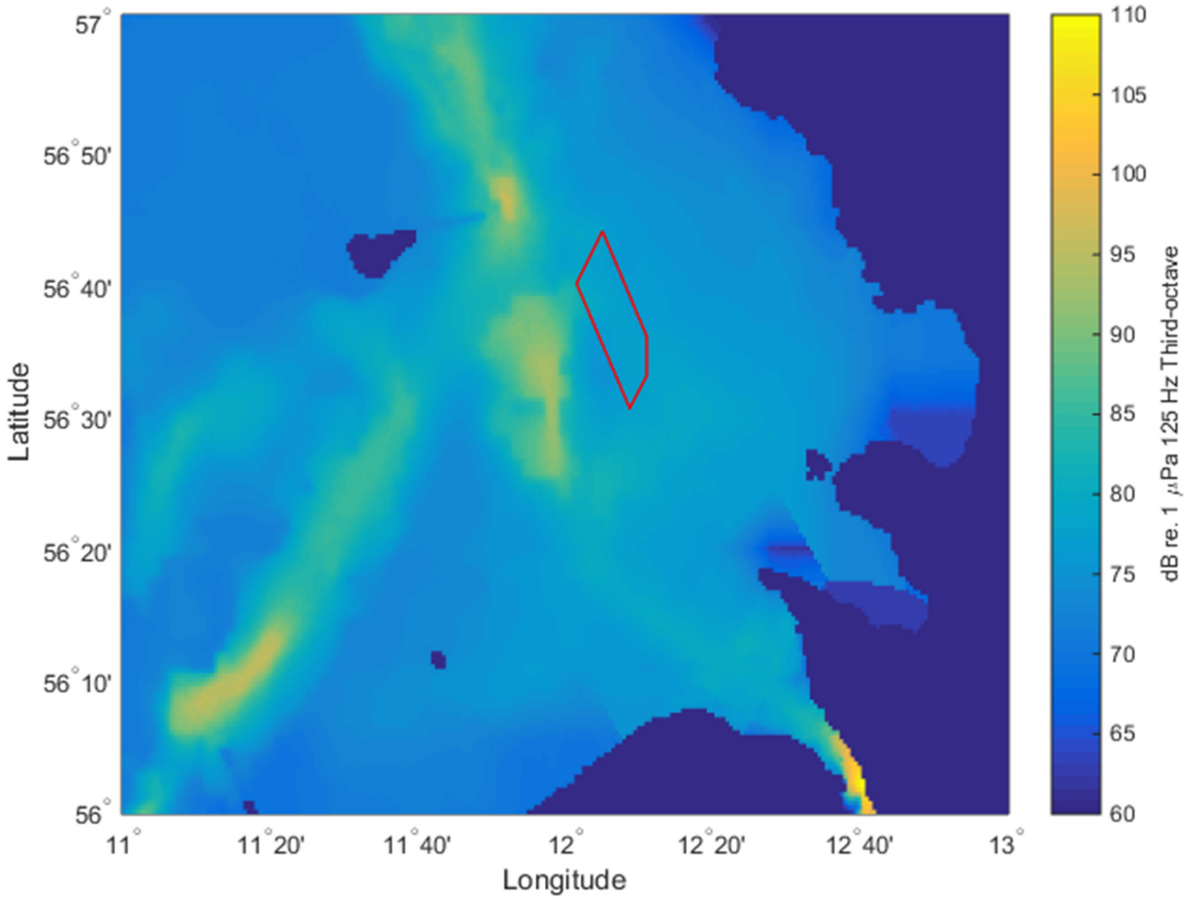


Figure 9.3. Modelled noise levels in the third-octave band centred at 125 Hz. The map shows the median noise level (L_{50}) for July 2014. Polygon shows outline of Natura 2000 sites Stora Middelgrund and Röda Bank. The shipping routes T and S running east of Anholt and into the Great Belt and the Sound, 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.

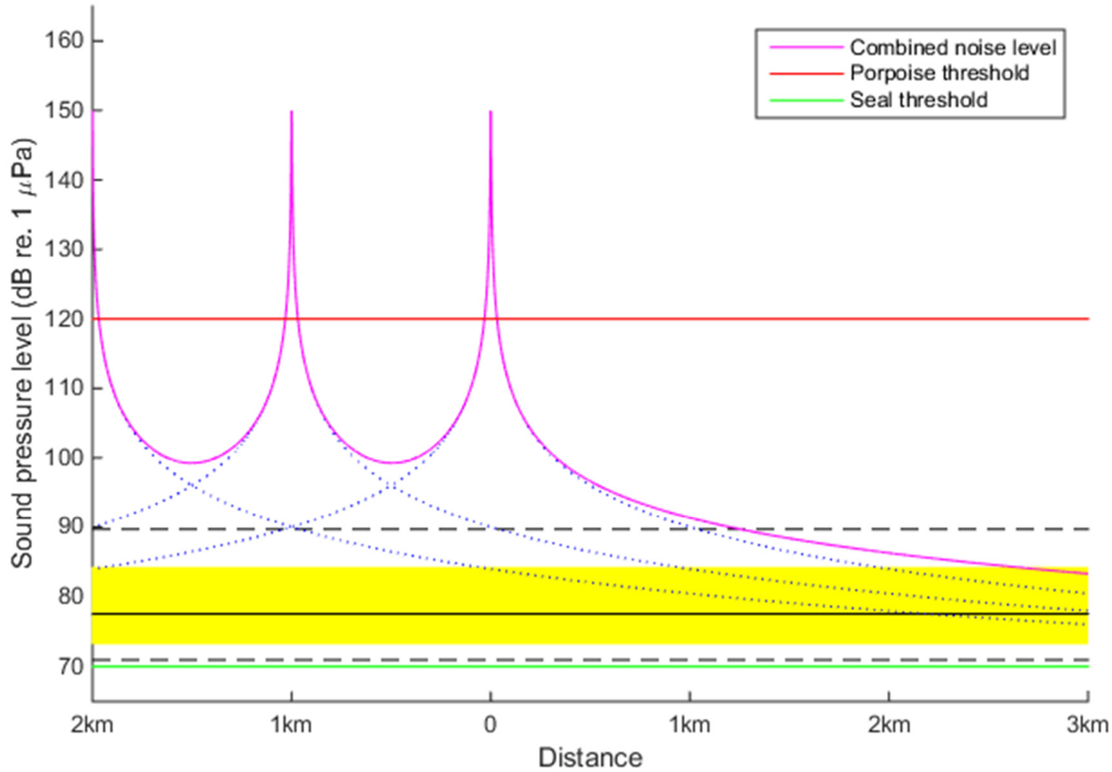


Figure 9.4. Idealized model of summation of noise from three identical turbines placed 1000 m apart. Each turbine is modelled as a point source with a spherical transmission loss (20 log r, dotted lines) and the combined noise level is found from **Equation 9.1**. (magenta line). The yellow band indicate 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 (Figure 9.3); 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 at Stora Middelgrund (Figure 9.4). 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.

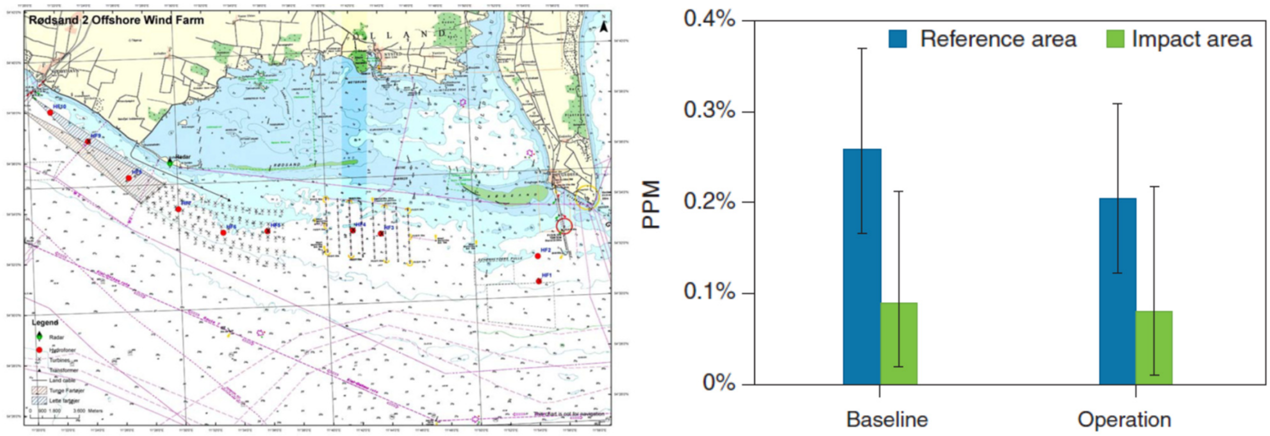


Figure 10.1. Harbour porpoise acoustic detections before and after construction of Rødsand 2 offshore wind farm. Porpoises were monitored acoustically inside the wind farm (five stations indicated with red dots in the western part of the map left and compared to two reference stations located to the east in the map. Two additional stations were located inside an older wind farm (Nysted), in centre of map. Right panel shows porpoise presence, quantified as average percent porpoise positive minutes before and after construction and inside the wind farm and at the reference stations. From Teilmann, et al. (2012).

One example is shown in Figure 10.1, which is from the Rødsand 2 offshore wind farm located in the Western Baltic Sea. Abundance of harbour porpoises were assessed by passive acoustic monitoring, where dataloggers (C-PODs), recorded the presence of porpoises through detection of their echolocation clicks (Teilmann, et al. 2012). Porpoise abundance was quantified as percent porpoise positive minutes, which expresses the fraction of a 24 h day where porpoise echolocation clicks could be detected, assessed minute by minute.

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

A later study in the Egmond aan Zee offshore wind farm off the Dutch North Sea coast (Figure 10.2) 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.

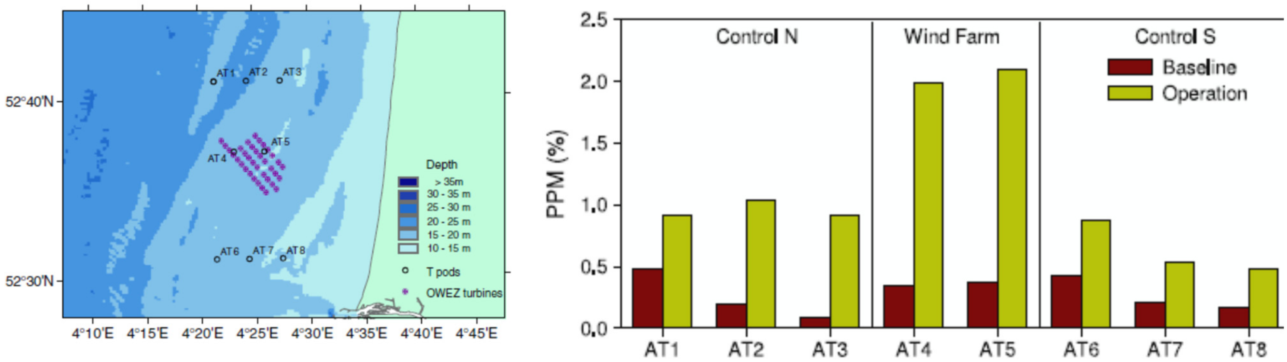


Figure 10.2. Another study of the effect of an offshore wind farm, Egmond aan Zee in the Dutch North Sea. Abundance inside the wind farm area (purple symbols in map, left) was compared to the abundance in two reference areas, north and south of the wind farm, respectively. Porpoise abundance before and after construction and separated out into each recording station (AT1-AT8), is shown to the right. From Scheidat, et al. (2011) .

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).

An earlier study (Teilmann and Carstensen 2012) looked at abundance of porpoises (measured by passive acoustic monitoring) around the Nysted offshore wind farm, the first large offshore wind farm established in the Baltic. This study showed a significant decrease in porpoise abundance during construction, followed by a recovery during operation. The recovery appeared incomplete, however, as 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. This conclusion is based on a number of observations:

- The baseline period was very short, essentially only covering a few months in the year prior to construction. It is thus not evident that the baseline activity was typical for the area over long time.

- A dedicated impact study (Diederichs, et al. 2008) failed to show any gradient in porpoise abundance away from the wind farm. Such a gradient would be expected if porpoises avoided the wind farm.

- The wind farm Rødsand 2 was later constructed adjacent to the Nysted offshore wind farm and did not affect the abundance of porpoises in the area (results described above and shown in Figure 10.1). Turbine foundations were larger, but of similar type (concrete gravitational) as in the Nysted wind farm. The lack of an effect of this wind farm supports that the baseline data from Nysted was not representative.

- Noise levels from Nysted offshore wind farm were measured and found to be comparable to what has been seen from other turbines (Betke and Glahn 2008). Noise is thus unlikely to be a disturbing factor and no other source of disturbance potentially capable of producing the deterrence needed could be identified.

The potential negative effects of an operational wind farm on Stora Middelgrund on porpoises is thus considered **negligible**. The magnitude of potential positive effects of artificial reefs and protection from fishery and shipping is not possible to assess based on existing evidence.

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. Figure 10.3 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.

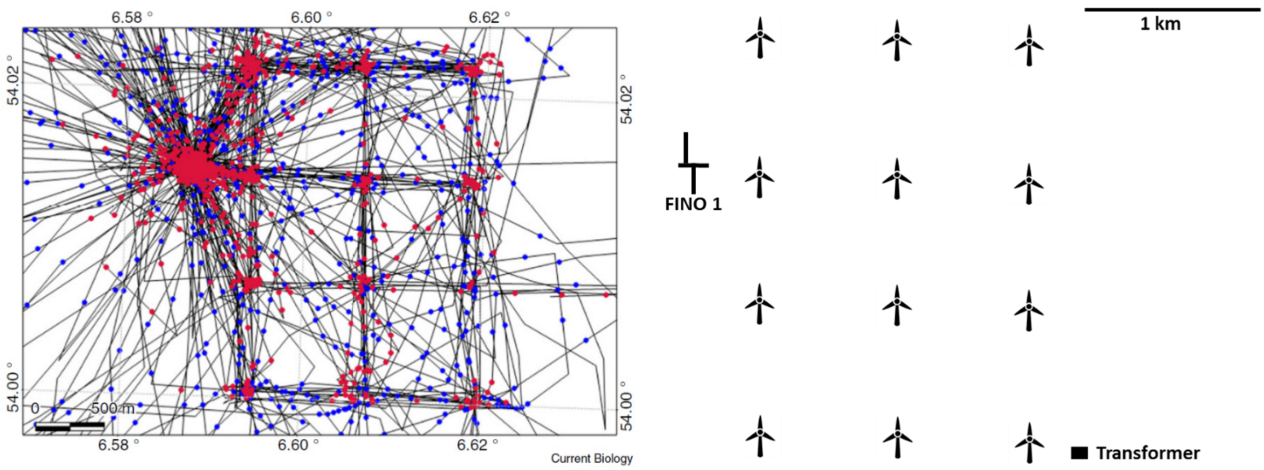


Figure 10.3. Tracks of a single harbour seal, tracked by GPS/satellite transmitter while swimming in and around the German offshore wind farm Alpha Ventus (outline shown on the right). It is evident that the seal actively seeks the turbine foundations, as well as the foundation of the research platform 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 10.3), nothing in the available data suggests that the seals are deterred from the operating wind farms. 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**. Whether there are potential positive effects is beyond the scope of this report to assess.

10.3 Impact on Natura 2000 sites

The net impact of the operating turbines inside the **Natura 2000 site is assessed to be acceptable** due to the low source level and frequency content of turbine noise during operation. 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 so low, that they are inaudible to porpoises, unless the animals are within tens of m from the turbines. The turbine foundations and any scour protection around the foundations will result in a direct loss of habitat, but not only is the area, which is lost very small compared to the total area of the Natura 2000 site (114 km^2), it will also be counteracted by a habitat gain from the hard substrates offered by the turbine foundations and scour protection.

11 Assessment of impact from sediment spill

During construction of an offshore windfarm several actions causes stirring of the seabed with resuspension of the sediment. This resuspension is coined sediment spill and its potential effects on marine mammals is assessed in this chapter. The potential sources of sediment spills are preparing the seabed for the installation, laying the cables, drilling for placing 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, 2020 #1130} was made available for this assessment 9th November 2020.

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 31st December.

11.1 Drilling

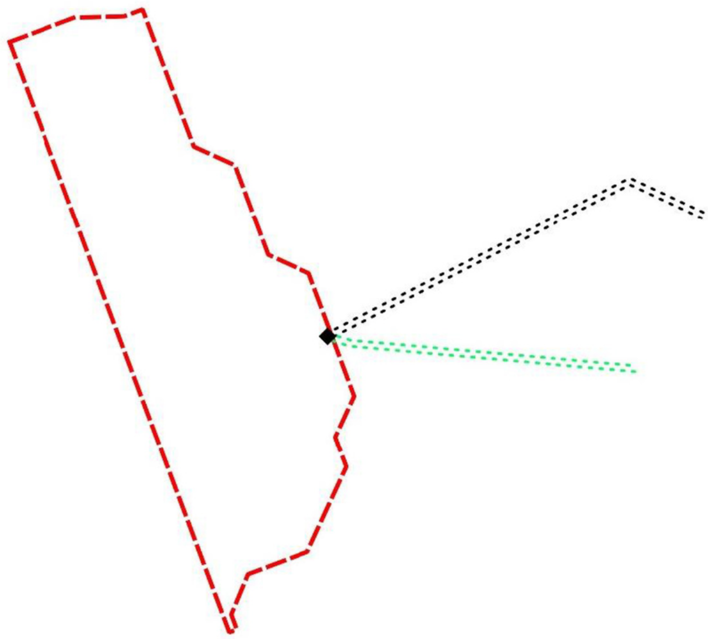
NIRAS has evaluated the geotechnical properties of the offshore Windfarm site and assessed that up to 15 % of the piles can be drilled to full depth, whereas the rest will be piled. Drilling will be done by a rotary drill head, cutting the soil loose and removing it from the drill head by use of an airlift system. The drill speed is 0.4-0.6 m / hr and the pump capacity 900 m^3 / hour (250 l / s) corresponding to 28.4 m^3 / hour or 56.7 ton / hour. The drilled material is pumped to the surface of the water column 10 m from the pile. For the 15 % of the monopiles assumed to be drilled the spill is estimated to 100 %.

11.2 Installation of cables

Two export cables will connect the offshore substation to shore each having a total length of around 34 km whereof only the first 10 km closest to the offshore windfarm was included in the modelling by NIRAS. However, the exact position of the routes has not been decided and two potential routes have been modelled for the sediment spill (figure 11.1.).

The cables will require some seabed preparation for burying the cables at a safe depth protected from anchors, fishing gears, etc. NIRAS has assessed that the seabed will be prepared by jetting as this installation methodology is the most conservative with a sediment spill of 100 %. For their modelling it was assumed that all cables were jetted.

Figure 11.1. Two potential routes for the cables connecting the Stora Middelgrund offshore wind-farm with the Swedish shore. The cables begins at the offshore substation (black square). Green turns east and black towards the north before going to shore. Copied from {NIRAS, 2020 #1130@@author-year}.



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 gravity foundation with the dimensions given in figure 11.2. The site needs preparation in the form of excavation assumed performed by jetting.

No	Length	Width	Scour protection	Operational safety margin	Excavation slope 1:3	Depth	Volume to be excava-ted	Total volume	Spill, 5%
[#]	[m]	[m]	[m]	[m]	[m]	[m]	[m^3/pos.]	[m^3]	[m^3]
1	100	50	5	2	3	2	16800	16800	840

Figure 11.2. Dimensions of the offshore substation with expected spill of 5 % amounting to 840 m^3. Copied from {NIRAS, 2020 #1130@@author-year}.

11.4 Model of sediment spill

For the modelling of the sediment spill, NIRAS assumed two scenarios based on the environmental temporal restrictions, narrowing the duration of the work to be performed between 1st September and 31st December:

One season of work:

18 MW monopile foundations with drilling of six positions.

Two seasons of work:

14 MW, 16 MW or 18 MW monopile foundations with drilling for 15 % of the positions. (Three different outputs).

The scenarios are shown in figure 11.3. In both scenarios, NIRAS included the installation of one offshore substation placed on a gravity foundation, jetting of two export cables (only for the first 6 km beginning at the substation) and jetting of the infield cables connecting the wind turbines with the offshore substation.

Item	Unit	Monopile		
Vattenfall layout	-	LSMG026	LSMG027	LSMG028
Capacity	MW	700	720	684
Capacity	MW/Unit	14	16	18
No.	#	50	45	38
Bottom diameter, base	m	10	11	12
Dredging/drilling depth	m	50	55	60
Vol. to be removed	m^3/pos.	3927	5227	6786
No. to dredged/drill	#	8	7	6
Total vol. foundation	m^3	31416	36588	40715
Spill, gross foundation	m^3	31416	36588	40715
Length infield cable	m	84453	87479	82685
Spill, gross infield cable	m^3	25336	26244	24806
Spill, gross	m^3	56752	62831	65521

Figure 11.3. The scenarios considered in NIRAS' modeled sediment spill analysis. Copied from {NIRAS, 2020 #1130@@author-year}.

The modeling showed that the larger the piles being drilled down, the more extensive the sediment spill is both in terms of area covered, duration and concentration (figure 11.4).

Case	Scenario	Duration										
		6	12	24	2	1	2	3	4	5	6	7
		[hours]	[hours]	[hours]	[days]	[weeks]	[weeks]	[weeks]	[weeks]	[weeks]	[weeks]	[weeks]
1, year 0	16 MW	1644	954	485	227	13	0	0	0	0	0	0
1, year 1	16 MW	972	446	168	54	32	22	16	5	0	0	0
1, year 0	18 MW	3813	2689	1804	1098	321	152	85	51	29	16	10
1, year 1	18 MW	966	455	179	54	32	21	15	5	0	0	0
2, MP	14 MW	2779	1778	1064	643	199	88	42	20	4	0	0
	16 MW	4232	2710	1655	977	324	128	52	19	7	2	0
	18 MW	4588	3136	2033	1179	339	160	88	53	29	17	10

Figure 11.4. Model output in hectares (ha) for concentrations above 10 mg/L equivalent to 0.01 kg/m^3 for the two scenarios: Scenario 1: two seasons of drilling, and scenario 2: one season of drilling. The Copied from {NIRAS, 2020 #1130@@author-year}.

11.5 Impact on marine mammals

Harbour porpoises forage by means of echolocation and therefore primarily dependent 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. Given that the habitat of the harbor porpoise also includes estuaries with heavy tide and thus suspended bottom material, it is assessed that the impact on harbor porpoises of this sediment spill, 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 harbor 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. 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, 2011). The impact from construction of the offshore windfarm at Stora Middelgrund is therefore assessed as **negligible** for seals of both species.

12 Conclusion

Construction and operation of an offshore wind farm on the Swedish part of Stora Middelgrund within the Stora Middelgrund & Röde Bank Natura 2000 site has been assessed with respect to impacts on marine mammals and Natura 2000 sites. 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 seals are abundant in the area and the population is in favourable conservation status. Harbour seals are assessed moderately sensitive to disturbance from underwater noise throughout the year as there are no haul-outs within the proposed offshore windfarm site.

- 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. Grey seals are assessed moderately sensitive to disturbance from underwater noise throughout the year, as there are no haul-outs within the proposed offshore windfarm site.

- Harbour porpoises are abundant and the population is in favourable conservation status. Harbour porpoises are assessed highly sensitive to disturbance from underwater noise throughout the year

- 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.

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

- Pile driving without noise abatement systems is unlikely to be allowed in the Natura 2000 site, but would expose seals and porpoises to levels capable of inflicting permanent hearing loss.

- Use of powerful noise abatement measures, such as a combination of hydro sound dampeners and double big bubble curtains 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 of both porpoises and seals are likely to occur at very large ranges for pile driving under worst case unabated conditions in February. For both seals and porpoises the impact of construction in winter months without noise abatement is assessed to be **major**.

- By following best environmental practise, restricting pile driving to periods 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) in combination with the use of best available technology in terms of noise abatement systems (e.g. HSD+DBBC), the impact on seal and porpoise populations by construction can be reduced to **minor**.

- 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**.

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

12.3 Impact on Natura 2000 sites

- Pile driving without noise abatement systems is likely to increase the noise to levels above the behavioural reaction threshold for harbour porpoises within all or most of the Natura 2000 sites Stora Middelgrund & Röde Bank, Lilla Middelgrund, Store Middelgrund (DK), Fladen, and Skånes Nordvästvatten; as well as significant parts of Anholt, Balgö, and Gilleleje Flak and Tragten Natura 2000 sites 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 areas during construction in winter months without noise abatement is assessed to be **unacceptable.**

- The impact of construction in periods of the year with sound propagation properties less favourable for long-range propagation, and with the use of effective noise abatement, the impact on the Stora Middelgrund & Röde Bank and Store Middelgrund (DK) Natura 2000 area is assessed to be **unacceptable** according to the JNCC guidelines**.**

- Use of best available technology, i.e. effective noise abatement system combining hydro sound dampeners and double big bubble curtains (or similar) to reduce emitted noise levels during pile driving combined with best environmental practise of choosing a period with reduced sound velocity, is likely to reduce the impacted area of Stora Middelgrund & Röde Bank Natura 2000 sites. However, in order to be below the JNCC threshold of maximum 20 % impacted area of a Natura 2000 site, an additional up to 11 dB mitigation is required, depending on season and location. If this can be achieved, the impact can be reduced to **acceptable**.

- Across the season (winter or summer), the average maximum disturbance threshold set by JNCC is 10 %. In order to achieve this under the above stated conditions of BAT, BEP and extra mitigation at the source, a piling schedule must be prepared in order to reduce the number of days with piling per season, to be below the 10 % threshold. If this can be obtained the impact is assessed as **acceptable** with regards to the JNCC guidelines.

- Under the same best case conditions with extra noise abatement, the impact on the nearby Natura 2000 sites Lilla Middelgrund, Skånes Nordvästvatten Fladen, Anholt, Balgö, and Gilleleje Flak and Tragten is accessed as **acceptable**.

- If pilling can be replaced by gravity foundations, the impact on the Store Middelgrund and Stora Middelgrund & Röde Bank Natura 2000 sites is assessed to be acceptable, as < 20 % of the combined Natura 2000 site is impacted.

12.4 Impact from operation

- Impacts from operation of the wind farm is less studied, but considered to have negligible negative impacts on marine mammals and may have positive effects in the form of creation of artificial reefs on the turbine foundations.

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Appendix 1 Sound propagation modelling

As described in section 5, the assessment method for the impact of underwater noise on marine mammals, requires extensive modelling of the underwater sound propagation of pile driving noise, in order to calculate sound exposure levels related to the marine mammal impact threshold criteria (section 6).

As described in section 5.6, it is proposed to combine the frequency weighted SEL_{cum} metric with the assumption that a marine mammal exposed to unpleasant sound levels will flee in the direction away from the noise. The metric is referred to as $SEL_{<Species>cum,fleeing}$ for the remainder of this appendix.

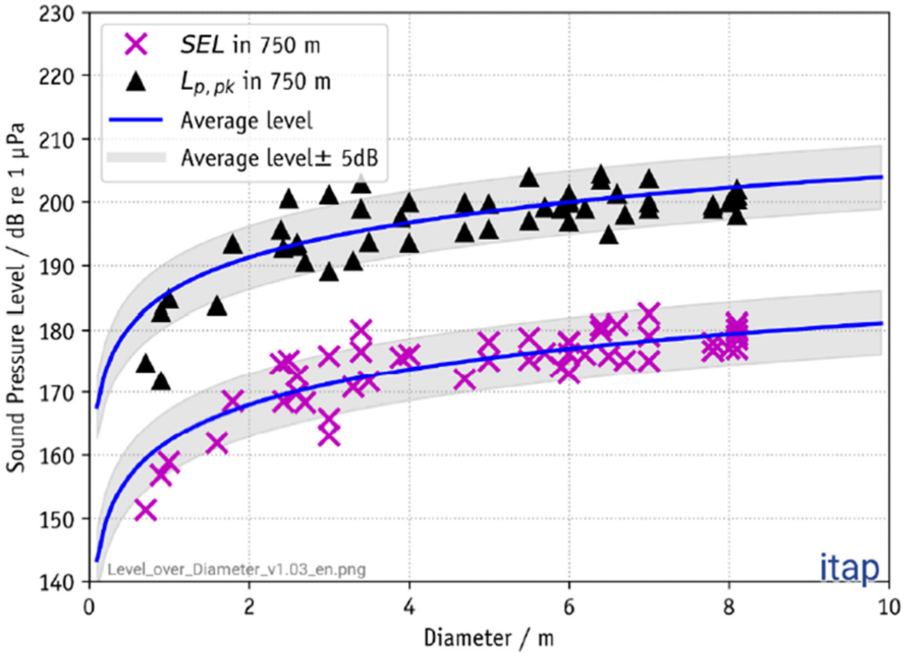
Source Characteristics

According to Vattenfall Stora Middelgrund Vind AB, wind turbine foundations will be monopiles of diameter 12 m or 15 m, depending on the chosen turbine model.

Pile driving source level

The newest published knowledge on measured sound levels from pile driving activities in (Bellmann, et al. 2020), provides a graphic summary of measured source levels as a function of pile size. This is shown in **Figure A1.1**.

Figure A1.1. Relationship between measured SPL and SEL levels at 750 m distance, and pile size (Bellmann, et al. 2020).



The measurements are all normalized to 750 m distance from the pile, as this is the required measurement distance in German underwater noise regulation.

Examining **Figure A1.1**,the blue curve indicates the best fit of the measurement results. For the Sound Exposure Level (SEL) results, this relationship between pile size and measured level is approximately $\Delta SL = 19 * log10(\frac{D2}{D1})$, D1 and D2 being the diameter of 2 piles, and ΔSL being the number of dB difference in source level between the two.

It should be noted however, that some variations for a certain pile size do occur, as indicated by the spread of datapoints, around the fitted lines. This is considered to be a result of varying site conditions and hammer efficiency applied for the individual pile installations. For any project, it should therefore be considered whether the site and project specific conditions call for a more cautious source level estimate.

Vattenfall Stora Middelgrund Vind AB has requested sound propagation modelling for the following monopile sizes and hammer energy combinations:

1. 12 m monopile installed at 40 m depth, using 6000 kJ

2. 15 m monopile installed at 40 m depth, using 7000 kJ

Extrapolating the curve to the requested pile sizes, would indicate sound levels at 750 m of $SEL_{unweighted,ss,750m} = 182.9\ and\ 184.8\ \ dB\ re\ 1\ \mu Pa^2 s$ for the 12 m and 15 m monopiles respectively.

Using Thiele's equation for sound propagation (Thiele, 2002) proposing a 4.5 dB increase in sound level pr. halving of distance, the resulting increase from 750 m distance to 1 m distance equals 43.1 dB.

This would indicate source levels at 1 m distance of $SEL_{unweighted,ss,1m} = 226.0\ and\ 227.9\ dB\ re.1\ \mu Pa^2 s$ for the three monopile sizes.

It is worth noting, that even the newest measurements are limited at 8.1 m monopiles, and that any extrapolation of source level of piles, beyond this size, is associated with considerable uncertainty. In our opinion the data of Bellmann et al.(Bellmann, et al. 2020) presents the best available knowledge in the field to date, and it is therefore used to dictate the extrapolation of source level.

Due to the high pile driving hammer energies proposed by Vattenfall Stora Middelgrund Vind AB, as well as installation at 40 m water depth, stiff clay sediment with gravel and boulders in a large part of the project area, a cautious 2.5 dB penalty is proposed of which the increased hammer energy is estimated to cause a 1.5 dB increase over average levels on the above figure.

The source levels $SEL_{unweighted,ss,1m}$ to be used for sound propagation modelling was therefore agreed with Vattenfall Stora Middelgrund Vind AB to be:

- 12 m monopile installed at 40 m depth, using 6000 kJ: SEL1m = 228.5 dB re. 1 µPa²s

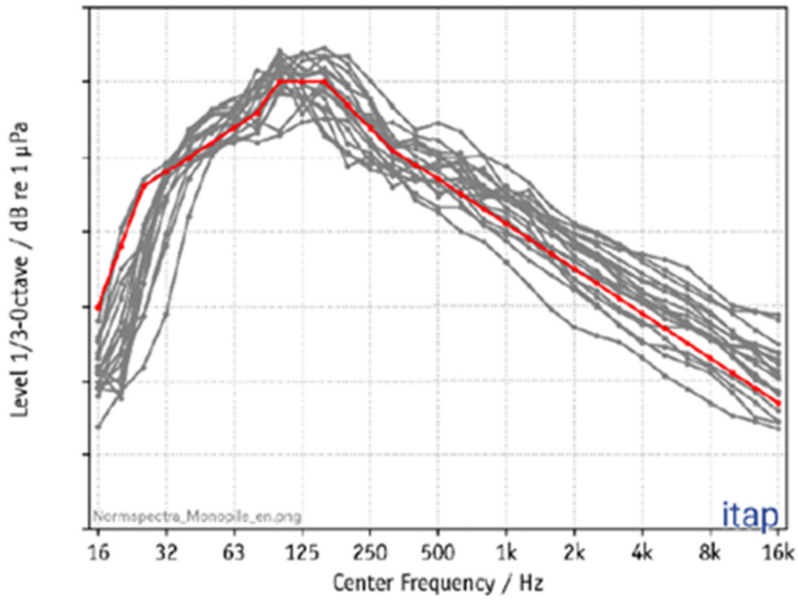
- 15 m monopile installed at 40 m depth, using 7000 kJ: SEL1m = 230.4 dB re. 1 µPa²s

Pile driving frequency spectrum

Given the unweighted source level $SEL_{unweighted,ss,1m}$ for the 12 m and 15 m monopile, the frequency composition of the source must be determined in order to determine the $SEL_{<Species>,ss,1m}$.

Due to the natural variations of measured frequency content between sites, piles, water depths, hammer energy levels and other factors, it was decided to use a generalised spectrum, as it is almost guaranteed that the frequency response measured for one pile will differ from that of any other pile. In (Bellmann, et al. 2020) it is proposed to use the idealized pile spectra, as presented in **Figure A1.2** (red), with detailed 1/3 octave band levels shown in Table A1.1 for the 15 m monopile. For the 12 m monopile, all values are 1.9 dB lower. It should be noted, that the red line represents the median of all measured impulses, and that it is only used to determine the source frequency spectrum, and does not have influence on the overall source level.

Figure A1.2. Idealized pile driving frequency spectrum (blue). Source:(Bellmann, et al. 2020).



Frequency spectrum range tests

To assess the frequency spectrum range of interest over long distances, test calculations were run in three directions from a random location within the Stora Middelgrund wind farm site. At both 750 m, 4 km and 10 km distance, all tests indicated that the noise level in the frequency band above 32 kHz were, at all distances, more than 10 dB below the highest level observed within the frequency range of 16 Hz – 32 kHz. Thus the upper frequency range of the modelling was limited to the 32 kHz octave band. It should furthermore be noted, that published information, such as (Bellmann, et al., August 2020), is typically limited to include frequencies up to 16 kHz/20 kHz. Modelling frequencies beyond this limitation is therefore connected with a degree of uncertainty.

Marine mammal weighted source levels

Combining the $SEL_{unweighted,ss,1m}$ with the idealized frequency spectrum presented in **Figure A1.2** (red), and the weighting curves for the marine mammal groups identified in section 2.5, it is now possible to determine weighted source levels $SEL_{<Species>,ss,1m}$, which are used for the impact assessment. The unweighted and weighted monopile source levels are all listed in Table A1.1, both as broadband, and for each 1/1-octave bands in the frequency range.

Table A1.1. Source level estimates in 1/1 octave frequency bands and overall weighted source level (SL) for a 15 m monopile. Unabated levels. Top row indicate octave band centre frequency (Hz). Levels are given in dB weighted according to the weighting given in the leftmost column, either no weighting (broad band), VHF-cetacean (porpoises) or phocid seals (harbour seal and grey seal). Unit for all values are dB re. 1 μPa²s.

Weighting	16	31.5	63	125	250	500	1k	2k	4k	8k	16k	32k	Broadband
Unweighted	210,8	219,4	223,9	227,9	220,6	210,1	202,9	198,5	192,1	187,4	182,5	179	230,4
VHF	109,5	128,9	144,2	159	162,4	162,8	166,2	172,4	176,1	179,8	180,2	178,8	185,4
PW	170,3	184,9	195,4	205,4	204	199,2	197,1	196,4	191,7	187,3	181	173,4	209,2

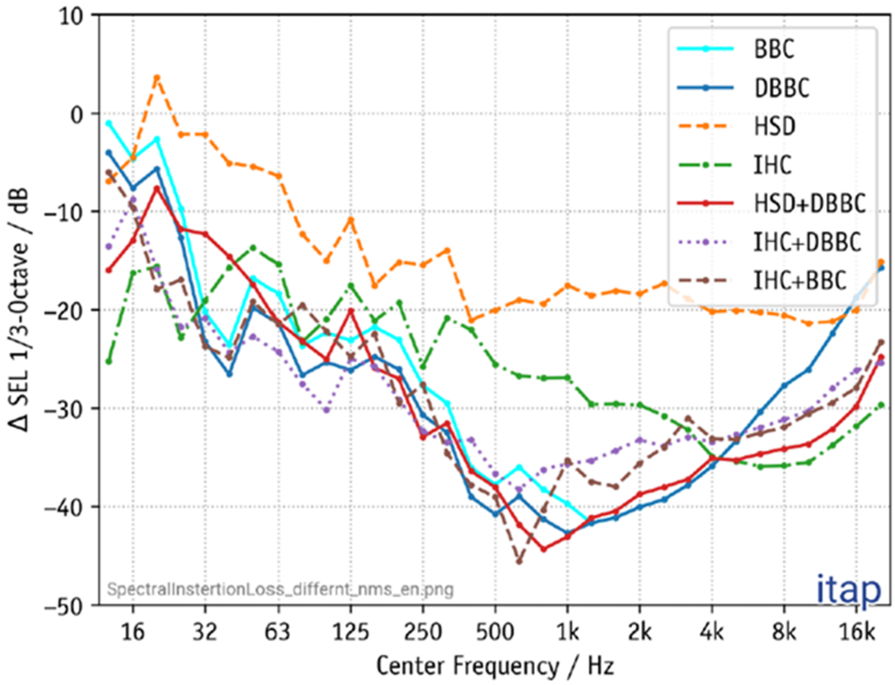
Source mitigation measures

Due to the high source level of the pile installation procedure, it is expected that source mitigation measures, commonly referred to as Noise Abatement Systems (NAS) will be required to avoid negative impact caused by excessive noise levels. In agreement with Vattenfall Stora Middelgrund Vind AB, an approach of best-available technology is applied, and must be included as a basic condition for the installation.

In this section, the technical aspect of the application of noise mitigation is described, whereas the reader is referred to section 3.6 for general information.

In (Bellmann, et al. 2020), the noise mitigation effect of different versions of Bubble Curtains (BC) and combinations of such with other systems for previous offshore wind farm installations are examined, and the achieved sound mitigation in dB is presented as the averaged difference spectra, in 1/3 octave bands, of the SEL05, defined as the 5% exceedance level, or the level that is exceeded only 5% of the time, see **Figure A1.3**. This is understood to be the average 1/3 octave level effect of an active mitigation system vs. reference (no mitigation system), as achieved in 95% of all pile installation samples included in the analysis. This includes samples from offshore wind farm constructions between 2011 – 2019, and given the continued scientific advances in development of noise abatement systems, it must therefore be assumed, that an average of the effect achieved throughout these years, would be conservative when applied to the achievable mitigation effect for future projects.

Figure A1.3. Achieved pile driving sound level attenuation from different noise abatement systems, given as SEL05, averaged over all tests (without mitigation vs. with mitigation system active). (Bellmann, et al. 2020).



As described in section 3.6.1, it was chosen to use the average Hydro Sound Damper & Double Big Bubble Curtain (HSD-DBBC) attenuation values from (Bellmann, et al. 2020) in the calculations. This is represented by the red solid line in **Figure A1.3**.

Table A1.2. Source level estimates in 1/1 octave frequency bands and overall weighted source level (SL) for a 15 m monopile, with HSD + DBBC source mitigation system. Top row indicate octave band centre frequency (Hz). Levels are given in dB weighted according to the weighting given in the leftmost column. Unit for all values are dB re. 1 µPa^{2}s. Compare to Table A1.1 for source characteristics without noise reduction implemented.

Weighting	16	31.5	63	125	250	500	1k	2k	4k	8k	16k	32k	Broad-band
Unweighted	200	206,3	202,6	203,6	189,3	170,7	160,1	159	156,3	153,7	152,6	160,8	209,8
VHF	98,7	115,8	122,9	134,7	131,1	123,4	123,4	132,9	140,3	146,1	150,3	160,6	161,2
PW	159,5	171,8	174,1	181,1	172,7	159,8	154,3	156,9	155,9	153,6	151,1	155,2	182,8

The HSD-DBBC mitigation was implemented in the software dBSea, and the resulting mitigated source levels are presented in **Table A1.2**. Overall broad band attenuation of the HSD-DBBC is 20.6 dB (found by comparing unweighted source levels from Table A1.1 and **Table A1.2**), while the effect for VHF-weighted SEL is 24.2 dB and for phocid-weighted SEL is 26.4 dB.

Calculation of sound propagation are only carried out with the proposed mitigation system in effect, as it is not considered realistic, that a no-mitigation installation will be possible / allowed.

Using the mitigation effect listed in literature is connected with a degree of uncertainty, as to whether the same effect will be achievable in this project for a number of reasons.

- Firstly, the mitigation data presented in (Bellmann, et al., August 2020), does not specify the results by specific projects, geographical location or oceanographic conditions.

- Secondly, the mitigation effect is summarized over multiple projects and pile locations, with differences in the mitigation system setup, including differences in bubble rate (air pressure through BBC hoses), as well as HSD design (element size, spacing and density).

- Thirdly, all results for measurements of applied mitigation systems have been for pile sizes significantly below those proposed in this project, and it is therefore uncertain whether the same effect is likely for larger piles

In summary, significant uncertainties are likely between mitigation effects achieved in previous projects, and what is achievable in future projects. However, there is a strong focus on the continued development of mitigation systems and pile installation methods, to reduce the underwater noise emission from pile installation. Mitigation systems are therefore expected to become more and more effective with time, and it is therefore assessed, that it is very likely that mitigation effects, as listed in (Bellmann, et al., August 2020), are indeed plausible for future projects.

Pile Installation Procedure

This section describes the expected pile installation procedure for the project, and identifies the parameter values S_i, N and Δt_i, which describes the pile driving hammer scenario used for this assessment (described in section 585.4). Foundations are expected to be installed at a maximum rate of one foundation per day. Each pile installation will consist of three phases. The first phase is a pre-piling deterrent phase, where marine mammals are deterred from the immediate surroundings of the pile location. See section 5.6 for additional details. The second phase is a soft-start piling phase, where a low hammer energy is used to settle the pile followed by a gradual ramp-up of hammer energy based on the sediment conditions, to account for the increased friction and resistance of harder sediment layers. Ultimately the third and final phase is reached, where piling continues with maximal hammer energy until the monopile has reached the desired depth.

For this assessment, a final pile design and driveability analysis has not been performed, and it is therefore not yet known what the frequency of pile strikes, nor the hammer energy applied, will be. It was therefore decided to take a precautious approach, for the sake of this assessment representing the worst-case scenario. This scenario was described in section 5.3.

Underwater Sound Propagation

This section will give a brief overview of underwater sound propagation theory and the software program used to model it, followed by a description of the environmental inputs required by the sound propagation model.

Underwater sound propagation theory

The theory in this section is drawn from the book, Computational Ocean Acoustics, 2nd edition (Jensen et al. 2011), chapter 1 and 3.

The section seeks to provide a brief introduction to sound propagation in saltwater. The interested reader is referred to Computational Ocean Acoustics, 2nd edition, for a more exhaustive explanation of underwater sound propagation theory.

In saltwater, the 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 pressure, salinity and temperature, all of which are dependent on depth and the climate above the ocean, and as such are very location specific.

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.

Snell's law states that:

Equation 1.1

$$\frac{\cos(\theta)}{c} = constant$$

Where θ is the ray angle, and c is the speed of sound [m/s], thus implying that sound bends 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 a very low 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. This scenario will always be the worst case situation in terms of sound transmission loss.

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 absorption and reflection of the seabed, that determines the transmission loss.

In any general scenario, the upward refraction scenario will cause the lowest transmission loss, and thus be considered worst case.

In waters with strong currents, the relationship between temperature and salinity is relatively constant as the water is well-mixed throughout the year. In the Kattegat however, 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 change between upward and downward refraction.

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 properties that define how the sound propagation is affected by the upper and lower 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. In rough seas, the sound waves will to a higher degree be reflected backwards toward the source location, and thus result in an increased transmission loss in the outward direction. In the context of implementing these changes into the model, the different surface conditions are simply too unpredictable, to serve as a reliable variable. It is therefore always the most conservative scenario, being a completely smooth sea surface, that is used in the calculations.

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

Equation 1.2

$$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 3.0 \times 10^{-4} f^2 \qquad (dB/km)$$

Where f is the frequency of the wave in kHz{Jensen, 2011, Computational Ocean Acoustics`, 2nd edition}. This infers that increasing frequency also leads to increased absorption.

Underwater noise modelling software

Software for underwater noise modelling software was dBSea version 2.2.5, developed by Marshall Day Acoustics (Pedersen and Keane 2016).

The software uses bathymetry, sediment and sound speed input data to build a 3D acoustic model of the environment. This model, paired with accurate sound propagation models, such as dBSeaPE, a Parabolic Equation algorithm and dBSeaRay, a Ray Theory algorithm, make for accurate prediction of the sound propagation.

Parabolic equation algorithms are known to be the most accurate for modelling low frequencies in shallow water scenarios, while ray theory algorithms deliver the best performance at higher frequencies.

As described in section 0, the sound propagation depends primarily on the site bathymetry, sediment and sound speed conditions. These are examined in the following.

Bathymetry

dBSea incorporates range-dependent bathymetry modelling, and supports raster and vector bathymetry import. Several open databases, such as the EMODnet Bathymetry portal - provide bathymetric maps for all of EU, however with limited resolution of 0.125 arc-minutes between data points.

For long range sound propagation modelling as is the case in this project, the resolution is generally considered sufficient. A bathymetry map from the EMODnet portal was therefore acquired, and implemented in dBSea.

dBSea provides the option of using either a single or a multi-point sediment model. The multi-point model allows for different sediment profiles within the project area, while the single point sediment model uses the same sediment composition for the entire project area.

For small project areas, the sediment variations in the project area will usually be acoustically insignificant, and single point models will therefore be preferred. For projects where long distance sound propagation is required, a multipoint model could deliver more accurate results.

Niras has, with the help of DCE, attempted to identify the different sediment layers in the surrounding area of Stora Middelgrund. Sources studied include the geological maps supplied by Vattenfall Stora Middelgrund Vind AB, the geological reports, and publicly available databases EMODnet-geology.EU, GEUS.dk, SGU.se. Also, the book "Danmarks Geologi" chapter 4, was used to identify the thickness of the chalk layer.

Due to the varying nature of sediment composition in the area around Stora Middelgrund, it was chosen to use a multi-point sediment model representing the broad average of the area. This resulted in an 8 point model as illustrated in **Figure A1.5**. Between points, dBSea interpolates the layer information. Acoustic parameters used for the different layers follow (Jensen, Kuperman, Porter, & Schmidt, 2011), as referenced in **Figure A1.4**.

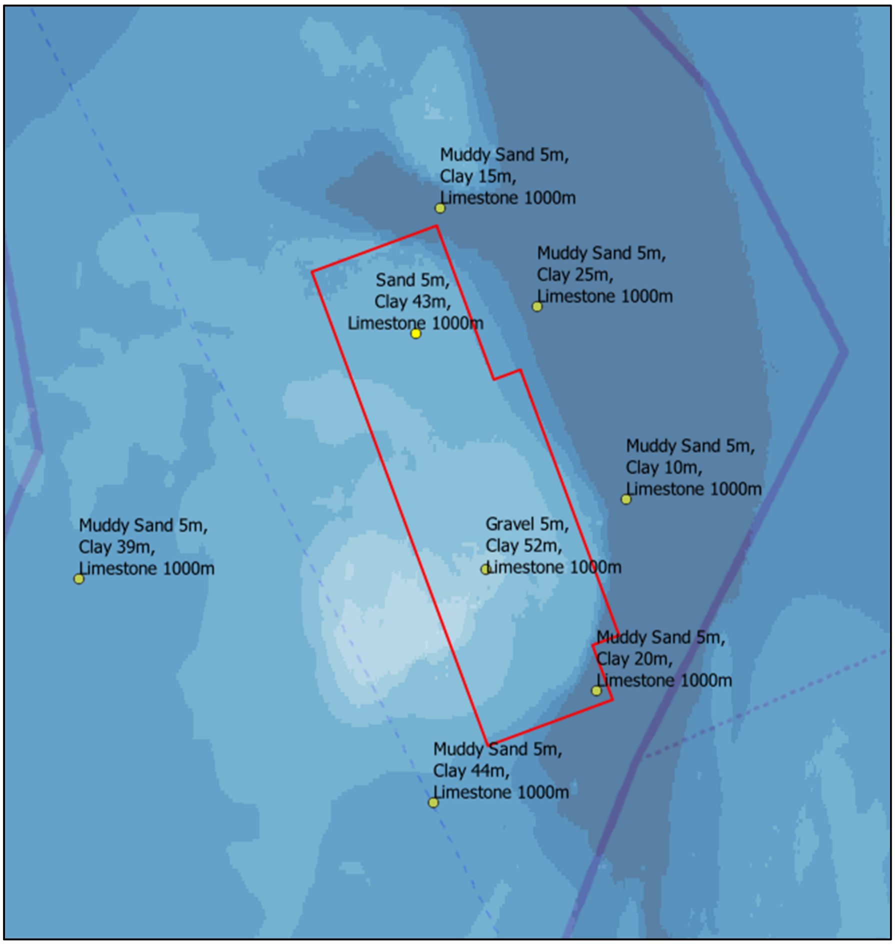
Figure A1.4. Geoacoustic properties of sediment layers used in the model (Jensen, Kuperman, Porter, & Schmidt, 2011).

Table 1.3 Geoacoustic properties of continental shelf and slope environments

Bottom type	p (%)	ρ_b/ρ_w –	c_p/c_w –	c_p (m/s)	c_s (m/s)	α_p (dB/λ_p)	α_s (dB/λ_s)
Clay	70	1.5	1.00	1500	<100	0.2	1.0
Silt	55	1.7	1.05	1575	$c_s^{(1)}$	1.0	1.5
Sand	45	1.9	1.1	1650	$c_s^{(2)}$	0.8	2.5
Gravel	35	2.0	1.2	1800	$c_s^{(3)}$	0.6	1.5
Moraine	25	2.1	1.3	1950	600	0.4	1.0
Chalk	–	2.2	1.6	2400	1000	0.2	0.5
Limestone	–	2.4	2.0	3000	1500	0.1	0.2
Basalt	–	2.7	3.5	5250	2500	0.1	0.2

$c_s^{(1)} = 80\,z^{0.3}$ $\quad c_w = 1500$ m/s, $\rho_w = 1000$ kg/m^3
$c_s^{(2)} = 110\,z^{0.3}$
$c_s^{(3)} = 180\,z^{0.3}$

Figure A1.5. Multi-point sediment model as implemented in dBSea.

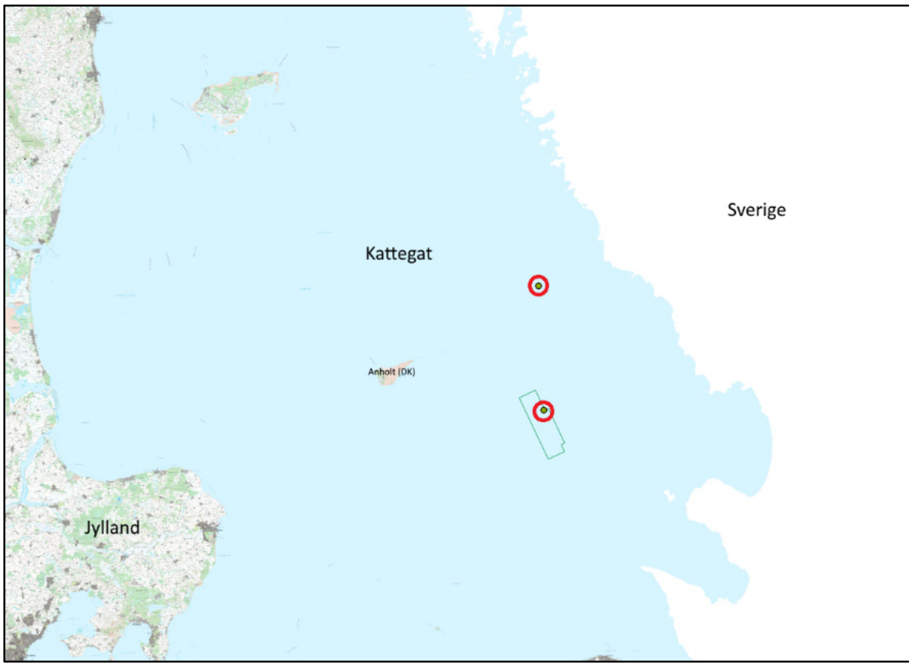


Sound speed profiles

As described, the sound propagation depends not only on bathymetry but also the season dependent sound speed profile. Temperature, depth and salinity information from NOAAs World Ocean Atlas database (WOA18), available from the "National Oceanic and Atmospheric Administration" (NOAA) at was thus inspected. Through the Coppens Equation, this was used to calculate the sound speed profile {A.B., 1981, Simple equations for the speed of sound in Neptunian waters} for all but 2 (July and August) months of the year at the location nearest Stora Middelgrund. It was decided to proceed with the months of February and May. February represents a worst-case scenario with a surface sound speed minimum, which will lead to upward-refraction of the sound and thus increased sound exposure in the water column. May represents a typical summer scenario, with near-iso speed sound profile and thus higher attenuation of sound over distance.

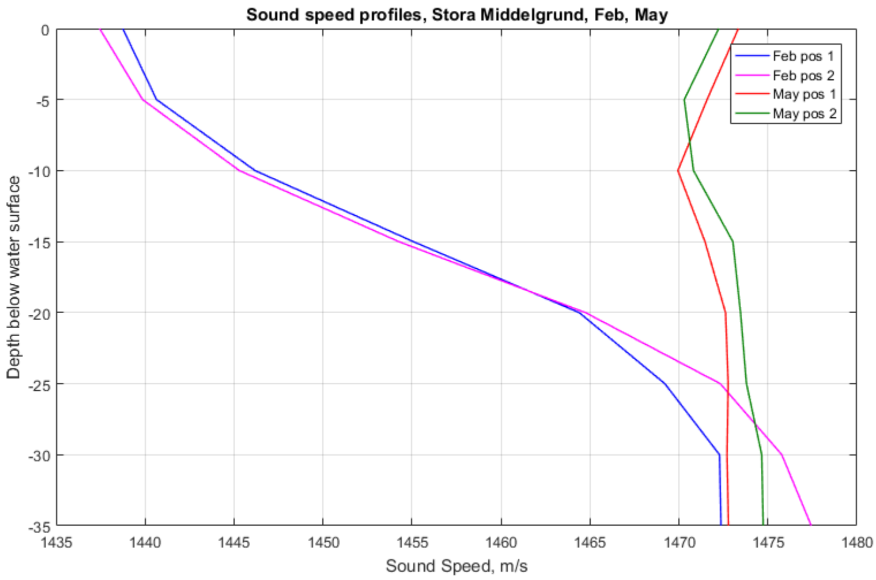
The WOA18 database was then accessed again, to extract additional information from the 2 positions nearest Stora Middelgrund, for which information was available for the month of February and May. The positions are shown on **Figure A1.6** and information from these locations have been assigned to the closest positions used in the sediment map.

Figure A1.6. Illustration of Store Middelgrund (green rectangular field), and the nearest data points from WOA18, (by red circles), with temperature and salinity information for the months of February and May.



The sound speed profiles calculated for the two positions, are shown in **Figure A1.7** for February (blue) and May (red), where the northern most position is labelled position 1, and the on-site position is labelled position 2.

Figure A1.7. Sound speed profile for the two positions in February (blue) and May (red).



As shown in **Figure A1.7** winter conditions tend to lead to upward refracting (lower calculated transmission loss), and summer to near-iso refraction (higher calculated transmission loss). In Table A1.3, the input parameters for the sound speed calculation (temperature and salinity profiles) are shown.

Table A1.3. Input parameters for the sound speed calculation.

Month:	February				May			
Position:	1		2		1		2	
Parameter: / Depth [m] below sea level	Temperature [°C]	Salinity [ppt]	Temperature [°C]	Salinity [ppt]	Temperature [°C]	Salinity [ppt]	Temperature [°C]	Salinity [ppt]
0	2,2	19,6	2	19,3	11,4	17,2	11,1	17,2
5	2,4	20,3	2,4	19,7	10,9	17,2	10,2	18,3
10	3,1	22,1	2,9	22,1	9,6	19,8	8,9	22,7
15	4	25,9	3,9	25,6	7,1	28,8	6,8	31
20	5,2	29,2	5,1	29,8	6,2	32,5	6	33,8
25	5,8	31	6,2	32,2	5,9	33,5	6	34
30	6,2	32,1	6,8	33	5,8	33,7	6,1	34,3
35	6,2	32,1	7,3	32,7	5,8	33,7	6,1	34,3
40	6,2	32,1	7,3	32,7	5,8	33,7	6,1	34,3

Summary of environmental inputs

- Bathymetry from EMODNET is used. Resolution is 0.125 arc-minutes.
- Sediment profiles are implemented in 8 positions on and around Stora Middelgrund
- Sound speed profiles for February and May have been calculated from WOA18 from the 2 nearest positions, and mapped to the 8 sediment positions.

Choice of pile installation locations

A layout for the wind farm has not yet been proposed, and it was therefore agreed to consider two positions, located at each end of the site to represent the sound propagation for the wind farm site. The positions are shown in Figure A1.8, where position 1, was chosen due to its location in the deeper part of the area, and position 2, positioned in the shallower part of the area. This to offer insight into the range of sound propagation within the site. Position 1 would in this respect represent a conservative noise emission scenario, while position 2, would determine the effect of the shallow waters.

The longitude, latitude coordinates (EPSG: 32632) are [689684 ; 6284128] for position 1 and [691176 ; 6273059] for position 2.

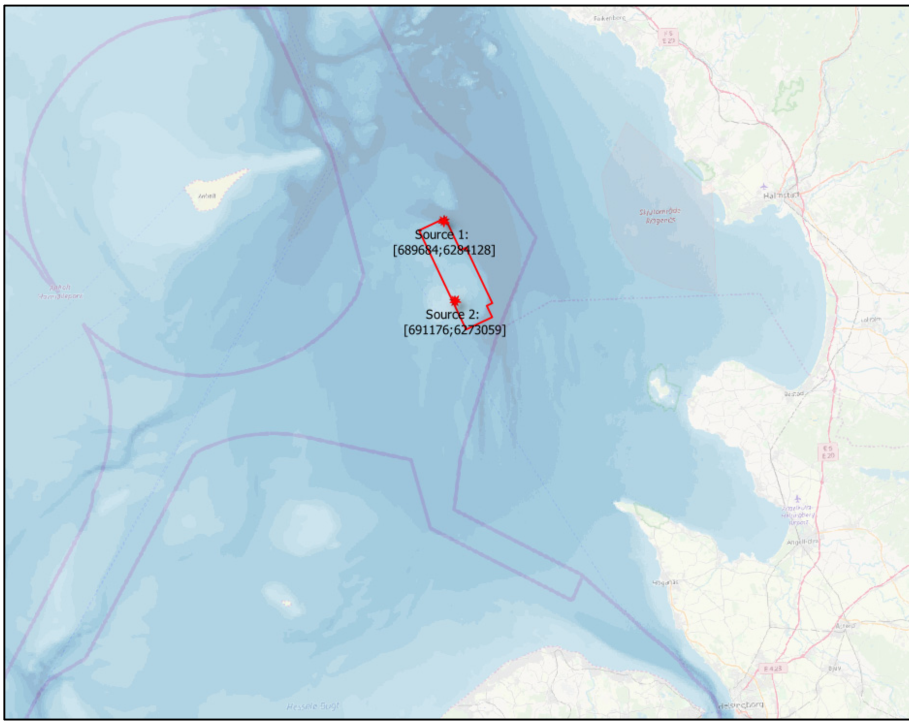


Figure A1.8. Overview of chosen pile installation positions for the Stora Middelgrund offshore wind farm, where Position 1: [689684 ; 6284128] and Position 2: [691176 ; 6273059].

Sound propagation modelling results

To determine the parameters κ and α required by the transmission loss model (section 2.4), a sound propagation model was built in dBSea 2.2.5, based on all source and environment information presented so far.

Based on the water depth for the area, it was decided to use a split-solver approach, where the dBSeaPE algorithm was used for the low frequencies from 16 Hz – 500 Hz, and where the dBSeaRay algorithm was used for the high frequencies from 1 kHz – 32 kHz.

It was decided to model the sound exposure level at $\cong 120\ m$ interval, matching the bathymetry detail level, and with a spatial resolution of 1° (360 directions). The depth interval between each sampling was 1 m. Individual models were designed in dBSea for each combination of source position (1, 2), months (February, May) and pile size. Calculations were carried out using a Noise Abatement System with a minimum effect corresponding to the HSD-DBBC presented in section 0.

From each of the models, the sound transmission loss was calculated through curve fitting, determining 95th percentile levels for each of the 360 calculated radials. This, combined with the conditions for incorporation of pile installation scenario and marine mammal fleeing speed, the impact distances for PTS, TTS and avoidance behaviour were determined for each of the scenarios in each direction.

In **Table A1.4**, the maximum threshold impact distance over all 360 radials, are given for each combination of month and position and impact threshold.

Table A1.4. Threshold impact distances for 12 m and 15 m monopile installation scenarios. All results include source mitigation equal to the effect of HSD-DBBC.

Hearing Group	Fleeing Speed [m/s]	Pilesize [m]	Position and month	Distance to impact threshold $SEL_{C24,weighting}$ TTS [m]	$SEL_{C24,weighting}$ PTS [m]	$SPL_{RMS,fast,VHF}$ Behaviour [m]
Very High frequency Cataceans	1.5	12	Position 1 February	<50	< 25	6450
			Position 1 May	<50	< 25	4200
			Position 2 February	<50	< 25	6050
			Position 2 May	75	< 25	2750
Phocid Pinniped			Position 1 February	< 50	< 25	-
			Position 1 May	< 50	< 25	-
			Position 2 February	< 50	< 25	-
			Position 2 May	< 50	< 25	-
Very High frequency Cataceans		15	Position 1 February	75	< 25	7650
			Position 1 May	<50	< 25	4700
			Position 2 February	50	< 25	6950
			Position 2 May	100	< 25	3300
Phocid Pinniped			Position 1 February	< 50	< 25	-
			Position 1 May	< 50	< 25	-
			Position 2 February	< 50	< 25	-
			Position 2 May	< 50	< 25	-

In addition to the maximum impact ranges, the more nuanced results, are shown graphically in noise contour maps where the overall area affected by noise over the impact threshold levels are shown. As shown in **Table A1.4**, the threshold impact distances for PTS and TTS are however very short, and are therefore not considered relevant to represent the noise contour maps. The focus is therefore on the longer impact distances for the avoidance behaviour threshold. These are shown in Appendix 2, with an example also shown in **Figure A1.9**.

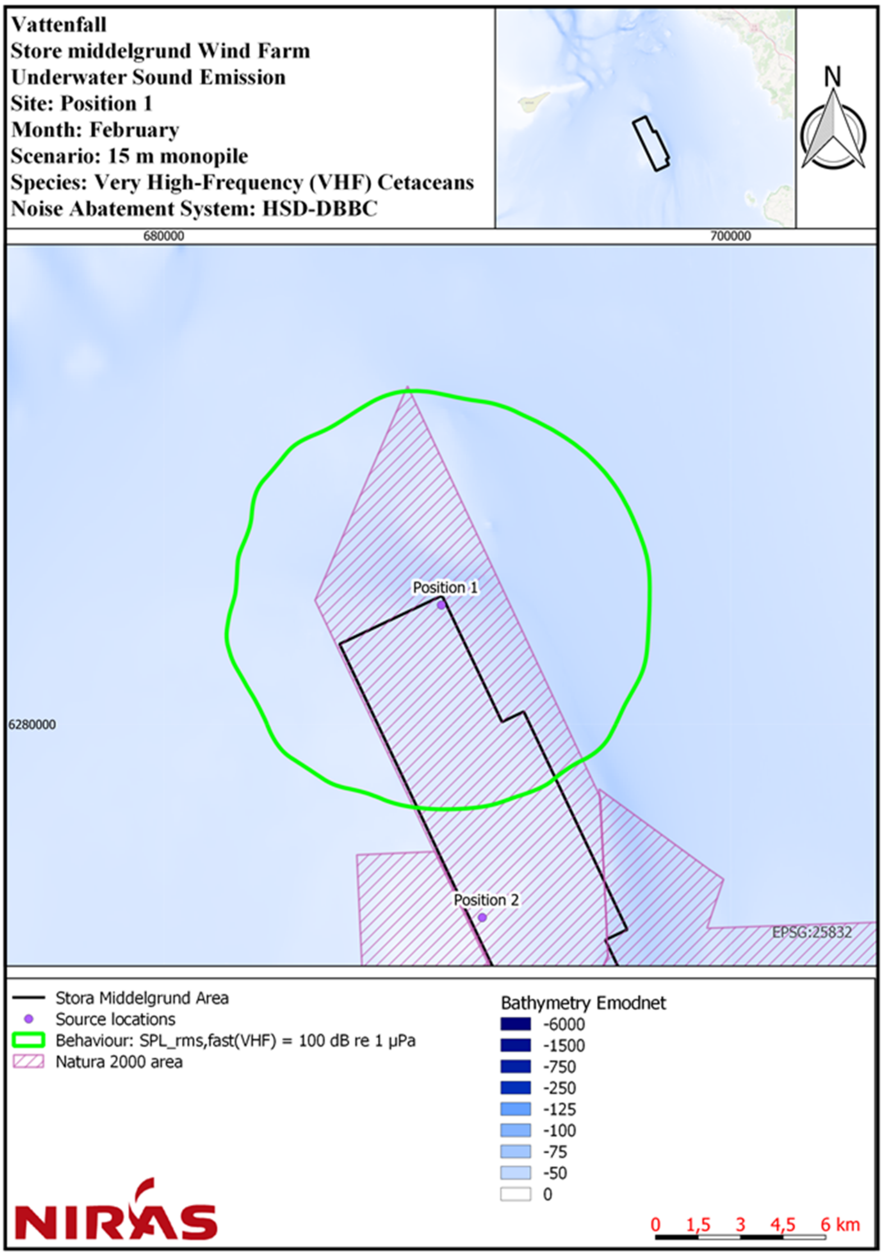


Figure A1.9. Noise contour map example, where the Behaviour threshold distance for a single pile strike at maximum hammer energy is shown (green contour).

Also analysed from the underwater sound propagation calculations, is the overlap between avoidance behaviour with the Natura 2000 sites (DK and SE Store Middelgrund). The overlapping areas are given in Table A1.5, and shown graphically in Appendix 2 – Sound propagation results.

Table A1.5. Overlapping area with Natura 2000 sites (DK and SE) Store Middelgrund. The combined area of the Natura 2000 site of 135 km2 is used for calculation of the overlap in %. The overlap assumes the use of a Noise Abatement System equal in effect to the HSD-DBBC

Scenario	Position 1 February	Position 1 May	Position 2 February	Position 2 May
12 m monopile	65 km^2 = 48,1%	32 km^2 = 23,7%	70 km^2 = 51,9%	19 km^2 = 14,1%
15 m monopile	72 km^2 = 53,3%	37 km^2 = 27,4%	77 km^2 = 57,0%	24 km^2 = 17,8%

One of the criteria, as described in section 4.5 above, is that an overlap of avoidance behaviour threshold with the combined Natura 2000 site for Store

Middelgrund (DK+SE) must not exceed 20% for any one pile installation. From Table A1.5, it is seen that for 6 of 8 pile installation scenarios, this overlap limit is exceeded. Only position 2 for the month of May is in compliance with the limit. In order for the remaining 6 scenarios to be in compliance with the limit, the source level must be mitigated further.

The additional required source level mitigation has been determined for the 6 scenarios, and are listed in Table A1.6, where the additional mitigation effect, provided as ΔSEL_{VHF}-values. This metric implies, that the additional mitigation effect to be achieved must be related to the VHF-frequency weighting function.

Table A1.6. Additional source mitigation requirements to comply with 20 % maximum overlap of Natura 2000 sites (DK and SE Store Middelgrund combined). The listed source mitigation requirements are in addition to the already included effect of the HSD-DBBC.

	Mitigations requirement [dB]			
Scenario	**Position 1 February**	**Position 1 May**	**Position 2 February**	**Position 2 May**
12 m monopile	**9**	**2**	**8**	**0**
15 m monopile	11	4	10	0

If a combined NAS with effect equal to or better than the used HSD-DBBC and additional source mitigation requirements as given in Table A1.6 is applied to the respective pile installations, the overlapping area will be limited to the overlaps listed in Table A1.8.

If installation would instead be carried out between September – December, it should be expected that additional mitigation requirements would instead be (in addition to the HSD+DBBC) in the range of $\Delta SEL_{VHF} = 7 - 9\ dB\ re. 1\ \mu Pa$ for a 15 m monopile. For the 12 m monopile, values would be 2 dB lower.

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. The 750 m SEL threshold values are shown in **Table A1.7**, 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 A1.7. 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	Position	Month	Sound Exposure Level, at 750 m $SEL_{SS@750m,VHF}$ $[dB\ re.1\mu Pa^2 s]$
Very High-Frequency Cetaceans	Harbour porpoise	Position 1	February	107.3 dB
			May	114.0 dB
		Position 2	February	107.0 dB
			May	114.0 dB

Table A1.8. Overlapping area with Natura 2000 sites (DK and SE) Store Middelgrund. The combined area of the Natura 2000 site of 135 km^2 is used for calculation of the overlap in %. The overlap assumes the use of a Noise Abatement System equal in effect to the HSD-DBBC and an additional source mitigation as listed in Table A1.6.

Scenario	Position 1 February	Position 1 May	Position 2 February
12 m monopile	26 km^2 = 19,3%	26 km^2 = 19,3%	25 km^2 = 18,5%
15 m monopile	26 km^2 = 19,3%	26 km^2 = 19,3%	25 km^2 = 18,5%

Noise contour maps showing the theoretical avoidance behaviour threshold distances with HSD-DBBC and additional source mitigation, are shown in Appendix 2 – Sound propagation results, however only for the 15 m monopile scenario. The maps also show the overlap with the Natura 2000 areas.

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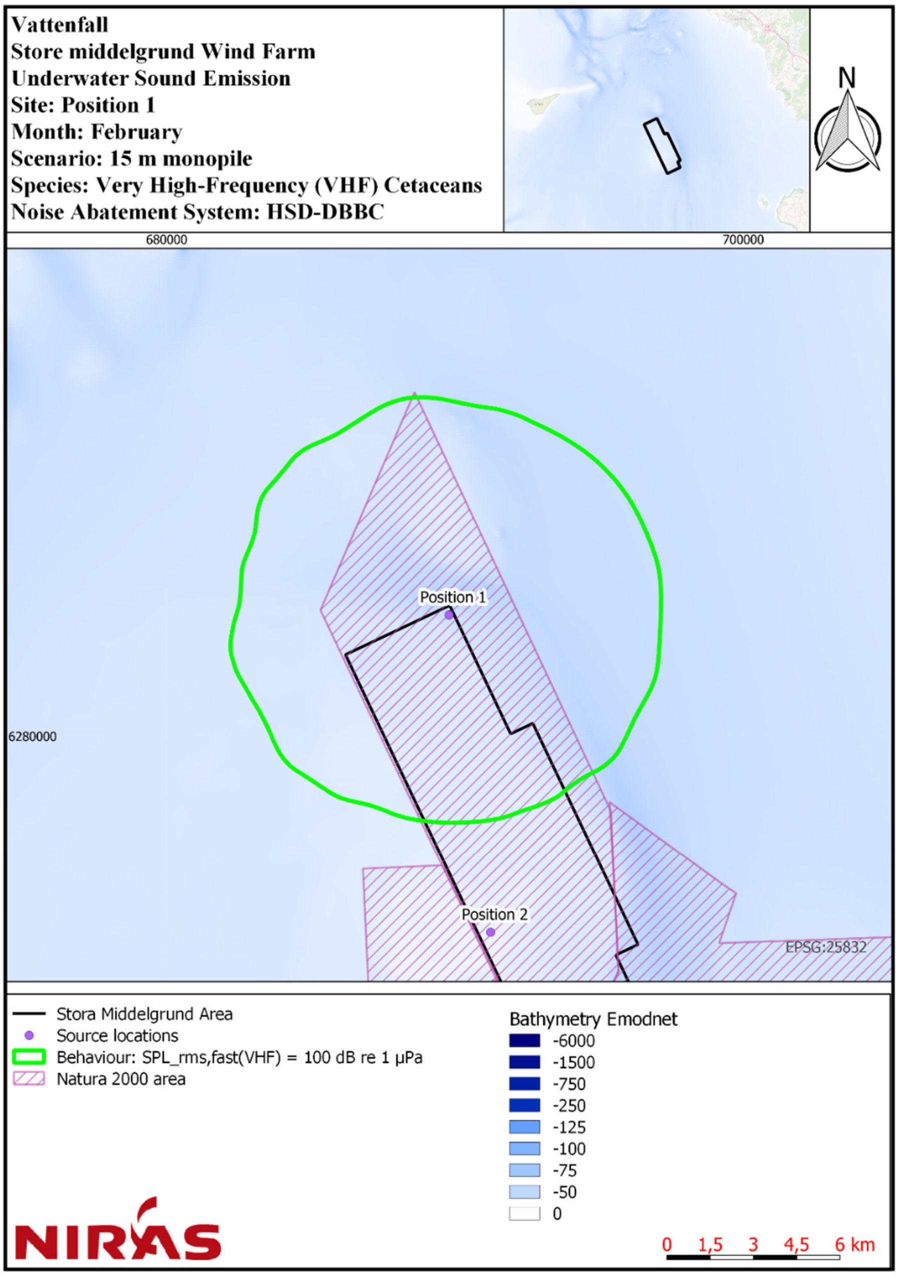
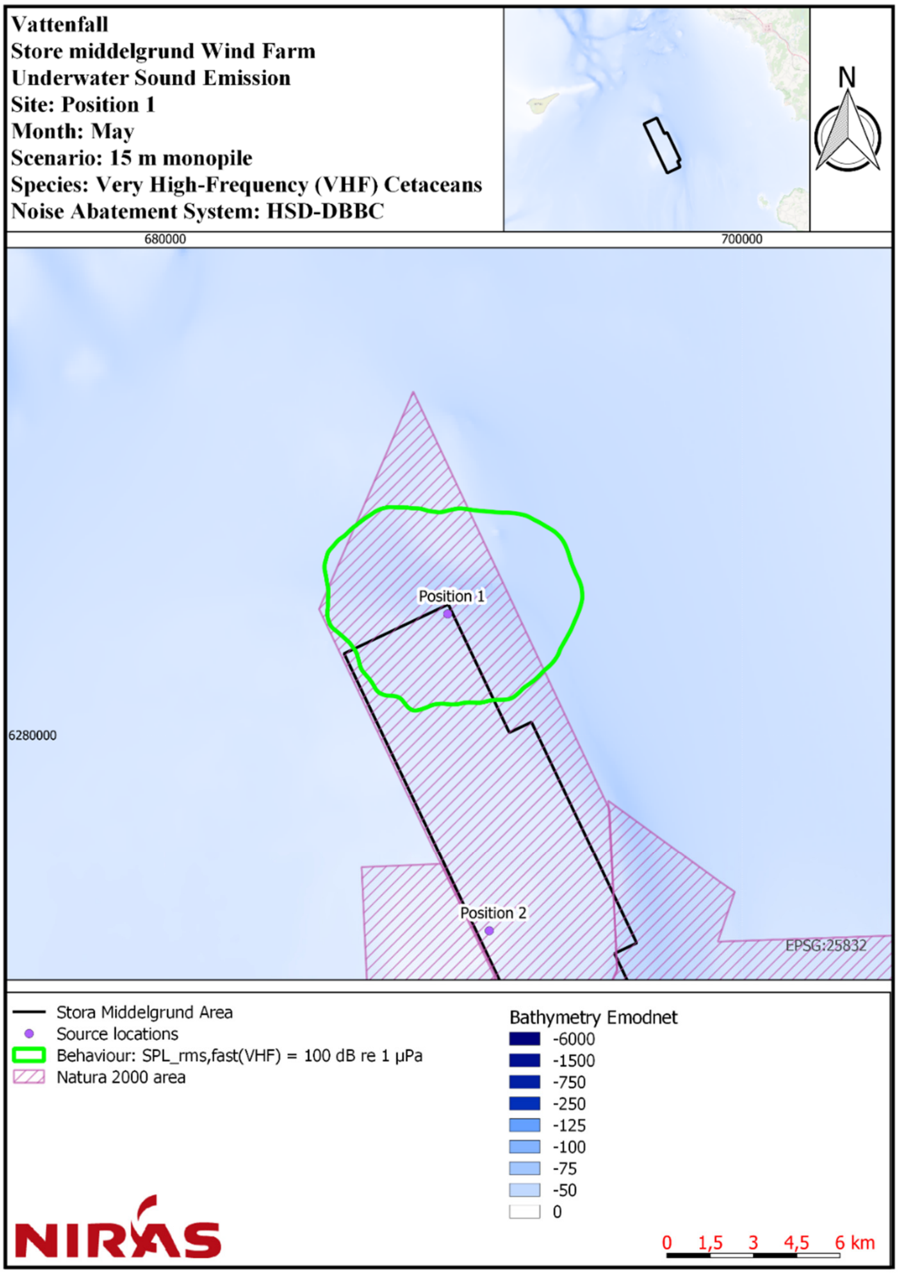
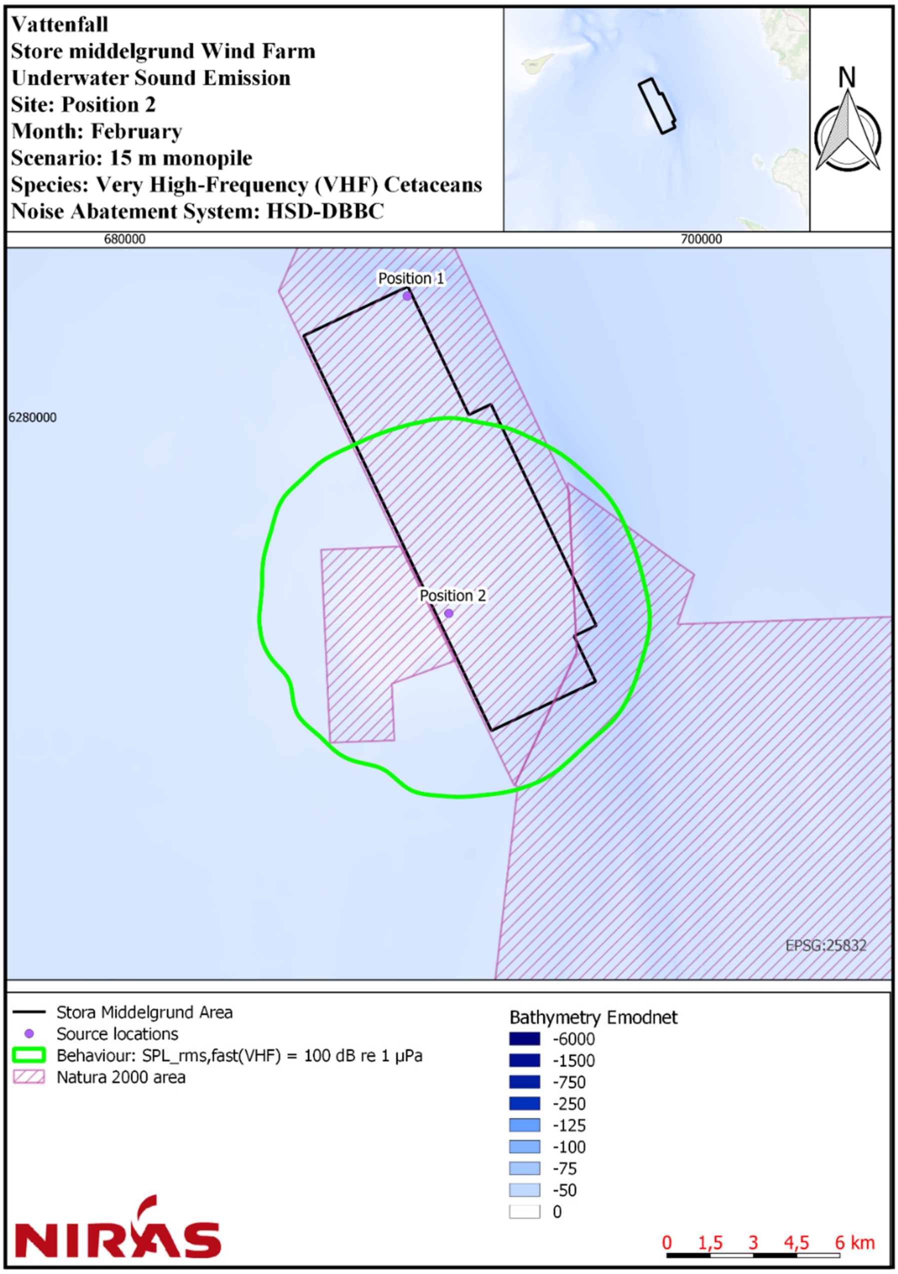
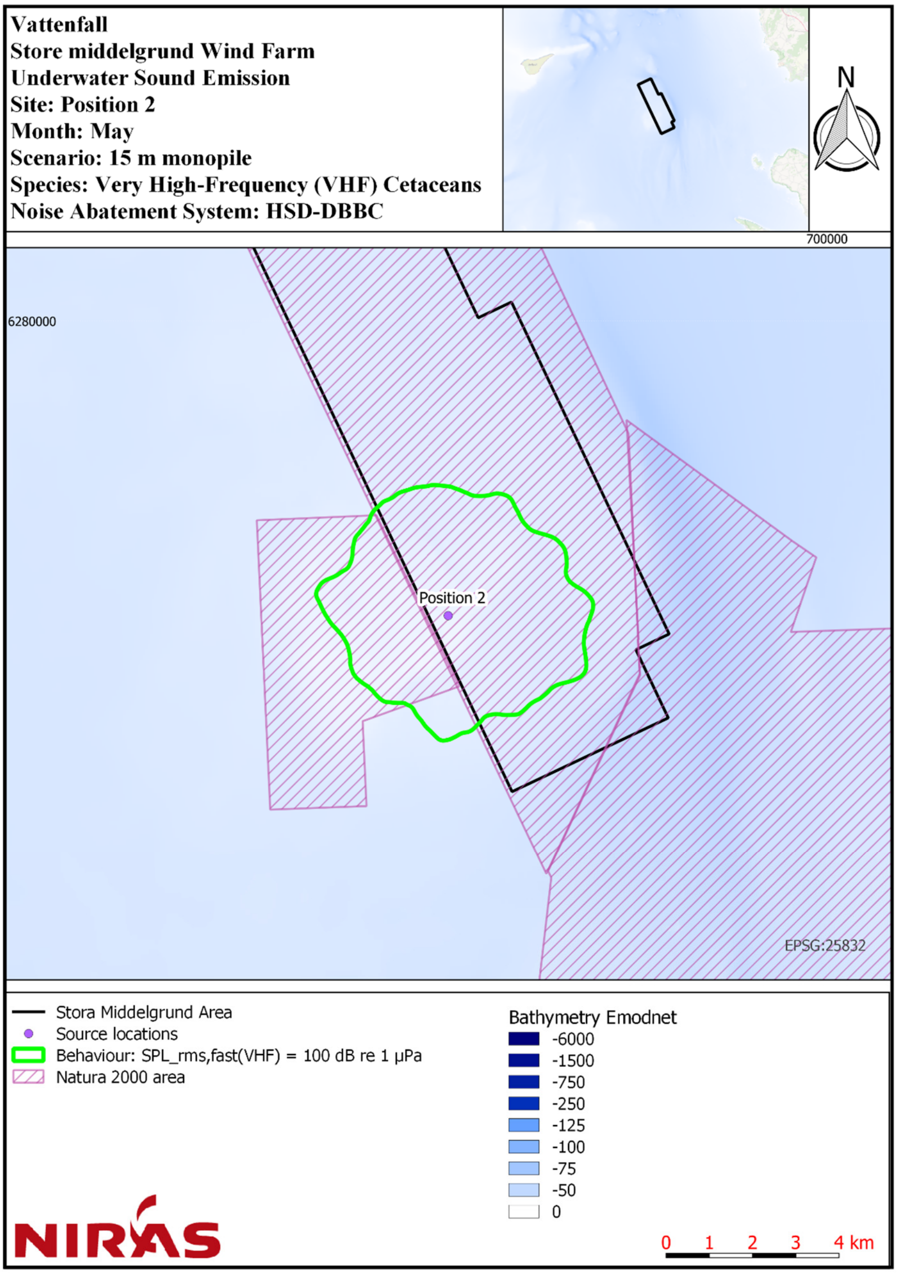
Appendix 2 – Sound propagation results

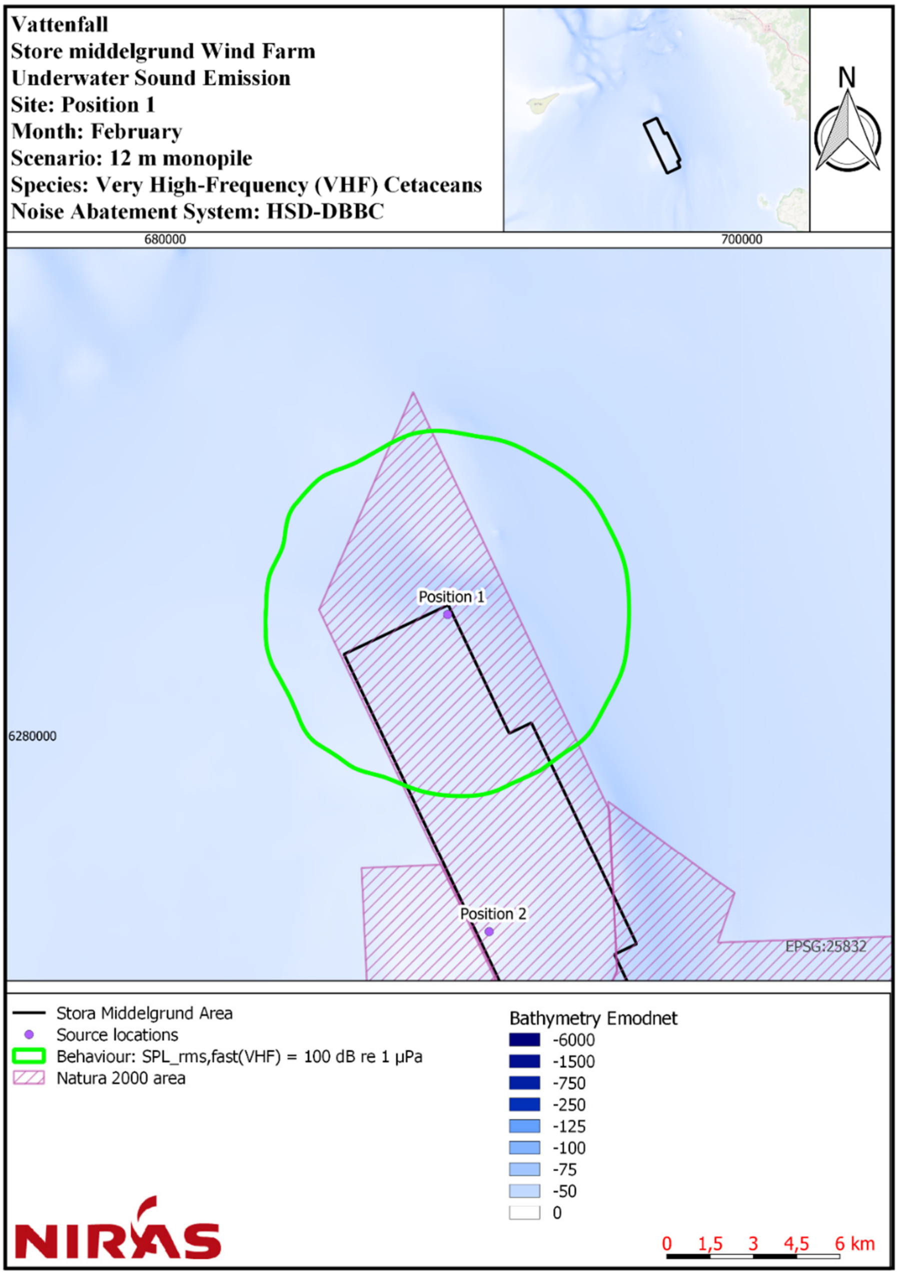
Noise contour maps (HSD-DBBC)



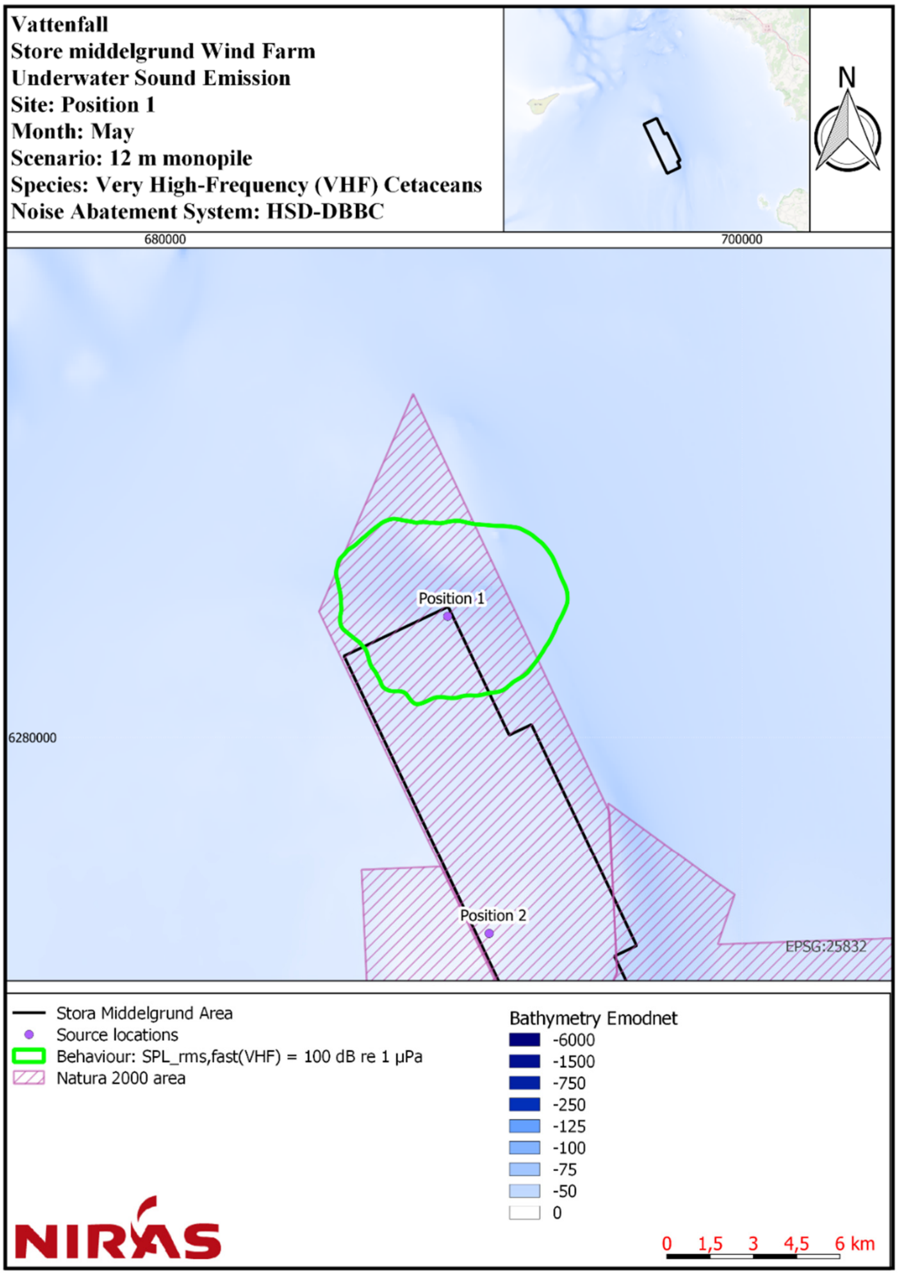

Vattenfall
Store middelgrund Wind Farm
Underwater Sound Emission
Site: Position 1
Month: May
Scenario: 15 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
700000
6280000
Position 1
Position 2
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
NIRAS
0 1,5 3 4,5 6 km

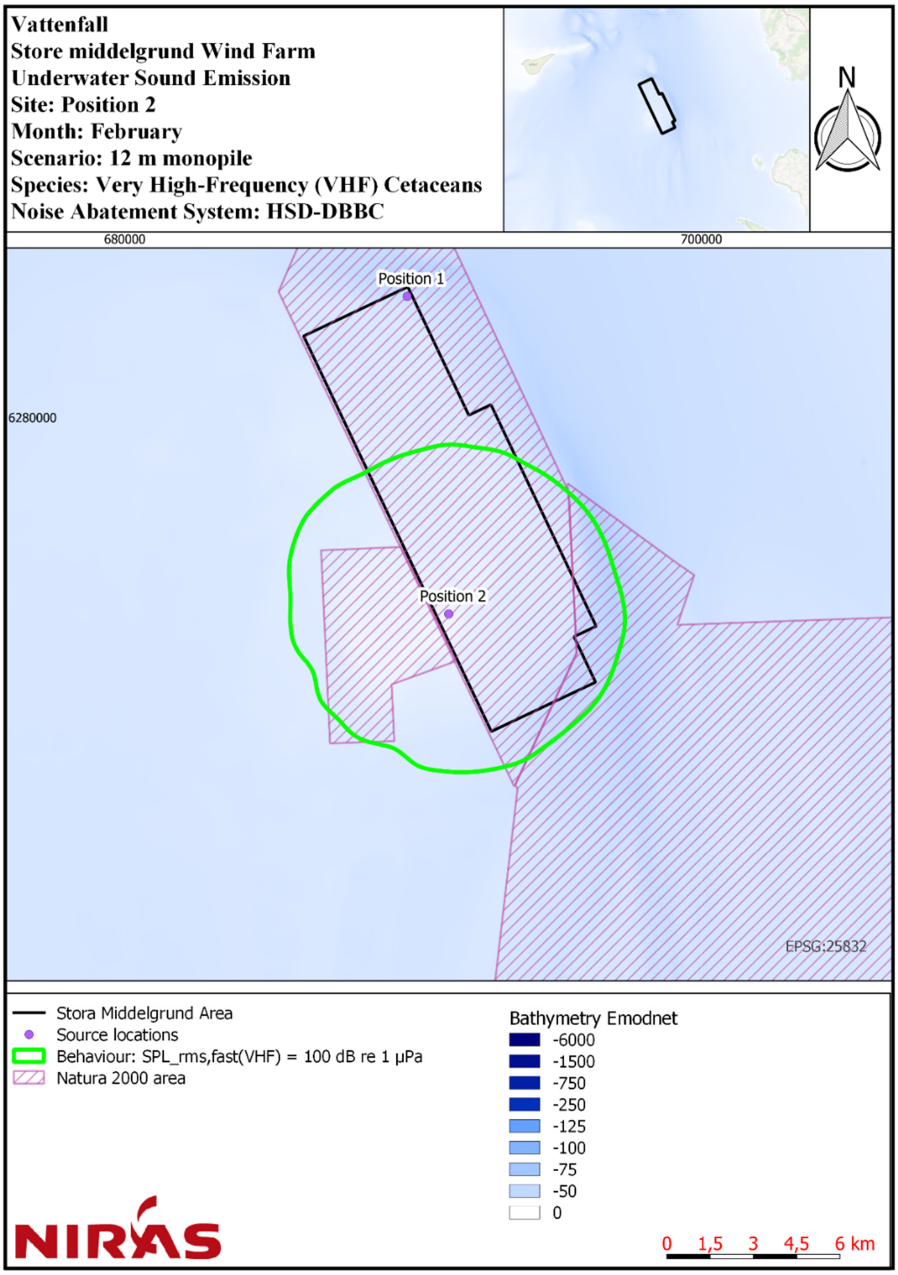

Vattenfall
Store middelgrund Wind Farm
Underwater Sound Emission
Site: Position 2
Month: February
Scenario: 15 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
700000
6280000
Position 1
Position 2
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
NIRAS
0 1,5 3 4,5 6 km

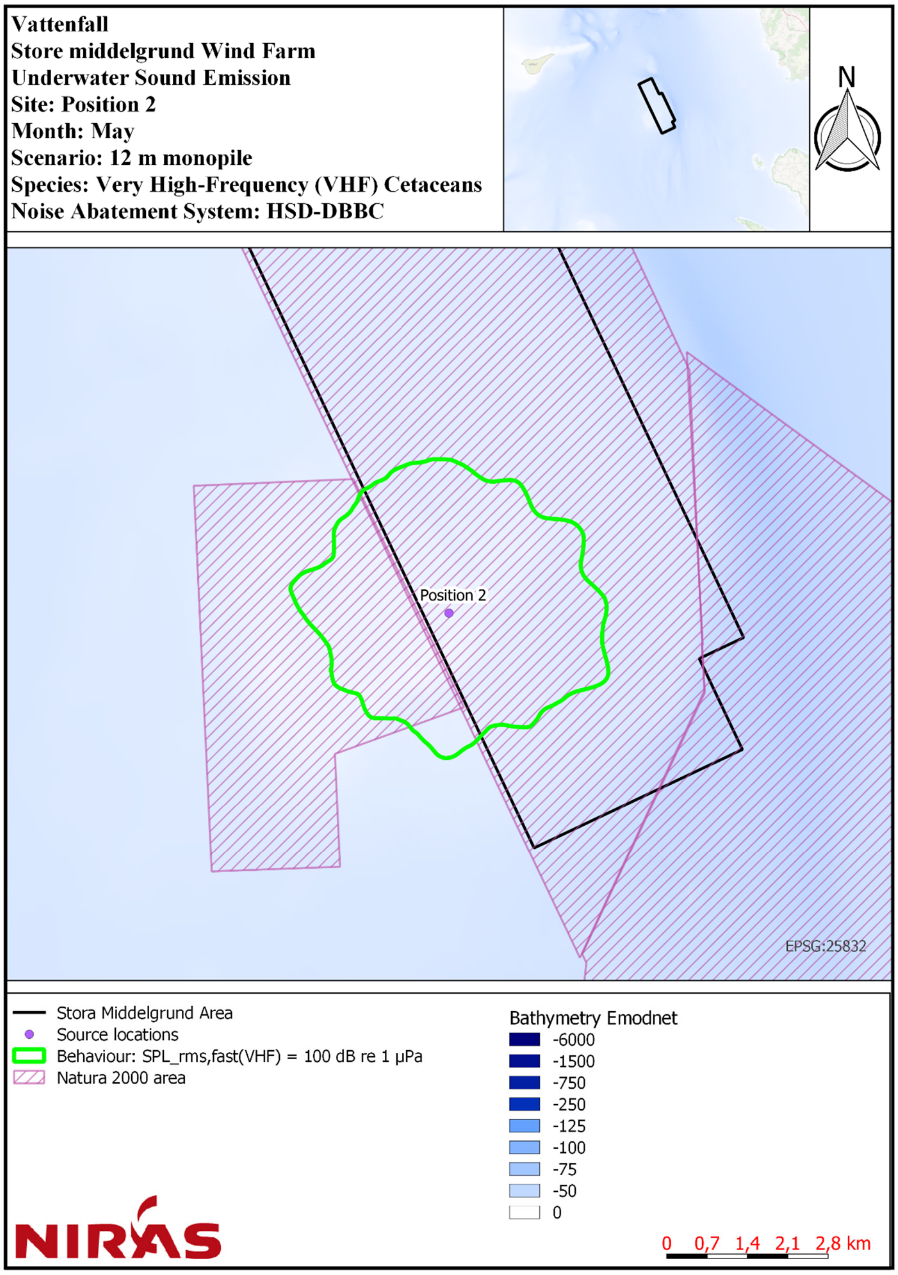

Vattenfall
Store middelgrund Wind Farm
Underwater Sound Emission
Site: Position 2
Month: May
Scenario: 15 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
700000
6280000
Position 2
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
NIRAS
0 1 2 3 4 km



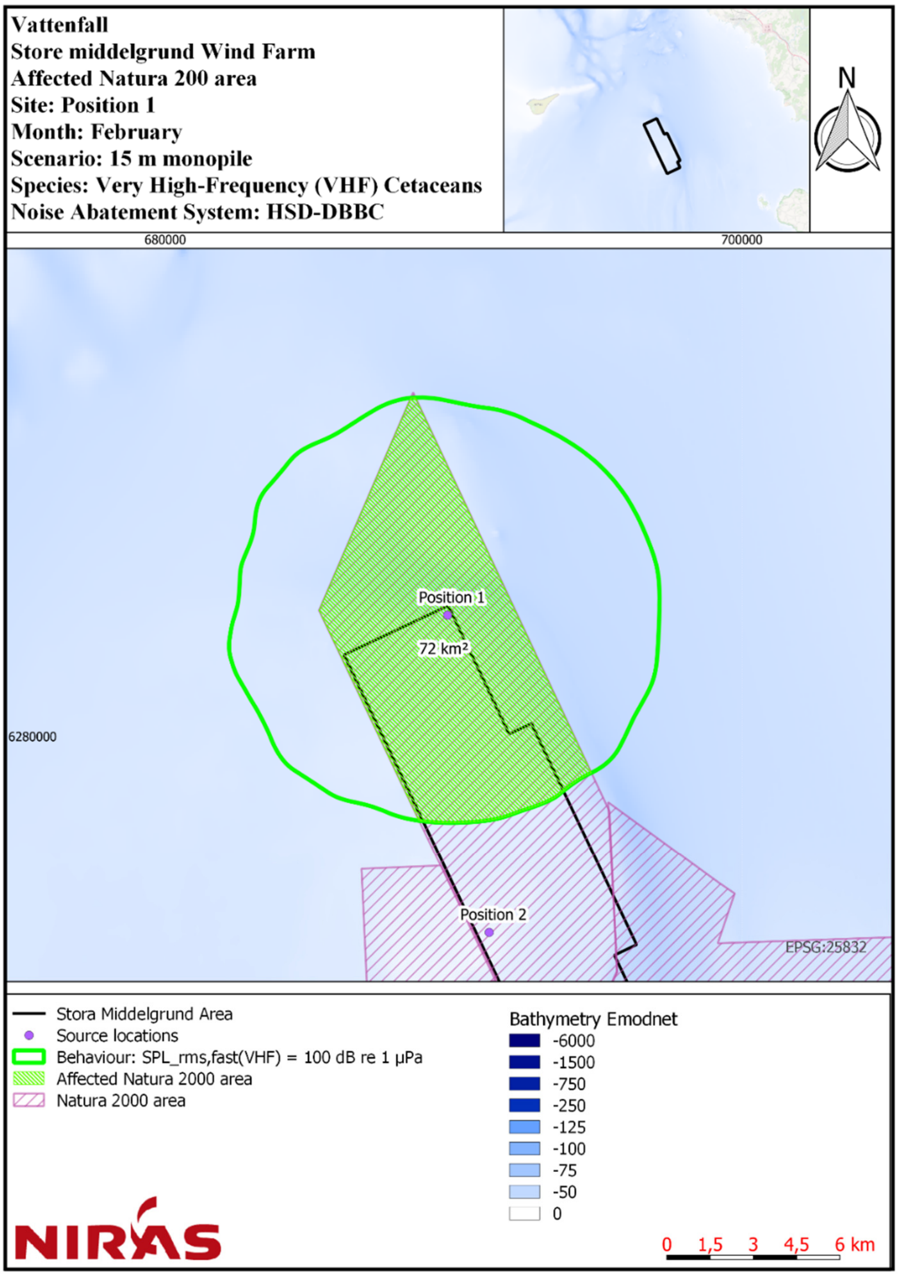
Vattenfall
Store middelgrund Wind Farm
Underwater Sound Emission
Site: Position 1
Month: February
Scenario: 12 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
700000
6280000
Position 1
Position 2
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
NIRAS
0 1,5 3 4,5 6 km

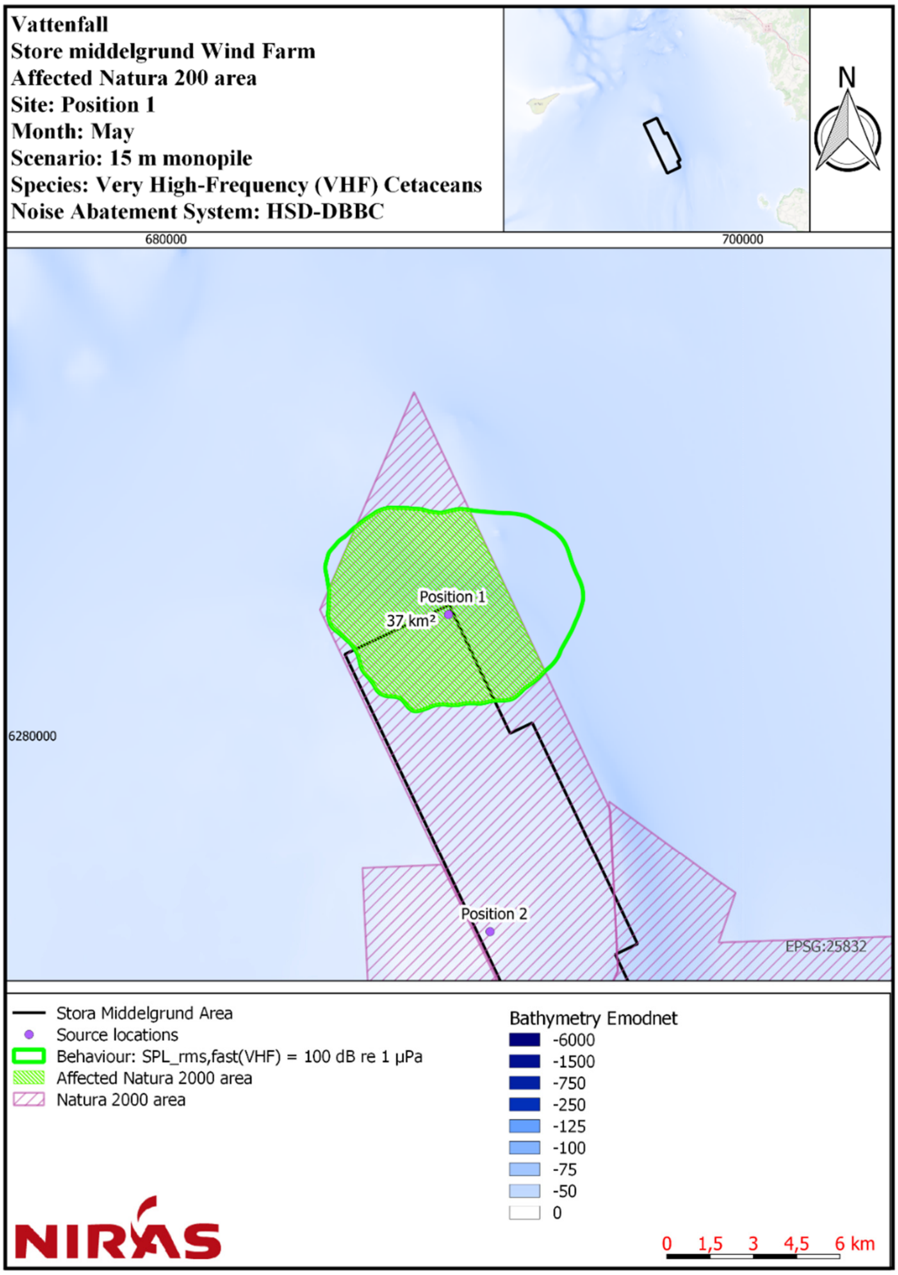

Vattenfall
Store middelgrund Wind Farm
Underwater Sound Emission
Site: Position 1
Month: May
Scenario: 12 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
700000
6280000
Position 1
Position 2
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
0 1,5 3 4,5 6 km

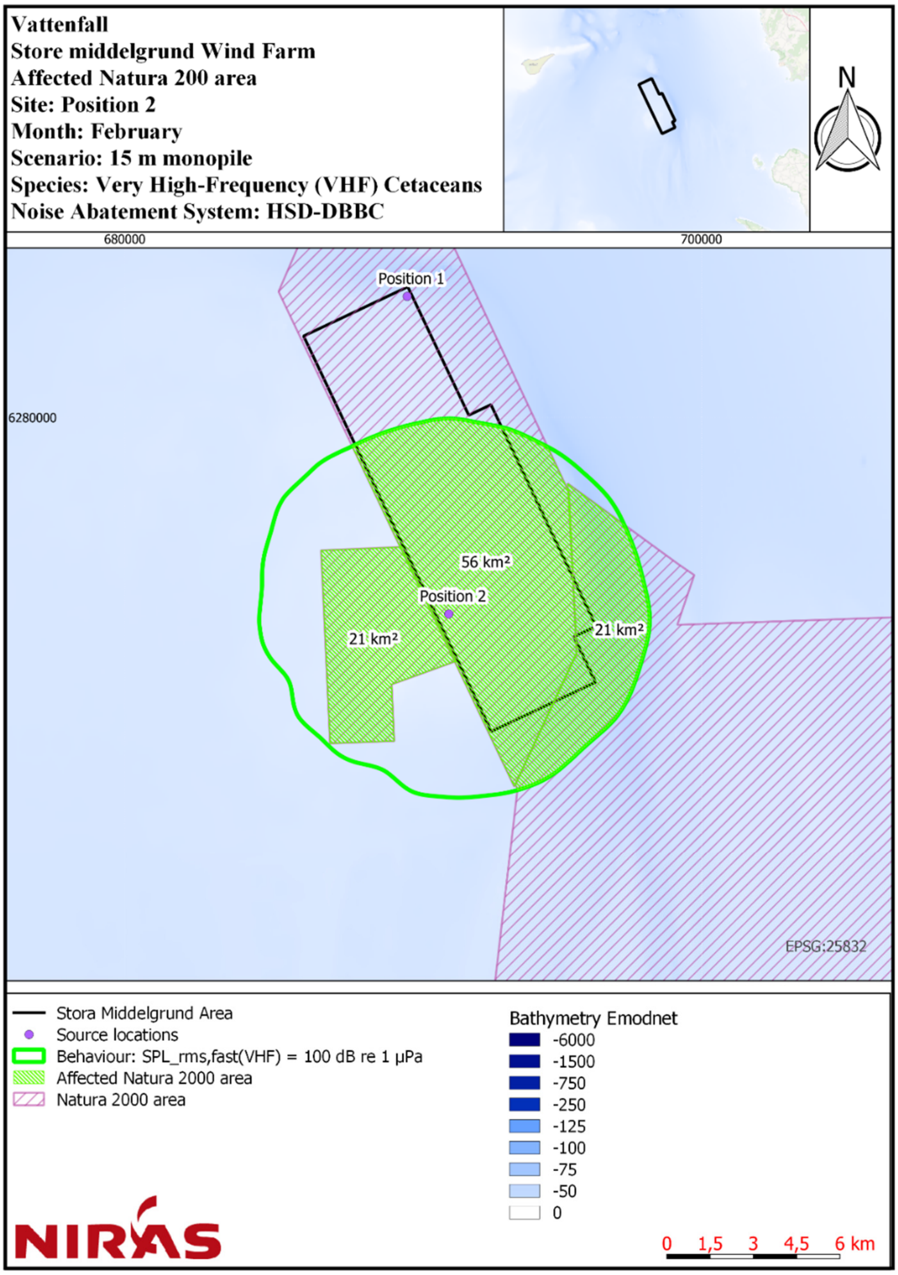

Vattenfall
Store middelgrund Wind Farm
Underwater Sound Emission
Site: Position 2
Month: February
Scenario: 12 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
700000
6280000
Position 1
Position 2
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
0 1,5 3 4,5 6 km

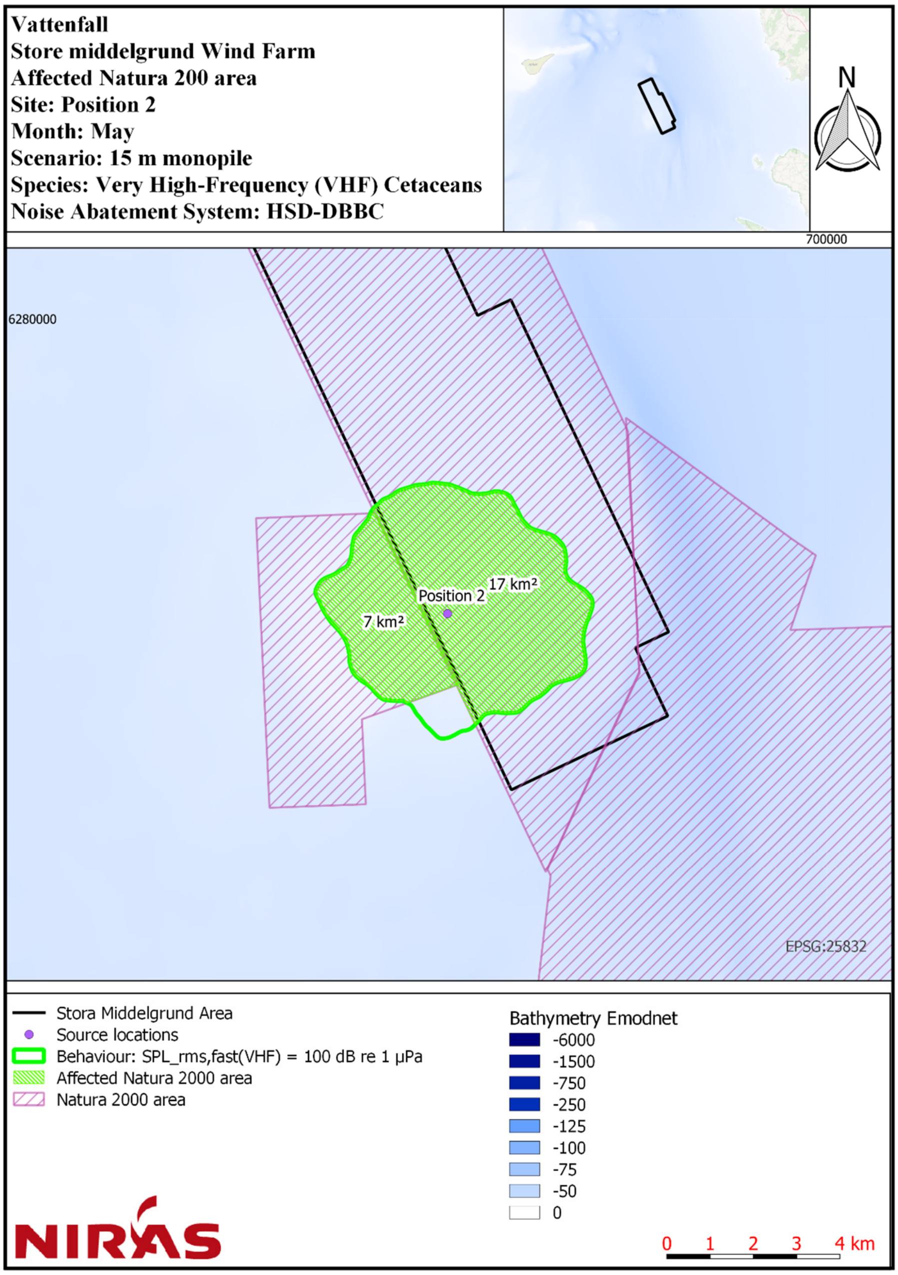

Vattenfall
Store middelgrund Wind Farm
Underwater Sound Emission
Site: Position 2
Month: May
Scenario: 12 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
Position 2
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
NIRAS
0 0,7 1,4 2,1 2,8 km

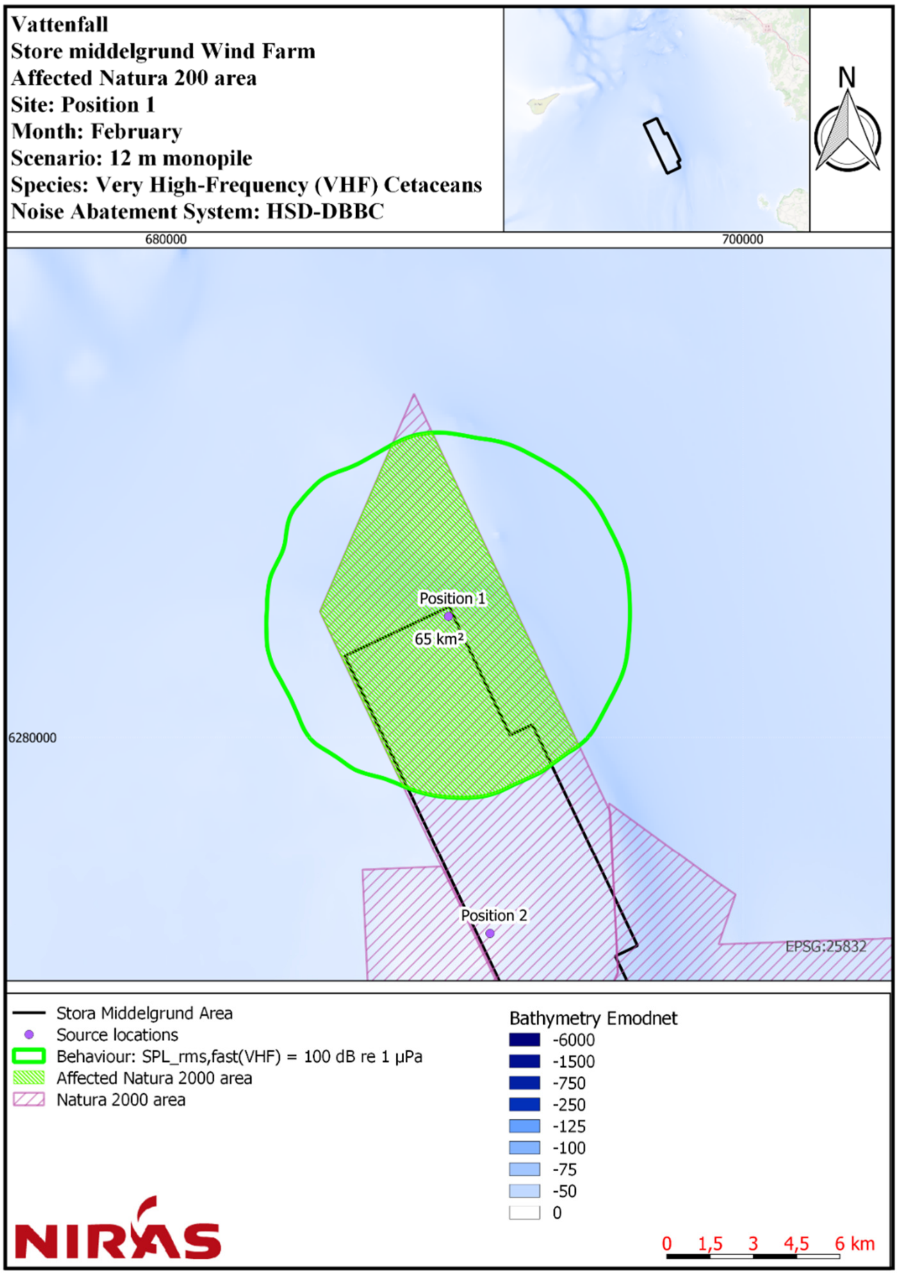
Overlap with Natura 2000 sites (HSD-DBBC)

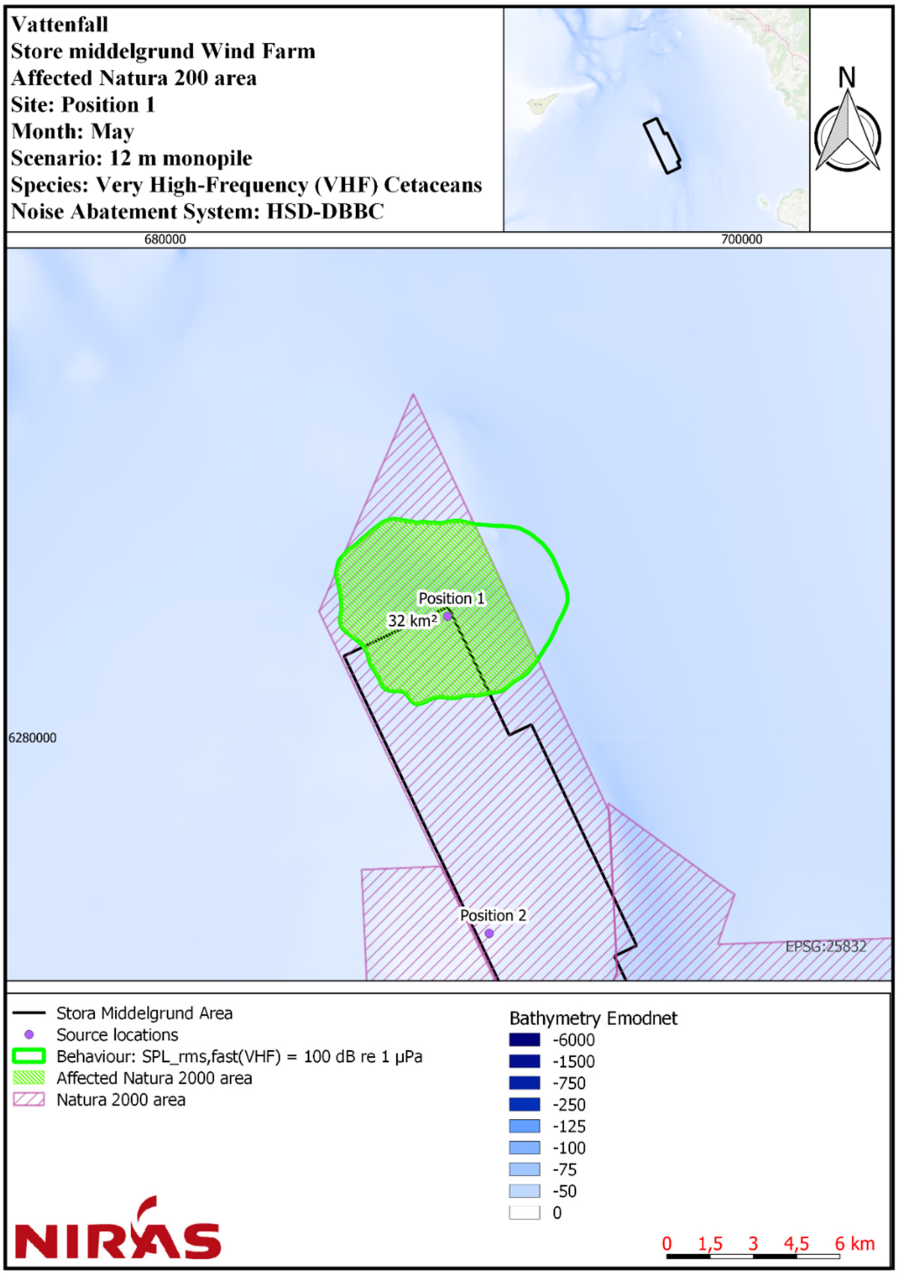



Vattenfall
Store middelgrund Wind Farm
Affected Natura 200 area
Site: Position 1
Month: May
Scenario: 15 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
700000
6280000
Position 1
37 km²
Position 2
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Affected Natura 2000 area
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
NIRAS
0 1,5 3 4,5 6 km

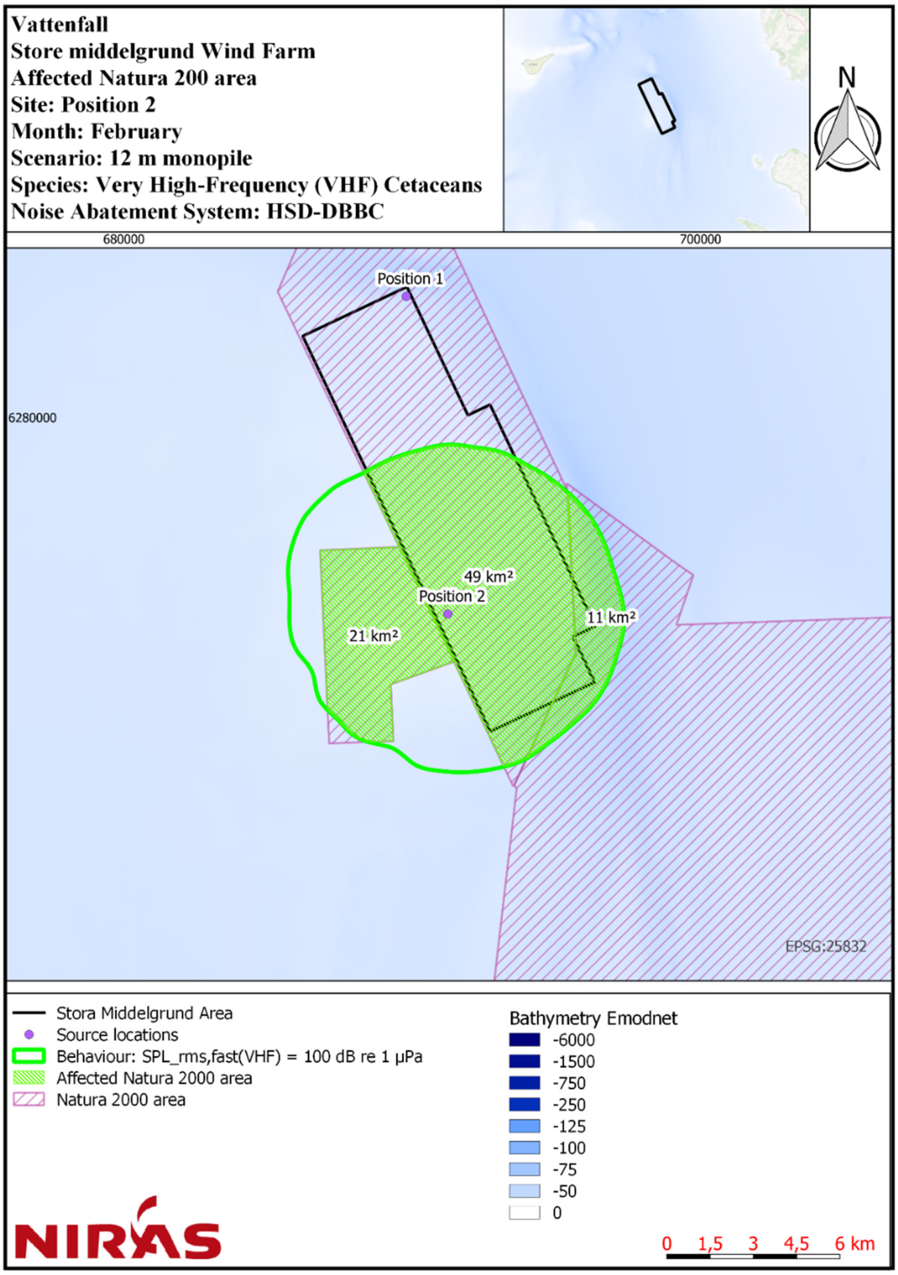

Vattenfall
Store middelgrund Wind Farm
Affected Natura 200 area
Site: Position 2
Month: February
Scenario: 15 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
700000
6280000
Position 1
Position 2
56 km²
21 km²
21 km²
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Affected Natura 2000 area
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
0 1,5 3 4,5 6 km


Vattenfall
Store middelgrund Wind Farm
Affected Natura 200 area
Site: Position 2
Month: May
Scenario: 15 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
700000
6280000
Position 2
17 km²
7 km²
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Affected Natura 2000 area
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
0 1 2 3 4 km

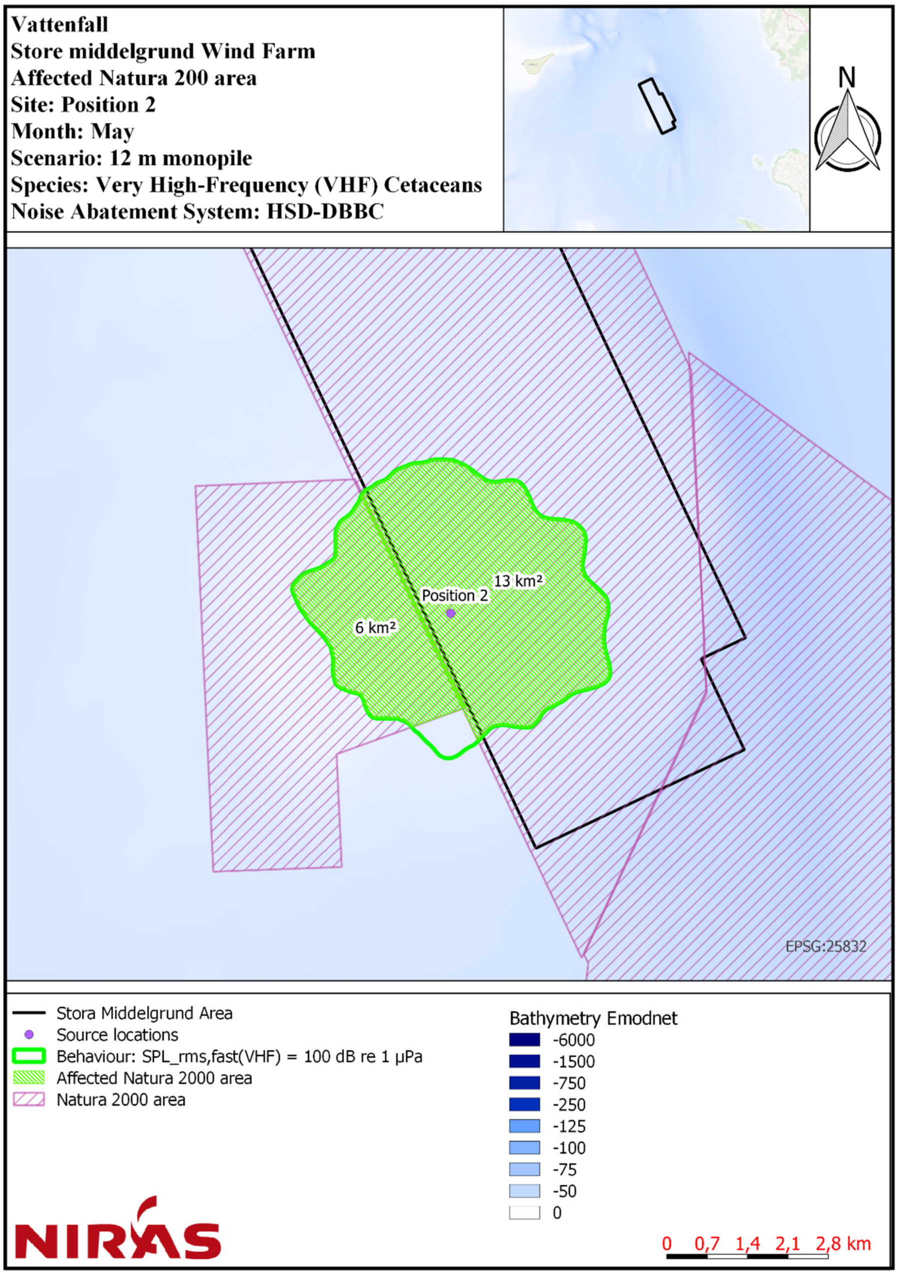

Vattenfall
Store middelgrund Wind Farm
Affected Natura 200 area
Site: Position 1
Month: February
Scenario: 12 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
700000
6280000
Position 1
65 km²
Position 2
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Affected Natura 2000 area
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
0 1,5 3 4,5 6 km



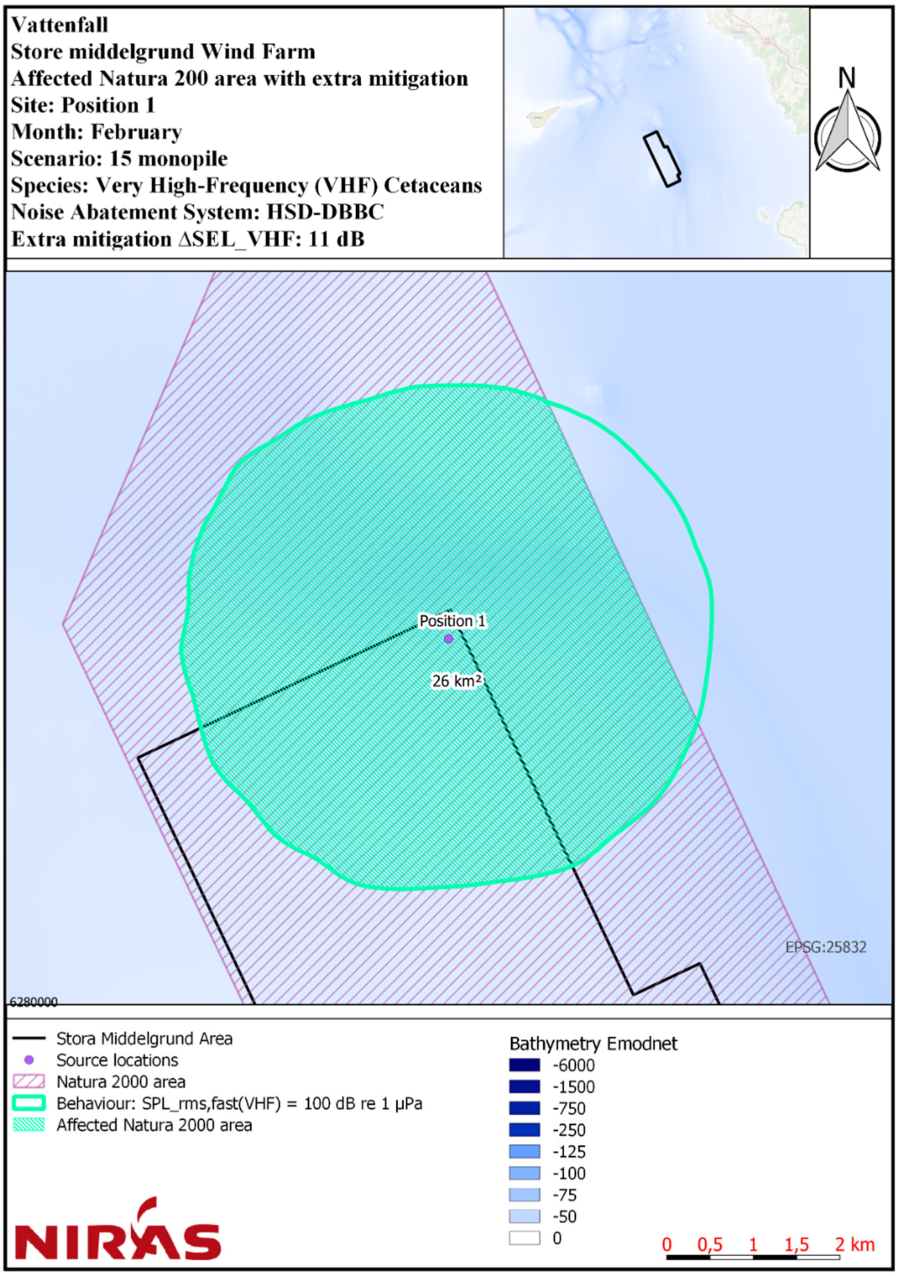
Vattenfall
Store middelgrund Wind Farm
Affected Natura 200 area
Site: Position 1
Month: May
Scenario: 12 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
700000
6280000
Position 1
32 km²
Position 2
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Affected Natura 2000 area
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
0 1,5 3 4,5 6 km

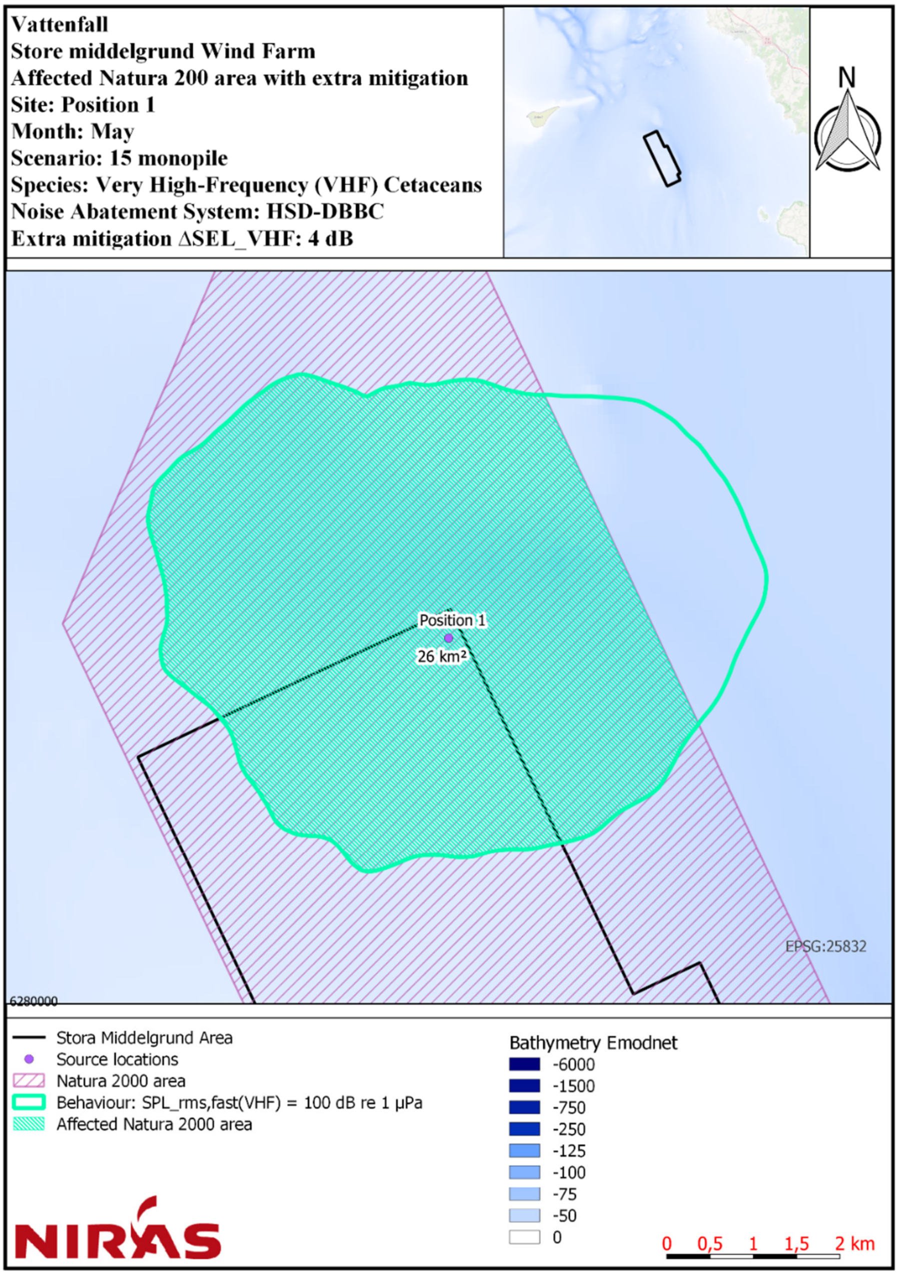


Vattenfall
Store middelgrund Wind Farm
Affected Natura 200 area
Site: Position 2
Month: February
Scenario: 12 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
680000
700000
6280000
Position 1
Position 2
49 km²
21 km²
11 km²
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Affected Natura 2000 area
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
NIRAS
0 1,5 3 4,5 6 km

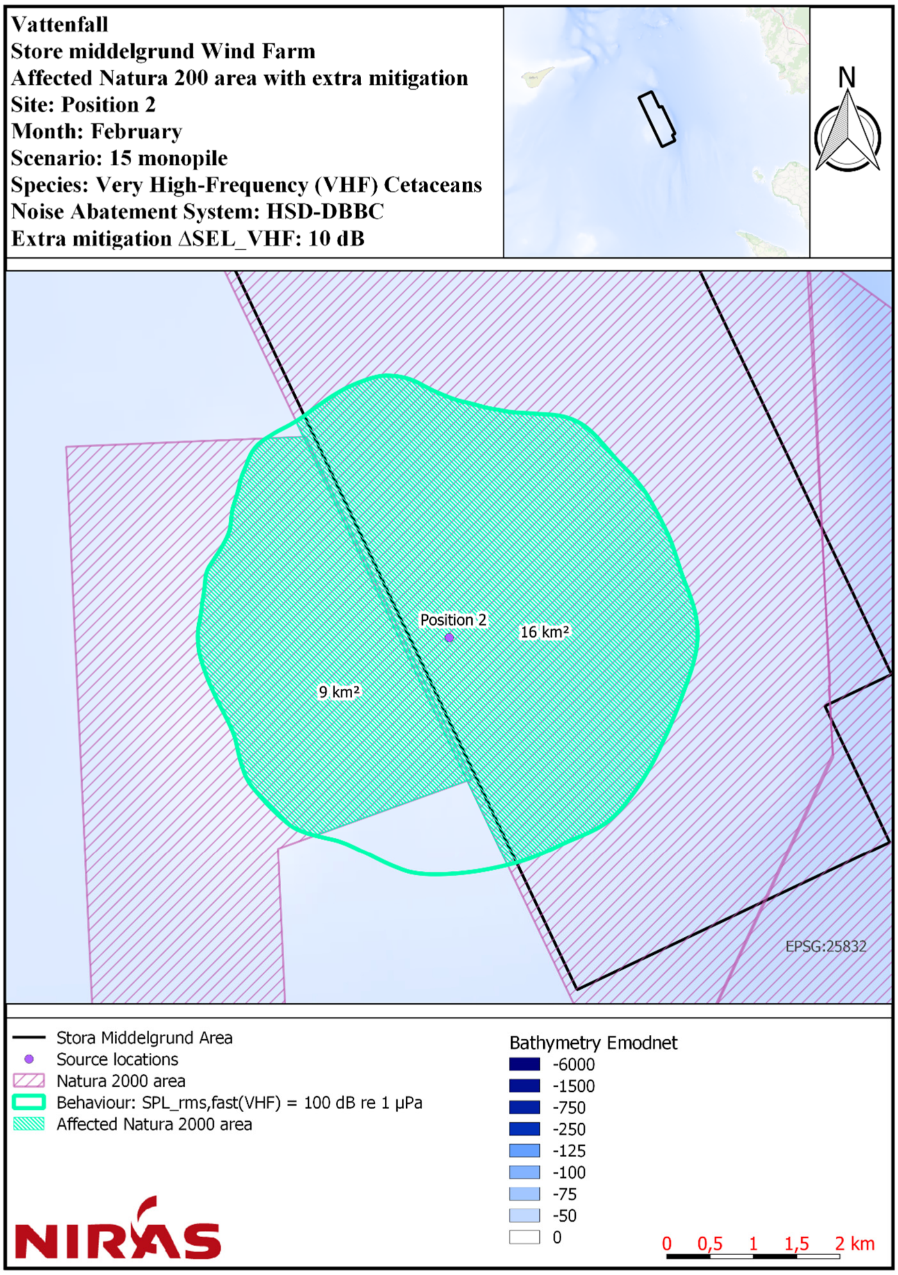

Vattenfall
Store middelgrund Wind Farm
Affected Natura 200 area
Site: Position 2
Month: May
Scenario: 12 m monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
N
13 km²
Position 2
6 km²
EPSG:25832
Stora Middelgrund Area
Source locations
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Affected Natura 2000 area
Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
0 0,7 1,4 2,1 2,8 km

Noise contour maps and overlap (HSD-DBBC+ΔSEL_{VHF})





Vattenfall
Store middelgrund Wind Farm
Affected Natura 200 area with extra mitigation
Site: Position 1
Month: May
Scenario: 15 monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
Extra mitigation ∆SEL_VHF: 4 dB
N
Position 1
26 km²
EPSG:25832
6280000
Stora Middelgrund Area
Source locations
Natura 2000 area
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Affected Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
0 0,5 1 1,5 2 km
NIRAS


Vattenfall
Store middelgrund Wind Farm
Affected Natura 200 area with extra mitigation
Site: Position 2
Month: February
Scenario: 15 monopile
Species: Very High-Frequency (VHF) Cetaceans
Noise Abatement System: HSD-DBBC
Extra mitigation ΔSEL_VHF: 10 dB
N
Position 2
16 km²
9 km²
EPSG:25832
Stora Middelgrund Area
Source locations
Natura 2000 area
Behaviour: SPL_rms,fast(VHF) = 100 dB re 1 µPa
Affected Natura 2000 area
Bathymetry Emodnet
-6000
-1500
-750
-250
-125
-100
-75
-50
0
0 0,5 1 1,5 2 km

STORA MIDDELGRUND OFFSHORE WIND FARM

Effects of underwater noise on marine mammals during the installation phase

Construction and operation of an offshore wind farm in the Swedish N2000 area Stora Middelgrund & Röde 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 February and May 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 February is predicted to result in significantly larger affected areas than construction in May due to differences in hydrography and hence sound propagation properties. Without noise abatement, 100 % of the Natura 2000 area will be exposed to noise levels above the reaction threshold for harbour porpoises and marine mammals are at risk of acquiring partial, but permanent loss of hearing. Provided best available technology for noise abatement is used, exemplified by the double Big Bubble Curtain in combination with the use of hydro sound dampeners, the risk of hearing loss is removed and the behavioural disturbance reduced significantly. If additional noise abatement of up to 11 dB is provided, the impact on the Natura 2000 sites is reduced to less than 20 % and then assessed as a minor impact. With such mitigation measures, the construction is not considered to have long-term impact 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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