KEC 5.0 report, Part B, marine mammals

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Summary

Introduction

Marine mammals may be affected by the construction, operation and decommissioning of offshore wind farms. It cannot be ruled out that the impulsive underwater sound produced during construction (and possibly during decommissioning) is such that it may lead to unacceptable effects on marine mammal populations. The Framework for Assessing Ecological and Cumulative Effects (*Kader Ecologie en Cumulatie* - KEC) was developed to prevent this happening. The KEC, which was used for the first time in 2016, includes an approach – the KEC procedure (see Intermezzo KEC Procedure) – for determining and assessing the cumulative effects on important populations of marine mammals of underwater sound produced during a specified period of time by the construction of wind farms.

KEC Procedure

The KEC procedure for calculating the effects of piling sound on marine mammal populations consists of a number of successive and clearly distinct steps. A realistic worst-case estimate is made of the magnitude for each step in the effect chain from sound production to the effect on the population. An important intermediate step is the calculation of animal disturbance days: the total of the number of animals disturbed on a piling day on each project during the total number of piling days and during all projects. This cumulative disturbance constitutes the input for the interim PCoD model[1] developed by the University of St. Andrews and distributed by SMRU Consulting to calculate the effects on the population. In the final steps, the calculated population effects are compared with the ecological standard and – if necessary – an assessment is made of the noise limit at which that standard can be met.

The effects on the population estimated using this approach are assessed on the basis of an ecological standard established by the government. In the case of the main marine mammal species in the Dutch North Sea – the harbour porpoise, the harbour seal and the grey seal – this means there must be a high degree of confidence (95%) that the population will not decline by more than 5%. A significant effect on the population can be ruled out if this standard is met. If the ecological standard is not met, it is necessary to mitigate the effects by imposing a stricter limit – the noise standard – on the amount of underwater sound that will be produced. This is defined as the unweighted broadband single strike sound exposure level (SELss) at a distance of 750 m from the piling location.
Since 2016, following changes in the government's ambitions for offshore wind development (stated in roadmaps), the KEC has been updated several times, most recently in 2022 (KEC 4.0). In addition to calculating the cumulative effects of a new scenario for offshore wind development, each update has also incorporated the latest insights relating to the effects of impulsive underwater sound. You are now reading the result of the latest update, the KEC 5.0 for marine mammals. As in previous KECs, in addition to the usual scenario and knowledge update, the final step has been to evaluate the cumulative effects of piling sound on the population on the basis of the ecological standard and the noise

[1] https://www.smruconsulting.com/population-consequences-of-disturbance-pcod

standard assumed in the scenario. The 2030 Supplementary Roadmap for Offshore Wind Energy (April 2024) constitutes the point of departure for the planned and completed wind farms in the Dutch section of the North Sea in the period 2016 - 2031.

KEC 5.0 for marine mammals

Rijkswaterstaat has developed new national and international scenarios for the construction of wind farms in the North Sea for the KEC 5.0. The main difference with the KEC 4.0 scenario is that the international scenario (including the Netherlands) is, at 123 GW, much larger in terms of total installed capacity than the previous scenario (78 GW). The Dutch scenario is comparable at 22 GW (21 - 27 GW in the case of the KEC 4.0). The Dutch scenario assumes the application of the noise standards set out in the site decisions for the wind farms that have already been constructed or that have yet to be constructed and a noise standard of SELss (750 m) = 164 dB re 1 μPa^{2}s for the wind farms for which the site decisions have yet to be taken. The prevailing restrictions in international waters have been assumed for estimating the production of underwater sound during the construction of wind farms in those locations.

New elements in the calculations for the KEC 5.0 are:
- Estimation of the effects of the clearance of unexploded ordnance (UXO) and the associated Acoustic Deterrent Devices (ADDs) deployed during this work in the wind farm sites and along the cable routes;
- Modifications in the calculation of the effects of the geophysical surveys for both the wind farm sites and the cable routes;
- Estimation of the effects of the sound produced by vibropiling;
- Evaluation of the relationship between sound level and the behavioural response of harbour porpoises used in the KEC 4.0;
- Reconsideration of the demographic parameters used in the interim PCoD population model for harbour porpoises;
- Assessment of the applicability of other modifications in the interim PCoD model. Those modifications involve the inclusion of density-dependent effects (resulting in population recovery after sound production ceases) and the implementation of a dynamic energy budget (DEB) model. This model is a substitute for expert opinions obtained in a formal expert elicitation process with the aim of quantifying the transfer functions that describe the relationships between noise disturbance and vital rates for harbour porpoises.

Results

Worst-case assumptions used in the determination of the effects of piling sound on harbour porpoises

The results show that the conservative assumptions used for the calculation of sound propagation and the dose-effect relationship result in very large disturbance distances for harbour porpoises in the case of projects where noise is not mitigated. These are mainly projects in the United Kingdom. There are no data confirming these large disturbance distances and they are also unlikely to be seen in reality, in part because the nature of underwater sound changes (becoming less impulsive) at larger distances from the source. The comparison of different, field-based, dose-effect relationships shows that the relationship selected for the KEC is a worst case. However, a substantiated choice for another relationship is not (yet) possible. It was therefore decided to adopt a cautious approach and assume the worst-case dose-effect relationship for the assessment of the estimated effects.

More realistic selection of demographic parameters results in smaller effects

On the basis of studies of harbour porpoises stranded on the North Sea coast, it was found that the calculations for the KEC 4.0 overestimated the birth rate as almost one a year. For the KEC 5.0, calculations were therefore also made for a more realistic rate of approximately one every three years. Because it has been assumed that the North Sea harbour porpoise population is stable, the adult mortality rate in the model was changed accordingly from 0.85 to 0.925. Assuming these more realistic parameters, the calculated effect on the total North Sea population falls from 26% to 16% (95% confidence)[2]. If density-dependent effects[3] are also included, the maximum effect on the total North Sea population falls further (from 16% to 8%) and there is total population recovery some 25 years after the start of wind-farm construction in 2016.

Linear relationship between harbour porpoise disturbance days and population decline

Given research into the effects of different assumptions for offshore wind development, dose-effect relationships and demographic parameters, calculations were made with a large number of scenarios for the KEC 5.0. Research into the relationship between the total number of harbour porpoise disturbance days and the population reduction calculated for the different scenarios shows that, for a given set of demographic parameters, the total number of disturbance days is the main explanatory factor for the calculated population reduction. The correlation is approximately linear. In other words, the population reduction as a percentage increases inversely with the number of harbour porpoise disturbance days. This makes it possible to derive, for a given ecological standard (= population reduction as a percentage), the number of harbour porpoise disturbance days at which that ecological standard is met. On the basis of the correlation found, it has been calculated that there is compliance with the current ecological standard for the harbour porpoise population in the Dutch section of the North Sea if the maximum number of harbour porpoise disturbance days is 2.3 million. The current estimate of the demographic parameters for the harbour porpoise population (birth rate of 0.34 per year) was used as an underlying assumption here.

Effects of piling sound during wind farm construction according to the 2030 Supplementary Roadmap

The results show that there is no risk of exceeding the ecological standard for harbour porpoises associated with the roll-out of the 2030 Supplementary Roadmap in line with the KEC 5.0 scenario if a noise standard of 164 dB re 1 μPa^2s (SELss at 750 m) is assumed for future projects. For this scenario, a total number of 1.7 million harbour porpoise disturbance days has been calculated. This also leaves some latitude for further offshore wind development.

Interim PCoD + DEB for harbour porpoises

Calculations have also been made for harbour porpoises using a new version of the interim PCoD model that became available very recently and in which expert judgement about the correlation between disturbance and vital rates (fertility and probability of survival) was

[2] Calculations with the *low fertility* demographic parameters predict a smaller effect than calculations with the *high fertility* parameters. In the interim PCoD model, piling noise mainly affects the vital rates ‘fertility’ and ‘probability of juvenile survival’. Adults are presumed to be less susceptible to the effects of disturbance. As a result, the variant with *low fertility* is less susceptible to the effects of disturbance that affect fertility and calf survival only.

[3] The maximum size of a population in an area (its density) is determined by factors that limit the growth of that population such as food availability, predation and disease. The carrying capacity of the environment determines the maximum size of the population. Density dependence means that a population that is at its carrying capacity level will recover to its original size after a temporary decline caused by anthropogenic or natural stressors. If this is taken into account when calculating the effects of behavioural disturbance on the population, the maximum effect may be smaller due to interim recovery.

replaced by a dynamic energy budget (DEB) model. Models of this kind track changes in individuals' energy intake and consumption over time and calculate how repeated disturbance can affect energy intake and therefore vital rates. The interim PCoD + DEB calculations for the KEC 5.0 scenario show that there is no risk of a fall in the harbour porpoise population. Because the possible explanations for the differences between the two versions of the model were not yet clear, it was decided to adopt a cautious approach and use the results of the calculations with the earlier version of the interim PCoD model for the time being.

Effects of piling sound on harbour and grey seals

Calculations were conducted for harbour and grey seals in the KEC 5.0 scenario using the same assumptions as for the KEC 4.0. This means that it has been assumed that the population of harbour seals is stable, and that the population of grey seals is growing by 1% annually. It is uncertain whether this assumption is valid for harbour seals since there is evidence that the population has been declining in recent years. The maximum monthly density was used as the worst case for local density around the piling locations. The results of the calculations indicate a very limited fall in the population of less than 2% for both harbour and grey seals.

Effects of other sound sources on marine mammals

<u>Alternative foundation techniques.</u> A range of alternatives for the hydraulic pile drivers used until now have been tested on a small scale in recent years. Most experience has been acquired with vibropiling. By contrast with the conventional approach, this technique produces continuous sound. Data about the sound levels produced by this technique and their effects on marine mammals are very limited or non-existent. The present report describes an approach for estimating the number of disturbed animals as a result of exposure to sound from vibropiling.

<u>Geophysical surveys.</u> Geophysical surveys are conducted before the installation of wind farms and cables in order to establish a picture of the soil conditions and map out the locations of unexploded ordnance from the Second World War. The equipment used during the geophysical surveys produces underwater sound that may disturb marine mammals. It was estimated for the KEC 5.0 that the total number of harbour porpoise disturbance days caused by surveys accounted for approximately 17% of the total number of harbour porpoise disturbance days calculated for piling. In the case of harbour and grey seals, the corresponding figures are 5% and 7% respectively of the number of seal disturbance days due to piling sound. Because the survey signals are very different from piling sound, these data were not included in the calculation of effects on populations.

<u>UXO clearance and Acoustic Deterrent Devices (ADDs)</u>. UXO clearance produces sounds that are so loud they can produce acute effects (hearing damage due to acoustic trauma) in animals, with mortality as a result. In animals further from the source, the sounds can cause permanent effects on hearing (PTS). To minimise these effects, the current practice is to turn on an ADD for 30 minutes prior to detonation, chasing away animals in the vicinity of the sound source. It has been estimated for the KEC 5.0 scenario that 26 harbour porpoises then experience acute effects and approximately 4,000 harbour porpoises suffer permanent hearing effects. The calculations also show that turning on the ADD for longer (for sixty minutes instead of thirty minutes) will lead to a significant additional mitigation of the effects in harbour porpoises. Assuming the same threshold used for harbour porpoises, 128 grey seals and 516 harbour seals would suffer acute effects, but exposure levels for explosion sound are lower almost everywhere than the criteria for the onset of PTS. Seals

benefit little from the longer deployment of ADDs. They would benefit from an increase in the effect distance resulting from the deployment of a louder ADD.
While swimming away as a result of ADD sound, the normal behaviour of animals is disturbed. This results in additional animal disturbance days on top of the animal disturbance days due to piling and geophysical surveys. For harbour porpoises, this amounts to approximately 4% of the number of harbour porpoise disturbance days due to piling; for harbour seals and grey seals, the additional disturbance days amount to less than 1% of the number of seal disturbance days due to piling. The comparison with the animal disturbance days calculated for piling has been made only to illustrate that there is less disturbance as a result of UXO clearance. Animal disturbance days cannot be compared directly. For example, the disruptions resulting from ADD deployment are much shorter: thirty minutes compared to approximately two hours for the piling activities (and an assumed disturbance duration of six hours).

Conclusions

- With the roll-out of the 2030 Supplementary Roadmap for offshore wind, there is no risk of unacceptable effects on populations of harbour porpoises, or harbour and grey seals, due to impulsive piling sound if a noise standard of 164 dB re 1 $\mu Pa^2 s$ (SEL_{ss} at 750 m) is imposed for the wind farms yet to be constructed.
- The underwater sound produced during geophysical surveys conducted prior to the construction of the wind farms may disturb the behaviour of marine mammals. In the case of harbour porpoises, the calculated number of animal disturbance days is some 17% of the number of animal disturbance days caused by piling. However, these numbers cannot be compared straightforwardly due to the fact that the sound sources are moving and because they are a different type of sound.
- UXO clearance in the wind farm sites and along the cable routes may cause acute effects (resulting in death) in harbour porpoises and seals. The hearing of harbour porpoises may also be permanently affected. The effects in harbour porpoises may be mitigated by turning on the ADD before detonation for longer and those in seals by deploying a louder ADD.
- ADDs used for UXO clearance disturb the behaviour of harbour porpoises and seals. However, the number of animals disturbed is much smaller than the number of animals disturbed by the effects of the piling sound and is negligible at the population level.
- Disturbance resulting from piling sound, geophysical surveys and the deployment of ADDs in UXO clearances varies, and so the animal disturbance days calculated for the various sources cannot be used directly as comparable input data for the iPCoD calculations. The possible cumulative effect of those various disturbances is not known.

Recommendations

- It continues to be essential to monitor underwater sound and behavioural responses in order to validate current findings. This applies not only to the effects of sound from the usual impact piling but also to the effect of alternative foundation technologies, sound from acoustic sources used in geophysical surveys, and the effect of UXO clearance.
- Further studies of the possibilities and limitations of the interim PCoD + DEB model are recommended.
- It is also recommended to investigate the applicability of proposals for alternative exposure measures for both impulsive and continuous sound, including the inclusion of frequency weighting when determining the effects of underwater sound on behaviour.

- It is recommended that the Ministry of Defence reconsiders the current practice for the deployment of acoustic deterrent devices in UXO clearance, looking at duration and source level.

Contents

Appendices

Abbreviations

ABC	Approximate Bayesian computation
ADD	Acoustic deterrent device
ASCOBANS	Agreement on the conservation of small cetaceans of the Baltic, North East Atlantic, Irish and North Seas
Bal	Activities in the Living Environment Decree
DEB	dynamic energy budget
DEMASK	Development and evaluation of noise management strategies to keep the North Sea healthy (InterReg North Sea project)
EMF	Electromagnetic field
HELCOM	Helsinki Commission
ICES	International Council for the Exploration of the Sea
IEC	International Electrotechnical Commission
iPCoD model	interim PCoD model
ISO	International Organization for Standardization
JNCC	Joint Nature Conservation Committee, UK
KEC	Framework for Assessing Ecological and Cumulative effects
MSFD	Marine strategy framework directive
LOBE	Level of Onset of Biologically adverse Effects
EIA	Environmental Impact Assessment
DCS	Dutch Continental Shelf
OSPAR	Oslo-Paris Convention
PAM	Passive acoustic monitoring
PCoD	Population consequences of disturbance
PCW	Phocid carnivores in water (Southall, et al., 2019)
PTS	Permanent Threshold Shift
RWS	Rijkswaterstaat
SCANS	Small Cetacean Abundance in the North Sea
SEL	Sound exposure level
SELcum	Cumulative SEL
SELss	Single strike SEL
SIMOX	Sustainable Installation of XXL Monopiles
SL	Source Level
SMRU	Sea Mammal Research Unit (University of Saint Andrews, Scotland)
SPL	Sound pressure level
TTS	Temporary Threshold Shift
UXO	Unexploded ordnance
VHF	Very high-frequency cetaceans (Southall, et al., 2019)
WOZEP	Offshore wind ecological programme

1 Introduction

1.1 Background

In 2020, both the European Commission and the European Parliament stated the ambition of reducing carbon emissions by 55% (rather than 49%) by comparison with 1990, indicating that offshore wind energy would have an important role to play. The Dutch cabinet therefore decided in early 2022 to establish a total capacity of approximately 21 GW of offshore wind energy by about 2030. This represents an additional capacity of 9.5 GW on top of the previously stated ambition of 11.5 GW. In the autumn of 2021, the government designated search areas for the construction of additional wind farms in order to provide the acceleration needed in the period up to 2030 (Ministry of Infrastructure and Water Management, 2021). These areas have been set out in the North Sea Programme (2022 - 2027).

The Framework for Assessing Ecological and Cumulative effects (KEC) was developed to ensure that the construction of wind farms does not result in unacceptable effects on the size of populations of important species in the Dutch section of the North Sea. On the basis of the most recent knowledge and insights at the time, the ‘underwater noise’ section included an approach for determining and assessing the cumulative effects on important populations of marine mammals of the impulsive underwater sound produced during construction as a result of piling for turbine foundations (KEC 1.0, underwater noise section: Heinis & de Jong et al., 2015). The minor update in 2016 (KEC 2.0) extended the KEC 1.0 to include an ecological standard for maximum permissible effects on the harbour porpoise population. The study indicated that effects on the harbour porpoise population would be normative. For the harbour porpoise population on the Dutch part of the Continental Shelf (DCS), the Minister of Agriculture, Nature and Food Quality (LNV) set as the ecological standard that ‘the reduction of the population should not exceed 5% with a high level of confidence (95%)’ as a result of the construction of the wind farms in the 2020 Roadmap. As a result of the publication of the 2030 Roadmap (27 March 2018) and the associated supplement, the KEC 2.0 was updated in 2019 and 2022 to incorporate the latest insights relating to impulsive underwater sound (and its effects) in the KEC 3.0 (Heinis & de Jong et al., 2019) and the KEC 4.0 (Heinis & de Jong et al., 2022) respectively. In addition, the methodology was extended in the KEC 4.0 in order to determine the effects on populations of harbour and grey seals as well. Any effects on seal populations were assessed in the same way as the effects on harbour porpoises.

The 2030 Supplementary Roadmap for Offshore Wind Energy, which was slightly modified relative to the version underlying the KEC 4.0, was published in April 2024. No new wind farm sites were included but the schedule was updated by comparison with earlier roadmaps. In order to make site decisions based on this roadmap, it is therefore necessary to update the KEC 4.0. This KEC 5.0 again includes the most recent insights (knowledge update) and, on the basis of an updated scenario for the development of offshore wind energy, estimates the effects on populations of harbour porpoises, harbour seals and grey seals. In addition, some modifications have been made to the calculation of the effects of the geophysical surveys and an estimate has been made of the effects of UXO clearance and the associated Acoustic Deterrent Devices (ADDs) deployed during this work in the wind farm sites and along the cable routes.

The location of the wind farm sites in the 2030 Supplementary Roadmap published in April 2024 is shown in Figure 1.1.

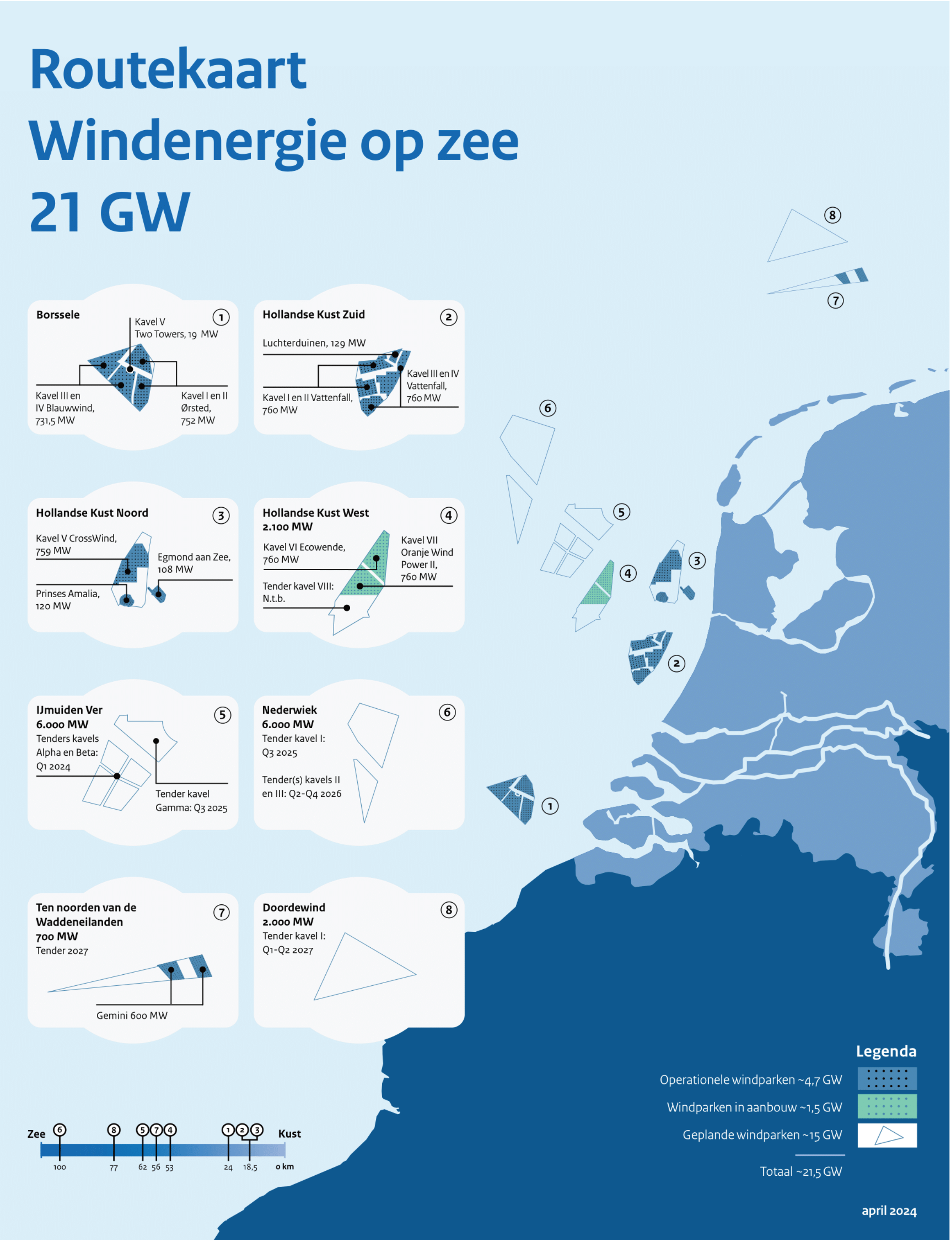

Figure 1.1: Offshore Wind Energy Roadmap ([Routekaart-windenergie-op-zee-april-2024.pdf (rvo.nl)]()).

1.2 Objectives

The objectives of the KEC 5.0 for part B Marine mammals are:

- To update the knowledge used in the KEC 4.0 to determine the cumulative effects of the installation of offshore wind energy on the harbour porpoise, harbour seal and grey seal populations.
- On the basis of the updated steps, to calculate the cumulative effects on the populations of harbour porpoises, harbour seals and grey seals of the installation of offshore wind energy in the national and international North Sea in accordance with a scenario provided by Rijkswaterstaat, including a consideration of the possible effects of sound production by geophysical surveys in the wind farm sites and along the cable routes, UXO clearance and alternative foundation techniques. Not enough knowledge is yet available to make any quantitative statements relative to the effects of shipping sound during the construction, or of operational sound (maintenance vessels and turbines). Chapter 6 (Uncertainties and gaps in knowledge) provides an overview of the latest knowledge and developments.
- Research into the effects on populations of different noise standards for wind farms planned in accordance with the Supplementary Roadmap and for which no noise standards have yet been adopted in site decisions; the imposition of a noise standard will ensure that the ecological standard for populations of harbour porpoises, harbour seals and grey seals is not exceeded during the construction of wind farms (assuming that underwater noise is normative for the extent of the effects).

1.3 Document structure

Chapter 2 of this report provides an overview of the relevant legislation and policies. The research approach is explained and demarcated in Chapter 3. This report separates the description of the methodology (Chapter 4) and the application of this methodology in the calculations for the KEC 5.0 scenarios for offshore wind developments in the North Sea (Chapter 5). Uncertainties and gaps in knowledge are described in Chapter 6.

2 Relevant legislation and policies

2.1 Introduction

Much of the relevant national and international legislation for the assessment of effects on the physical living environment has been included in the Dutch Environment Act (Ow) since 1 January 2024. This new act replaced several separate acts and regulations, including the Nature Protection Act. With respect to marine mammals, it provides for the protection of areas and species (EU Habitats Directive) and the objectives for achieving a Good Environmental Status for marine ecosystems (EU Marine Strategy Framework Directive). In addition, the agreements under ASCOBANS (Agreement on the Conservation of Small Cetaceans of the Baltic, North East Atlantic, Irish and North Seas) and the recommendations from the OSPAR Convention (Oslo-Paris Convention) are important.

2.2 EU Habitats Directive

With the exception of the Birds Directive Areas Friese Front and Bruine Bank, all eight marine and estuarine Dutch Natura 2000 areas have conservation objectives for harbour porpoises, harbour seals and grey seals. When site decisions for offshore wind energy are made, it must be demonstrated that there will be no negative impact on the conservation objectives for species that have been designated for the Natura 2000 sites. In most wind farm sites, this involves ‘indirect externalities’. This means that if a significant effect on the population cannot be ruled out, negative effects for conservation objectives cannot be ruled out either.

In addition to being protected as species through the protection of Natura 2000 sites, harbour porpoises are also protected by species protection measures. The disturbance of harbour porpoises as a result of the construction of a wind farm may be considered by the competent authority as a violation of prohibitions in Article 11.46(1)(b) (intentional disturbance) of the Activities in the Living Environment Decree[4] (Bal). This involves ensuring that the activity does not jeopardise the Favourable Conservation Status of the species, which is the case if it can be shown that significant effects on the population can be excluded. Seals have been assigned to the ‘Other species’ category, which is subject to the prohibitions in Article 11.54(1)(a) and (b) of the Bal (intentional killing or capture, and the damage/destruction of permanent breeding sites or resting places respectively).

2.3 Marine Strategy Framework Directive (MSFD)

The Marine Strategy Framework Directive (European Parliament and Council Directive 2008/56/EC[5]) requires Member States to take the measures required to protect and restore the Good Environmental Status (GES) of the North Sea and to further sustainable use. The GES is assessed with a set of eleven descriptors. For the purposes of this report, the

[4] https://wetten.overheid.nl/BWBR0041330/2024-10-26
[5] https://eur-lex.europa.eu/legal-content/NL/TXT/?uri=celex:32008L0056

descriptors 'D1 biodiversity: Sea Mammals' and 'D11 Introduction of Energy: Underwater Noise' are relevant for marine mammals[6].

The construction of wind farms may, via the effects of underwater sound, affect the indicators of descriptor D1 relating to abundance (D1C2), distributional range (D1C4) and, temporarily, habitat quality (D1C5). The effects of wind farms in the 2030 Supplementary Roadmap on these indicators are addressed in Sections 4.8.3 (Effect Assessment - Method) and 5.7 (Testing). It is not expected that there will be permanent negative effects on the quality of the habitat due to changes in the availability of prey in the wind farms during the operational phase.

With regard to descriptor D11, a distinction is made between short-lived sounds (D11C1: impulsive sounds, such as the sounds from geophysical surveys, piling during the construction of wind farms and platforms, and explosions) and long lasting sounds (D11C2: continuous sounds such as sound from various forms of shipping and alternative foundation techniques). Decision 2017/848/EU[7] states a criterion for these sounds: 'The spatial distribution, temporal extent and levels of anthropogenic impulsive and continuous low-frequency noise do not exceed levels that adversely affect populations of marine animals.' The effects of the wind farms in the 2030 Supplementary Roadmap on these indicators are addressed in Sections 4.8.3 (Impact Assessment - Methodology) and 5.7 (Testing).

2.4 ASCOBANS

The most relevant question when assessing the consequences of the construction of wind farms for harbour porpoises is whether it endangers the conservation status of the population. Under the Agreement on the Conservation of Small Cetaceans in the Baltic, North East Atlantic, Irish and North Seas (ASCOBANS), the interim target that has been set for harbour porpoises is that the population should not fall below 80% of the carrying capacity (ASCOBANS, 2006).

2.5 OSPAR

The recommendations from the OSPAR Convention apply only to the harbour porpoise and they have all now been implemented in the Netherlands through legislation (the Environment Act) and policy (the harbour porpoise protection plan) (Ministry of Agriculture, Nature and Food Quality, 2020). Section 4.8.3 discusses international developments in the context of determining the cumulative effects of impulsive underwater sound.

[6] Effects of human activity could also have knock-on effects on marine mammals via effects on food. Effects of this kind are assessed using descriptor D4 (food web) and they have not been included in this report (see also Section 3.2).

[7] https://eur-lex.europa.eu/eli/dec/2017/848/oj/eng

3 Demarcation and approach to research

3.1 Demarcation of the sources of underwater sound

As in the KEC 4.0, this KEC 5.0 for marine mammals has, in addition to the sound from piling for the construction of wind turbines, taken the following sources of impulsive underwater sound into account:

- Piling sound generated during the construction of the transformer platforms in the Dutch section of the North Sea;
- Piling sound generated by the construction of wind farms in the non-Dutch section of the North Sea; this is relevant for both harbour porpoises and seals because the harbour porpoises and, in particular, the harbour seals on the DCS are part of a larger North Sea or Wadden Sea populations respectively;
- Sound produced during the geophysical surveys prior to the construction of the wind farms and for the purposes of the routing of the cables (for the Dutch wind farms only); the associated effects have been looked at separately and not included in an integrated way in the calculation of effects on populations;
- The sound from UXO clearance in the wind farm sites and along the cable routes (effects on hearing) and the acoustic deterrent devices (effects on behaviour) used during that work to prevent the most severe effects;
- Sound produced during the installation of turbine foundations using vibropiling rather than impact pile-drivers (indicative calculations).

To estimate cumulative effects, the following sources of underwater sound from wind farms were not considered or considered in a descriptive way only:

- Continuous sound produced, in particular by ships, during the construction and operational phases; not enough quantitative data are yet available for this form of disturbance to make statements about possible population effects. Chapter 6 (Uncertainties and Gaps in Knowledge) provides an overview of the most recent insights and developments;
- Continuous sound from operational wind turbines is generally only of interest when ambient sound from wind and shipping is very low (Tougaard et al., 2020);
- Underwater sound caused by wind farm decommissioning (see also Section 3.2 below).

In addition, the following sources of underwater sound have not been included:

- Impulsive sound generated during seismic exploration for oil and gas extraction since this is not a new activity and it has been going on for a long time. Any effects have already been included implicitly in the population modelling;
- Military sonar systems used for submarine detection due to the fact that these systems are used so little in the Dutch section of the North Sea that they make only a very limited contribution to the total amount of underwater sound (Ministerie van IenW & Ministerie van LNV, 2018);

- The sound caused by UXO clearance and the acoustic deterrent devices used for that work outside the wind farm sites, since this is not a new activity.

3.2 Demarcation of effects

Marine mammals may be affected by the planned wind farms in the North Sea during the construction, operational and decommissioning phases. Overviews of the potential adverse effects on marine mammals during the various phases have been included in Sections 3.2.1 - 3.2.3 below, including an indication of the nature and extent of effects <u>not</u> considered in this report.

3.2.1 Effects of wind farm construction

1. ***Installation of monopile, tripod and jacket foundations***
   A lot of sound is produced during piling work on foundations for wind turbines and seismic surveying, resulting in very high levels of sound around the piling location. Depending upon how far animals are located from the source, this can affect marine mammal behaviour or induce temporary or permanent effects on hearing (TTS = *temporary threshold shift* and PTS = *permanent threshold shift*). This is also the case when vibropiling to install foundations generates a level of sound that is not negligible. This report addresses the effects of both sources of underwater sound during the installation of foundations. The primary focus is on the effects of impact piling, the method used almost exclusively for installation work until now. Because vibropiling is not used widely for a range of reasons, knowledge about the sound generated by this technology is limited, as is knowledge about the possible effects on marine mammals. This report provides an indicative estimate of the effects of vibropiling.

   Indirect effects on harbour porpoises and seals as a result of the reduction of foraging opportunities due to effects of piling sound on fish can be ruled out. Effects of this kind are possible only if the disturbance distance relative to the piling location for fish is larger than for marine mammals so that any marine mammals that may be driven away/disturbed by underwater sound end up in areas where less prey is available. This is not the case: a range of research has demonstrated that fish are less sensitive to underwater sound from impact piling than harbour porpoises and seals in terms of behavioural responses. For example, in studies by van der Knaap et al. (2021) and Hubert et al. (2024) it was found that tagged cod did not leave the area where a wind farm was being constructed. Unlike most demersal fish species, cods have a swim bladder and are therefore relatively sensitive to impulsive sound. In addition, the levels at which the hearing of fish can be affected are higher than those for harbour porpoises and seals (cp. Popper et al., 2014; Southall et al., 2019).

2. ***Installation of floating and gravity-based foundations***
   It is reasonable to assume that the wind turbines in the 2030 Supplementary Roadmap will be installed on monopile foundations, although it cannot be ruled out that tripod or jacket foundations will be used. The effects of installing these types of foundation can be investigated for a project EIA on the basis of the approach described in the present report. The effects of floating and gravity-based foundations are not addressed because they are unlikely to be used in the relatively shallow North Sea. Installing gravity-based foundations will result in lower sound levels than the installation of monopile, tripod or jacket foundations (see, for example Potlock et al., 2023). It is not known whether this is also the case with piling work for the anchors required for the installation of floating turbines but the sound levels in this case are not expected to exceed those generated by

piling work for monopile foundations (Maxwell et al., 2022).

3. ***Geophysical surveys***
In preparation for the construction of offshore wind farms, geophysical surveys are conducted in the wind farm site and along the planned cable routes. This research uses equipment that generates sound, such as multi-beam and side-scan sonars, sub-bottom profilers, sparkers and acoustic positioning systems. Because these sound levels can sometimes be high, effects on marine mammals cannot be ruled out beforehand. This report includes an indicative quantification of the potential effects of underwater sound from geophysical surveys on harbour porpoises and seals.

4. ***UXO clearance and deployment of Acoustic Deterrent Devices***
Prior to the construction of offshore wind farms, any explosives found in the area (unexploded ordnance such as World War II bombs) must be cleared. Exposure to the sound of underwater explosions can cause internal bleeding (blast trauma), acute acoustic trauma (hearing loss due to injury to the inner ear) or a permanent elevation of the hearing threshold (PTS) in marine mammals. To mitigate this risk, the current practice is to use a seal scarer (an acoustic deterrent device, or ADD) to drive animals away before ordnance is detonated. This has been set out in the work instructions 'Destroying explosives offshore' (version 20-05-2022). This report provides an indicative quantification of the potential effects of UXO clearance on harbour porpoises and seals.

5. ***Presence of shipping***
Shipping present during the construction of a wind farm may disturb the marine mammals in the vicinity. Results of recent research demonstrate that harbour porpoises may already be affected before actual piling operations begin (Graham et al., 2017; Benhemma-Le Gall et al., 2023). The underwater sound produced during the various activities is the most plausible explanation here. That may include the sound of ships (and particularly the sound of propellers), the sound of acoustic sensors, anchor chains, the lowering of a jack-up vessel's legs etc. However, it is not possible to make quantitative statements about the possible population effects of shipping-related sound associated with wind farm construction and operation. The available data about the number of ship movements, sound levels and associated thresholds of disturbance for harbour porpoises and seals are inadequate for this purpose. This report is limited to an update of the available knowledge and current research (Chapter 6).

6. ***Cable laying***
Activities for the construction and decommissioning of the in-field cables and foundations that disturb the seabed may have local effects on water quality associated with turbidity (caused by silt plumes). Any direct impact on marine mammals can be ruled out because harbour porpoises and seals do not hunt by sight. Harbour porpoises use their echolocation system and seals track down prey primarily with their whiskers. Foraging opportunities for marine mammals may be affected indirectly, however, because some of the species on which they prey, namely non-bed-dwelling fish species that hunt by sight may avoid the affected (more turbid) area. This is a temporary and localised effect and is therefore unlikely to be of any significance in conjunction with the effects of underwater sound. This report will therefore not examine the effect in greater detail. However, a project EIA in preparation for a site decision may examine this potential effect more closely.

3.2.2 Effects during wind farm operation

1. ***Rotating turbines***
   Continuous sound from operational wind turbines is generally only of interest when ambient sound from wind and shipping is very low (Tougaard et al., 2020; Bellmann et al., 2023). Potential impacts are being investigated further in the context of the InterReg project DEMASK[8]. As soon as that project provides clearer information about the nature and extent of the potential effects on marine mammals, it will be possible to make more precise statements in a future KEC update.

2. ***Presence of shipping***
   Where wind farms are present, there may be more sound from shipping from, to and inside the wind farms. The possible effects are being investigated further in context of the InterReg project DEMASK (2024-2026). Once there is more clarity from that project on the nature and extent of potential impacts on marine mammals, conclusions may be stated in a subsequent update of the KEC.

3. ***Presence of cables***
   The electricity generated by the wind turbines is transmitted through in-field cables to the TenneT platform and from there to land through underwater cables. The alternating or direct electric current flowing through cables generates electromagnetic fields (EMF) around the cables. An EMF consists of a magnetic and an electric field. The electric field is shielded by the sheath of the in-field cables and is not released in the immediate vicinity of the cable. The magnetic field is not fully shielded and it can be observed in the immediate vicinity of the cable. In addition, when organisms move through the magnetic field, a weak electric field – the induced electric field (iE field) – is generated (Hermans & Schilt, 2024). The magnetic field therefore does radiate out into the surroundings (up to tens of meters beyond the cable), and it can in this way have effects on marine organisms.

   It is unlikely that **seals** are affected by electromagnetic fields because they do not have ampullae of Lorenzini or other electroreceptors that allow seals to perceive them (Hermans & Schilt, 2024). It cannot be ruled out that **harbour porpoises** can perceive magnetic fields because of the presence of structures in the tongue and mandible that are similar to electroreceptors in some fish species (Klinowska, 1990). However, this does not necessarily mean that the magnetic fields generated by the cables of the wind farms (whether buried or not) can also be felt and, if so, whether that leads to an effect on behaviour. A study by Teilmann et al. (2002) shows that harbour porpoises continue to swim through areas in which wind farms are located and where power lines are therefore present. Nonetheless, even though this does demonstrate that there may not be a full barrier effect, it does not mean that magnetic fields around wind farm cables do not affect harbour porpoises. Orientation ability may be influenced or migration patterns disrupted (Kirschvink, 1990) as quoted in (Hermans & Schilt, 2024). Monitoring around the Borssele Wind Farm AC export cables using a Passive Acoustic Monitoring Network (PAM) showed no correlation between the strength of EMFs and the presence of harbour porpoises (Geelhoed et al., 2022). However, the distance from the PAM stations closest to the cable was still relatively large. On the basis of this study, therefore, it is not possible to arrive at a conclusion about whether, or to what extent, the foraging behaviour and/or other behaviours of harbour porpoises at locations closer to the cable are affected. Furthermore, no conclusions can be drawn based on this study about any effects of EMFs

[8] https://www.interregnorthsea.eu/demask

around DC export cables or AC in-field cables, which, while generating weaker EMFs, are usually not buried as deeply, if at all.

The conclusion is that we do not know what the exact effects are of the presence of power cables inside the wind farms or along the cable routes on the behaviour of marine mammals, and particularly harbour porpoises (this is therefore a gap in our knowledge).

3.2.3 Effects of decommissioning/dismantling wind farms

1. ***Decommissioning of foundations***
   During the decommissioning of a wind farm, the same types of effect can be expected as during its construction (in other words, disturbance by underwater sound). No examples are yet available of how offshore wind farms will be decommissioned and therefore whether this will produce underwater sound or, if so, how much. New techniques are being developed to remove monopiles in a sustainable and cost-effective way. The hydraulic extraction of monopiles is one of the new methods for removing the entire pile. This approach makes it possible to reclaim and recycle all the steel. However, this technique is still in the research phase. The effect will therefore not be examined further in this report.

2. ***Presence of shipping***
   See item 5 of Section 3.2.1.

3. ***Decommissioning cables***
   See item 6 in Section 3.2.1.

3.3 Demarcation of species

As in the KEC 4.0, the KEC 5.0 focuses exclusively on the three native species of marine mammals commonly found in the Dutch section of the North Sea (harbour porpoise, harbour seal and grey seal). In the Dutch section of the North Sea, other marine mammal species are observed almost annually (minke whale, white-beaked dolphin) or with some regularity (other dolphin species[9], pilot whale, beaked whale, northern bottlenose whale, sperm whale), albeit in low numbers (Geelhoed, 2024). Based on the results of the North Sea-wide SCANS IV survey, it has been estimated that there are 1,115 white-beaked dolphins in the Dutch section of the North Sea and the neighbouring German and British waters (Gilles et al., 2023; Geelhoed, 2024)). Like minke whales, they are present in the Dutch North Sea in low numbers, but mainly in the northernmost areas (where no wind farm sites have yet been designated) and in a strip along the western border, roughly from the Brown Bank northwards. Figure 3.1 shows the observations of the minke whale and white-beaked dolphin during the SCANS IV survey conducted in 2022. All in all, the probability of these two species being present in the wind farm sites of the 2030 Supplementary Roadmap is so low that population impacts can be excluded a priori.

[9] Bottlenose dolphin, short-beaked common dolphin, striped dolphin, Atlantic white-sided dolphin, Sowerby's beaked whale.

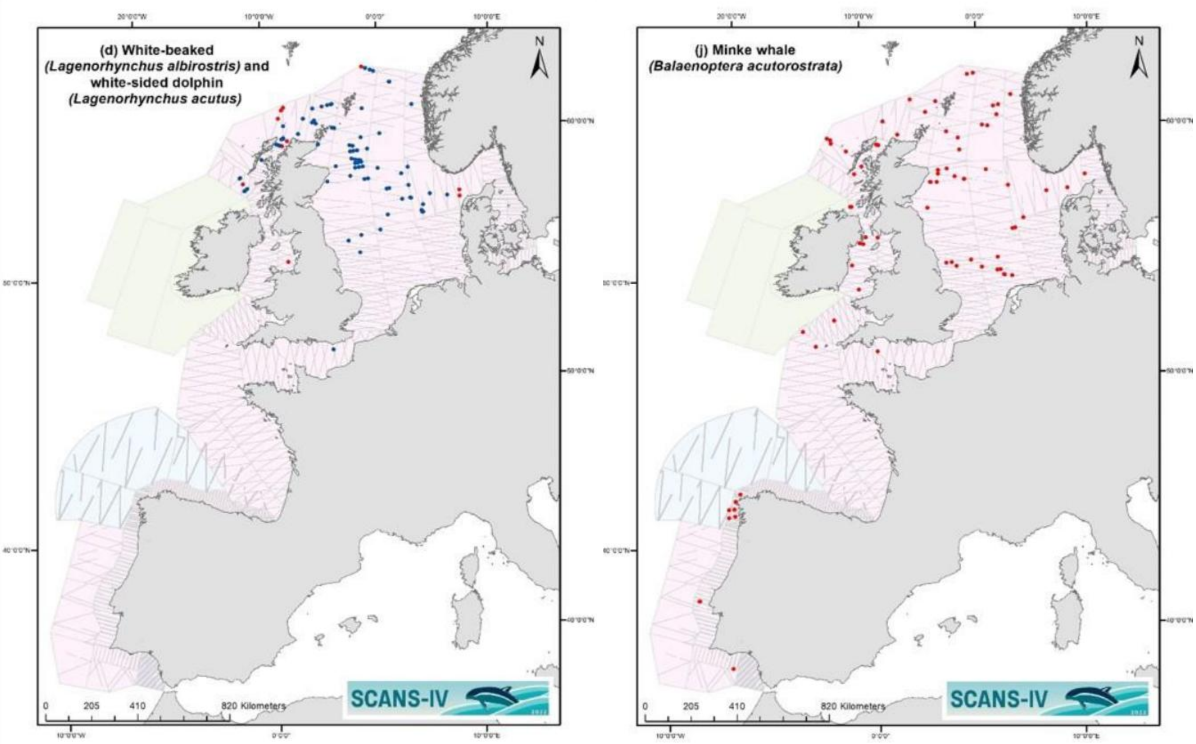

Figure 3.1: **Sightings of white-beaked dolphin (left, blue dots) and minke whale (right, red dots) during the SCANS IV survey (Gilles et al., 2023).**

3.4 Update and effect calculations

3.4.1 Method

No changes have been made in the KEC procedure itself with respect to the KEC 4.0 (see Section 4.1. below). However, new insights have been included in various steps of the procedure and the extent to which this affected the results of the calculations was examined. This relates to:

- Effects of different dose-response curves for behavioural disturbance;
- Effects of using different demographic parameters and density dependence in the interim PCoD model (version 6.02, an update of the 5.2 version used in the KEC 4.0);
- Effects based on calculations with a new interim PCoD model that became available very recently, in which expert elicitation for formulating the effects of disturbance in terms of vital rates has been replaced by a Dynamic Energy Model incorporated in the interim PCoD model (interim PCoD + DEB).

In addition, methods have been described and calculations performed for two sound sources not previously included in the KEC:

- Behavioural disturbance in harbour porpoises and seals as a result of sound from vibropiling. These are indicative calculations based on limited data. Results that have become available recently from a trial with vibropiling conducted in Germany (the KASKASI project) suggest that this is probably a worst-case approach;
- The effects of sound production during UXO clearance and from the acoustic deterrent devices deployed in the process on the hearing and behaviour of harbour porpoises and seals.

New data about sound production and the deployment of equipment have become available for calculating the effects of the geophysical surveys conducted in the wind farm sites and on the cable routes. The calculation method has therefore been changed by comparison with the one used in the KEC 4.0.

3.5 Scenario calculations

Changes with respect to the KEC 4.0 are that calculations have been conducted for a new and larger international scenario and that the scenario for the Netherlands has been amended and based on the 2030 Supplementary Roadmap (see Section 1.1). For the wind farm sites where development is planned from 2026 onwards (IJmuiden Ver and later), it has also been assumed that a noise standard of 164 dB re 1 μPa^2s will be imposed during construction for single-strike sound exposure level (SELss) (at 750 m from the sound source). In addition, the potential consequences of imposing lower or higher noise standards during the construction of these wind farms have been examined.

4 KEC methodology

This chapter provides a description of the methodology used in the present KEC 5.0 report, including a description how the adjustments and additions from Section 3.4.1 have been incorporated. The results of the calculations based on this methodology will follow in Chapter 5.

4.1 Phased procedure

To determine the cumulative effects of impulsive sound on harbour porpoises and seals due to the construction of offshore wind farms, a phased procedure was developed for the KEC 1.0 to quantify the various steps in the effect chain (Heinis & de Jong et al., 2015). This phased procedure was used again in the KEC 3.0 and KEC 4.0 that followed to quantify and assess the effects of the ongoing roll-out of offshore wind on marine mammals (Heinis & de Jong et al., 2019; Heinis & de Jong et al., 2022). In the KEC 5.0, the phased procedure once again constitutes the underlying principle for the quantification of the cumulative effects of underwater sound produced by the construction of offshore wind farms on harbour porpoises, harbour seals and grey seals. Permanent effects on hearing (*Permanent Threshold Shift,* PTS) due to cumulative exposure to impulsive sound from piling and UXO clearance have been considered separately (see Sections 4.2, 4.3, 4.5 & 4.6 for methods and Sections 5.1 to 5.4 for result calculations). This also applies to the effects of behavioural disturbance resulting from the geophysical surveys in the wind farm sites and along the cable routes (see Section 4.3 for methods and Sections 5.2 and 5.3 for result calculations).

The KEC procedure distinguishes between the following phases described in Figure 4.1:

1. The calculation of a realistic worst case for the propagation of sound resulting from a single piling strike for each wind farm; this calculation is based on information about the source strength, local factors (including bathymetry and seabed structure) and knowledge about how sound propagates in water. The result of this step is a map showing the acoustic field resulting from sound produced by the source;
2. The calculation of the size of the area disturbed by impulsive sound for each location; this is determined by the calculated sound propagation and a sound dose-effect relationship for the occurrence of a significant behavioural change in harbour porpoises and seals;
3. The calculation of the number of harbour porpoises and seals disturbed by sound per piling day on the basis of the calculated disturbed areas multiplied by the local density of animals[10];
4. The calculation of the number of animal disturbance days on the basis of the number of disturbed animals per piling day multiplied by the number of days on which piling takes place (= the number of turbine foundations; it has therefore been assumed in principle that no more than one pile is driven every 24 hours (see Section 4.4.3 for a calculation of the effects of the simultaneous driving of multiple piles));
5. The estimation of the possible impact on the population using the interim PCoD model (version 6.02);
6. Determination of the estimated population decline and assessment of that decline on the basis of the ecological target set by government for the roll-out of offshore wind

[10] Harbour porpoises: average summer density; seals: maximum density per location during the year.

energy until 2030 for harbour porpoises (Rijkswaterstaat Zee en Delta, 2019 a, b) and the comparable target for seals proposed in the KEC 4.0 (see Heinis & de Jong et al., 2022);
7. Adjustment of the noise standard to be imposed if the effects on the population are found to be unacceptable (in other words, if they exceed the ecological standard).

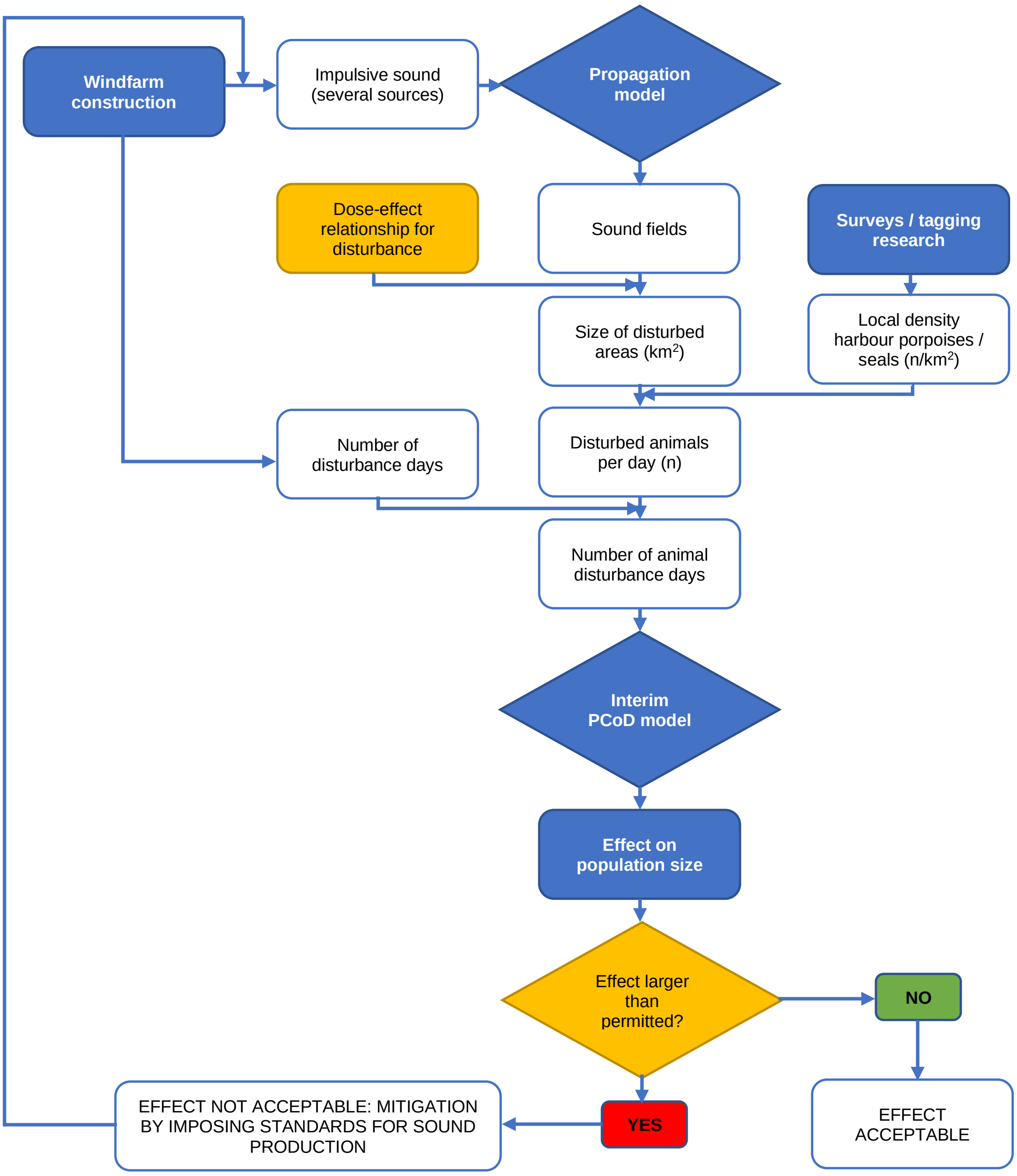

Figure 4.1: Schematic representation of the steps in the staged procedure for determining and assessing the cumulative effects of impulsive underwater sound on harbour porpoises and seals during the construction of wind farms.

In the sections that follow here, the different phases in the staged procedure for harbour porpoises and seals are discussed in more detail and a description is given of the amendments that have been made with respect to the KEC 4.0 version on the basis of recent insights and research results.

4.2 Underwater sound modelling

The purpose of calculating sound propagation is to make it possible to estimate the sound levels to which harbour porpoises and seals may be exposed during the construction of offshore wind farms. This section provides guidelines for modelling underwater sound.

4.2.1 Acoustic exposure measure

When assessing the effects of underwater sound on marine life, the scientific literature for marine mammals (Southall et al., 2019) and fish (Popper et al., 2014), and regulations such as the European Marine Strategy Framework Directive (MSFD) distinguish between impulsive sound (as caused by piling, explosions and geophysical surveys) and continuous sound (as from shipping and operational wind farms).

Impulsive sound

In the KEC, impulsive sound is expressed as a sound exposure level (SEL; symbol L_E) that quantifies the total acoustic energy in impulsive sound. This is defined as (ISO 18405, 2017):

$$L_E = 10\log_{10}\left(\frac{1}{E_0}\int_{t_1}^{t_2} p^2(\mathrm{t})\mathrm{dt}\right)\ \mathrm{dB} \qquad (1)$$

Here, p is the sound pressure and t is time. t_1 and t_2 are the start and end times of the impulsive sound and $E_0 = 1\ \mu\mathrm{Pa}^2\mathrm{s}$ is the reference unit for sound exposure.
The unweighted broadband single-strike sound exposure level (SELss) of the loudest piling strike during the driving of a turbine foundation pile is used as a measure of exposure to piling sound. SELss is a useful measure of behavioural disturbance (see, for example (Diederichs et al., 2014: Brandt et al., 2018; de Jong et al., 2023)) with respect to the sound of piling strikes, which is shorter than the integration time of the animals' hearing. For this KEC, in line with previous national and international studies, the broadband SELss that is not weighted on the basis of the frequency sensitivity of hearing has been used for this purpose.

Continuous sound

In the KEC, continuous sound is described in terms of a sound pressure level (SPL; symbol L_p) that quantifies the time-averaged sound pressure over a specified time interval T. This is defined as (ISO 18405, 2017):

$$L_p = 10\log_{10}\left(\frac{1}{p_0^2 T}\int_{t_1}^{t_2} p^2(\mathrm{t})\mathrm{dt}\right)\ \mathrm{dB} \qquad (2)$$

Here, p is the sound pressure and t is time. t_1 and t_2 are the start and end times of the time interval T and $p_0 = 1\ \mu Pa^2$ is the reference unit for sound pressure.
Time and frequency weighting could also be useful for continuous sound. See the Intermezzo below.

Intermezzo: Alternative acoustic units
Cumulative SEL based on multiple exposures and weighted for hearing frequency sensitivity is clearly related to effects on animal hearing such as a temporary or permanent shift in the hearing threshold (TTS and PTS). See Southall et al. (2019).
There is evidence that using an SELss weighted for hearing sensitivity could be better for determining a behavioural response as well (Kastelein et al., 2022). However, this is still considered too problematic for implementation in the KEC. See de Jong et al. (2023).
An alternative measure that takes into account the hearing sensitivity of animals is a time- and frequency-weighted sound pressure level similar to the $L_{A,F,max}$ measure for airborne sound that is used in sound level meters with an IEC standard (IEC 61672-1, 2013). For marine mammals, the same *Fast* time weighting (time constant 125 ms) as in those sound level meters could be used in combination with a frequency weighting from (Southall, et al., 2019). See, for example, Tougaard & Beedholm (2029). Using a measure of this kind also makes it possible to compare impulsive sound and continuous sound (and the effects), see Lucke et al. (2024). At present, not enough experience has been acquired with a measure of this kind to implement it in this version of the KEC. Further investigation is recommended see Chapter 6.

4.2.2 Modelling piling sound: source model – propagation

In previous versions of the KEC, underwater sound from piling was calculated using TNO's Aquarius 4 computing model (de Jong et al., 2019). That model calculates the spatial distribution of underwater sound from piling dependent on data relating to the piling hammer, foundation piles and the surroundings (bathymetry and geology). In principle, models other than the Aquarius 4 model can also be used for KEC calculations. However, when alternative models are applied, it is necessary to take into account the properties of both the hammer and the pile (by modelling them not as a single point source but as sound propagation over the length of the pile) and seabed properties and bathymetry (for propagation). The details have been described in Appendix B.

The implementation and use of applied models should be verified and validated. The use of the COMPILE benchmark studies presented in Lippert et al. (2016) and Lippert et al. (2018) is recommended.

4.2.3 Modelling underwater sound from vibropiling

Unlike hydraulic pile drivers, vibropiling systems produce continuous sound. Much less is known about both the sound levels produced and their effects on marine mammals than in the case of conventional impact piling. The joint industry project *Sustainable Installation of XXL Monopiles* (SIMOX)[11] is investigating the feasibility of vibropiling for the installation of monopiles for offshore wind turbines. On that basis, a paper[12] was drafted in 2023 for RWS-WVL for the calculation of the cumulative effects of continuous underwater sound on harbour porpoises (de Jong, 2023).

Details of the proposed modelling of vibropiling sound can be found in Appendix B. Due to a lack of usable monitoring data, that description is based on measurements of underwater sound during the vibropiling of a mooring pile in Rotterdam's Beneluxhaven. Scaling these

[11] https://grow-offshorewind.nl/project/simox
[12] https://www.noordzeeloket.nl/@286645/notitie-berekening-cumulatieve-effecten-continue/

measured data in line with the dimensions of piles and pile-drivers for offshore wind turbines was considered to be a practical conservative first estimate at that time.
Recently, Bellmann et al. (2024) have reported monitoring data for underwater sound from the vibropiling of monopiles in the German KASKASI II wind farm. They confirm that the estimate of underwater sound proposed in the paper by de Jong (2023) leads to an overestimation of underwater sound at frequencies relevant for harbour porpoises and seals (see Appendix B and Section 4.3.2).

The amount of available monitoring data is still inadequate for a reliable estimate of underwater sound from vibropiling. Unfortunately, the offshore vibropiling trial in SIMOX in 2023 had to be terminated after a short time due to technical problems. New vibropiling trials that also measure underwater sound are planned in the SIMPLE-III[13] project in spring 2025.

4.2.4 Modelling sound from geophysical surveys

Prior to the construction of wind farms and cable routes, geophysical surveys are conducted to map out soil conditions in different layers and check for the presence of UXO (see Section 4.2.5). That work is done with a range of acoustic sources such as multibeam and sidescan sonars, sub-bottom profilers and sparkers. The survey signals are very different from piling sound. The sources that cause significant sound levels at frequencies audible to harbour porpoises and seals are the sub-bottom profilers, sparkers and the ultra-short-baseline (USBL) location system often used with side-scan sonars. Details of the modelling of sound from geophysical surveys can be found in Appendix B.

4.2.5 Modelling sound from UXO detonations and the ADDs deployed in the process

❭ ***Detonations***

The calculations for the detonation of UXO use an acoustic source and propagation model for underwater explosions in shallow water. It consists of a semi-empirical source model for the underwater explosion and the Aquarius 3 propagation model with an empirical correction factor for explosions in shallow (26 m) water (von Benda-Beckmann et al., 2015). Comparisons with measured sound levels from UXO in the North Sea show that this gives a good match (~ 3 dB) with broadband SEL and a SEL weighted for harbour porpoise hearing (Southall et al., 2019) down to approximately 15 km (von Benda-Beckmann et al., 2015; Salomons et al., 2021). Using this model, wideband unweighted SELs and frequency-weighted SELs were calculated in a band of 10 Hz - 20 kHz.

❭ ***Acoustic Deterrent Devices (ADDs)***

To protect the environment, current practice is to use a seal scarer as an acoustic deterrent device to drive animals away before ordnance is detonated. This has been set out in the work instructions 'Destroying explosives offshore' (version 20-05-2022). An ADD is typically deployed for 30 minutes before the detonation. The ADD used by the Ministry of Defence (the Lofitech seal scarer[14]) emits pulses with a basic frequency of 14.5 kHz and a source level of SL = 189 dB re 1 μPa^2m^2. See, for example, Brandt et al. (2013).

[13] https://grow-offshorewind.nl/project/silent-installation-of-monopiles-iii-simple-iii
[14] https://www.lofitech.no/product

4.3 Behavioural disturbance caused by sound

4.3.1 Piling sound: dose-effect relationship for disturbance

The disturbance of animals by sound varies from individual to individual and depends on the context in which the animals are exposed to the sound. Tyack and Thomas (2019) emphasise the importance of applying dose-effect relationships when estimating the number of animals potentially affected. Relationships between the sound level (unweighted broadband Single Strike Sound Exposure Level) and the occurrence of a significant behavioural response[15] were derived as much as possible from recent peer-reviewed literature.

A dose-effect relationship describes the probability of an animal being disturbed (effect) as a function of the sound level (dose) to which the animal is exposed. This means that the calculations take into account differences in the probability of the disturbance of animals that are close to the piling location, where the sound level is higher, and animals that are further away. A dose-effect relationship of this kind is used by, among others, the U.S. Navy and the Royal Netherlands Navy for the assessment of the potential consequences of using sonar (Miller et al., 2014). This relationship is usually expressed with a logistic function (the 'S-Curve'). See equation (3)[16]

$$\mathrm{P_{resp}}(L) = \frac{1}{1+\mathrm{e}^{-\mathrm{k}(\mathrm{L}-L_{50\%})}} \tag{3}$$

Here, $\mathrm{P_{resp}}$ is the probability of disturbance and L the exposure dose. $L_{50\%}$ is the dose at which the probability of disturbance is 50% and k is the parameter used to fit the function to available data.

The unweighted broadband single-strike sound exposure level (SELss) of the loudest piling strike during the driving of a turbine foundation pile is used as a measure of exposure to piling sound.

❯ ***Harbour porpoises***

In the KEC 4.0, a dose-response relationship for the disturbance of harbour porpoises was derived from measurements made during the construction of the Beatrice wind farm in the UK (Graham et al., 2019). A decrease in the number of detected echolocation clicks of harbour porpoises during operations was interpreted here as an indicator of avoidance behaviour. In the KEC 4.0, it was decided to adopt, as the worst case, the dose-effect relationship determined by Graham et al. (2019) for the avoidance response of harbour porpoises to the turbine foundation that was piled first. It was decided to adopt a cautious approach and disregard the habituation observed in the measurements by Graham et al. (2019) leading to a reduced probability of disturbance when there are successive piling days. For the KEC 5.0, the selection of this dose-effect relationship has been reconsidered on the basis of more recent information.

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[15] Behaviour with a score of 5 or higher on the behavioural response scale of Southall et al. (2007). These are behaviours such as changes in swimming behaviour and breathing, avoiding a particular area and changes in calling or clicking behaviour (for the purposes of communication or foraging).

[16] This notation of the function is clearer than the one given in the KEC 4.0 $\mathrm{P_{resp}}(\mathrm{L}) = (1 + \exp(-\mathrm{a} - \mathrm{b} \cdot \mathrm{L}))^{-1}$. These functions are the same for $L_{50\%} = -b/a$ and $k = b$.

Monitoring data for underwater sound and the detection of harbour porpoise clicks during the construction of the Gemini and Borssele wind farms have been analysed in the WOZEP programme (de Jong et al., 2023). The dose-effect relationship found on the basis of the Gemini data shows a significantly smaller probability of disturbance than the one calculated on the basis of the relationship used in the KEC 4.0. Figure 4.2 provides an overview of the dose-effect relationships found in various studies and Table 4.1 gives the corresponding parameters used to describe the dose-effect relationship (equation 3).

The 'Brandt et al.' curve is based on a review of studies of harbour porpoise disturbance during the construction of seven offshore wind farms in Germany (Brandt et al., 2018). It shows that, in these studies, when there is exposure to a piling sound level (SEL_{05}) of approximately 154 dB re 1 µPa²s, there was an approximately 50% probability that harbour porpoises would avoid piling sound. Here, SEL_{05} is the unweighted broadband level exceeded by up to 5% of the piling strikes when installing a single pile.

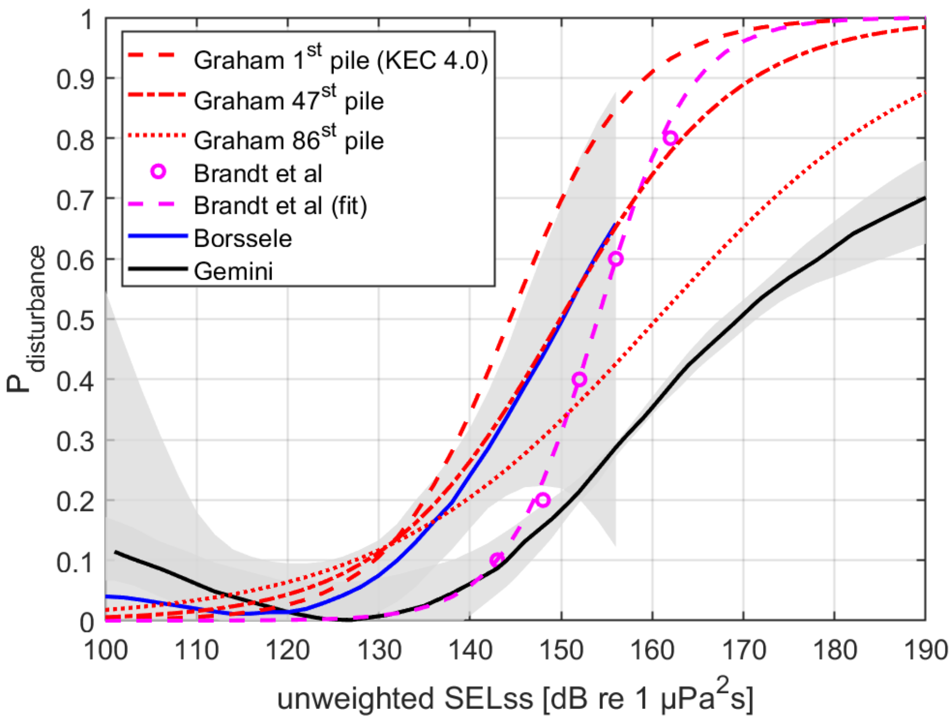

Figure 4.2: Dose-response relationships for the disturbance of harbour porpoises by piling sound: probability of disturbance P_{dist} as a function of the unweighted broadband SELss. The red lines are the dose-effect relationships from Graham et al. (2019). The KEC 4.0 uses the dose-effect relationship for harbour porpoise disturbance by the piling sound for the first pile in the area. The relationships from Graham et al. (2019) show that the probability of disturbance decreases as work progresses in the same area. The markers (o) have been estimated on the basis of Figure 4 from Brandt et al. (2018). The solid lines follow from the statistical analysis of measured data during the construction of the Gemini (without noise standard) and Borssele (with noise standard) wind farms in de Jong et al. (2023). The grey areas show the 95% confidence intervals for these models. Note that the curves for exposure levels (SELss) below 130 dB are based on very little monitoring data and so they are very uncertain.

Table 4.1: Parameters used to describe the dose-effect relationship (equation 3).

Curve	SELss(50%)	k
Graham et al. (2019): 1st pile (KEC 4.0)	144.3 dB	0.1484
Graham et al. (2019): 47th pile	149.9 dB	0.1035
Graham et al. (2019): 86th pile	160.5 dB	0.0663
Brandt et al. (2018)	154.0 dB	0.1997

In principle, the added dose-effect relationships all lead to a lower estimate of the number of harbour porpoises that are disturbed. Several dose-effect relationships were investigated in this KEC 5.0 study. Figure 4.2 shows the uncertainty in the estimation of the dose-effect relationship. This illustrates that the relationship already applied in the KEC 4.0 results in a conservative estimate of the probability of disturbance. Since firm grounds are as yet lacking for the selection of a different relationship, it was therefore decided to adopt a cautious approach and use the same relationship in the KEC 5.0 as the one previously used in the KEC 4.0 to estimate the number of harbour porpoises that are disturbed.

The masking of piling sound by background noise, from ships and from breaking waves on the water surface has not been taken into consideration in the analysis of disturbance in the KEC. This contributes to the uncertainty in the estimating of the probability of disturbance at lower exposure levels (<130 dB), in other words at larger distances from the piling location.

Incidentally, there is no convincing evidence that piling sound will still cause disturbance at long distances. A recent report from the research project RaDIN for the Offshore Renewables Joint Industry Programme (ORJIP) for Offshore Wind (Matei et al., 2024) described how piling sound becomes less 'impulsive' with increasing distance from the piling location. As a result, the distance at which TTS/PTS can occur is smaller than predicted on the basis of the dose-effect relationship for impulsive sound. It is likely that the effect distance for behavioural disturbance is also smaller.

Seals

The monitoring data from which a dose-effect relationship for disturbance by piling sound can be derived are also scarce for seals. In the KEC 4.0, the observations of Russell et al. (2016) and Whyte et al. (2020) were used to estimate a dose-effect relationship for harbour seals in which the number of harbour seals fell at exposure to SEL_{SS} = 142 - 151 dB re 1 $\mu Pa^2 s$. This would seem to be reasonably consistent with the observations of Aarts et al. (2018), who observed changes in the diving behaviour of grey seals starting at approximately 12 km and up to a maximum of 48 km from the piling locations in the Gemini and Luchterduinen wind farms. This corresponds approximately to a probability of disturbance starting at exposure to SEL_{SS} = 144 – 150 dB re 1 µPa2s. Because of the correspondence between the observations of the responses of harbour seals and grey seals, the same dose-effect relationship for the two species has been assumed for the time being.

Figure 4.3 shows the assumed dose-effect function for seals. It is centred around the threshold of 145 dB assumed previously and the bandwidth is comparable with the observations. The dose-effect curve was approximated by the logistic function (equation 3) with parameters $L_{E,50\%} = 145\ \mathrm{dB}$ and $k = 0{,}3/\mathrm{dB}$.

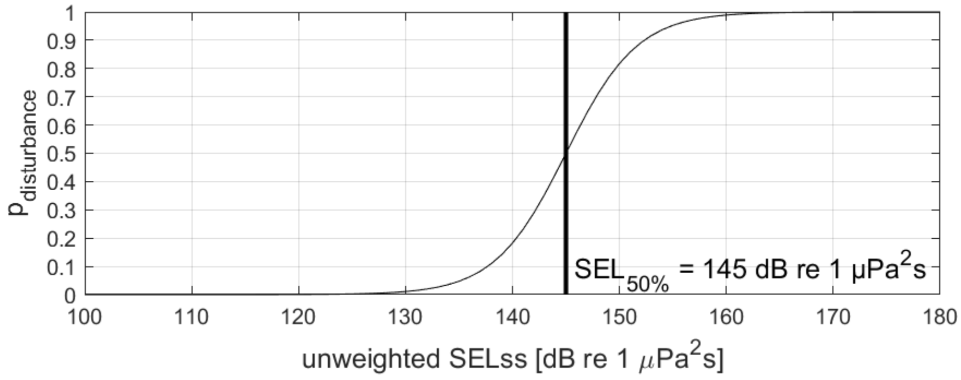

Figure 4.3: Relationship between sound dose (SELss) and probability of a behavioural response in seals. The vertical line shows at which SELss there is a 50% probability of the animals being disturbed.

4.3.2 Sound of vibropiling

The sound of vibropiling, like the sound of ships and offshore structures, falls into the category of 'continuous' sound. Work is still in progress on the establishment of criteria for marine mammal disturbance as a result of continuous underwater sound, see Southall et al. (2021). Pending the results, the approach proposed by Tougaard et al. (2015 (see also de Jong & von Benda-Beckmann, 2018) has been adopted here. On the basis of the limited data available, it has been assumed for the time being that the behaviour of harbour porpoises is disturbed when they are exposed to sound levels 45 dB higher than the hearing threshold and that of seals when they are exposed to sound levels 60 dB higher than the hearing threshold. The data required to derive a non-discrete dose-effect relationship as in the case of piling sound (Section 4.3.1) are lacking.

Because the measurement of hearing thresholds is not standardised and published data about individual animals do not always overlap, the generalised audiograms from Southall et al. (2019) were used: the *very high-frequency cetaceans* (VHF) audiogram for harbour porpoises and the *phocid carnivores in water* (PCW) audiogram for seals. Figure 4.4 shows the resulting threshold values.

For illustrative purposes, the proposed thresholds here were compared with estimates of vibropiling sound at 750 m from a pile. Figure 4.4 shows an example in which the conservative estimate of vibropiling sound (based on 'Beneluxhaven') exceeds the disturbance thresholds by a considerable margin, while the measurement results for vibropiling in the KASKASI II wind farm barely exceed the threshold for harbour porpoises, but do so for seals, especially at frequencies lower than 1 kHz.

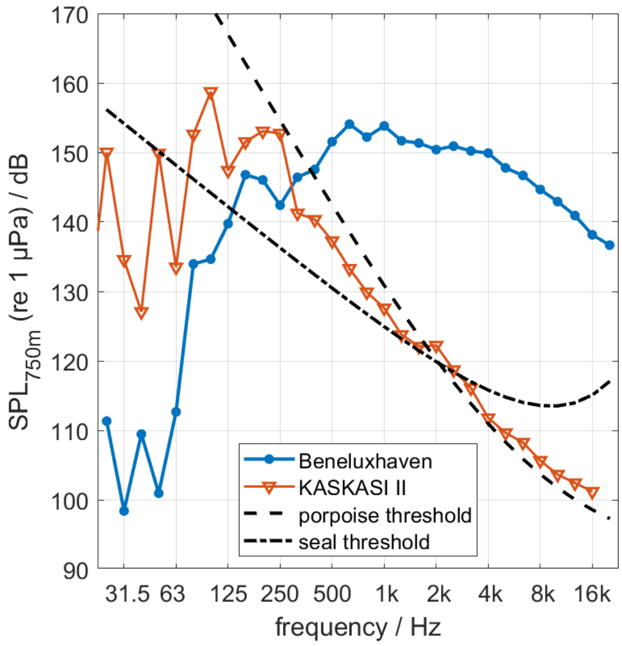

Figure 4.4: Decidecade spectrum for the estimated sound level at 750 m from the pile when using a vibro hammer with an eccentric moment of 1920 kg m and a frequency of 23 Hz based on the scaling of monitoring data from the Rotterdam Beneluxhaven (Binnerts et al., 2018) and the KASKASI II project (Bellmann et al., 2024). The black lines show proposed thresholds for behavioural disturbance at 45 and 60 dB above the VHF (harbour porpoise) and PCW (seal) audiograms respectively from Southall et al. (2019).

This illustrates the uncertainty in the proposed approach for estimating the potential number of animals disturbed by vibropiling sound. Improving the estimate mainly requires more data from the monitoring of underwater sound and behavioural responses during future wind farm construction and, if possible, from behavioural studies in laboratory conditions.

4.3.3 Sound from geophysical surveys

Current data about how harbour porpoises and seals respond to sounds produced during geophysical surveys are very limited. Generic thresholds for behavioural disturbance derived in a review conducted in the context of WOZEP (de Jong & von Benda-Beckmann, 2018) have therefore been used here. The estimate of the number of disturbed animals is explained in Appendix D.

For each geophysical survey, an estimate was made of the number of animals that may be located in the disturbance area of the applied sound source during a survey day. The sum of that number for the number of days on which surveys take place and for the projects results in the reported number of animal disturbance days. Disturbance from the sound of geophysical surveys is not the same as disturbance from piling sound, in part because the sound source moves during surveys. Because knowledge is lacking about how to consider the accumulated effects of these disturbances, the determination of the consequences for the population of disturbance (Section 4.7) in this study is limited to the effects of piling sound. The possible consequences of this decision are discussed in Section 5.6.1.

4.3.4 Sound from UXO clearance

It is unlikely that behavioural disturbance resulting from exposure to the sound of a single UXO detonation will have an effect on marine mammal populations (Southall et al., 2007). For the effects of UXO detonations on hearing, see Section 4.6.

The ADD (the Lofitech seal scarer) used by the Ministry of Defence emits pulses of 500 ms and a frequency of 14 kHz at a source level of SL = 189 dB re 1 μPa^2m^2 at random intervals (0.6-90 s). This ADD was selected with the aim of chasing animals long distances from the source. A recent study by Elmegaard et al. (2023) with tagged harbour porpoises shows that five of the six tagged animals swam away at a typical speed of approximately 1.5 m/s from the ADD when the observed sound level exceeded 98 dB re 1 μPa^2 (approximately 45 dB above the hearing threshold). This seems to be consistent with previous studies in which animals were observed swimming away and in which a reduction in echolocation (indicating that the animals are swimming away) was detected (Brandt et al., 2013; Elmegaard et al., 2023) and also with levels at which harbour porpoises are disturbed (Tougaard et al., 2015). See also de Jong & von Benda-Beckmann (2018). At higher levels, there is an increasing likelihood that animals will swim away. Several observations of both wild and captive animals show systematic disturbance at exposure to sound from the Lofitech ADD at levels of approximately 120 dB re 1 μPa^2. In a typical North Sea location, this corresponds to a disturbance distance of approximately 7 km (this is systematic disturbance, in other words a high probability of the animal swimming away) to 18 km (low probability of swimming away) for the Lofitech ADD. On the basis of observations from Gordon et al. (2019), a disturbance distance (50% probability) of 1 km has been assumed for seals.

An estimate of the number of animals that may be present in the ADD disturbance area was made for each UXO detonation. The sum of that number for the total UXO detonations (solely for the purposes of the construction of the NL wind farms) results in the reported number of animal disturbance days. Disturbance by sound from ADDs is not the same as disturbance by piling sound, in part because the duration of ADD deployment is more limited. Because knowledge is lacking about how to consider the accumulated effects of these disturbances, the determination of the consequences of disturbance for the population (Section 4.7 in this study) is limited to the effects of piling sound. The possible consequences of this decision are discussed in Section 5.6.1.

4.4 Behavioural disturbance caused by piling sound: number of disturbed animals

The number of animals disturbed by piling sound is estimated on the basis of the calculated sound propagation map. The dose-effect relationship is used to determine the probability of disturbance for each grid cell on the map. That probability is interpreted as the fraction of the number of animals in a given grid cell (in the animal distribution map) that will react to the sound exposure. In the case of vibropiling sound, geophysical surveys and ADDs, the lack of data means that only an estimated threshold is available and the dose-effect relationship is therefore discrete. The probability of disturbance is 1 for exposure to sound levels above the threshold and 0 for exposure levels below the threshold.

4.4.1 Animal distribution maps

The calculations draw on the same distribution maps for harbour porpoises and harbour and grey seals as in the KEC 4.0. The local density for **harbour porpoises** is derived from the map drawn up by Gilles et al. (2020) for Rijkswaterstaat (see Figure 4.5). This is an update of the summer density map for harbour porpoises from Gilles et al. (2016), supplemented with data from the 2016 SCANS-III survey and annual summer counts from Belgium, the Netherlands (by Wageningen Marine Research), Germany and Denmark during the period 2014 – 2019. Due to the lack of up-to-date maps for the other seasons, it has been assumed for this study, as in the KEC 4.0, that the average distribution map from Gilles et al. (2020) applies for the year as a whole. An average North Sea population of 373,310 animals was calculated on the basis of this map. In the Dutch section of the North Sea, the average is 62,771 animals, in other words 17% of the total.

A fourth North Sea-wide SCANS survey was conducted in 2022. These data, along with results from more recent counts, are being used to draw up a new distribution map for harbour porpoises. However, that map had not yet been completed during the research for the KEC 5.0. The data show that harbour porpoise distribution is dynamic, and that spatial shifts in harbour porpoise distribution (over the course of the year and between years) continue in the North Sea as a whole and in the Dutch section. Since the publication of the distribution map by Gilles et al. (2020), the following changes have occurred in harbour porpoise distribution (Geelhoed, 2024):
- The modelled effects for the mainland coast extending to the west of Texel will be an overestimate since the densities off the coast of North Holland would appear to have been lower in recent years (post-Gilles et al., 2020);
- Modelled effects to the north of the Wadden Islands will be an underestimate because the densities in recent years (post-Gilles et al., 2020) are higher and extend over a larger area.

This qualitative information is not appropriate for the modification of the results of the estimates of effects made for the KEC 5.0 (with their own uncertainties), but it does illustrate the need to update Gilles et al.'s 2020 map.

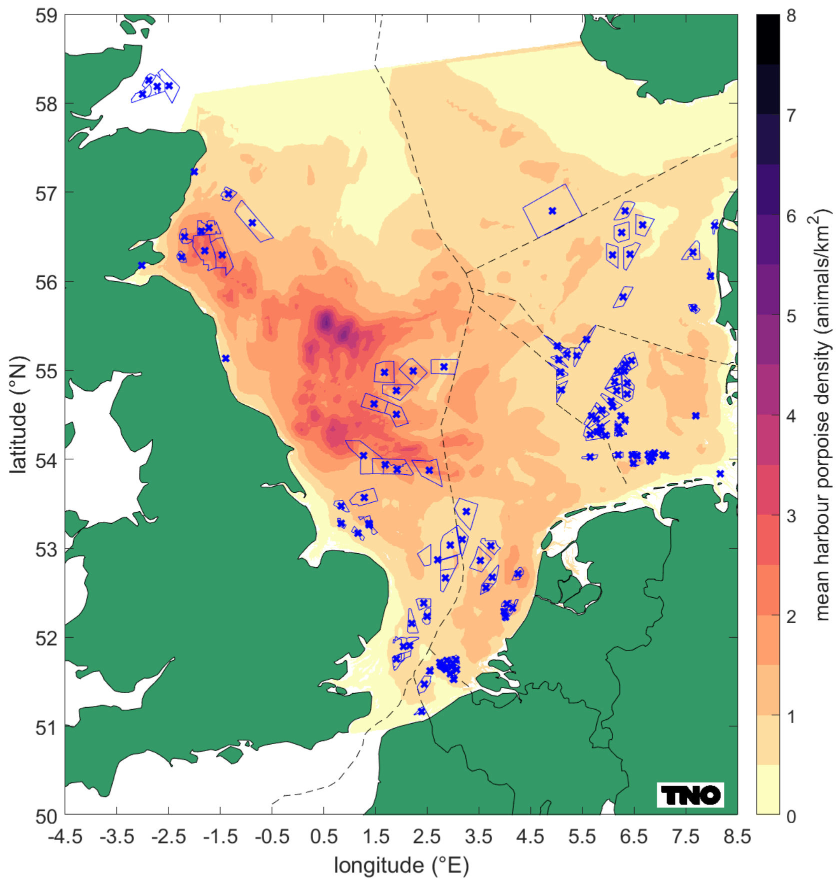

Figure 4.5: Average density of harbour porpoises during the summer months, from Gilles et al. (2020). Blue crosses and contours indicate (planned) wind farm areas.

The composite maps produced by (Aarts, 2021) for the KEC 4.0 have been used for **seals** on the DCS. Those maps model, on the basis of all the tagging data collected in the period 2006 - 2019, the density of harbour seals and grey seals for each month (see Aarts et al. (2016) for a description of the methods). Figure 4.6 includes maps of the maximum density per grid cell (~300 m × 400 m) over the course of the year, which was used as a worst case in the calculations[17]. Annually, approximately 55,000 harbour seals and 20,000 grey seals are found on average in the area shown in the figure. In the Dutch section, the numbers are about 18,000 and 15,000, approximately one-third and three-quarters of the total respectively.

Ninety percent of the transmitter data used to draw up the maps are from the years 2006 - 2016. It is not certain that the maps are still representative for the current distribution of harbour and grey seals. For example, recent data from six tagged, juvenile harbour seals from a rehabilitation centre indicate a possible change in foraging strategy from previous years. They seemed to forage over longer distances and move farther away from resting locations than juveniles tagged previously (in the wild) (Brasseur & Aarts, 2024). The significance of this change for the results of the effect calculations is discussed in Section 4.6.1 and Section 5.3.1.

[17] N.B. By selecting the maximum density per grid cell, the map provides a not entirely realistic seal distribution. The maximum density may be in different months for different grid cells. It, therefore, can be considered a worst case for the number of seals disturbed by piling noise.

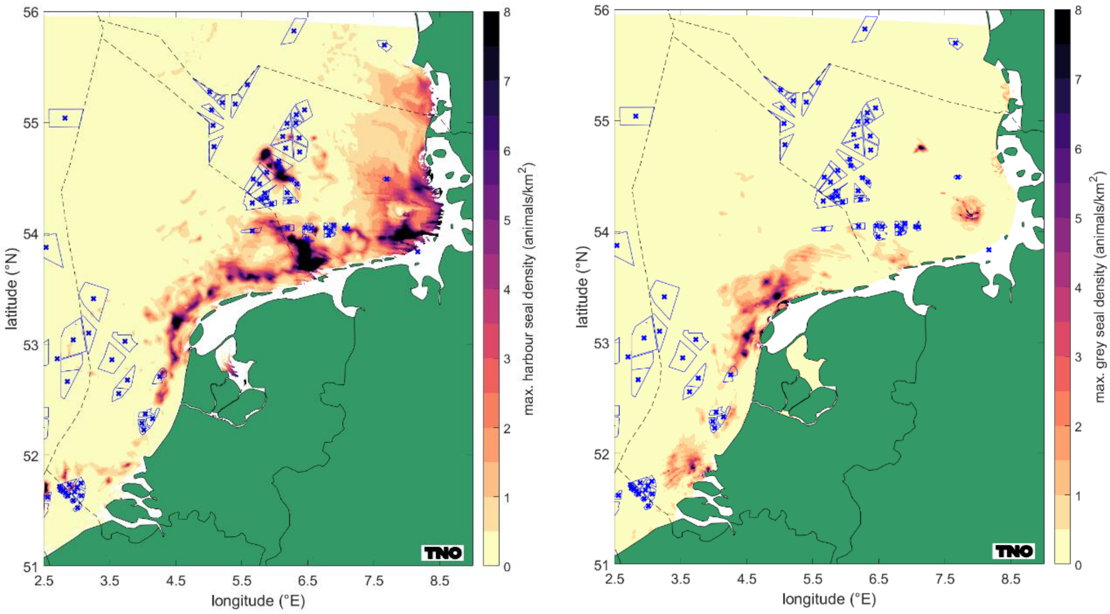

Figure 4.6: Estimated maximum density of harbour seals (left) and grey seals (right) by grid cell over the year (after Aarts, 2021).

4.4.2 Calculation of the effective area as a result of piling sound

The effective area in which animals may be disturbed by underwater sound from piling is determined by combining the calculated sound propagation with the dose-effect curve. As described in Section 4.2.2, the *single strike sound exposure level* (SELss) is calculated on a grid of positions around the source so that a sound map can be established. See, for example, Figure 4.7a. The probability of disturbance at the points in the grid is calculated with the dose-effect relationship (equation 3), which is used to create a map of the probability of disturbance. See, for example, Figure 4.7b. The ‘effective disturbance area’ is determined by totalling the probability of disturbance multiplied by the area of the grid cell (~300 m × 400 m) for all the grid points on the map.

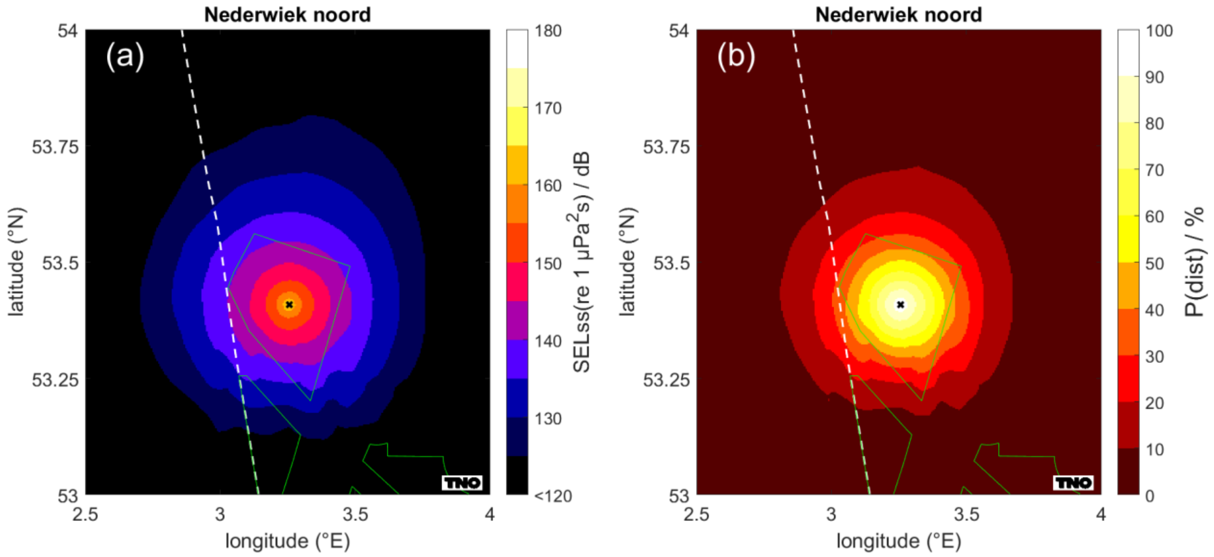

Figure 4.7: Example for piling at the central location in Nederwiek Noord of (a) the calculated sound propagation (SELss) applying a noise limit of SELss (750 m) = 164 dB re 1 µPa^{2}s and (b) the associated probability of the disturbance of harbour porpoise behaviour.

4.4.3 Calculation of the number of animals possibly disturbed by piling sound

To calculate the number of animals possibly disturbed by piling sound, the probability of disturbance (Figure 4.7b) is multiplied by the estimated number of animals per grid cell on the basis of the animal density map (see e.g. Figure 4.5).

❯ *Variance*

In an environmental impact assessment for individual areas, a calculation for multiple piling sites can be used to estimate the variance in the number of disturbed animals per location in the area. This variance is determined by differences in water depth at the pile locations and differences in animal density around the piles. No information is available about the variation of animal density over time. Assuming that these estimates are normally distributed, the total number of disturbed animals for N piling days is on average equal to N times the average number of disturbed animals per piling day, with a standard deviation (square root of variance) equal to $\sqrt{N}$ times the standard deviation for the number of disturbed animals per piling day.

❯ *Simultaneous piling*

The total number of harbour porpoise disturbance days is highly dependent on the number of piling days. The number of harbour porpoise disturbance days could be reduced by installing several piles a day on condition that there is enough overlap in harbour porpoise disturbance in place and time.

The KEC calculations (Heinis et al., 2022) assume that a harbour porpoise disturbance day corresponds to a period of six hours a day during which the harbour porpoise cannot forage. No explicit distinction is made here between a continuous period or a total of several disturbance periods.

Assuming simultaneous piling (during the period of six hours of overlapping piling), there will be only one disturbance day for animals disturbed by both piles. The maximum SELss resulting from the driving of a single pile is also a realistic measure of exposure with simultaneous piling. In theory, two pulses could coincide exactly, exposing harbour porpoises to a higher SEL (of a maximum of 3 dB more), but overlap in exposure to piling strikes from two piles will be infrequent because of the short duration of a single piling strike (less than 0.5 s) and the very small probability that both pulses will also be equally strong. The likelihood of animals being exposed to higher sound levels during simultaneous piling is therefore negligible.

An estimate of the order of magnitude of the reduction in the total number of harbour porpoises disturbed can be made by assuming that the disturbance area around the piles is a circle with an effective radius of R, see Figure 4.8. The overlapping area between the circles around two piling locations at a mutual distance D (for $D \leq 2R$) is $2R^2 \cos^{-1}\left(\frac{D}{2R}\right) - \frac{1}{2}D\sqrt{4R^2 - D^2}$. Without an overlap ($D > 2R$), the total area of disturbance around the two piles is $2\pi R^2$; full overlap ($D = 0$) halves the total area of disturbance to πR^2. Figure 4.9 shows the effect of the distance between two piling locations on the total disturbed area when the piles (the centres of the disturbance circles) are close together and the disturbed areas overlap.

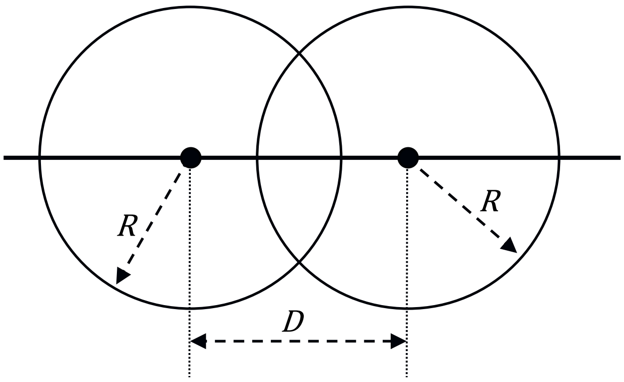

Figure 4.8: **Overlap between two effective disturbance areas (radius R, distance D).**

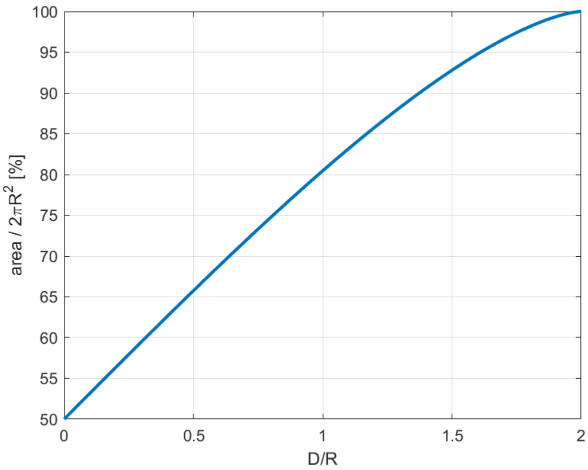

Figure 4.9: Normalised total area of two circles with a radius R and a distance D between their centres.

Assuming that the animal density is uniform over the area of the two disturbance circles, this simplified analysis indicates that the number of animal disturbance days due to the driving of two piles will be reduced by 20% when those two piles are driven simultaneously at a distance equal to the distance over which animals are disturbed (D/R=1), and by 65% when the distance between the piles is half as large (D/R=0.5).

A more accurate estimate of the reduction in the number of disturbed animals achieved with simultaneous piling can be made by determining the overlap in calculated maps of the number of disturbed animals for the two piling locations (each calculated by multiplying the density map by the map of the probability of disturbance on the basis of the calculated sound field). This would require calculating the sound field for multiple locations for each wind farm, which is beyond the scope of this study.

4.5 Effects of piling sound on hearing

Underwater sound can also have a physiological effect on hearing, in which animals suffer a temporary (TTS: temporary threshold shift)[18] or permanent (PTS: permanent threshold shift) impairment of hearing as a result of prolonged exposure to increased sound levels. An effect on behaviour is seen as soon as the sound begins: animals react to the first piling strike. Effects on hearing (TTS or PTS) are related to the total sound dose, in other words the ‘total’ of multiple sound pulses to which animals are exposed during the driving of a single pile (cumulative SEL). It should be noted here that the calculated cumulative SEL is probably an overestimate of the actual exposure because it does not take into consideration hearing recovery during the quieter periods between piling strikes (Kastelein et al., 2014).

With piling sound, the area in which harbour porpoises suffer TTS or PTS is much smaller than the area in which behaviour may be affected. Furthermore, if PTS is prevented by mitigation measures, hearing will recover in all the animals that may be affected (in the vast majority within a few hours after they have left the affected area or after piling has ceased). The frequencies at which TTS can occur in harbour porpoises after exposure to piling sound are not in the frequency range that is important for finding food using echo location. In the case of a harbour porpoise exposed to recorded piling sound, it was found that the hearing threshold shift was limited to a relatively small band of low frequencies (Kastelein et al., 2015). Seals, which are less sensitive to effects on hearing, primarily use their whiskers alongside hearing and sight when searching for food. Exposure studies show that the probability of TTS due to exposure to piling sound is much lower in seals than in harbour porpoises (Kastelein et al., 2018). For the KEC 5.0 it is concluded that such a temporary, small increase in the hearing threshold (TTS) caused by piling does not adversely affect the ability to find and capture food in any of the three species, and that it therefore does not affect their survival rate.

The cumulative exposure dose (SEL_{CUM}) is calculated to determine whether an animal is at risk of PTS as a result of piling activities. The SEL_{CUM} weighted for the hearing sensitivity of the animal is compared to a frequency-weighted threshold for cumulative sound exposure leading to PTS (Southall et al, 2019):

- Harbour porpoises: VHF weighted $L_{E,VHF}$ > 155 dB re 1 μPa^{2}s
- Seals: PCW weighted LE,PCW > 185 dB re 1 μPa^{2}s

[18] Temporary hearing loss (TTS) may be a physiological adaptive mechanism, but this is not the case with permanent effects (PTS).

In accordance with the procedure described in the KEC 4.0 report (Heinis et al., 2022), the SEL_{CUM} is determined for the driving of a foundation pile over the piling period. This takes into account the piling scenario (the variation of the hammer strike energy during piling) and the swimming scenario, depending on the distance from the piling location where the animal is located when piling starts. This procedure largely corresponds to what is prescribed in Denmark (Danish Energy Agency, 2023).

4.6 Effects of UXO clearance

4.6.1 Acute acoustic and blast trauma

There are concerns about the acute effects of explosions during UXO clearance on marine mammals. This can include damage to the middle ear and blast trauma resulting in internal bleeding. This leads to significant hearing damage in a wide frequency range and mortality (Ketten, 2004; von Benda-Beckmann et al., 2015). It is reasonable to suppose that echolocation in harbour porpoises will cease to function due to the acoustic trauma and that this can be used as a lower limit for lethal sound exposure (Siebert et al., 2022).

Consistent with the analysis in von Benda-Beckmann et al. (2015), a risk of acoustic trauma is assumed for marine mammals at exposure to an unweighted SEL exceeding 203 dB re 1 $\mu Pa^2 s$. Because there are no observations of seals exposed to explosions, the same criterion as for harbour porpoises is used here in a cautious approach on the assumption that the hearing of seals is more robust than that of harbour porpoises given the higher threshold value for PTS (see above; Southall et al., 2019).

4.6.2 PTS

For the KEC 5.0, in addition to possible effects of piling sound on hearing, the effects of UXO clearance, which may involve very loud sounds, were calculated for harbour porpoises and seals. In the case of UXO clearance, SEL_{CUM} corresponds to the SEL of a single explosion. The same thresholds for the occurrence of PTS are used as for the effects of piling (see Section 4.5 above).

4.6.3 Effects on behaviour as a result of the deployment of ADDs

Acoustic Deterrent Devices (ADDs) are deployed to reduce the effects of UXO detonations. ADDs are currently used for thirty minutes before an UXO detonation.

The reasoning adopted to determine the effect of animals swimming away on the number of animals affected is as follows:

- If the distance (R_{effect}) at which animals are at risk of PTS or acoustic trauma is larger than the disturbance distance (R_{ADD}) of the ADD ($R_{\mathrm{effect}} > R_{\mathrm{ADD}}$), the mitigation effect of the ADD is not sufficient.
- If the distance at which animals are at risk of PTS or acoustic trauma is smaller than the disturbance distance of the ADD ($R_{\mathrm{effect}} \leq R_{\mathrm{ADD}}$), animals have the opportunity to reduce the risk by swimming away. Assuming, for example, that harbour porpoises swim away from the ADD (and therefore from the UXO) at a speed of 1.5 m/s, they can travel a distance of 2.7 km in the thirty minutes between ADD deployment and detonation. This means that the PTS distance is reduced by 2.7 km.

The number of affected animals has been estimated on the basis of $N_{\mathrm{PTS/trauma}} = n\pi R^2_{\mathbf{effect}}$, with n being the average animal density per location.

4.7 Population effect of behavioural disturbance by piling sound

For the determination of the possible effects of piling on marine mammals, the KEC approach assumes that behavioural disturbance has been adopted as the criterion and that mitigation measures (the use of 'slow start' and noise standards, where appropriate in combination with ADDs) will prevent permanent effects on hearing (PTS). See Section 4.5.

4.7.1 Interim PCoD model

For the three species of marine mammals, it was decided in previous versions of the KEC to use the *interim Population Consequences of Disturbance* (iPCoD) model from SMRU/University of St. Andrews (King et al., 2015; Harwood et al., 2013). The iPCoD model establishes a quantitative relationship between behavioural change (= number of days during which the normal behaviour of an animal is disturbed) and factors such as survival probability and reproductive success (the vital rates). A *Leslie matrix* was used for this purpose in the iPCoD model (Caswell, 2001). Given the lack of enough empirical data, the relationship between disturbance and vital rates was derived by consulting experts in a formal expert elicitation process since monitoring data for the development of a 'full' PCoD model are lacking for many species (National Research Council, 2005). That process involved the use of a range of techniques to weight the experts' opinions independently and to provide a numerical estimate of the uncertainty in the relationship. Two workshops took place in 2018 in which relationships were again derived for harbour porpoises and seals using expert elicitation based on new knowledge and improved understanding (Booth & Heinis, 2018; Booth et al., 2019). The calculations for the KEC 4.0 used version 5.2 of the iPCoD model[19].

The KEC 5.0 uses the latest version (6.0.2). The implementation of density dependence has been corrected in this version. The density dependence option has not been used in the KEC calculations to date. If density dependence is not taken into account, the difference between versions 5.2 and 6.0.2 for the KEC calculations is demonstrably negligible. This is also the case for seals insofar as this aspect has been considered.

❯ ***Demographic parameters***

The help file accompanying the interim PCoD model (Sinclair et al., August 2024) contains two different sets of demographic parameters for the North Sea harbour porpoise population (with high and low fertility), both of which result in a stable population for calculation scenarios without disturbance (*growth rate* = 1). See Table 4.2. That means it is assumed that effects other than disturbance by piling sound are implicitly included.

[19] https://marine.gov.scot/information/interim-population-consequences-disturbance-model-ipcod

Table 4.2: Demographic parameters for harbour porpoises and seals in the North Sea, as proposed for the interim PCoD model, version 6.0.2 (Sinclair et al., August 2024).

Species	Note	Age at which a young animal first becomes independent	Age at which the animal gives birth	Survival			Fertility	Growth rate
				calf / pup	juvenile	adult		
harbour porpoise	high fertility	1	5	0.6	0.85	0.85	0.958	1.000
	low fertility	1	5	0.8455	0.85	0.925	0.34	1.000
Harbour seal		1	4	0.55	0.61	0.9451	0.88	1.000
Grey seal		1	5	0.222	0.94	0.94	0.84	1.010

The *high fertility* parameters were chosen in all previous iPCoD calculations (KEC 3.0 and KEC 4.0). However, the *low fertility* parameters are a much better fit with the fertility estimated from recent studies, including those for the southern North Sea (Murphy et al., 2020; Sinclair et al., 2020; IJsseldijk et al., 2021). The calculations for the KEC 5.0 scenario were therefore also made with this second set of demographic parameters. See Section 5.5.1 and Appendix G.1.

For the effects of behavioural disturbance on seal populations, the same demographic parameters were used for the KEC 5.0 calculations as in the KEC 4.0. This means that it was assumed that the population of harbour seals is stable and that the population of grey seals increases by 1% annually (see Table 4.2). The results of annual censuses indicate that the population of harbour seals in the international Wadden Sea has fallen since 2021. It is not yet clear whether this fall will continue and what the underlying mechanisms are (Brasseur & Aarts, 2024).

⟩ *Effect of disturbance*

The iPCoD calculations assume that, during a ‘harbour porpoise disturbance day’, a harbour porpoise cannot eat for a period of 6 hours, and that there is therefore no energy intake. Agreement was reached about this period of time during the expert elicitation for the iPCoD model (Booth et al., 2019). It is based on observations of tagged harbour porpoises (van Beest et al., 2018) and the response of harbour porpoises to exposure to piling sound (Brandt et al., 2018).

The expert elicitation for the iPCoD model (Booth et al., 2019) quantified only the effect of disturbance on the birth rate (*fertility*) and on the survival rate of young animals (harbour porpoise calves in their first year and juvenile seals). The probability of a fall in the adult survival rate due to disturbance was considered negligible by the experts and was not included in the model.

⟩ *Density dependence*

The iPCoD calculations have assumed until now that the harbour porpoise population is stable and that population development does not depend on density. This means that, after the one-off inclusion of an effect on the population, in other words a fall in numbers as a result of the activities, the population in the model outcomes will not recover after the activities cease. As indicated in Heinis et al. (2022), this is probably not realistic.

The interim PCoD model provides the option of taking the effect of density dependence into account. However, until now, the data needed for a reliable estimate of model parameters have been lacking. For the purposes of the KEC 5.0, John Harwood estimated model parameters (see Annex G.3) on the basis of calculations with the iPCoD + DEB model (Section 4.7.2) that were used to examine the effect of density dependence on the calculations. See Section 5.5.1.

4.7.2 iPCoD + DEB for harbour porpoises

In May 2024, SMRU made a new version of 'iPCoD+DEB' available for harbour porpoises – see Sinclair et al. (August 2024) – in which estimates based on expert opinion were replaced by a 'Dynamic Energy Budget' (DEB) model. A model of this kind explicitly models the energetics of animals and the effect of disturbance on them. See Chudzínska et al. (2023) and Gallagher et al. (2021). The model used for harbour porpoises is an adaptation of a dynamic bioenergetics model for pilot whales based on individuals (Hin et al., 2019). Implementation has been described in reports from (Harwood et al. (2020) and Harwood et al. (2021).

The iPCoD+DEB model for harbour porpoises assumes (theoretically) that the energy intake for every day that an animal is disturbed by piling sound is 25% lower than normal. This corresponds in broad terms to the disturbance assumed in the expert workshop (Booth et al., 2019) for six hours a day. The model splits the year of a female harbour porpoise into four periods during which the animal is more or less sensitive to the effects of disturbance (Harwood et al., 2020). It does therefore matter when piling is scheduled over the course of a year. Uncertainty in the parameters of the DEB model is taken into account using a statistical Approximate Bayesian Computation (ABC) analysis, see Chudzínska et al. (2023).

iPCoD+DEB also includes the option of calculating the effect of density dependence (increasing population growth if the population density falls, and vice-versa), see Hin et al. (2021). It is assumed that all harbour porpoises can benefit from the increase in food availability if the harbour porpoise population declines. Food availability is seen here as the most important factor determining population size.

4.8 Risk estimation and assessment

4.8.1 Netherlands

- ***Ecological standard for effects of behavioural disturbance in harbour porpoises and seals***

The final stage of the staged procedure is the assessment of the estimated population decline and the assessment on the basis of the acceptable level of impact, as determined by the government, on the population. The associated principles have been set out in the 2016 KEC update (Ministerie van Economische Zaken & Ministerie van Infrastructuur en Milieu, 2016). The guiding principle for the assessment of the effects on the harbour porpoise population was that it had to be possible to establish, with a high degree of confidence (95%), that the harbour porpoise population (in the Netherlands) will not decline by more than 5% as a result of the construction of offshore wind farms. This ecological standard was maintained in the subsequent KEC 3.0 and KEC 4.0 and adopted for harbour seals and grey seals. If this standard is met, additional effects of the construction of Offshore Wind on the population are not considered to be significant and consequences for the fulfilment of the conservation objectives for the N2000 areas can be ruled out. In addition, the conservation status of the species is then not an issue and there are no effects on the indicators of EU descriptor D11 (see section 2.3). The KEC 5.0 assumes the same ecological standard as in previous KECs. It should be noted that a clarification of the ecological standard will be needed if density dependence is included in the calculations, and that the population will recover after a decline caused by the effects of disturbance. No decision has yet been made in this regard pursuant to the results presented in this report.

❯ *PTS*

PTS and blast trauma are seen as permanent injury of an animal. The Environment Act includes the *specific duty of care* (Bal, Article 11.27). It states that any person who engages in activities and knows or can reasonably suspect that those activities may have adverse effects on a specific species must take all measures that can reasonably be required from that person to prevent, mitigate or limit those effects.

4.8.2 Standards for limiting the effects of underwater sound in other countries

❯ *Germany*

The German Bundesamt für Naturschütz has set out its strategy for protecting harbour porpoises from sound resulting from offshore wind farm construction in the Schallschutzkonzept[20, 21]. Underwater sound must be limited during piling in German waters. The maximum for the unweighted broadband SELss at 750 m from the piling location is 160 dB re 1 µPa²s and the maximum for the peak sound pressure level (L_{pk-pk}) at 750 m is 190 dB re 1 µPa. The Schallschutzkonzept argues that this allows harbour porpoises (as an indicator species) to be protected from hearing effects (TTS) and limits behavioural disturbance (avoidance) up to a maximum distance of some eight kilometres from the piling location.

The KEC calculations assume the SELss limit of 160 dB re 1 µPa²s at a distance of 750 m for the German farms.

❯ *Denmark*

The Danish Ministry of Energy has published guidelines on underwater sound from offshore piling: *Guideline for underwater noise. Installation of impact or vibratory driven piles* (Danish Energy Agency, 2023). Underwater noise must be limited during piling in Danish waters. The guidelines focus on preventing hearing effects (PTS) in marine mammals. This means that the cumulative sound exposure (SELcum) has to be determined over the entire installation time of a pile (with a maximum of 24 hours). This approach takes into consideration that the animals swim away from the piling location in response to sound from both the ADDs to be deployed before piling and the piling itself. When assessing the risk of PTS, application of the SELcum thresholds weighted for the hearing sensitivity of the animals from Southall et al. (2019) is recommended.

Tougaard and Mikaelsen (2023) recently compared the Danish and German guidelines. On the basis of the major differences between the approaches and conclusions they found, they conclude that the international harmonisation of assessment frameworks is needed.
The KEC calculations assume a SELss limit of 160 dB re 1 µPa²s at a distance of 750 m for the Danish farms.

[20] https://www.bfn.de/sites/default/files/2022-03/Schallschutzkonzept_Schweinswale_bf.pdf
[21] Translated into English for ASCOBANS. See https://www.ascobans.org/sites/default/files/document/AC21_Inf_3.2.2.a_German_Noise_Protection_Concept.pdf

› ***United Kingdom***
The mitigation guidelines issued by the Joint Nature Conservation Committee (JNCC)[22] are used for permit procedures for offshore wind farm construction in the United Kingdom. That can involve the application of measures to reduce underwater sound. However, the measures that are often applied focus primarily on reducing the risk of effects on hearing (PTS) by ensuring that animals are not in the vicinity of piling operations. Animals are therefore driven away with ADDs, and visual and acoustic monitoring for the presence of marine mammals is required.

The KEC calculations assume there is no noise mitigation in the UK farms during piling.

› ***Belgium***
In Belgium, the *Description of Good Environmental Status & Setting of Environmental Targets for Belgian Marine Waters*[23] stipulates that the level of anthropogenic impulsive sound must be less than 185 dB re 1 µPa (zero to maximum SPL, in other words $L_{0\text{-}pk}$) at 750 m from the source. On the basis of the empirical relationship derived by Lippert et al. (2015) this threshold value corresponds broadly to the noise standard applicable in Germany of SELss(750m) = 160 dB re 1 µPa²s.

The KEC calculations assume an SELss limit of 160 dB re 1 µPa²s at a distance of 750 m for the Belgian farms.

› ***France***
In France, permits for offshore wind farms are issued on a case-by-case basis. Noise standards are not prescribed but, in some cases, noise mitigation (in the form of bubble screens) is required.

The KEC calculations assume there is no noise mitigation during piling in the farms in France.

› ***Norway***
In Norway, no noise standards are used during piling for offshore wind.
The KEC calculations assume there is no noise mitigation during piling in the farms in Norway.

4.8.3 Assessment of effects on criteria for MSFD descriptor D11

The criteria for descriptor D11 (Underwater noise) are specified in Decision 2017/848/EU[24] as follows:
- **impulsive noise** (**D11C1**): described as the monopole energy source level re 1µPa²s) in dB or the zero to peak monopole source level re 1µPa²m² in dB, both measured over the frequency band 10 Hz to 10 kHz.
- **continuous low-frequency noise** (**D11C2**): the annual average, or another unit of measurement agreed at the regional or subregional level, of the squared sound pressure in each of two '1/3-octave bands', one centred on 63 Hz and the other on 125 Hz, expressed as a level in decibels in dB re 1µPa, with appropriate spatial resolution relative to the pressure.

22 https://jncc.gov.uk/our-work/marine-mammals-and-noise-mitigation/
23 http://www.vliz.be/en/imis?module=ref&refid=220232#_blank
24 https://eur-lex.europa.eu/eli/dec/2017/848/oj/eng

Recently, the Commission notice C/2024/2078[25] established the following threshold values for underwater noise through cooperation at the Union level:

- **D11C1**: For short-term exposure (1 day, i.e., daily exposure), the maximum proportion of an assessment/habitat area utilised by a species of interest that is accepted to be exposed to impulsive noise levels higher than the Level of Onset of Biologically adverse Effects (LOBE), over 1 day, is 20 % or lower (≤ 20 %). For long-term exposure (1 year), the average exposure is calculated. The maximum proportion of an assessment/habitat area utilised by a species of interest that is accepted to be exposed to impulsive noise levels higher than LOBE, over 1 year on average, is 10 % or lower (≤ 10 %).
- **D11C2**: 20 % of the target species habitat having noise levels above LOBE not to be exceeded in any month of the assessment year, in agreement with the conservation objective of 80 % of the carrying capacity/habitat size.

When updating their marine strategies, Member States may decide not to use the threshold values set at the EU, regional or subregional level to the extent that the threshold values relate to descriptors or indicators which they have decided not to apply in accordance with the terms of the directive and the decision. Member states are responsible for defining 'assessment/habitat areas', 'species of interest' and 'Level of Onset of Biologically Adverse Effects (LOBE)'.

In the Netherlands, the approach to assessing the threshold values set by the European Commission has not yet been determined. This report therefore provides an indicative assessment of the effect of piling on criterion D11C1 (see Section 5.7).

[25] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=OJ%3AC_202402078

5 KEC calculations

5.1 Scenarios for the construction of wind farms in the North Sea

Rijkswaterstaat summarised the technical assumptions for the KEC 5.0 wind farm scenarios in a memorandum (RWS, 2024). The assumptions and guiding principles were drafted on the basis of input from the teams working on site decisions, the Wozep Steering Committee, the Ministry of Climate Policy and Green Growth, RVO and TenneT.

As in previous versions of the KEC, 2016 has been adopted as the benchmark year for the underwater noise calculations.

5.1.1 National scenario for the construction of wind farms on the DCS

Table 5.1 provides an overview of the national scenario for the construction of wind farms for the KEC 5.0. The scenario covers wind farms constructed or planned as of 2016 in line with:

- the 2023 Roadmap as constructed (Borssele, Hollandse Kust Zuid, Hollandse Kust Noord);
- the 2030 Roadmap (Hollandse Kust West Sites VI & VII, IJmuiden Ver Alpha& Beta and IJmuiden Ver Gamma);
- Supplementary Roadmap for 2030 (Nederwiek Zuid, Nederwiek Noord, Hollandse Kust West Site VIII, Ten Noorden van de Waddeneilanden, Doordewind Site I).

Table 5.1: The indicative scenario provided by RWS for the KEC 5.0 for the construction of wind farms on the Dutch Continental Shelf in the years 2016-2030.

Name	Start of construction	Total capacity MW	Turbine capacity MW	Number of turbine piles	Number of platform piles
Borssele Site III	2019	366	9.5	39	6
Borssele Site IV	2019	366	9.5	39	
Borssele Site I	2020	376	8	47	6
Borssele Site II	2020	376	8	47	
Borssele Site V	2021	19	9.5	2	
Hollandse Kust Zuid Site I	2021	385	11	35	6
Hollandse Kust Zuid Site II	2021	385	11	35	
Hollandse Kust Noord Site V	2022	759	11	69	6
Hollandse Kust Zuid Site III	2022	385	11	35	6
Hollandse Kust Zuid Site IV	2022	374	11	34	
Hollandse Kust West Sites VI & VII	2025	1520	15	108	12

Name	Start of construction	Total capacity MW	Turbine capacity MW	Number of turbine piles	Number of platform piles
IJmuiden Ver Gamma	2027	2295	15	153	16
IJmuiden Ver Alpha & Beta	2027	4020	15	268	32
Nederwiek Noord	2028	4600	15	306	32
Nederwiek Zuid	2028	2295	15	153	16
Doordewind Site I	2029	2300	20	115	16
Hollandse Kust West Site VIII	2029	760	20	38	6
Ten Noorden van de Waddeneilanden	2029	795	15	53	6
	total	**22376**		**1576**	**166**

The scenario corresponds to the Reference Scenario from the Partial Revision of the North Sea Programme[26]. An 'overplanting' scenario has been included for IJmuiden Ver Gamma as a worst-case approach. This involves installing a maximum of 15% more capacity than the maximum originally assumed for the areas (highest number of turbines and therefore highest number of disturbance days).

5.1.2 International scenario for the construction of wind farms in the North Sea

To determine cumulative effects on marine mammal populations, the scenario provided includes the current estimate of construction of all wind farms in the North Sea. This includes only those farms for which piling is planned, assuming that monopiles will be used for the turbine foundations in all cases. Farms in the United Kingdom with floating wind turbines have not been considered. To keep the scenario calculations manageable, piling for the turbine foundations only has been considered. The relatively small number of additional piling days for constructing transformer platforms outside the DCS has been disregarded. Piling for the platforms for the Dutch wind farms has been included.

Table 5.2 provides an overview of the total installed turbine capacity and the total number of piling days in line with the scenario provided by comparison with the scenario calculated in the KEC 4.0 for the same period and area. By contrast with the situation in the Netherlands, this shows that the capacity to be installed has increased substantially internationally since the KEC 4.0.

[26] https://open.overheid.nl/documenten/ronl-dcb1d882dd665c47368f2fa6eb9726a8469632da/pdf

Table 5.2: Comparison of the scenario provided by RWS for the KEC 5.0 with the scenario from the KEC 4.0 (Heinis et al., 2022).

2016-2032	Total capacity GW		Number of piling days	
KEC 4 international (incl. NL)	77.5		6498	
KEC 4 NL (variant III)	26.7	34% of international	1876	29% of international
KEC 5 international (incl. NL)	123.4	KEC 4 + 59%	8972	KEC 4 + 38%
KEC 5 NL	22.4	18% of international	1742	19% of international

Figure 5.1 shows where the farms are planned in the KEC 4.0 and KEC 5.0 scenarios.

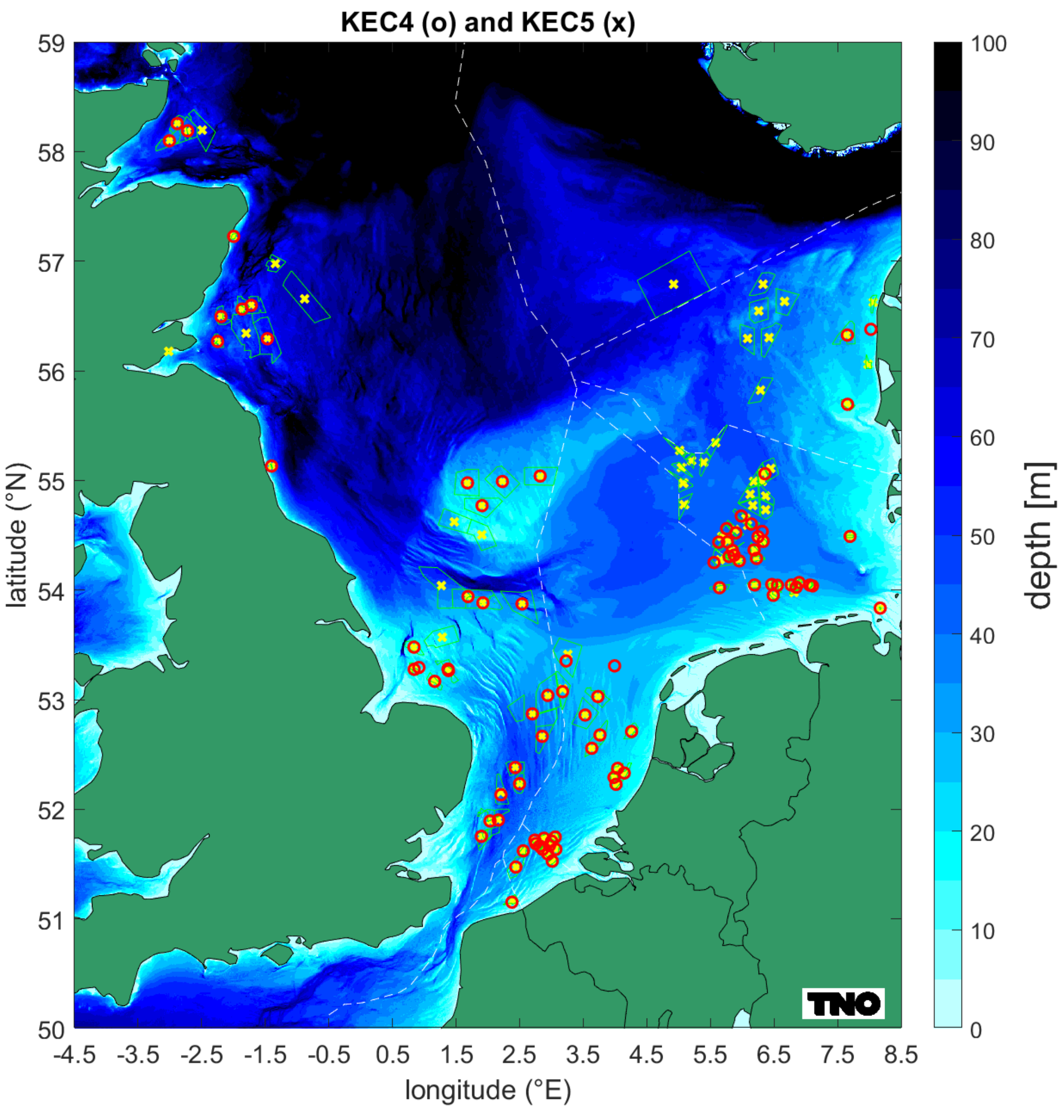

Figure 5.1: Overview of offshore wind farm locations in the KEC 5.0 scenario (yellow x-markers and contour lines). The red o-markers show the locations from the KEC 4.0 scenario. The blue colours show the water depth (EMODnet).

5.1.3 Piling calendar

On the basis of the data provided, TNO drew up a generic calendar using the following steps:

- STEP 1: scenario supplied by RWS states the year of construction for each wind farm (project).
- STEP 2: a calendar of piling days was generated using that scenario on the basis of the following assumptions:
  - Since detailed information about the piling days could not be made available for this project, an arbitrary starting date is selected for each project.
  - Because the maximum number of projects that can be executed simultaneously is limited by the number of available piling vessels, it is assumed that a maximum of two Dutch piling projects can be executed simultaneously, plus a maximum of five in total for the other North Sea countries.
  - In all cases, it is assumed that three piles are always driven on consecutive days, after which there are days without piling to bring in new piles. This generic assumption is based on an analysis of the piling data for the Borssele wind farms (de Jong et al., 2023).
  - The transformer platforms will be installed one year before the construction of the wind turbines and be considered only for the Dutch wind farms.

Figure 5.2, Figure 5.3 and Figure 5.4 provide an overview of the resulting scenario.

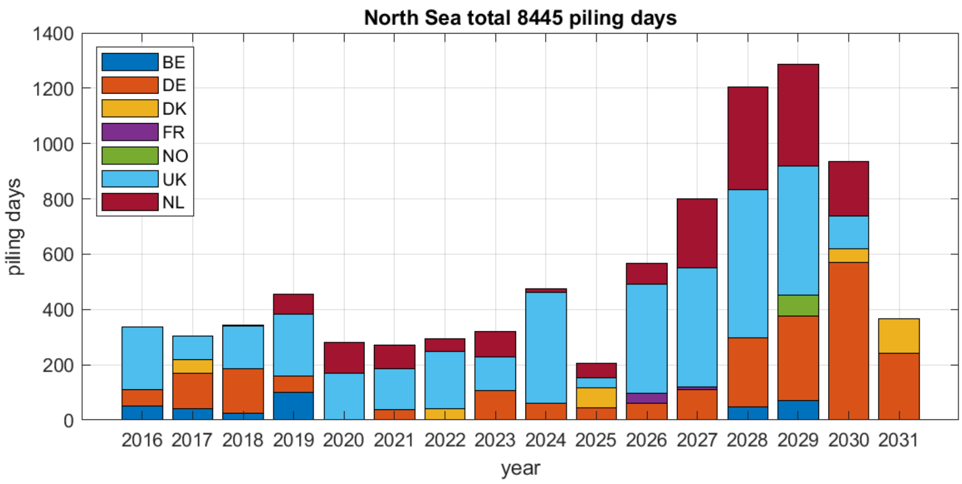

Figure 5.2: Overview of the number of piling days in the North Sea by country and year based on the elaborated KEC 5.0 scenario.

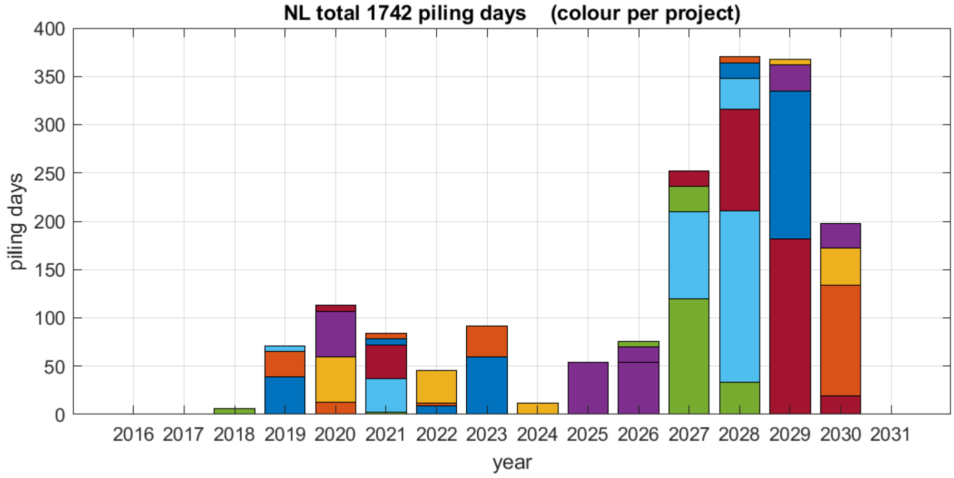

Figure 5.3: Overview of the number of piling days per year for the Dutch projects from the elaborated KEC 5.0 scenario. The colours show the number of piling days per wind farm construction project.

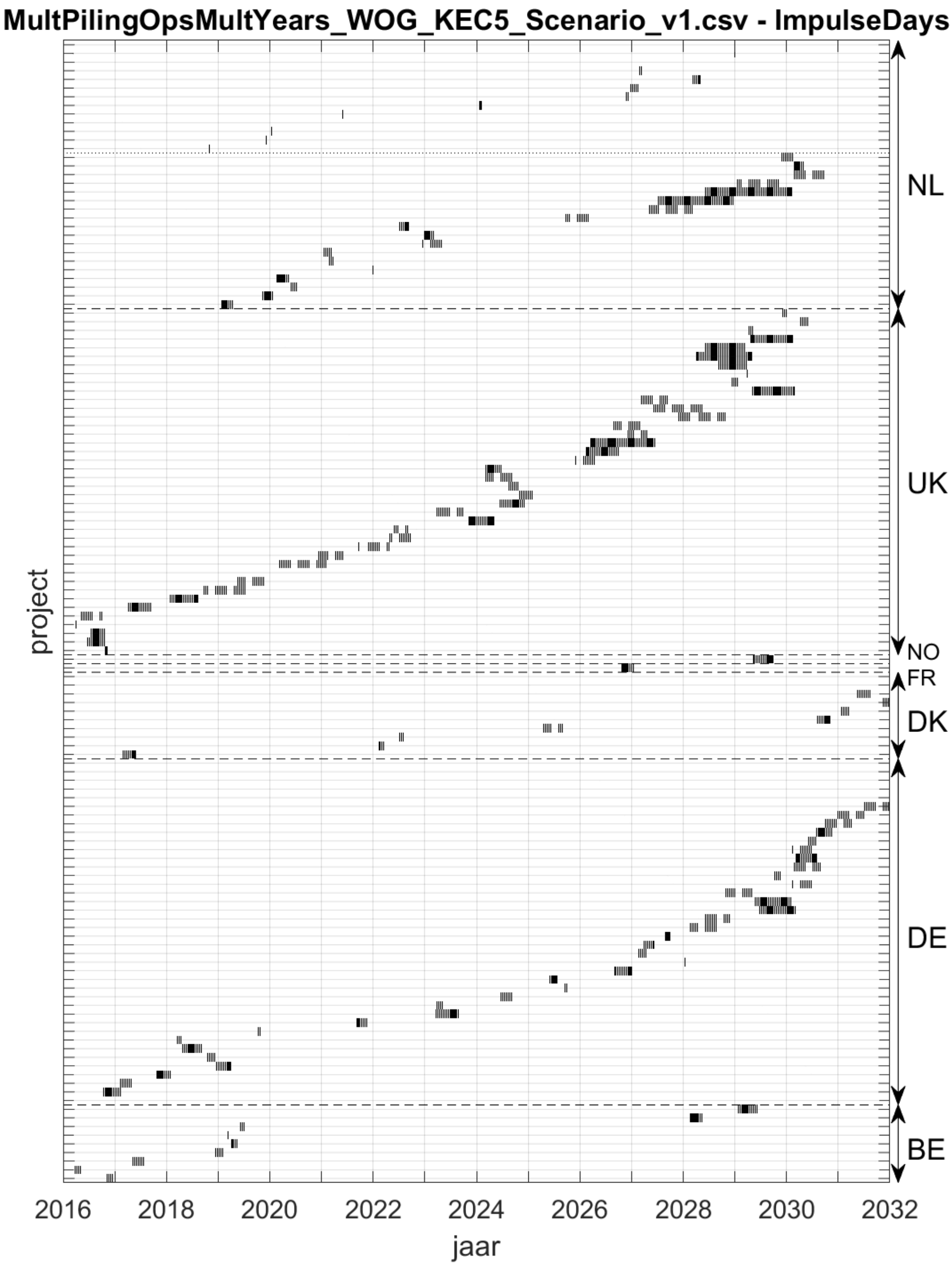

Figure 5.4: Calendar of piling days based on the international scenario for the KEC 5.0 generated from RWS input and the assumptions described above.

5.1.4 Technical assumptions for underwater sound calculations

RWS also supplied GIS shape files and a table listing national and international wind farms, including a range of technical assumptions, along with the scenario. This includes the actual turbine types and noise standards for the farms already built. The approved boundary conditions from the site decisions are included for the farms for which permits have been granted. Where no site decisions have yet been made, technical assumptions have been used.

To keep the number of piling-sound calculations for the international scenario manageable, one calculation was performed for each project for the driving of a foundation pile at the centroid of the area contours provided as shape files by Rijkswaterstaat.

Details about the driving of turbine foundations for future projects are not yet known in many cases. The KEC calculations assume that all the wind turbines are installed on monopile foundations. The table provided by RWS includes an estimated pile diameter for each project location. The monopiles are modelled as uniform cylinders with a wall thickness estimated using the formula (American Petroleum Institute, 2002): $t = 0.01D + 6.35 \times 10^{-3}\ \mathrm{m}$, with D being the pile diameter in metres. As in the KEC 4.0 calculations, a maximum hammer energy of 4000 kJ has been assumed for driving the monopiles for turbines larger than 12 MW[27], and the hammer ram mass has been estimated at 200 tonnes. For the driving of monopiles for smaller turbines, a maximum hammer energy of 2000 kJ has been assumed, and the hammer ram mass has been estimated at 100 tonnes. The mass of the anvil that is struck is assumed to be equal to the ram mass. The contact stiffness between ram and anvil is 20 GN/m in all calculations.

TenneT provided the following data for piling for the high-voltage platforms. They have been used in the KEC 5.0 calculations.

- Number of piles per DC platform: 16
- Number of piles per AC platform: 6
- 1 day of driving per pile
- Pile diameter: 2.5 m
- Pile wall thickness: 60 mm
- Hammer energy: 2000 kJ
- Hammer ram mass: 126 tonnes
- Anvil mass: 126 tonnes

The noise standard for the Dutch farms is as stipulated in the site decisions. In the case of the construction of farms from IJmuiden Ver (2027) onwards, the KEC 5.0 scenario assumes a noise standard of 164 dB. The prevailing noise standard of the respective country has been adopted as the noise standard in the other North Sea countries. See Section 4.8. The same noise standard was used in this study for piling for both platforms and turbines. This is not in accordance with the permit granted for the platforms in all cases. The effect of this anomaly is negligible for the total.

[27] Larger hammers are now available with a higher maximum energy of over 6000 kJ. This has not been considered in the KEC 5.0 calculations. However, where a noise standard applies, more underwater noise will not be permitted with a larger hammer.

5.1.5 Geophysical surveys

Geophysical surveys use sound to map the subsurface. Geophysical surveys are conducted over a period of time of several (1-5) years prior to the construction of a wind farm in order to map out the seabed structure in different layers and to determine whether any unexploded ordnance is present. These surveys cover both the piling area (turbines and platforms) and the route along which the cables are laid to land.

Details of the scenario for the surveys can be found in Table 5.3 and Appendix D.1.

Table 5.3: Overview of the total scenario for geophysical surveys for the construction of the NL wind farms during the years 2016-2030.

	Surface surveys	Number of survey days
Surveys of farms	4681 km^2	710
Surveys of cable routes	2388 km^2	2298
Total	km7069	3008

5.1.6 UXO clearance

This study assumes the most likely scenario from the estimates for future wind farms based on an inventory conducted by Arcadis on behalf of Rijkswaterstaat (Dinjens, 2024). A number of locations not yet included in the Arcadis report have been included in the KEC 5.0. Construction in these locations is not expected during the period covered by the KEC 5.0. However, the UXO surveys conducted beforehand may take place during that period. In addition, the area covered by some search areas has been made consistent with the geophysical surveys (Section 5.1.5).

Details of the scenario for the UXO clearance operations can be found in Appendix E.

5.2 Underwater sound calculations

5.2.1 Piling for turbine and platform foundations

The Aquarius 4 model was used to calculate sound propagation for unmitigated piling for the 132 project sites in the scenario (Section 5.1). The model calculates the maximum unweighted SELss for ten points uniformly distributed over the water depth at each location in the decidecade bands from 16 Hz through 20 kHz. These data are used to produce maps of the unweighted broadband SEL around each project location (a single central location for each wind farm).

The calculation method is described in Section 4.2.2 and Appendix B, and the technical assumptions in Section 5.1.4.

Figure 5.5 shows histograms of the variation of the parameters for the construction of the different wind farms in the international scenario, and of the corresponding maximum unweighted broadband SELss calculated with Aquarius 4 at 750 m from the pile when piling sound is unmitigated.

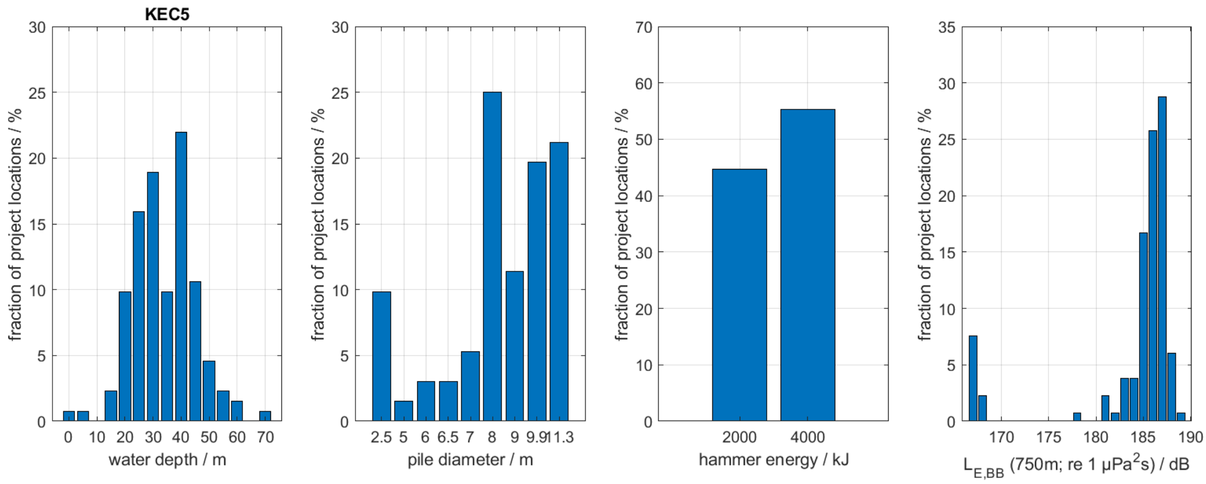

Figure 5.5: Variation of the water depth at the piling location, pile diameter, the applied hammer strike energy and the calculated maximum unweighted broadband SELss(750m) for the 132 project locations.

For the majority of locations, Aquarius 4 calculates an SELss(750m) of 185 to 187 dB for unmitigated piling for wind turbines. The calculated SELss(750 m) is considerably lower (167-168 dB) for the driving of the much smaller pin piles for the energy platforms. Figure 5.6 shows the calculated SELss(750m) for each project as a function of local water depth and pile diameter. The levels increase with increasing water depth and with increasing pile diameter. In accordance with the conservative assumptions in the Aquarius 4 calculations, the levels (with the exception of the thinner pin piles) are around the upper limit of the monitoring data from Bellmann et al. (2023).

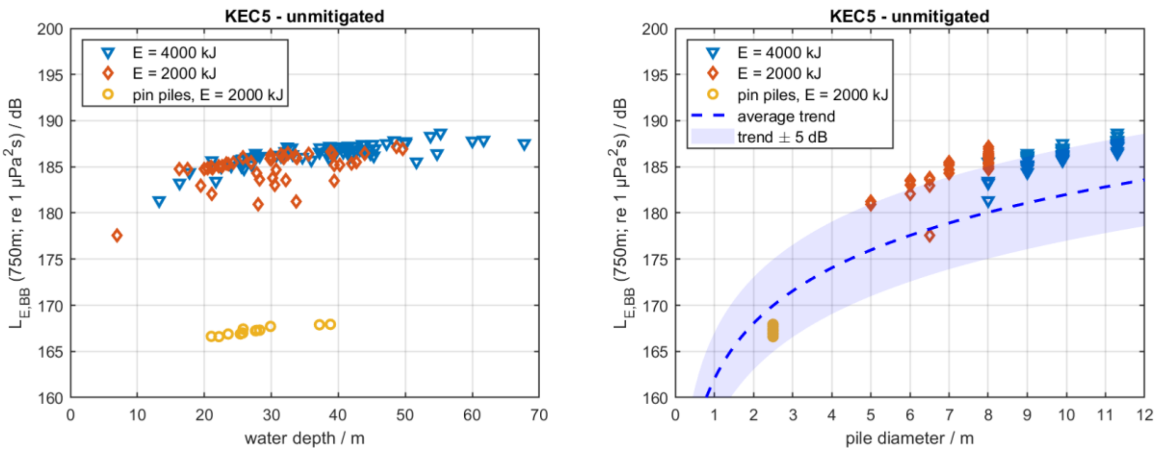

Figure 5.6: Calculated maximum unweighted broadband SELss(750m) for each project location as a function of local water depth (left) and pile diameter (right) for unmitigated piling. Compared with the average trend (± 5 dB) from measurements of piling (up to a maximum diameter of 8 m) from Bellmann et al. (2023).

The calculated sound level for piling at the individual locations depends not only on the pile diameter but also on a range of model parameters describing the surroundings (bathymetry and sediment) and the hammer (energy, hammer masses and impact plate). The scaling rules for these dependencies proposed by von Pein et al. (2022) are primarily applicable when determining the expected sound level at 750 m from the pile to determine whether it is possible to comply with any noise standard that may apply. Estimating the number of potentially disturbed animals requires a model that can calculate sound propagation to greater distances.

For projects where a noise standard applies, a constant value is subtracted from the calculated sound propagation (SELss) for each piling location so that the SELss at 750 m from the pile is less than or equal to the noise standard in all directions (see Appendix B.5).

5.2.2 Geophysical surveys

No location-specific sound calculations have been made for the geophysical surveys but an average disturbance distance for harbour porpoises and seals has been estimated for each sound source (see Appendix D).

5.2.3 UXO clearance and deployment of ADDs

No location-specific sound calculations have been made for UXO clearance and the deployment of acoustic deterrent devices (ADDs), but estimates have been made for each sound source of the average disturbance distance for harbour porpoises and seals (see Appendix E).

5.3 Calculation of animal disturbance days

5.3.1 Piling for turbine and platform foundations

⟩ *Harbour porpoises*

The calculated sound propagation (Section 5.2.1) for each pile location has been used to draw up a map with the probability of disturbance (Section 4.3.1) on the basis of the dose-effect relationship (Section 4.4.2) . The effective disturbance surface area per piling location follows from the integral of the probability of disturbance (depending on the local SELss) across the map (see Section 4.4.2). The effective disturbance distance is the radius of a circle with that same area. Figure 5.7 provides an overview of the calculated effective disturbance distances for the 132 project locations.

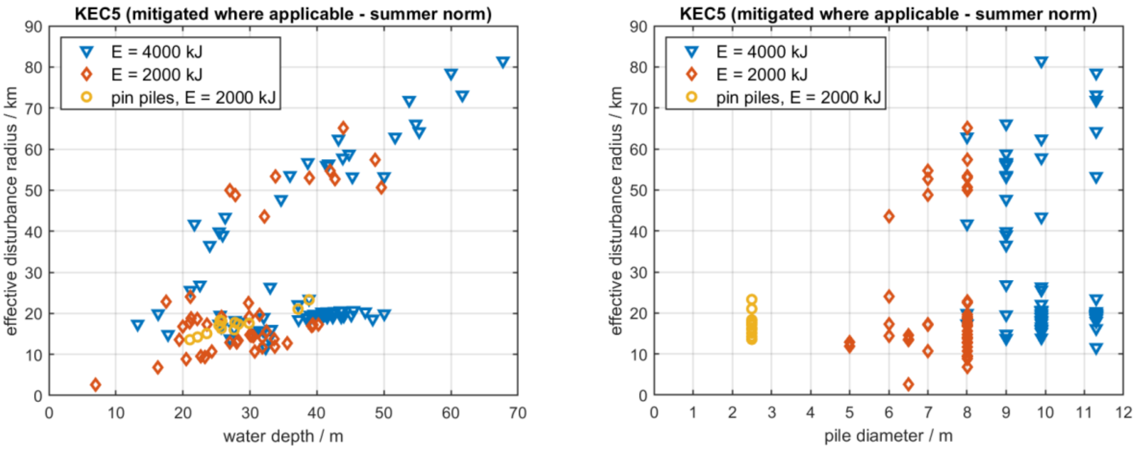

Figure 5.7: Calculated effective disturbance distance (effective radius of the disturbed surface area) as a function of local water depth (left) and pile diameter (right) for piling with the prevailing noise standard.

These figures show that there is considerable variation in Aquarius 4 results between project locations. The calculated disturbance distances would seem to be too large in some cases by comparison with current observations (Brandt et al., 2018; de Jong et al., 2023; Graham et al., 2019). The United Kingdom (UK) (see (JNCC, 2020)) uses 26 km as the effective disturbance distance for projects without a noise standard; the Aquarius 4 calculations provide disturbance distances of up to ~80 km for UK projects. A recent study looking at the installation of seven monopiles (9.5 and 10 m diameter) for the Moray West Offshore Wind Farm determined effective disturbance distances of less than 10 km (Benhemma-Le Gall et al., 2024), suggesting that 26 km is probably an overestimate.

Figure 5.8 shows that there is no linear relationship between the SELss(750m) and the calculated disturbance distance. Although the disturbance distance increases on average with increasing SELss(750m), there are major variations, mainly depending on local bathymetry.

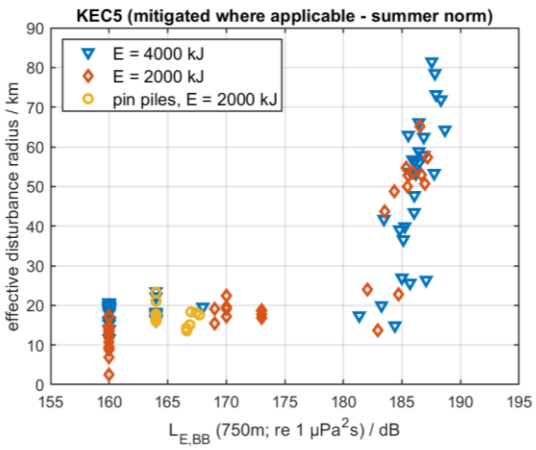

Figure 5.8: Calculated effective disturbance distance (effective radius of the disturbed surface area) as a function of the local unweighted broadband SELss(750m) for piling with the prevailing noise standard.

Figure 5.9 shows that there is also no linear relationship between the SELss(750m) and the calculated number of harbour porpoises disturbed per piling day at the different project locations. There are major differences, not only because of local bathymetry but also because of local harbour porpoise densities.

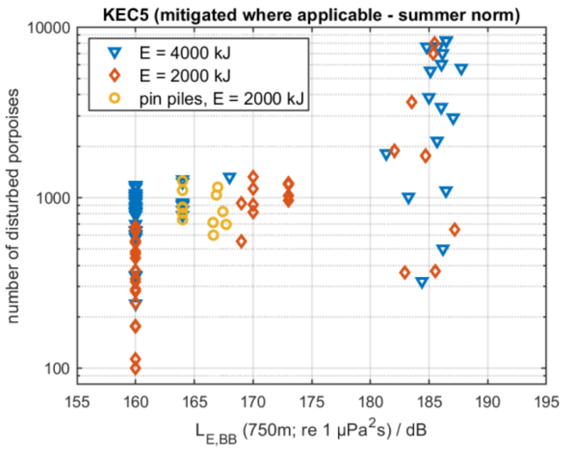

Figure 5.9: Calculated number of harbour porpoises disturbed per piling day as a function of local unweighted broadband SELss(750m) for piling with the prevailing noise standard. The y-axis has a logarithmic scale that shows the large differences clearly.

It can be concluded from this that the KEC 5.0 calculations most likely overestimate the number of disturbed harbour porpoises, particularly in the case of projects without a noise standard where disturbance distances of 26 km and more are found. How large that overestimate is, cannot be quantified on the basis of current knowledge.

❭ *Variance*

As indicated in Section 4.4.3, it is possible, for each wind farm or search area, to estimate the variance in the number of disturbed animals for each location in an area by making calculations for multiple piling locations. An example of such an estimate can be found in the study (TNO memorandum 2022 M11242[28]) for the IJmuiden Ver Alpha and Beta site decisions. In this study, calculations were made for nine piling locations in the area (the centre of the entire area, the centres of the four sites and the deepest points in the four sites). The standard deviation for the calculated number of harbour porpoises disturbed in these nine locations was approximately 10%. For the estimate of the total number of disturbed animals during 268 piling days, the standard deviation is therefore approximately equal to $10\%/\sqrt{268} \approx 0.6\%$.

❭ *Effect of the applied dose-effect relationship*

The selected dose-effect relationship determines the calculated number of harbour porpoise disturbance days. It was decided to adopt a cautious approach and the KEC 4.0 therefore assumes the relationship based on the observed response during the driving of the first piles for the Beatrice wind farm (Graham et al., 2029).

Table 5.4 shows the effect of the applied dose-effect relationship on the number of calculated harbour porpoise disturbance days for the KEC 5.0 scenario by comparison with the KEC 4.0.

Table 5.4: Total number of harbour porpoise disturbance days as a function of the selected dose-effect relationship; the dB value refers to the applied noise standard for NL wind farms for which construction is planned from 2026 onwards.

Curve	Harbour porpoise disturbance days (KEC5 - 164 dB)	
	International	NL
Graham 1st pile (KEC 4.0)	$44.9 \cdot 10^6$	$1.7 \cdot 10^6$
Graham 47th pile	$36.7 \cdot 10^6$	$1.8 \cdot 10^6$
Graham 86th pile	$29.6 \cdot 10^6$	$2.2 \cdot 10^6$
Brandt et al.	$20.0 \cdot 10^6$	$0.3 \cdot 10^6$
Graham 1st pile + max. 26 km	$13.5 \cdot 10^6$	$1.7 \cdot 10^6$
	Harbour porpoise disturbance days (KEC 4 – NL III – 160 dB)	
Graham 1st pile (KEC 4.0)	$23.9 \cdot 10^6$	$1.4 \cdot 10^6$

Graham et al. (2019) found that piling sound disturbed harbour porpoises less as the construction of the farm progressed (Section 4.3.1, Figure 4.2). In the case of the international scenario, applying the dose-effect relationships for later piles therefore results in a significant decrease in the calculated number of harbour porpoise disturbance days (left-hand column in Table 5.4). However, in the case of the Dutch projects, the calculated number of harbour porpoise disturbance days increases. This is attributable to the application of a noise standard in the Dutch projects, which results in low sound levels. Due

[28] https://www.commissiemer.nl/projectdocumenten/012369_3662_MER_kavel_IV_Bijlage_III.pdf

to the fit of the dose-effect curves, the probability of disturbance at low exposure levels (SELss < 130 dB) would appear to rise for later piles. This can be seen as an artefact of curve-fitting (Figure 4.2) and it is also not supported by data. This illustrates the uncertainty in the calculated number of harbour porpoise disturbance days, where application of the dose-effect curve for the 1st pile does not necessarily result in a worst-case estimate.

› *Seals*

Table 5.5 shows the effect of the applied dose-effect relationship on the number of calculated seal disturbance days for the KEC 5.0 scenario. The number of seal disturbance days was calculated on the basis of the year-long average density per location (300 x 400 m grid cell) but also, as a worst case, on the basis of the maximum year-long calculated density per location.

Table 5.5: Total number of seal disturbance days for the international scenario; the dB value refers to the applied noise standard for NL wind farms for which construction is planned from 2026 onwards (see Appendix A for the noise standards used).

	Seal disturbance days (KEC 5.0 - 164 dB)	
	International	NL
Harbour seal, average density	$567 \cdot 10^3$	$146 \cdot 10^3$
Harbour seal, maximum density	$1420 \cdot 10^3$	$268 \cdot 10^3$
Grey seal, average density	$231 \cdot 10^3$	$94 \cdot 10^3$
Grey seal, maximum density	$295 \cdot 10^3$	$118 \cdot 10^3$

As indicated earlier in Section 4.4.1, it is not certain that the distribution maps shown Figure 4.6 are still representative of the current distribution of harbour seals in particular. For example, on average, six recently tagged juvenile harbour seals seemed to make longer foraging journeys and move further away from resting locations than juveniles previously tagged (in the wild). If this were also to be the case in the older animals, the number of calculated seal disturbance days could also be underestimated. Because the average length of the foraging journeys of these animals was approximately 50 km and the distance from the resting locations to the wind farms yet to be constructed is generally larger, but also because the maximum density per site was assumed for further calculations, there is probably only a limited underestimate, if any.

5.3.2 Geophysical surveys

› *Harbour porpoises*

The estimate of the number of harbour porpoise disturbance days per project can be found in Appendix F.2.

The estimated total number of harbour porpoise disturbance days resulting from the geophysical surveys for the Dutch wind farm areas and cable routes is approximately 282,000. That is approximately 17% of the estimated 1.7 million harbour porpoise disturbance days due to piling for the same wind farms (on the basis of the Graham 1st pile dose-effect relationship).

The comparison with the animal disturbance days calculated for piling has been made only to illustrate that surveys result in less disturbance. The disturbance patterns cannot be compared directly, in part because the sources for the geophysical surveys move. The determination of the population consequences of disturbance (Section 4.7) in this study is limited to the effects of piling sound. The possible consequences of this decision are discussed in Section 5.6.1.

❱ *Seals*

The estimated total number of seal disturbance days resulting from the geophysical surveys for the Dutch wind farm areas and cable routes is approximately 13,000 for harbour seals and approximately 4,000 for grey seals. That is approximately 5% and 7% respectively of the estimated number of seal disturbance days due to piling for the same wind farms (on the basis of the maximum densities per grid cell during the year).

5.3.3 Deployment of ADDs for UXO clearance

The deployment of ADDs before UXO clearance reduces the risk of PTS and acoustic trauma but also leads to additional disturbance. To quantify how much disturbance there is as a result of ADD deployment, the number of harbour porpoise disturbance days has been calculated using $\mathrm{HPDD} = n\pi R_{\mathrm{ADD}}^2 N_{\mathrm{d}}$, with n being the local harbour porpoise density, N_{d} the number of days UXO clearance lasts and R_{ADD} the disturbance distance. The results of the calculations for each wind farm area can be found in Appendix F.3.

In the case of **harbour porpoises**, the calculations (see Section 4.3.4) used $R_{\mathrm{ADD}} = 7{,}1\ km$ (probable disturbance) and alternatively $18\ km$ (possible disturbance) to provide an estimate of the range of results. The calculated total number of harbour porpoise disturbance days due to ADD deployment is approximately 75,000 for a probable disturbance up to 7.1 km, or approximately 479,000 for a possible disturbance up to 18 km. That is approximately 4% (likely) or 28% (possible) of the estimated 1.7 million harbour porpoise disturbance days due to piling for the same wind farms (on the basis of the Graham 1st pile dose-effect relationship).

In the case of **seals**, the calculations (see Section 4.3.4) used $R_{\mathrm{ADD}} = 1\ km$. The estimated total number of animal disturbance days is approximately 480 for harbour seals and approximately 220 for grey seals.

The comparison with the animal disturbance days calculated for piling has been made only to illustrate that there is less disturbance as a result of UXO clearance. Animal disturbance days cannot be compared directly. For example, the disruptions resulting from ADD deployment are much shorter: 30 minutes relative to approximately 2 hours for piling activities (and an assumed disturbance duration of 6 hours). The determination of the population consequences of disturbance (Section 4.7) in this study is limited to the effects of piling sound. The possible consequences of this decision are discussed in Section 5.6.1.

5.4 Effects on hearing (PTS)

5.4.1 Worst-case scenario for the calculations of the probability of PTS as a result of piling

The consequences of the updated assumptions for the calculation of the probability of PTS were studied using a calculation example for a worst-case scenario on the DCS. Furthermore, this worst-case calculation does not take into account a possible 'soft start and ramp up' in which the hammer strike energy and hammer frequency are gradually raised to the maximum value. Table 5.6 provides an overview of the main input data for this calculation.

Table 5.6: Data for the scenario for calculating the probability of PTS.

Parameter	Value
Water depth	39 m
Unweighted broadband SEL_{ss}(750m)	187 dB (unmitigated) and 164 dB re 1 µPa²s noise standard
Piling scenario	35 strikes / minute, max. 5000 simultaneous strikes
Swimming speed	0.5 to 3 m/s in 0.5 m/s increments

⟩ *Result of worst-case calculations*

Figure 5.10(a) shows the calculated exposure dose for the worst-case scenario as a function of the distance of the animals from the piling location when piling starts. Figure 5.10(a) shows that animals are at risk of hearing impairment (PTS) when they are at a fixed distance from the piling location during piling (5,000 pile strikes) (in the case of unmitigated piling up to ~7.5 km for harbour porpoises and seals, and in the case of piling with a noise standard of 164 dB up to 0.3 km for seals and up to 1 km for harbour porpoises).

Figure 5.10(b) shows that, even if it is assumed that animals swim away from the piling sound (avoidance behaviour), there is a risk of PTS for animals located within a radius from 2 to a maximum of 6 km from the pile during unmitigated piling. That probability is significantly lower when a noise limit is applied. For piling with a noise standard of 164 dB, seals and harbour porpoises that are 100 m or more from the piling location at the start of piling are not at risk of PTS, provided they swim away faster than 0.5 m/s. This is a significantly lower swimming speed than the 2 m/s assumed in the KEC 4.0 report, see Heinis et al. (2022).

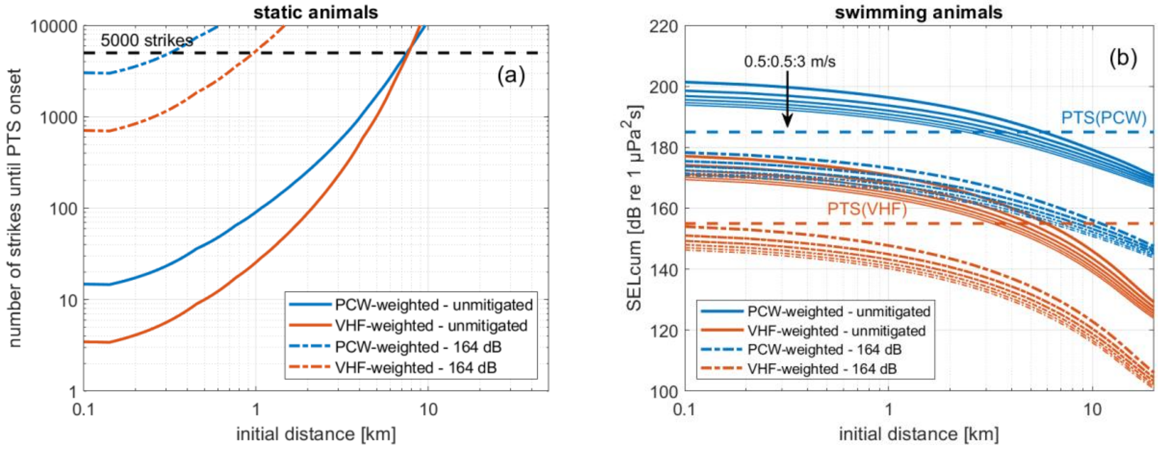

Figure 5.10: (a) Number of piling strikes after which the cumulative sound exposure dose (SELCUM, VHF-weighted for harbour porpoises and PCW-weighted for seals) for static animals exceeds the PTS threshold value and (b) cumulative exposure dose for swimming animals by comparison with the PTS thresholds (- -). Results for the worst-case scenarios considered here (see Table 5.6) for piling without mitigation and with a SELss(750m) noise standard of 164 dB re 1 µPa²s. The grouped lines show the effect of swimming speed (0.5 to 3 m/s in 0.5 m/s increments), with SEL_{CUM} decreasing as the swimming speed increases.

⟩ *Conclusion*

From the worst-case calculation, it follows that there is a negligible probability of harbour porpoises or seals suffering a permanent increase in the hearing threshold (PTS) as a result of the underwater sound from piling for the construction of offshore wind farms if the underwater sound is limited to a noise standard of SEL_{SS} (750m) = 168 dB re 1 µPa²s. Additional calculations show that this applies to a noise standard of SEL_{SS} (750m) = 168 dB re

1 μPa²s or lower (i.e. stricter). This conclusion results in part from the scientific insight reported by Southall et al. (2019) that the damage to hearing when there is exposure to underwater sound depends on the frequency-dependent hearing sensitivity of the animals.

5.4.2 UXO clearance

The detailed results of estimates of the number of animals at risk of harm from sound exposure from UXO clearance can be found in Appendix E.

› ***Effect of the deployment of ADDs***

Without mitigation, all animals within the effect distance (R_{PTS}) of an explosion will be at risk of PTS. The number of exposed animals can be estimated by multiplying the PTS area (πR_{PTS}^2) by the estimated local animal density.
The PTS area can be reduced by driving animals away prior to the detonation of an explosive at sea. In current practice, an ADD (Lofitech seal scarer) is deployed for this purpose, which is turned on approximately thirty minutes before detonation. In a typical North Sea location, the Lofitech ADD has a disturbance distance of approximately 7 km (a high probability of the animal swimming away) to 18 km (low probability of swimming away). See also Section 4.6.3.

It is assumed that, during those thirty minutes, animals will swim away from the ADD at a speed of 1.5 m/s as long as they are within the disturbance distance of the ADD (R_{ADD}). As a result, they will be at a maximum distance of R_{swim} = 2.7 km further away from the detonation location at the time of the detonation than if the ADD were not to be deployed. This mitigation is effective only if $R_{\mathrm{ADD}} > R_{\mathrm{PTS}}$. All animals located at a distance less than the swimming distance (R_{swim}) from the PTS distance of the detonation prior to ADD deployment can then avoid the risk of PTS. In this way, the number of animals exposed to the risk of PTS is reduced to $\pi(R_{\mathrm{PTS}} - R_{\mathrm{swim}})^2$ times the local animal density. In this simplified analysis, any further increase in the effect distance of the ADD results in no benefit. Increasing the period of deployment of the ADD does do so since it results in a longer swimming distance.

A more realistic estimate of the effectiveness of ADD deployment would require a dose-effect relationship describing the probability of swimming away and the swimming speed and direction as a function of the ADD sound exposure level.

The same approach can be used to determine the effectiveness of using the ADD to reduce the number of animals at risk of acute acoustic trauma.

› ***Harbour porpoises***

The total number of harbour porpoises exposed to the risk of PTS from UXO clearance during the period 2016 - 2030 is estimated at approximately 4,000, and the number of animals at risk of acoustic trauma at approximately 40. This assumes the deployment of an ADD with a disturbance distance of 7 km, a swimming speed of 1.5 m/s and deployment of the ADD starting 30 minutes before detonation. The calculations show that ADDs are very effective. Without the effect of an ADD, the current estimate is that there would be approximately 22,000 animals at risk of PTS, and approximately 1,400 animals at risk of acoustic trauma. The effectiveness of the ADD does not increase significantly with an increase in the ADD's disturbance distance (from 7 to 18 km) because, after the ADD is deployed 30 minutes prior to detonation, the animals cannot swim more than 2.7 km away from the location of the UXO. Earlier deployment of the ADD does have an effect. When the ADD is turned on 60 minutes before detonation, the animals can swim 5.4 km away, reducing the number of harbour porpoises at risk of acoustic trauma to 28 and the number at risk of PTS to approximately 240. Further increasing the waiting time results in a limited reduction of these numbers (see Appendix E).

› ***Seals***

The levels of exposure to explosive sound are lower almost everywhere than the criteria for PTS in the case of both grey and harbour seals (Southall et al., 2019). On the basis of the same threshold as that used for harbour porpoises, 128 grey seals and 516 harbour seals would suffer blast trauma. Without mitigation, the numbers would be 141 and 548 respectively. The limited effectiveness of the ADD is due to its limited disturbance distance (approximately 1 km). A louder ADD would reduce the number of affected seals. Deploying the Lofitech ADD more than 30 minutes before detonation results in no benefit for seals.

5.5 Population effect calculation

As in the KEC 4.0, population effects are determined using the interim PCoD model. A number of new developments were studied in this respect (see Section 4.7).

5.5.1 Interim PCoD 6.0.2

The iPCoD model (Sinclaier et al., August 2024) simulates the effects of disturbance on harbour porpoise and seal populations on the basis of a statistical distribution of the effects of the disturbance of the birth rate (i.e. fertility) estimated by experts and on the survival rate of juveniles (harbour porpoise calves in their first year and juvenile seals). The simulation is iterated many times (at least 1000), with new parameter values being derived each time from a statistical distribution that accounts for the uncertainty in the model parameters. Each simulation is run twice, with and without disturbance, allowing the effect of the disturbance to be determined.

› ***Harbour porpoises***

Table 5.7 provides an overview of the calculated population reduction in a range of scenarios for which interim PCoD (6.0.2) calculations were made (see Appendix G.1 for details of the scenario calculations).

Table 5.7: Calculated reduction of the harbour porpoise population (percentage of the North Sea population of 373,310 animals) due to underwater sound from piling for the construction of wind farms in the North Sea in the years 2016 to 2030 for the international scenario (Section 5.1.2) with and without the NL wind farms and applying a range of dose-effect relationships and demographic parameters. (HPDD = harbour porpoise disturbance days). The probability refers to exceedance of the calculated population reduction.

Scenario	Dose-effect relationship	HPDD / 10^6	population reduction / %			
			high fertility		low fertility	
			50% probability	5% probability	50% probability	5% probability
International	Graham et al. 2018 (1st pile)	44.9	5.9 ± 0.2	25.7 ± 0.8	3.67 ± 0.05	15.8 ± 0.2
	Brandt et al. 2018	20.0	1.69 ± 0.07	11.2 ± 0.4	1.08 ± 0.02	6.94 ± 0.08
	Max. 26 km	13.5	0.41 ± 0.01	7.3 ± 0.1	0.27 ± 0.01	4.6 ± 0.1
International, without NL projects	Graham et al. 2018 (1st pile)	43.2	5.5 ± 0.2	24.7 ± 0.8	3.44 ± 0.04	15.7 ± 0.1
	Brandt et al. 2018	19.6	1.70 ± 0.08	11.0 ± 0.3	1.08 ± 0.02	6.90 ± 0.08
	Max. 26 km	11.8	0.29 ± 0.01	6.3 ± 0.1	0.19 ± 0.01	3.9 ± 0.1

Figure 5.11 shows the calculated population reduction (percentage of North Sea population) as a function of the total number of harbour porpoise disturbance days per scenario. With a given set of population demographic parameters, the total number of harbour porpoise disturbance days would seem to be the main explanatory factor for the calculated population reduction. The relationship is approximately linear (the population decrease is inversely proportional to the number of harbour porpoise disturbance days).

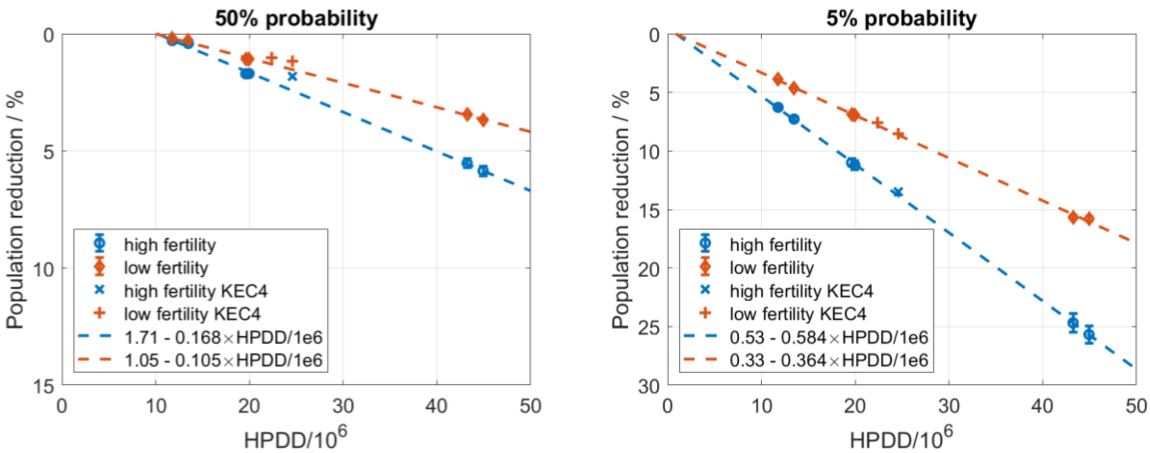

Figure 5.11: Relationship between number of harbour porpoise disturbance days and population reduction for two different sets of demographic parameters (see Table 4.2). The dotted lines show the result of fitting a linear relationship between population reduction and harbour porpoise disturbance days for the different KEC 5.0 scenarios. The '+' symbols show the results for the KEC 4.0 scenario (Heinis et al., 2022).

Calculations with the *low fertility* demographic parameters predict a smaller effect than calculations with the *high fertility* parameters. In the interim PCoD model, piling sound mainly affects the vital rates 'fertility' and 'probability of juvenile survival'. As a result, the variant with *low fertility* is less susceptible to the effects of disturbance that affect fertility and calf survival only.

The trend lines show a linear relationship between additional population reduction and harbour porpoise disturbance days. This means that the effect of the Dutch projects on the Dutch harbour porpoise population can be estimated more robustly than on the basis of a direct comparison of the calculated population reductions for the scenarios with and without the Dutch projects. The result of this calculation is shown in Table 5.8. The reduction is formulated as the percentage of the estimated part of the harbour porpoise population on the DCS (62,177 animals) to which the Dutch ecological standard applies.

Table 5.8: Calculated additional population reduction (percentage of DCS population) due to underwater piling sound for NL wind farm construction on the DCS in the years 2016 to 2030 on the basis of the number of harbour porpoise disturbance days by the NL projects ($\mathrm{HPDD_{NL}}$) using the linear trends from Figure 5.11: population reduction = $C \times \frac{\Delta\mathrm{HPDD_{NL}}}{10^6} \times \frac{N_{\mathrm{tot}}}{N_{\mathrm{NL}}}$%, in which the North Sea population is $N_{\mathrm{tot}} = 373.310$, the DCS population $N_{\mathrm{NL}} = 62.771$ and C is the trend factor.

	Dose-effect relationship	$\mathrm{HPDD_{NL}}$ / 10^6	population reduction / %			
			high fertility		low fertility	
			50% probability	5% probability	50% probability	5% probability
		C	0.168	0.584	0.105	0.364
Contribution of NL projects	Graham et al. 2018 (1st pile)	1.7	1.7%	5.9%	1.1%	3.7%
	Brandt et al. 2020	0.3	0.3%	1.2%	0.2%	0.8%
	Max. 26 km	1.7	1.7%	5.9%	1.1%	3.7%

The linear relationship found between population reduction and harbour porpoise disturbance days could depend on the scheduling of disturbance days (the season and number of consecutive disturbance days). The trend fit is now based on two overlapping schedules (KEC 5.0 scenario with and without NL projects). The results of the calculations for the KEC 4.0 scenario (Heinis et al., 2022), which are also shown in Figure 5.11, follow the fitted linear relationship for the 5% probability but they are slightly lower for the median (50% probability). It is recommended that, for future KEC scenario studies with different schedules, the linear relationship found here should not be assumed without being verified with interim PCoD calculations. It is also advisable to conduct a parameter study to investigate the extent to which this result will depend on the selected schedule.

❭ ***Seals***

Table 5.9 shows the results of iPCoD 6.0.2 calculations for the seal populations. The maximum calculated population decrease is less than 2%.

Table 5.9: Calculated population reduction for the KEC 5.0 scenarios for the number of seal disturbance days based on the maximum density.

Scenario	Species	Seal disturbance days / 10^6	population reduction / %	
			50% probability	5% probability
International	Harbour seal	1.4	0.15 ± 0.02	2.7 ± 0.3
	Grey seal	0.3	0.03 ± 0.01	2.1 ± 0.1
International, without NL projects	Harbour seal	1.1	0.10 ± 0.01	2.2 ± 0.2
	Grey seal	0.2	0.02 ± 0.01	1.3 ± 0.1
Contribution of NL projects			Reduction in DCS population / %	
	Harbour seal	0.3	0.2 ± 0.1	1.5 ± 1.1
	Grey seal	0.1	0.01 ± 0.01	1.1 ± 0.2

5.5.2 Interim PCoD + DEB

In May 2024, SMRU published a new version, iPCoD+DEB (for harbour porpoises), in which estimates based on expert elicitation were replaced by the explicit modelling of animal energetics in a *dynamic energy budget* (DEB) model (see Section 4.7.2 for a description of the model).

Figure 5.12 shows the population trend calculated with the iPCoD+DEB model and the effect of disturbance calculated with the KEC 5.0 scenario.

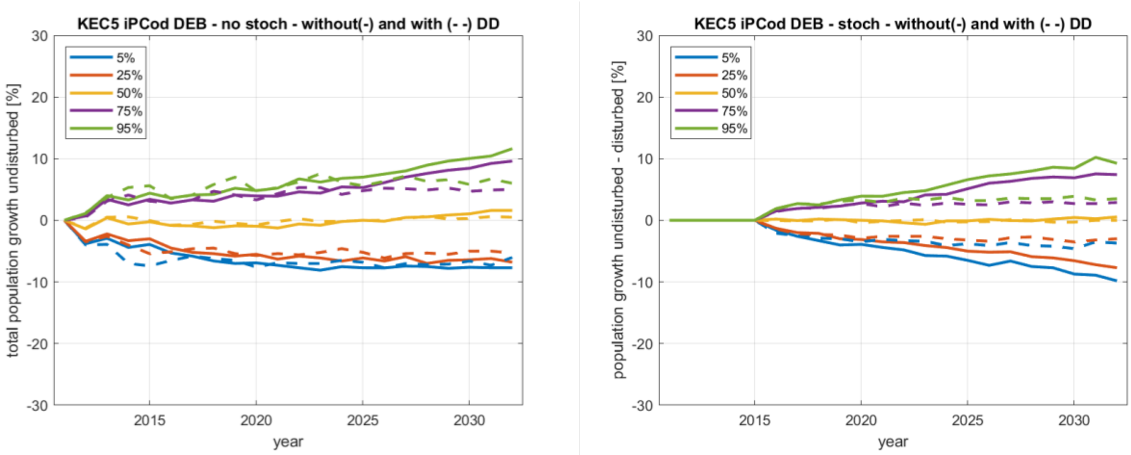

Figure 5.12: Percentiles of (left) the development of the undisturbed harbour porpoise population and (right) the effect of disturbance resulting from piling sound for the international KEC 5.0 scenario (2016-2031) on the development of the harbour porpoise population (relative to the undisturbed population), as calculated with the iPCoD+DEB model, with and without density dependence (DD).

The iPCoD+DEB model predicts a more stable population, leading to less spread in the calculated population trends. Unlike the iPCoD 6.0.2 model, the iPCoD+DEB model does not predict a significant reduction in the harbour porpoise population in the KEC 5.0 scenario. It does predict a spread in the population development, but this is symmetric around 0 and an effect of the stochastics in the calculation method. In addition, the iPCoD+DEB model provides an option to include stochastics in food availability. See Sinclair et al. (August 2024). This parameter has hardly any influence on the calculated effect of disturbance.

5.5.3 Conclusion iPCoD

Although the iPCoD+DEB model provides a realistic description of the effects of disturbance on the energy balance of the animals, it is not yet clear whether this model can replace the results of the expert elicitation for iPCoD. Effects on health (*vital rates*) involve more than energy management. During project consultations, SMRU advised the consideration of the results of both models in the effect assessment. In addition, there is still little experience with the iPCoD+DEB model. It is advisable to conduct a further investigation of the sensitivity of the input parameters to the outcomes of that model. In a cautious approach, the effects calculated with iPCoD 6.0.2 have been assumed for the time being for the comparison with the ecological standard.

5.6 Comparison with ecological standard

The guiding principle for the assessment of the effects on the harbour porpoise population is that it must be possible to establish, with a high degree of certainty (95%), that the harbour porpoise and seal populations (in the Netherlands) will not decline by more than 5% as a result of the construction of the offshore wind farms.

5.6.1 Harbour porpoises

On the basis of the trend lines presented in Figure 5.11, it emerges that there is compliance with the ecological standard for the harbour porpoise population in the Dutch section of the North Sea when the maximum number of harbour porpoise disturbance days is 2.3 million, assuming current demographic parameters for the harbour porpoise population (low fertility). It has been calculated that the construction of the wind farms in the 2030 Supplementary Roadmap will result in approximately 1.7 million porpoise disturbance days. The assumption here is that a noise standard of SELss(750 m) = 164 dB re 1 $\mu Pa^2 s$ will be applied during the construction of the wind farms in the wind farm sites IJmuiden Ver, Nederwiek, Doordewind, Hollandse Kust West Site VIII and Ten Noorden van de Waddeneilanden, in other words from 2026 onwards.

If, as in the KEC 4.0, high fertility parameters are assumed, the maximum number of harbour porpoise disturbance days corresponding to the ecological standard is 1.4 million. In the calculated scenario, this number is exceeded by approximately 300 thousand. This illustrates that the demographic parameters assumed previously led to a conservative estimate. On the basis of more recent information by Murphy et al. (2020) and IJsseldijk et al. (2021), this study also assumes the calculations based on the low fertility parameters.

This means that, under the KEC 5.0 scenario with the noise standard of 164 dB used in that scenario, wind farms in the 2030 Supplementary Roadmap can be constructed from 2026 onwards without an unacceptable risk of exceeding the ecological standard.

The calculated number of approximately 1.7 million harbour porpoise disturbance days with a noise standard of 164 dB effective 2026 is well below the maximum of 2.3 million harbour porpoise disturbance days at which the ecological standard is met. Figure 5.13 shows the calculated effect of the selected noise standard for wind farm construction from 2026 onwards on the total number of harbour porpoise disturbance days due to piling for the Dutch wind farms (2016-2030). This suggests that, with a noise standard of 168 dB from 2026 onwards, the ecological standard for the harbour porpoise population will still be met. However, the calculations do not yet take into account the disturbance resulting from the geophysical surveys and UXO clearance, and the ongoing development of offshore wind after 2030.

Disturbance resulting from piling sound, geophysical surveys and the deployment of ADDs in UXO clearances varies and so the disturbance days calculated for the various sources cannot be used directly as comparable input data for the iPCoD calculations. The possible cumulative effect of those various disturbances is not known.

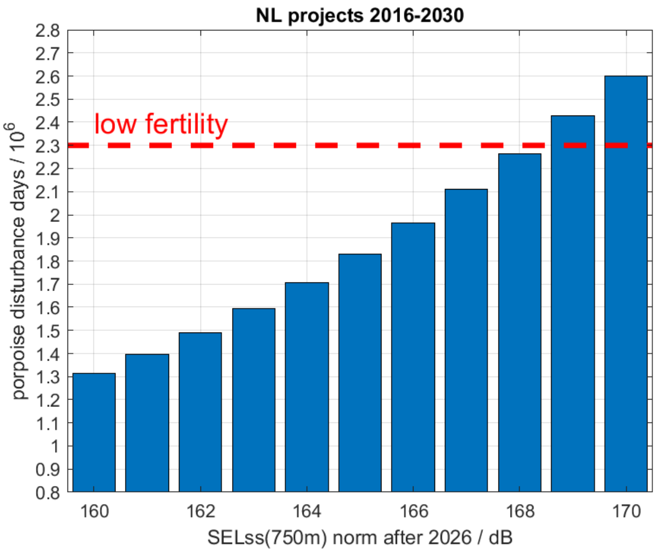

Figure 5.13: Calculated total number of harbour porpoise disturbance days due to piling for the Dutch wind farms (2016-2030) as a function of the noise standard for the wind farms after 2026 (from IJmuiden Ver) using the dose-effect relationship (Graham 1st pile) from the KEC 4.0. The red line in the figure shows the threshold values at which the ecological standard is met with the selection of the current demographic parameters in the iPCoD model. See Section 5.5.1.

5.6.2 Seals

Results from iPCoD 6.0.2 calculations (Table 5.9) show that, as with the KEC 4.0 scenario, no significant effects on seal populations are expected for the KEC 5.0 scenario.

5.7 Assessment on the basis of the threshold values in the EU Marine Strategy Framework Directive

The D11C1 criterion requires underwater sound per day from piling operations to remain below the LOBE (to be determined) in more than 20% of the surface area of the 'assessable/habitat area'. Averaged over the year, the maximum is 10% of the area.

The D11C1 criterion applies to the accumulation of impulsive underwater sound as recorded, for example, for OSPAR and HELCOM at ICES[29]. In addition to piling for wind farms, impulsive sound is also produced by air guns for seismic surveys, sonar and explosions. The spatial and temporal overlap of exposure to these sounds is limited and it has been omitted from the following analysis.

For the KEC 5.0, the effects of piling sound on the DCS have been tested indicatively against the threshold values. The surface area of the DCS is approximately 57,000 km² (~10% of the North Sea). Assuming that piling takes place at a maximum of two locations on the DCS on a single day (and that piling activities in surrounding countries do not disturb the DCS on those days), the D11C1 criterion of a 20% maximum of disturbed area per day corresponds to a maximum effective disturbance distance of approximately 43 km. In the KEC 5.0 scenario, piling takes place as an average over the year at a maximum of one location a day. The D11C1 criterion of a 10% maximum for the disturbed area on average per year then corresponds per location to a maximum effective disturbance distance of approximately 42 km. For projects planned through to year-end 2027, this is larger than the disturbance distance calculated with Aquarius 4 for unmitigated piling. However, for projects planned after that (in deeper water), Aquarius 4 calculates larger disturbance distances (up to 64 km). For those years (2028-2030), the D11C1 criterion for harbour porpoises on the DCS requires some noise mitigation, with the limiting of SELss(750 m) to 175 dB re 1 µPa²s being adequate to reduce the calculated disturbance distance to a maximum of 42 km.

[29] https://www.ices.dk/data/data-portals/Pages/impulsive-noise.aspx

6 Uncertainties and gaps in knowledge

Each step in the procedure used to determine the effects on populations and the associated parameters involves a certain degree of uncertainty. These may be uncertainties due to a variation known to a greater or lesser extent or uncertainties about the nature or speed of technical developments but also uncertainties due to the fact that little or virtually nothing is known about a particular parameter (this is a knowledge gap).

6.1 Quantification of source sound and sound propagation

- Despite the fact that significant improvements have been made in the Aquarius 4 model (de Jong et al., 2018) with respect to the description of the physics of the radiation and propagation of underwater sound from the driving of foundation piles, the quantitative prediction of the SELss remains uncertain. This is particularly true of the high-frequency component of the sound, but this is not important for the unweighted broadband SEL_{SS}. The results of the modelling with Aquarius 4 were a good match with the unweighted broadband SEL_{SS} measured during the construction of the Gemini wind farm. In order to introduce more confidence into the predicted sound levels, particularly in relation to the acoustic properties of the seabed, it will be necessary to validate the model for more scenarios (different hammer configurations and local variables). Moreover, in the Aquarius 4 model, the effects of mitigating measures such as mantles and bubble screens have been included as a retrospective correction rather than being explicitly calculated.
- It is not yet possible to model underwater sound from vibropiling accurately. This report therefore proposes estimating this underwater sound on the basis of the limited monitoring data available. Ongoing joint-industry projects such as SIMOX[30] and SIMPLE-III[31] are focusing on the acquisition of more monitoring data and developing models further where possible.
- The validation of modelling for underwater sound from geophysical surveys and UXO clearance is also limited and therefore uncertain due to a lack of monitoring data. It is essential to collect and analyse monitoring data in order to reduce uncertainty.

6.2 Quantification of disturbance/changes in behaviour

- As discussed in Section 4.3.1, the KEC calculations for harbour porpoise and seal disturbance by piling sound in this study were conducted with a worst-case dose-effect relationship. For the time being, the calculations do not take the hearing sensitivity of the exposed animals as a result of the frequency into consideration. It is reasonable to

[30] https://grow-offshorewind.nl/project/simox
[31] https://grow-offshorewind.nl/project/silent-installation-of-monopiles-iii-simple-iii

assume that the application of an SEL value weighted with the frequency sensitivity of the animals' hearing provides a better prediction of the behavioural response. That is demonstrated by, for example, exposure studies such as Kastelein et al. (2022). Frequency weighting is used on the basis of Southall et al. (2019) for effects on hearing (PTS). However, the observed disturbance of harbour porpoises during the construction of the Borssele wind farms was not predicted better by the frequency-weighted SELss than by the unweighted SELss (de Jong et al., 2023). It was therefore decided to maintain the assessment based on the unweighted SELss for the time being. In addition, the calculations do not take into consideration that piling sound becomes less 'impulsive' with increasing distance from the piling location, as a result of which the sound may become less disruptive. Moreover, the masking of piling sound by background noise in the sea is not taken into account either. This contributes to uncertainty in the estimation of the probability of disturbance at larger distances from the piling location. The effects of frequency weighting, decreasing impulsivity and masking could be investigated in exposure studies such as Kastelein et al. (2022).

- There is also uncertainty about the effect of disturbance in relation to the animals' circadian rhythms. PAM studies by de Jong et al. (2023) have found day/night and tide-dependent activity in harbour porpoises, probably as a result of foraging. The calculations do not currently take into account any variation in sensitivity to disturbance during the day.
- The dose-effect relationships applied in this study for harbour porpoise and seal disturbance resulting from underwater sound from vibropiling and from geophysical surveys and UXO clearance were estimated on the basis of the very limited data available and expert assessment. The monitoring of underwater sound and animal responses in future projects is required to validate and/or further develop these relationships.

6.3 Quantification of the number of disturbed animals

- For harbour porpoises, the distribution map from Gilles et al. (2020) has been used, which provides an estimate of the average summer density of harbour porpoises in the southern North Sea over the period 2016 – 2019. This means that seasonal variations in the distribution of the animals were not taken into account in the calculations. Furthermore, almost nothing is known about any possible season-dependent migration patterns, site fidelity, and possible sex- and age-specific variations in these factors. A relatively large number of tagging studies have been conducted in Danish waters, making more information available about individual animals (Sveegaard et al., 2011; Nielsen et al., 2018). However, this gap will not be remedied in the short term for the southern section of the North Sea. The Dutch government is investigating the possibilities of gathering more knowledge in this area by tagging harbour porpoises. See Vrooman et al. (2024) for an overview of current knowledge about tagging harbour porpoises. However, it will be several years before this work produces enough representative results. This makes it difficult to provide a more precise estimate of the number of animals affected at different times of the year.
- Although data are available for seals about season-dependent differences in distribution, they have not been included in the KEC 5.0 calculations. By selecting the maximum density per grid cell in the distribution maps of seals for the calculations, a worst-case situation for the number of seals disturbed by piling sound is assumed. For realistic modelling, more information about the seasonal distribution of wind farm construction would also have to be available. In addition, the calculations do not take into account the effects of the site fidelity of seals, which is probably higher than in harbour porpoises. As

a result, the proportion of the seal populations that regularly spends time in the search areas may be more likely to be disturbed for several days than is currently assumed in the calculations. On the other hand, this is only a small part of the population for most of the search areas and the rest of the population will be less likely to be disturbed in that case. Annex D of Heinis & de Jong et al. (2022) discusses the potential effects of animal movement on the results of the interim PCoD model for seals. Calculations for the KEC 5.0 assumes that the population of harbour seals is stable. However, a steady decline in the population has been seen since 2021 (Brasseur & Aarts, 2024). It is not yet clear to what extent this constitutes a trend.

6.4 Extrapolating the effects on individual animals to population effects

- Assumptions in iPCoD model about population development and demographic parameters:
  The iPCoD model assumes that the harbour porpoise population is stable and that population development does not depend on density. This means that, after the one-off inclusion of an effect on the population, in other words a fall in numbers as a result of the activities, the population in the model outcomes will not recover after the activities cease. This is probably not realistic. We need to know more about the density-dependent effects on population change in order to arrive at a more realistic estimate of changes in the population during the years when there is disturbance, but above all after the disturbance ceases. Has the carrying capacity been reached and, if so, what are the factors limiting population growth? Does competition for food play a role if animal population density increases when the animals are driven out of a particular area by underwater noise?
- Extrapolation of harbour porpoise disturbance to effects on vital rates:
  The iPCoD model was thoroughly updated and improved in 2018. To determine the relationship between disturbance and vital rates for harbour porpoises, the experts drew on the results of calculations made with the state-of-the-art energy budget model developed by the University of Amsterdam with the University of St. Andrews. In the meantime, an energy budget model of this kind has also been included in iPCoD+DEB. The initial calculations with that new model, by contrast with the iPCoD 6.0 model based on expert elicitation, do not predict a significant reduction in the harbour porpoise population in the KEC 5.0 scenario. For now, this outcome is still thought to be too conservative. One question is whether replacing expert opinions with an energy budget model will include all the impacts relevant to animal health. It would be advisable to investigate the number of disturbance days at which the iPCoD+DEB model does predict an effect on the population. In the iPCoD+DEB model, the time of year and the number of successive animal disturbance days are also important. It would be advisable to conduct further research to determine how the scheduling of piling operations influences the effect on the population. There should be a further examination in collaboration with the developers of iPCoD+DEB of the validity of the selected model parameters (such as the vulnerable periods for the different age classes, and the birth and death rates). The implementation of density dependence (more food availability as the population size decreases) also requires further investigation (see previous point).
- The size of the vulnerable subpopulation is one of the parameters in the interim Population Consequences of Disturbance (iPCoD) model. The KEC 5.0 calculations, which were the basis for the calculations in this report, assumed a vulnerable subpopulation of harbour porpoises equal to the total size of the North Sea population (derived from Gilles et al., 2020). The main reasons for this are that (1) there are no clear indications that

there are subpopulations in the harbour porpoise population in the North Sea that are bound to a smaller area, and (2) Nielsen et al. (2018) have shown that the home range of harbour porpoises can be very large. The sensitivity of the model for three different sizes of the vulnerable subpopulation was investigated for the KEC 1.0 (Heinis, de Jong & RWS Werkgroep Onderwatergeluid, 2015). These analyses showed that the size of the vulnerable subpopulation starts to play a role when there is a calculated population reduction of approximately half the size of the vulnerable subpopulation. The total effect is limited to approximately 80% of the vulnerable subpopulation. This also means that, at higher values, the calculated population reduction increases with the selected size of the vulnerable subpopulation. Opting for a relatively large vulnerable sub-population (which, in the calculations for harbour porpoises, is equal to the total North Sea population) therefore reduces the risk of underestimating effects.

- Applying the iPCoD Model to extrapolate the effects on harbour and grey seals:
  As a result of tagging studies, large amounts of data are available about the natural behaviour of harbour and grey seals in the wild. They include both population estimates and knowledge about the movements of individual animals. In combination with experimentally determined data about the energetic costs of behavioural change (see, for example, Rosen et al. (2007), Sparling & Fedak (2004), Thompson (2007)), the effect on the population could be estimated by combining an agent-based model (see, for example, Nabe-Nielsen et al. (2018)) with a dynamic energy budget (DEB). WMR has now started work on the development of a model of this kind in collaboration with SMRU/University of St. Andrews (Chudzinska et al., 2021). However, it will be several years before this model is operational. To estimate effects on harbour seals and grey seals on the DCS, the 2019 update of the iPCoD model was therefore used in the same way as for harbour porpoises. Here too, it has been assumed that all seals present on the DCS belong to the vulnerable subpopulation. Furthermore, it has been assumed that the population of harbour seals is stable and that the population of grey seals grows by 1% per year (see Sinclair et al. (2020) for other demographic parameters).

6.5 Alternative piling techniques

- Applicability of alternative installation techniques. The data about underwater sound for techniques other than impact piling and vibropiling, such as GDP (gentle driving of piles), vibrojetting, jetting and EQ piling, are still sparse or non-existent. These techniques may be quieter than the piling techniques currently in use. In the SIMPLE-III (silent installation of monopiles) project, an offshore test for vibrojetting is planned for 2025 in which underwater sound will be measured. Ørsted claims there was a ‘dramatic reduction’ in sound levels when testing their new jetting technology during the construction of the Gode Wind farm in Germany, but the relevant data are not yet available.
- Uncertainty about the effects of using other types of foundations, including tripod and jacket foundations, gravity-based foundations and floating wind farms, now and in the future. This study assumes that the turbines in all the wind farms considered in the Netherlands and other countries will be installed on monopile foundations. This is a reasonable assumption for the wind farms that have been built and will be built in the relatively shallow southern section of the North Sea, but not for wind farms that will be constructed in deeper water, such as many of the wind farms in the United Kingdom, where jackets or tripods are often used. Piling a jacket foundation (3 - 4 piles) probably takes more time than piling a single monopile foundation. However, if that takes several days, the number of animal disturbance days and therefore the calculated effect on the population will also increase.

6.6 Operational underwater sound from wind turbines

Continuous sound from operational wind turbines is generally of interest only when there is little ambient sound from wind and shipping (Tougaard et al., 2023).

6.7 Underwater sound from shipping

Continuous sound is produced, in particular by shipping, during the construction and operational phases. Results of recent research demonstrate that harbour porpoises may already be affected before actual piling operations begin (Graham et al., 2017; Rose et al., 2019). In part, this is due to the use of acoustic deterrent devices (ADDs), which prevent PTS. However, at various wind farms, reduced activity around the piling location in harbour porpoises was already observed before the ADD was turned on. The underwater sound produced during the various activities is the most plausible explanation here. That may include sound from shipping (and particularly from propellers), the sound of sonars, anchor chains, the lowering of the jack-up vessel's legs etc. The mitigation of piling sound also requires a lot of additional activity (involving shipping). All these activities result in shorter disturbance distances than the distances caused by non-mitigated piling sound. A recent German review study by Belmann et al. (2023) cautiously concludes that wind-farm-related shipping may cause a limited increase in underwater sound inside the wind farm, but that the increase is limited outside, certainly in the case of wind farms near shipping lanes. The DEMASK[32] project is conducting further research into mapping underwater sound in and around operational wind farms.

6.8 Underwater sound during wind farm decommissioning

Several offshore wind farms are reaching the end of their life cycles, and more and more of these farms will be decommissioned in the next two or three decades. No examples are yet available of how offshore wind farms will be decommissioned and therefore whether this will produce underwater sound and, if so, how much. New techniques are being developed to decommission the monopiles in a sustainable and cost-effective way. The hydraulic extraction of monopiles is one of the new methods used to remove the entire monopile. This approach makes it possible to reclaim and recycle all the steel. However, this technique is still in the research phase.

6.9 Other uncertainties

Little is known about the effects on the behaviour of marine mammals of the presence of power lines inside wind farms or along cable routes.

[32] https://www.interregnorthsea.eu/demask

6.10 Looking ahead to the knowledge update and KEC 6

This report is the first result of a multi-year assignment including plans for two KEC updates (KEC 5.0 and KEC 6.0) and an annual update with the latest insights and knowledge transfer. The KEC 6.0 will present calculation results for an updated scenario for offshore wind development in the North Sea. Where possible, it will use new harbour porpoise distribution maps from the SCANS IV survey[33].

Among other things, the interim knowledge update will further examine the capabilities and limitations of the iPCOD+DEB model and explore the applicability of alternative exposure measures for both impulsive and continuous sound, as proposed in Lucke et al. (2024), in greater detail.

[33] https://storymaps.arcgis.com/stories/6435641aed5745d1b2471e5e59e6af94

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Appendix A
KEC 5.0 Scenario

Table A.1: KEC 5.0 scenario for the construction of wind farms in the North Sea in the years 2016-2030.

Name	Country	Expected start of construction	Max capacity / MW	Turbine capacity / MW	Pile diameter / m	Number of turbine monopiles	Number of platform piles	Noise standard: unweighted SEL_{SS} at 750 m (dB re 1 $\mu Pa^2 s$)
Nobelwind	BE	2016	82.5	3.3	5.0	25		160
Nobelwind	BE	2016	82.5	3.3	5.0	25		160
Rentel	BE	2017	309	7	7.0	42		160
Norther	BE	2018	369.6	8.4	8.0	44		160
Northwester 2	BE	2019	219	9.5	8.0	23		160
Seamade - Mermaid	BE	2019	235	8.4	8.0	28		160
Seamade - Seastar	BE	2019	252	8.4	8.0	30		160
Noordhinder Noord	BE	2028	700	15	9.9	47		160
Princess Elisabeth - (Fairybank/NordHinder)	BE	2028	2800	20	11.3	70		
Nordergründe	DE	2016	110.7	6.15	6.5	18		160
Veja Mate	DE	2016	402	6	6.0	67		160
Merkur Offshore	DE	2017	396	6	6.0	66		160
Nordsee One	DE	2017	332.1	6.15	6.5	54		160
Borkum Riffgrund 2	DE	2018	450	8.3	8.0	56		160
Deutsche Bucht	DE	2018	252	8.4	8.0	31		160
EnBW Hohe See	DE	2018	497	7	7.0	71		160
Trianel Windpark Borkum	DE	2018	203	6.34	6.5	32		160
Albatros	DE	2019	117.6	7	7.0	16		160
KASKASI II	DE	2021	342	9	8.0	38		160
Borkum Riffgrund 3	DE	2023	913	11	8.0	83		160
Gode Wind 3	DE	2023	253	11	8.0	23		160

Name	Country	Expected start of construction	Max capacity / MW	Turbine capacity / MW	Pile diameter / m	Number of turbine monopiles	Number of platform piles	Noise standard: unweighted SEL_{ss} at 750 m (dB re 1 $\mu Pa^2 s$)
EnBW He Dreiht	DE	2024	900	15	9.9	60		160
N-3.7	DE	2025	225	15	9.9	15		160
N-3.8	DE	2025	433	15	9.9	29		160
N-7.2	DE	2026	980	15	9.9	65		160
N-3.5	DE	2027	420	15	9.9	28		160
N-3.6	DE	2027	480	15	9.9	32		160
N-6.6	DE	2027	630	15	9.9	42		160
N-6.7	DE	2027	270	15	9.9	18		160
N-12.1	DE	2028	2000	20	11.3	100		160
N-12.2	DE	2028	2000	20	11.3	100		160
N-9.1	DE	2028	2000	15	9.9	133		160
N-9.2	DE	2028	2000	15	9.9	133		160
N-9.3	DE	2028	1500	15	9.9	100		160
N-10.1	DE	2029	2000	20	11.3	100		160
N-10.2	DE	2029	500	20	11.3	25		160
N-11.1	DE	2029	2000	20	11.3	100		160
N-11.2	DE	2029	1500	20	11.3	75		160
N-12.3	DE	2029	1500	15	9.9	100		160
N-13.1	DE	2029	500	15	9.9	30		160
N-13.2	DE	2029	1000	15	9.9	60		160
N-13.3	DE	2030	2000	20	11.3	100		160
N-14.1	DE	2030	2000	20	11.3	100		160
N-15.1	DE	2031	2000	20	11.3	100		160
N-16.1	DE	2032	2000	20	11.3	100		160
N-17.1	DE	2032	1000	20	11.3	50		160
N-18.1	DE	2032	1000	20	11.3	50		160
N-16.2	DE	2033	2000	20	11.3	100		160

Name	Country	Expected start of construction	Max capacity / MW	Turbine capacity / MW	Pile diameter / m	Number of turbine monopiles	Number of platform piles	Noise standard: unweighted SEL_{ss} at 750 m (dB re 1 $\mu Pa^2 s$)
N-18.2	DE	2033	2000	20	11.3	100		160
Horns Rev III	DK	2017	406.7	8.3	8.0	49		160
Vesterhav Nord	DK	2022	193.2	8.4	8.0	23		
Vesterhav Syd	DK	2022	151.2	8.4	8.0	18		
Thor	DK	2025	1008	14	9.0	72		
Nordsøen - Tender 10	DK	2030	1000	20	11.3	50		160
Nordsøen - Tender 1	DK	2031	1000	20	11.3	50		
Nordsøen - Tender 2	DK	2031	1000	20	11.3	50		
Nordsøen - Tender 3	DK	2031	1000	20	11.3	50		
Nordsøen - Tender 4	DK	2033	1000	20	11.3	50		
Nordsøen - Tender 5	DK	2033	1000	20	11.3	50		
Dunkerque	FR	2026	598	13	9.0	46		
Sørlige Nordsjø	NO	2028	1520	20	11.3	76		
Aberdeen Offshore W/F	UK	2016	96.8	8.8	8.0	11		
Dudgeon	UK	2016	402	6	6.0	67		
Galloper	UK	2016	353	6	6.0	56		
Methil Demo	UK	2016	7	7	7.0	1		
Race Bank	UK	2016	573.3	6.3	6.5	91		
Beatrice Offshore Wind Farm	UK	2017	588	7	7.0	84		
East Anglia ONE	UK	2018	714	7	7.0	102		
Hornsea 1 (East)	UK	2018	1218	7	7.0	174		
Moray Offshore Windfarm (East)	UK	2019	950	9.5	8.0	100		
Blyth Demo Phase 1	UK	2020	41.5	8.3	8.0	5		
Hornsea Project 2 - Phase 1 (Breesea)	UK	2020	1320	8	8.0	165		
Triton Knoll	UK	2020	857	9.5	8.0	90		
Seagreen Phase 1 Windfarm	UK	2021	1075	10	8.0	114		
Dogger Bank A	UK	2022	1235	13	9.0	95		

Name	Country	Expected start of construction	Max capacity / MW	Turbine capacity / MW	Pile diameter / m	Number of turbine monopiles	Number of platform piles	Noise standard: unweighted SEL_{ss} at 750 m (dB re 1 µPa²s)
Neart Na Gaoithe Offshore Wind	UK	2022	448	8	8.0	54		
Dogger Bank B	UK	2023	1235	13	9.0	95		
East Anglia THREE	UK	2023	1400	14	9.0	95		
Dogger Bank C	UK	2024	1200	14	9.0	87		
East Anglia ONE NORTH	UK	2024	800	14	9.0	67		
Seagreen 1A Wind Farm Firth of Forth	UK	2024	425	12	8.0	36		
Sofia	UK	2024	1400	14	9.0	100		
Z1_WDA	UK	2024	882	14	9.0	60		
East Anglia TWO	UK	2025	900	14	9.0	75		
Berwick Bank Firth of Forth	UK	2026	2300	20	11.3	115		
Hornsea Project Three (HOW03)	UK	2026	2852	14	9.0	231		
Inch Cape Offshore Wind Farm	UK	2026	1100	15	9.9	72		
Marr Bank Firth of Forth	UK	2026	1860	20	11.3	93		
1_BP Alternative Energy Investments	UK	2027	2900	15	9.9	191		
Hornsea Project Four (HOW04)	UK	2027	2600	15	9.9	180		
Round 4 Preferred Project 3	UK	2027	1500	15	9.9	100		
9_Ocean Winds	UK	2028	2000	13	9.0	150		
Dudgeon Extension	UK	2028	402	15	9.9	27		
Five Estuaries	UK	2028	360	20	11.3	18		
Norfolk Boreas	UK	2028	1400	14	9.0	100		
Norfolk Vanguard East And West	UK	2028	2800	14	9.0	200		
Round 4 Preferred Project 1	UK	2028	1500	10	8.0	150		
Round 4 Preferred Project 2	UK	2028	1500	10	8.0	150		
Sheringham Shoal Extension	UK	2028	318	12	8.0	27		
Bowdun	UK	2029	1000	20	11.3	50		
North Falls	UK	2029	510	15	9.9	34		
Borssele Site III	NL	2019	366	9.5	8.0	39	6	170

Name	Country	Expected start of construction	Max capacity / MW	Turbine capacity / MW	Pile diameter / m	Number of turbine monopiles	Number of platform piles	Noise standard: unweighted SEL_{ss} at 750 m (dB re 1 μPa^2s)
Borssele Site IV	NL	2019	366	9.5	8.0	39		170
Borssele Site I	NL	2020	376	8	8.0	47	6	169
Borssele Site II	NL	2020	376	8	8.0	47		169
Borssele Site V	NL	2021	19	9.5	8.0	2		170
Hollandse Kust Zuid Site I	NL	2021	385	11	8.0	35	6	173
Hollandse Kust Zuid Site II	NL	2021	385	11	8.0	35		173
Hollandse Kust Noord Site V	NL	2022	759	11	8.0	69	6	170
Hollandse Kust Zuid Site III	NL	2022	385	11	8.0	35	6	173
Hollandse Kust Zuid Site IV	NL	2022	374	11	8.0	34		173
Hollandse Kust West Sites VI & VII	NL	2025	1520	15	9.0	108	12	168
IJmuiden Ver Gamma	NL	2027	2295	15	9.9	153	16	164
IJmuiden Ver Alpha & Beta	NL	2027	4020	15	9.9	268	32	164
Nederwiek Noord	NL	2028	4600	15	9.9	306	32	164
Nederwiek Zuid	NL	2028	2295	15	9.9	153	16	164
Doordewind Site I	NL	2029	2300	20	11.3	115	16	164
Hollandse Kust West Site VIII	NL	2029	760	20	11.3	38	6	164
Ten Noorden van de Waddeneilanden	NL	2029	795	15	9.9	53	6	164

Appendix B
Modelling piling sound

In previous versions of the KEC, underwater sound from piling was calculated using TNO's Aquarius 4 computing model (de Jong, et al., 2019). That model calculates the spatial distribution of underwater sound from piling dependent on data relating to the piling hammer, foundation piles and the surroundings (bathymetry and geology). Application of the Aquarius 4 model is not a requirement for KEC calculations. However, when alternative models are applied, at least the aspects described below should be considered.

Figure B.1 provides a schematic overview of the piling hammer, the pile and the locality. Piling causes underwater sound because the strike delivered to the pile by the impact hammer, via an impact plate or anvil, creates vibrations that travel through the pile wall to the bottom of the pile. Lateral contraction means the pile also moves in a radial direction, producing underwater sound. Because the speed of the vibration waves (approximately 5000 m/s for a steel pile) is faster than the speed of sound in water, the sound radiation from the pile takes the form of 'Mach waves' (Reinhall & Dahl, 2011) so that the sound is radiated by the pile at an angle of approximately 17 degrees below the horizon. As a result, modelling the pile as a point source is not a valid approach: the sound emission over the length of the pile (a line source) must be considered.

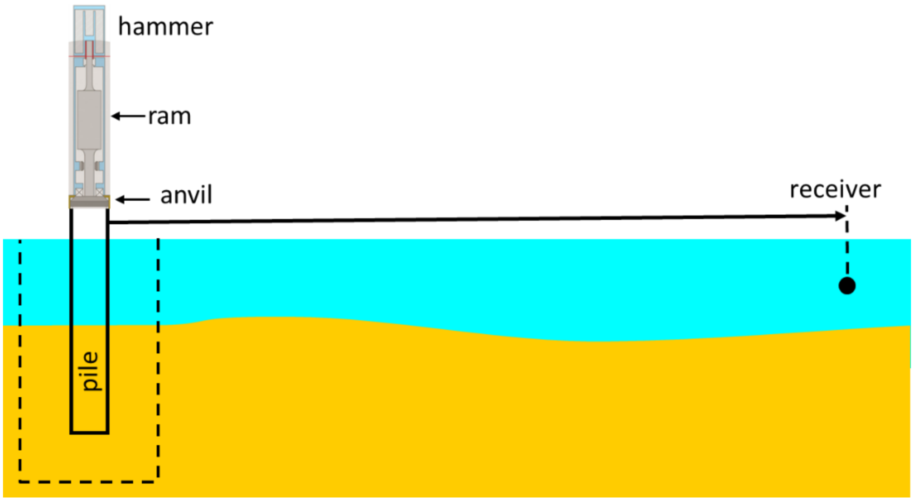

Figure B.1: Sketch of piling hammer, pile and vicinity. The dotted line around the pile marks the area near the pile where detailed models of the pile and the vicinity can be applied that can be linked to far-field models for underwater sound propagation further away.

B.1 Hammer force

A piling model starts by quantifying the force applied to the pile by the impact hammer.

A **first-order estimate** of that force can be made using the analytical model of Deeks and Randolph (1993), which has been applied in Aquarius 4. It calculates the spectrum of the force delivered on the basis of the kinetic energy of the hammer mass, the anvil mass, and the contact stiffness between the hammer and the anvil. This simple model can be used mainly at the dominant low frequencies in the piling sound spectrum.

Better predictions can be obtained at higher frequencies by applying semi-analytical models (Fricke & Rolfes, 2015), geotechnical models for piling such as TNO Wave (Middendorp & Verbeek, 2006) and finite element models (Heitmann, 2017) in exchange for an increase in complexity and computing time. It is important for the implementation of the applied model to have been verified by independent comparison with benchmark solutions, and, if possible, to be experimentally validated.

B.2 Sound emission

The model next describes the propagation of vibrations through the pile and the sound emission of those vibrations to the underwater environment.

Once again here, a **first-order estimation** can be applied as in Aquarius 4 (de Jong, et al., 2019). In this approach, the pile is modelled as a vertical array of point sources uniformly distributed over the section of the pile between the seabed and the surface, with the travel time of the waves through the pile being taken into consideration. See also, for example (MacGillivray, 2014). The source strength of the point sources is calculated from the radial acceleration of the pipe wall on the basis of material properties (Young's modulus, Poisson constant and density) and pile diameter and wall thickness. The one-dimensional discretisation of the pile into segments with a length dz is a useful approximation as long as dz is small relative to the wavelength in the water at the maximum frequency for which the emitted sound is to be calculated. At 20 kHz, the maximum frequency according to the ISO standard for piling sound measurements (ISO 18406, 2017), that wavelength is approximately 7.5 cm. The Aquarius 4 calculations were therefore adopted for dz=5 cm. The model assumes axi-symmetric motion of the pile wall. Any contributions to underwater sound emission from higher-order deformations of the pile cross-section are not considered in this first-order approximation. The validity of this approach is limited if the wavelength of the vibration waves in the pile is smaller than the circumference of the pile, or above the 'ring frequency' $f_{\mathrm{ring}} = c_p/\pi D$, where c_p is the velocity of the axial waves in the pipe wall ($c_p \approx 5000\ m/s$) and D the pile diameter. For realistic monopile diameters, the usefulness of the applied first-order approximation is therefore less above, for example, 320 Hz for a 5 m pile diameter and 160 Hz for a 10 m pile diameter.

A better prediction of pile vibrations at higher frequencies can be obtained by applying geotechnical models for piling such as TNO Wave (Middendorp & Verbeek, 2006), or semi-empirical (Tsouvalas, 2020) or finite element models (Heitmann, 2017) in exchange for an increase in complexity and computing time. It is important for the implementation of the applied model to have been verified by independent comparison with benchmark solutions, and, if possible, to be experimentally validated.

B.3 Sound propagation

The array of point sources is used as input for the calculation of underwater sound propagation. The travel time of the vibration waves should be taken into account here. Several computational models can be used to calculate sound propagation in the relatively shallow water in which wind turbines are installed on monopiles (Jensen et al., 2011).

Numerical efficiency is an important prerequisite for the large-scale calculation of underwater sound during the construction of all wind farms in the North Sea over a period of several years. A range of simplifications have therefore been selected in Aquarius 4 (de Jong, et al., 2019). In the **first-order estimation** in Aquarius 4, the locality is modelled as a 'Pekeris waveguide' (Pekeris, 1948), which consists of two layers – the seawater and the seabed – both of which are modelled as an equivalent fluid with uniform sound velocity, density and absorption. Here, Aquarius 4 uses an efficient 'normal mode' implementation based on the *KRAKEN* solver[34] in line with Sertek (2016). Variations in water depth are considered by applying adiabatic coupling to the modes for the different depths. The sediment is modelled as an equivalent uniform liquid (without shear stiffness or layers). De Jong et al. (2010) have shown that this assumption results at low frequencies in a good match with measurements of the underwater sound during piling for the Gemini wind farm, provided that a frequency-dependent absorption in the sediment is taken into account.

Table B.1 provides an example of the values for the environmental parameters used in the KEC 5.0 calculations (Chapter 5). The bathymetry (relative to the lowest astronomical tide) was obtained from the EMODnet data portal. Tidal variations may be taken into account. However, since the timetable for piling operations is often not known at the time of the calculations, this is seldom done. The remaining data are based on standard values from Ainslie (2010), with an adjusted absorption at frequencies below 250 Hz in line with a validation of the calculation results on the basis of monitoring data for the piling of a turbine foundation in the Gemini offshore wind farm (de Jong, et al., 2019).

Wind at sea and waves disturb the surface of the water, scattering and absorbing sound, particularly at higher frequencies. The calculations assume the worst-case scenario in which the effect of wind and waves is disregarded.

Table B.1: Input data for the Aquarius 4 sound propagation calculations, as applied for the KEC 5.0.

Water depth	EMODnet[35] bathymetry, 1/8 minute resolution
Soil type	'medium sand' (Ainslie, 2010: Table 4.18; ϕ=1.5)
Seabed sound velocity	1797 m/s
Seabed density	2136 kg/m^3
Seabed absorption per wavelength (de Jong, et al., 2019)	0.88 dB for f $\geq$ 250 Hz $\left(\frac{f}{250\ \mathrm{Hz}}\right)^{0.8} \times 0.88$ dB for f < 250 Hz
Seawater sound velocity	1500 m/s
Seawater density	1024 kg/m^3

In local studies where more information is available, it is possible to predict sound propagation more accurately. Several mathematical models are available for this purpose (Jensen et al., 2011) that can calculate, for example, the variation in water and sediment properties as a function of depth, or the effects of shear waves in the sediment. It is important for the implementation of the applied model to have been verified by independent comparison with benchmark solutions, and, if possible, to be experimentally validated. The application of advanced propagation models also generally requires an expert

34 https://oalib-acoustics.org/website_resources/AcousticsToolbox/manual/kraken.html
35 http://www.emodnet-bathymetry.eu/

user. The international COMPILE workshops (Lippert et al, 2016; Lippert et al., 2018) provided an opportunity to compare different models for a number of well-defined scenarios.

B.4 Acoustic map

Propagation calculations are performed in two dimensions (depth-distance) along radial trajectories from the pile. See, for example, Figure B.2(left). Bathymetry is interpolated in this trajectory, which starts 100 m from the pile and is discretised in 100 m increments up to a maximum distance of 100 km. In the Aquarius calculations for the KEC, 48 radial trajectories were selected that were uniformly distributed over 360 degrees. The propagation loss to different locations along the trajectory is calculated for ten depths that are uniformly distributed between 1 m above the seabed and 1 m below the water surface.
The calculations are made for the centre frequencies of the decidecade (ISO 18405, 2017) frequency bands from 31.5 Hz to 8 kHz (incl.). As a result of the sound calculations, the maximum value is presented for the unweighted broadband SELss over the water depth. The results for the trajectories are then interpolated in a regular latitude-longitude grid (resolution 1°/360 latitude and 1°/180 longitude; » 311 m´366 m) and shown on a map. See the example in Figure B.2(right).

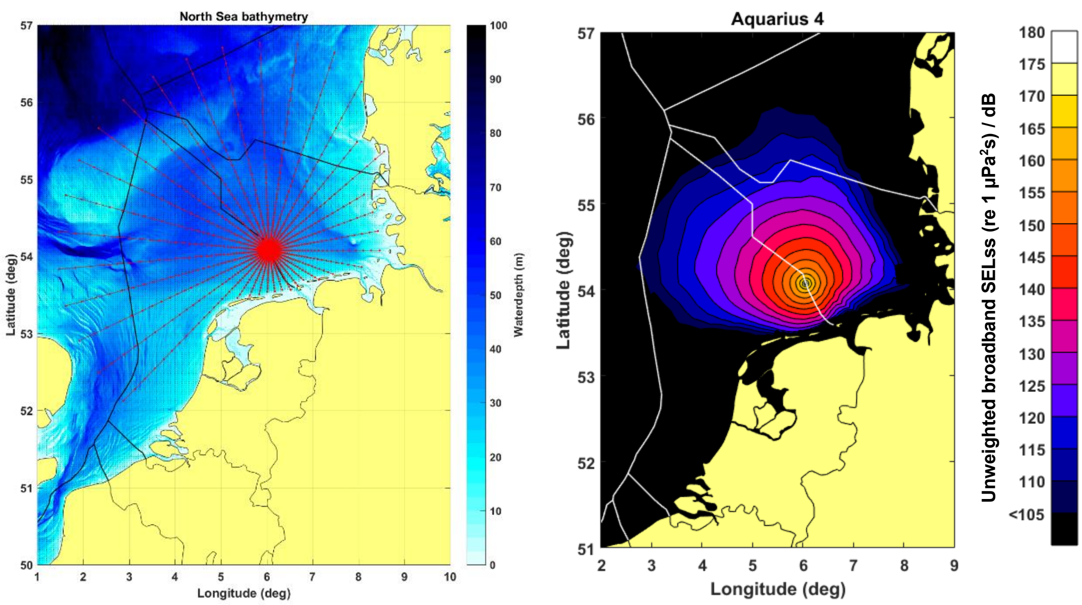

Figure B.2: Left: Bathymetry map of the North Sea showing an example of the grid (red points connected by lines) on which piling sound calculations are performed in Aquarius 4. Right: Example of a map of the maximum value over the depth of the unweighted broadband SELss for piling near the German-Dutch border from (de Jong, et al., 2019).

B.5 Noise reduction

There are regulations for underwater sound from piling for wind turbines and platforms. Site decisions for offshore wind areas require that measures be taken to ensure that underwater sound at a reference distance of 750 m from the pile is below a specified limit (standard). Several technical solutions for reducing piling sound are now available. See, for example Verfuss et al. (2019) or Belmann et al. (2020).

Modelling the effectiveness of noise reduction measures is largely still under development. Although progress has been made in the JIP Bubbles[36] study, for example, it has not yet resulted in a validated model for the effectiveness of bubble screens. For now, the effectiveness of noise reduction measures is best estimated on the basis of data from previous projects. A lot of data are available from German projects in particular, see Belmann et al. (2020). These make it possible to consider the spectrum of the measure's insertion loss, as long as the measure to be applied is known.

When planning for future wind farms, the noise standard ($L_{E,\mathrm{standard}}$) is often known. However, the technical solution is not. The noise reduction measures have therefore not been explicitly included in the KEC scenario calculations (Chapter 5). As an alternative, the noise standard is applied to the calculated sound distribution for piling without reduction measures ($L_{E,\mathrm{unreduced}}$). A constant value ($\Delta L_{\mathrm{reduction}}$) is subtracted from this sound distribution (unweighted broadband SELss) for each project that ensures that the broadband SELss (maximum value over the water depth) at 750 m from the pile is less than or equal to the noise standard in all directions.

$$\Delta L_{\mathrm{reduction}} = \max\left(L_{E,\mathrm{unreduced}}(750\ \mathrm{m})\right) - L_{E,\mathrm{standard}} \quad \text{(B.1)}$$

The distribution of the broadband SELss for the mitigated piling sound at all locations (x, y) is then calculated:

$$L_{E,\mathrm{reduced}}(x,y) = L_{E,\mathrm{unreduced}}(x,y) - \Delta L_{\mathrm{reduction}} \quad \text{(B.2)}$$

Any effect on the shape of the spectrum as a result of the selected mitigation measure is therefore not included in these calculations. Bubble screens, for example, are particularly effective at higher frequencies (Dähne et al., 2017). In addition, this approach does not provide a picture of the feasibility of the required noise mitigation.

[36] grow-offshorewind.co.uk/project/bubbles-jip !!https://grow-offshorewind.nl/project/bubbles-jip

Appendix C
Modelling underwater sound from vibropiling

By contrast with impact piling, vibropiling produces continuous sound. Much less is known about both the sound levels produced and their effects on marine mammals than in the case of conventional impact piling. The joint industry project 'Sustainable Installation of XXL Monopiles' (SIMOX)[37] investigated the feasibility of vibropiling for the installation of monopiles for offshore wind turbines. In this context, a provisional methodology was drawn up for quantifying the effects of vibropiling sound on harbour porpoise and seal populations.

C.1 Underwater sound from vibropiling

Vibropiling involves vibrating the pile with eccentrically rotating masses (Figure C.1). Those vibrations reduce the resistance of the soil into which the pile then penetrates because of its mass. Depending on the bed structure, this technology can result in faster pile placement, with lower peak loads on the pile and sediment than in impact piling.

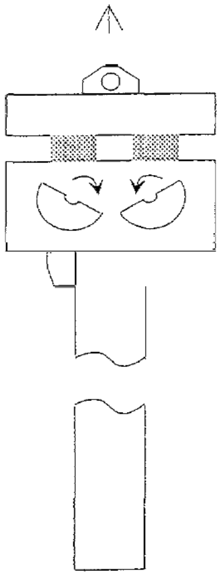

Figure C.1: Sketch of the operation of a vibratory hammer from (Houze, et al., 1995).

Meanwhile, new technologies combining vertical vibration with torsional vibration (*Gentle Driving of Piles*[38]) or with water jets (*Vibrojetting*[39]) are also under development to reduce bed resistance further. No measurements of underwater sound are yet available for these technologies.

[37] https://grow-offshorewind.nl/project/simox
[38] https://grow-offshorewind.nl/project/gentle-driving-of-piles
[39] https://grow-offshorewind.nl/project/silent-installation-of-monopiles-iii-simple-iii

Because vibropiling has not often been used in offshore projects, little information is available about the underwater sound it generates. And because there are no national or international measurement standards, the published data are often not easily comparable. The sound from vibropiling can be classified as broadband continuous sound with strong tonal components, as illustrated in Figure C.2. The tonal sound is seen at the vibrating frequency of the hammer (typically between 14 and 23 Hz) with a series of harmonics that are sometimes observable up to 1 kHz. Due to instability in the driving process, these tones are less observable at higher frequencies. Nevertheless, the hammer still produces a broadband sound that exceeds the background noise. Measurements show that the underwater sound level of a vibratory hammer varies over time (10-20 dB). See, for example (Matuschek & Betke, 2009). This is probably attributable to variations in the resistance that the pile encounters as it penetrates different layers in the bed.

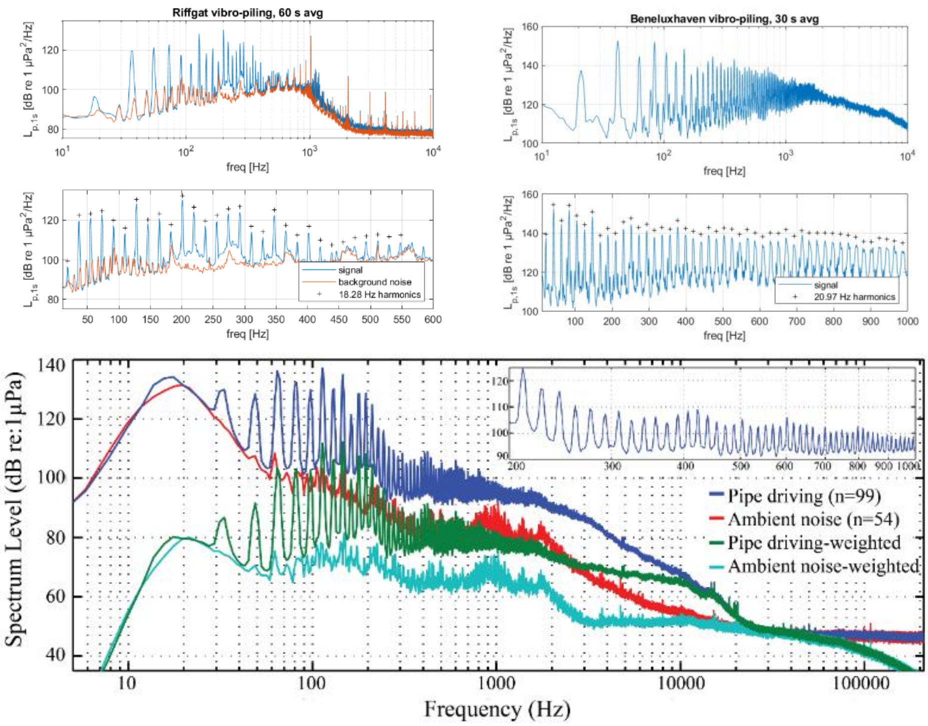

Figure C.2: Examples of measured underwater sound spectra from vibropiling during monopile installation operations at the Riffgat (Jansen, Staats, & Groen, 2012), Beneluxhaven (Binnerts, de Jong, & Kruyen, 2018) and Hong Kong (Wang, et al., 2014) locations.

C.2 Modelling underwater sound from vibropiling

No validated models are yet available for the SPL of underwater sound resulting from vibropiling to install a monopile. The mechanisms affecting sound generation are still under investigation (Molenkamp, Tsouvalas, & Metrikine, 2023) and there is a lack of coherent monitoring data that can be used to link sound to the design and use of vibropiling.

Nevertheless, a first-order estimate of underwater sound can be made on the basis of the limited information available. The current approach is summarised here.

Pending the development of practical modelling approaches, an initial estimate can be made based on previously measured sound spectra generated by vibropiling in representative conditions. As an initial estimate, it can be assumed here that the sound energy is linearly proportional to the kinetic energy of the hammer. Since the kinetic energy of a vibratory hammer scales approximately with the total static moment $M$of the rotating masses and with the square of the speed of rotation Ω, the following approximation applies:

$$L_p^{M,\Omega} \approx L_p^{M_{\mathrm{ref}},\Omega_{\mathrm{ref}}} + 10\log_{10}\left(\frac{M}{M_{\mathrm{ref}}}\right)\ \mathrm{dB}\ + 20\log_{10}\left(\frac{\Omega}{\Omega_{\mathrm{ref}}}\right)\ \mathrm{dB} \tag{C.2}$$

The subscript ‘ref’ here refers to the available monitoring data.

In studies for the tender for the IJmuiden Ver Alpha and Beta wind farms[40], a worst-case reference based on underwater sound measurements during vibropiling for a mooring pile in the Rotterdam Beneluxhaven was used provisionally. This was a pile 1.7 m in diameter that was installed with a vibratory hammer with eccentric moment M=110 kgm and a rotation speed of 23 Hz (1350 rpm). The 90$^{\mathrm{th}}$ percentile of the measured SPL is consistent with broadband levels in the guideline issued by the California Department of Transportation (Buehler, Oestman, Reyff, Pommerenck, & MItchell, 2015) for estimating the effects of piling sound on fish.

VISSKA project

The recent report for the VISSKA project (Bellmann, Remmers, Brüers, & Poppitz, 2024) presented monitoring results for underwater sound from the vibropiling of six piles for the KASKASI II offshore wind farm. Because of the bed resistance, none of these piles could be driven to the final depth, and the installation operation was completed with an impact driver. As previous studies have also shown, sound varies considerably during the piling period.

Figure C.3 shows the measured underwater sound during vibropiling on one of the piles. Confirming previous measurements (Figure C.2), the sound is dominated by tones at the harmonics of the vibration frequency. A sharp increase in high-frequency sound was measured at the end of the vibropiling, when the vibratory hammer could no longer overcome the bed resistance (‘pile refusal’). As a result, the sound measurement is not representative for vibropiling in which there is no ‘refusal’.

40 TNO memo 2023 M12655 to RWS ZD (Calculation of the number of porpoises potentially disturbed by offshore vibropiling noise).

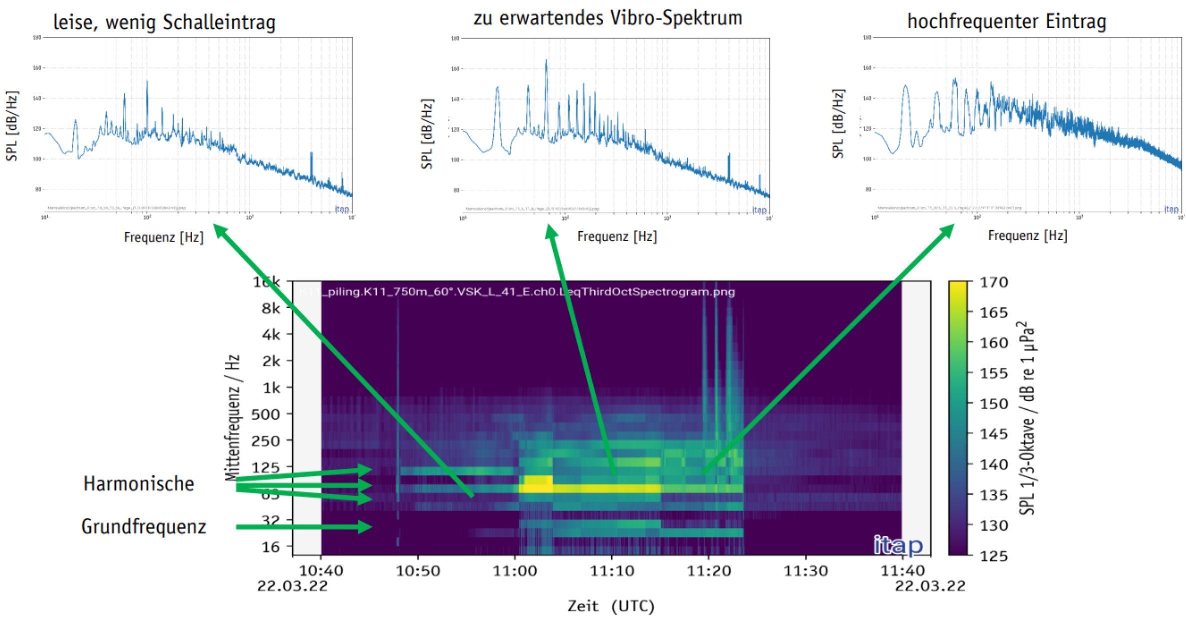

Figure C.3: Sound spectrum ($L_{p,5s}$) measured 750 m away from the vibropiling of a foundation pile for the KASKASI II offshore wind farm. This operation involved a monopile with a diameter of 6.5 m that was driven with a Cape Holland TRIPLE CV-640 VLT-U hammer, vibration frequency 23 Hz. Figure 16 from (Bellmann, Remmers, Brüers, & Poppitz, 2024).

The analysis of the vibropiling sound in (Bellmann, Remmers, Brüers, & Poppitz, 2024) was made on the basis of the broadband sound level. This varies widely between the different piles and depending on the directions in which measurements were made. See Figure C.4. It is suggested that the variation in direction is mainly caused by the presence of the piling vessel.

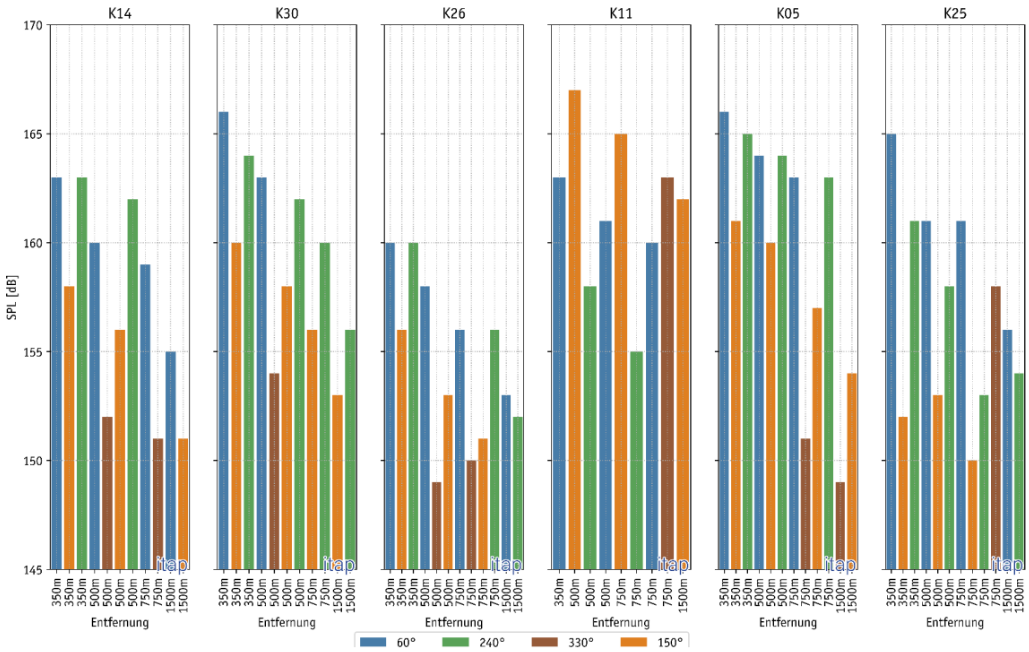

Figure C.4: Broadband sound level (L_p) from the vibropiling of six foundation piles for the KASKASI II offshore wind farm as a function of the measurement location (distance/direction). Figure 17 from (Bellmann, Remmers, Brüers, & Poppitz, 2024).

Even at the maximum monitoring distance – 13 km from the pile – the vibropiling sound was clearly measurable (more than 10 dB above the background noise).

Information about the spectral distribution of vibropiling sound is limited to a single illustration in this report. Figure 15 from (Bellmann, Remmers, Brüers, & Poppitz, 2024) gives as an example a sound spectrum measured 350 m from pile K14.

C.3 Modelling the propagation of underwater sound from vibropiling

The estimate of underwater sound from vibropiling described in the previous section does not result in a source strength that can be applied in a propagation model. Like impact piling, vibropiling generates vibration waves in the pile and so there is no change in the transfer of sound from the hammer to underwater sound. The underwater sound from vibropiling can therefore be estimated by scaling the calculated sound field of impact piling for the same pile to the estimated spectrum of the sound of the vibropiling at the reference location.

The frequency spectrum for the transmission loss (TL; symbol ΔL_{TL}) from the reference location (x_{ref}, for example at 750 m from the pile) to the wider vicinity of the pile is the same for the SELss (symbol L_E) of impact piling and the SPL (symbol L_p) of vibropiling:

$$\Delta L_{\mathrm{TL}}(x,f) = L_E(x,f) - L_E(x_{\mathrm{ref}},\mathrm{f}) = L_p(x,f) - L_p(x_{\mathrm{ref}},\mathrm{f}) \tag{C.3}$$

This means that the sound propagation from vibropiling (SPL) can be estimated by adding the transmission loss from ΔL_{TL} propagation calculations for impact piling to the estimated spectrum of the sound from vibropiling at the reference location:

$$L_p(x,f) = L_p(x_{\mathrm{ref}},\mathrm{f}) + \Delta L_{\mathrm{TL}}(x,f) \tag{C.4}$$

This non-validated approach provides no more than a preliminary estimate. Ongoing model development and validation are essential to estimate underwater sound from vibropiling reliably.

Figure C.5 provides an example in which scaled monitoring data from the Beneluxhaven in Rotterdam (Binnerts, de Jong, & Kruyen, 2018) are compared with measurement data from the KASKASI II project (Bellmann, Remmers, Brüers, & Poppitz, 2024). This illustrates that the tentative approach is far from accurate. However, it overestimates the vibropiling sound levels over a large part of the frequency range of relevance for seals and porpoises, so it can be considered a conservative approach.

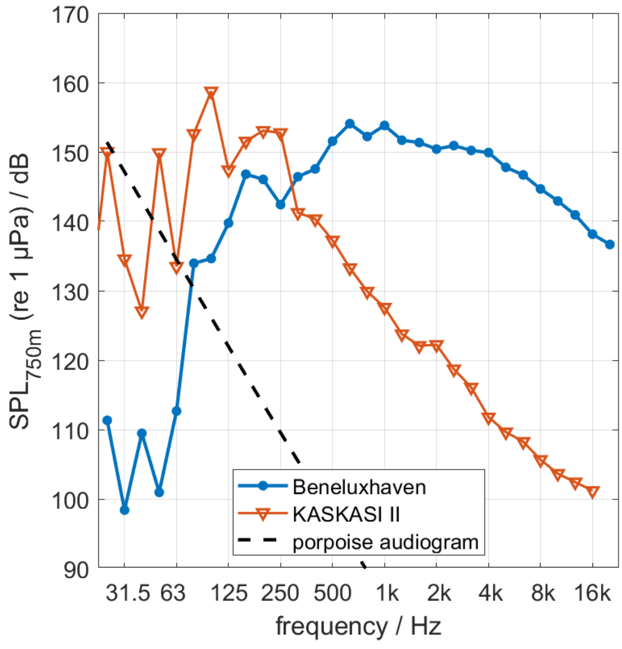

Figure C.5: Decidecade spectra of the SPL ($L_p^{M_{ref},\Omega_{ref}}$) at a distance of 750 m from a monopile installed with a vibratory hammer with $M_{ref} = 1920\ kgm$ and $\Omega_{ref} = 23\ Hz$, estimated by scaling monitoring data from the Beneluxhaven in Rotterdam (Binnerts, de Jong, & Kruyen, 2018) and the KASKASI II project (Bellmann, Remmers, Brüers, & Poppitz, 2024).

Appendix D
Geophysical surveys

Geophysical surveys are conducted to map soil conditions in different layers and determine the possible presence of UXO (see Section 2.2.5). That involves the use of a range of acoustic sources such as multibeam and side scan sonars, sub-bottom profilers and sparkers. The survey signals are very different from piling sound. The sources that cause significant sound levels at frequencies audible to harbour porpoises and seals are the sub-bottom profilers, sparkers and the USBL positioning system for the side-scan sonars.

D.1 Scenario for geophysical surveys

A range of geophysical surveys are conducted before offshore wind farm construction. In consultation with RFO and TenneT, the following representative scenario was drawn up for this purpose:

1) Global survey of the seabed in the area of the future wind farm.
   - Execution approximately five years before the construction of the farm.
   - It is assumed for these surveys that a multi-channel sparker in particular will result in sound disturbance.
2) Detailed survey of the locations of the future turbines, the platforms (offshore high voltage stations; OHVS) and the infield cables connecting the turbines to the platforms.
   - It is assumed for these surveys that a sub-bottom profiler in particular will result in sound disturbance.
   - Typically executed 1 to 2 years prior to the construction of the farm. We assume one year before construction here.
   - This survey detects obstacles and magnetic contacts (in other words, UXO). UXO clearance takes place in the same year.
3) Survey of the cable route from the wind farm site to land.
   - This is a global survey of the route from the wind farm site to land.
   - It is assumed for these surveys that a multi-channel sparker in particular will result in sound disturbance.
   - Typically executed four years prior to the construction of the farm.
   - This survey detects obstacles and magnetic contacts (in other words, UXO). UXO clearance takes place in the same year.
4) UXO survey of the cable route.
   - It is assumed for these surveys that a sub-bottom profiler in particular will result in sound disturbance.
   - Typically executed two years prior to the construction of the farm.
5) Pre-lay survey of the cable route.
   - This is a detailed survey of the cable route and platform location.
   - It is assumed for these surveys that a sub-bottom profiler in particular will result in sound disturbance.
   - Typically executed one year prior to the construction of the farm.

6) Post-lay survey of the cable route
   - This is a detailed survey of the cable route.
   - It is assumed for these surveys that a sub-bottom profiler in particular will result in sound disturbance.
   - Typically executed in the same year as the construction of the farm.

Overviews of the wind/search areas and cable routes can be found in Table D.1 and Table D.2.

Table D.1: Scenario supplied by, inter alia, TenneT about the surface area surveyed and number of survey days for the geophysical surveys of the search areas for Dutch wind farms.

Search area	Year of construction	Surface area (km^2)	Number of survey days	Survey speed (km^2/day)
Borssele Site III	2019	61	6	10.2
Borssele Site IV	2019	61	6	10.2
Borssele Site I	2020	56	6	9.3
Borssele Site II	2020	56	6	9.3
Borssele Site V	2021	1	0.1	10.0
Hollandse Kust Zuid Site I	2021	52	5	10.4
Hollandse Kust Zuid Site II	2021	52	5	10.4
Hollandse Kust Noord Site V	2022	94	9	10.4
Hollandse Kust Zuid Site III	2022	54	5	10.8
Hollandse Kust Zuid Site IV	2022	54	5	10.8
Hollandse Kust West Sites VI & VII	2025	140	14	10.0
IJmuiden Ver Gamma	2027	200	76	2.6
IJmuiden Ver Alpha & Beta	2027	400	40	10.0
Nederwiek Noord	2028	730	140	5.2
Nederwiek Zuid	2028	200	50	4.0
Doordewind Site I	2029	600	150	4.0
Hollandse Kust West Site VIII	2029	70	7	10.0
Ten Noorden van de Waddeneilanden	2029	70	7	10.0
Doordewind Site II*	2030	730	73	10
Lagelander*	2031	400	40	10
Area 6/7 subarea 1*	2033	600	60	10

* Not constructed during the KEC 5.0 planning period, but a geophysical survey of the search area may already have been completed.

Table D.2: Estimated length of cable routes from the transformer platforms to land, and the corresponding area of the geophysical survey of each cable route.

Platform	Type	Length of route (km)	Surface area surveyed (km²)			
			Route (sparker)	UXO (SBP +USBL)	Pre-lay (SBP +USBL)	Post-lay (SBP +USBL)
Borssele (Site I, II) – Alpha	220 kV AC	61.0	73.2	9.8	6.1	3.7
Borssele (Site III, IV, V) - Beta	220 kV AC	67.5	81.0	10.8	6.8	4.1
Hollandse Kust Zuid – Alpha	220 kV AC	42.2	50.6	6.8	4.2	2.5
Hollandse Kust Zuid – Beta	220 kV AC	33.8	40.6	5.4	3.4	2.0
Hollandse Kust Noord	220 kV AC	33.4	40.1	5.3	3.3	2.0
Hollandse Kust West – Alpha	220 kV AC	69.0	82.8	11.0	6.9	4.1
Hollandse Kust West - Beta	220 kV AC	65.1	78.1	10.4	6.5	3.9
IJmuiden Ver Alpha	525 kV DC	164.0	164.0	13.1	8.2	4.9
IJmuiden Ver Beta	525 kV DC	146.8	146.8	11.7	7.3	4.4
IJmuiden Ver Gamma	525 kV DC	157.0	157.0	12.6	7.9	4.7
Nederwiek Zuid (Site I)	525 kV DC	205.2	205.2	16.4	10.3	6.2
Nederwiek Noord (Site II)	525 kV DC	203.8	203.8	16.3	10.2	6.1
Nederwiek Noord (Site III)	525 kV DC	285.0	285.0	22.8	14.3	8.6
Ten Noorden van de Waddeneilanden *	220 kV AC	100.0	120.0	16.0	10.0	6.0
Hollandse Kust West (Site VIII) *	220 kV AC	75.0	90.0	12.0	7.5	4.5
Doordewind Site I *	525 kV DC	180.0	180.0	14.4	9.0	5.4
Doordewind Site II *,**	525 kV DC	180.0	180.0	14.4	9.0	5.4
Doordewind Site III *,**	525 kV DC	215.0	215.0	17.2	10.8	6.5
Lagelander *,**	525 kV DC	150.0	150.0	12.0	7.5	4.5

* Estimated by the KEC team.
** Not constructed during the KEC 5.0 planning period, but a geophysical survey of the search area may already have been completed.

Figure D.1: **Route map with cable routes (https://windopzee.nl/onderwerpen/wind-zee/viering-routekaart-2023/).**

The number of survey days for the cable routes depends on the distance to land and the type of cable connection (AC or DC) and it has been estimated based on the following assumptions:

3) Route survey: 1000 m wide for 2 GW (525 kV DC) and 1200 m for the 700 MW (220 kV AC) projects.
   - 2 km^2 per day as the speed due to the relatively large linear distance.
4) UXO Survey: 80 m wide around each cable. So, for 2 GW, this is 1 × 80 m and, for 700 MW, 2 × 80 m.
   - Speed 0.3 km^2 per day (small linear distance).

5) Pre-lay survey: 50 m wide around each cable. So, for 2 GW, this is 1 × 50 m and, for 700 MW, 2 × 50 m.
   - Speed 0.3 km^2 per day (small linear distance).
6) Post-lay surveys: 30 m wide around each cable. So, for 2 GW, this is 1 × 30 m and, for 700 MW, 2 × 30 m.
   - Speed 0.3 km^2 per day (small linear distance).

The route and pre-lay surveys are 100% certain. The other two depend on the contractor but will be included in the KEC. Estimates for the surface area to be surveyed depend on the distance to land and the type of cable connection (AC or DC).
Other assumptions are:

- Energy transport via an island or other forms of energy transport (such as hydrogen) have not yet been taken into consideration. This results in a possible overestimation of the number of cables and platforms.
- The effects of geophysical surveys were considered generically, and not in a site-specific way (there was no consideration of factors such as water depth).
- For the determination of animal disturbance by the geophysical surveys, the source with the largest disturbance distance has always been assumed. In the case of the generic surveys, this is the sparker and, in the case of the detailed surveys, it is the USBL positioning system for the side-scan sonar.
- Surveys continue 24/7. Possible postponements due to weather conditions have not been considered; only operational days are counted. On days with weather delays, the equipment is not used.
- Factors such as sailing outside the area because of turning distances, or other sailing manoeuvres in order to avoid sailing lanes are not taken into consideration;

D.2 Disturbance of harbour porpoises and seals by sound from surveys

Current data about how harbour porpoises and seals respond to sounds produced during geophysical surveys are very limited. Generic threshold values for behavioural disturbance derived in a review conducted as part of WOZEP have therefore been used here (de Jong & von Benda-Beckmann, 2018).

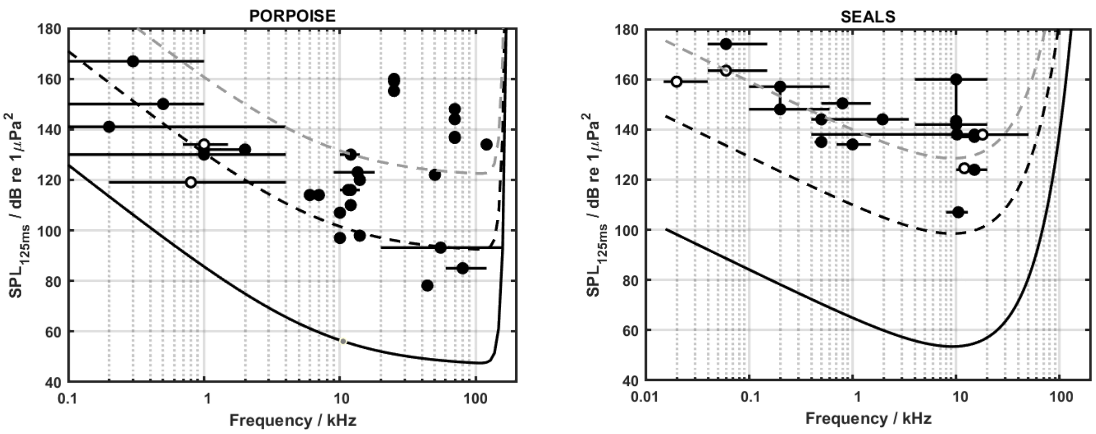

Figure D.2: SELss threshold values for harbour porpoise and seal disturbance (dotted line) for sources with higher frequencies than piling used as a basis for estimating effect distances. SELs of 45 dB (for harbour porpoises) and 70 dB (for seals) above the hearing threshold in a decidecade frequency band were assumed here.

On the basis of global information about the acoustic sources in combination with a threshold value weighted by the frequency sensitivity of harbour porpoise hearing, an estimate was made of the disturbance distance for different types of systems used in these surveys (Table D.3).

Table D.3: Typical systems used during geophysical surveys for the construction of wind farms, platforms and cable routes. The third column provides an estimate of disturbance distances for the different types of system.

		Maximum estimated effect distance	
System type	System example	harbour porpoise	seal
Multibeam echo sounder:	Kongsberg EM2040 Dual Head, Dual Swath / Dual Ping – Frequency 400 kHz	Above threshold for harbour porpoise hearing; Expected effect distances small (and negligible);	Above threshold for harbour porpoise hearing; Expected effect distances small (and negligible);
Sidescan Sonar + USBL:	Edgetech 4200 300/600 – Frequency: 239 kHz (LF) and 555 kHZ (HF) A USBL positioning system is often deployed during the use of SSS. Frequency: 25 kHz.	SSS: Above threshold for harbour porpoise hearing; Expected effect distances small (and negligible); USBL: maximum effect distance approximately 3 km.	SSS: Above threshold for harbour porpoise hearing; Expected effect distances small (and negligible); USBL: maximum effect distance approximately 600 m.
Sub-bottom profiler: Magnetometer: Geomatrix G882 Cesium vapour magnetometer	Innomar SES 2000 Standard parametric sub-bottom profiler – Power: > 50kW; Frequency: 8 – 100 kHz	Maximum effect distance approximately 0.7 km	Primary frequency not easily heard by seals. At secondary frequencies, the expected distance is small (and negligible).
Sparker Single Channel	GSO 200-tip sparker (assumed operated at 500 J)	Maximum effect distance approximately 3.8 km	Maximum effect distance approximately 0.5 km
Sparker Multi-channel	GSO 360-tip Sparker seismic source + 2000 J PSU (operated at 900 J) GSO 540 (360+180)-tip sparker (1250 J)	Maximum effect distance approximately 3.8 km	Maximum effect distance approximately 0.5 km

The assumptions for the estimates of disturbance distances are looked at in further detail in the following sections.

D.2.1 Echo sounders, side-scan sonars and USBL

The echo sounders used during geophysical surveys are high-frequency (> 200 kHz) and probably not audible for harbour porpoises. Measurements of this type of system indicate that hardly any acoustic energy is emitted at lower frequencies (see, for example (Crocker, et al., 2019; Pace, Robinson, Lumsden, & Martin, 2021).

However, when side-scan sonars are deployed, an acoustic ultra-short-baseline (USBL) positioning system is often also used to determine an accurate underwater position of the side-scan sonar source. This USBL emits short pulses (t_{pulse} ~20 ms) at around 25 kHz (between 20 and 30 kHz) with a SL ~ 184 dB re 1 μPa m and a typical pulse repetition time of 0.5 s -1 s (Pace, Robinson, Lumsden, & Martin, 2021).

USBL signals are clearly audible for both harbour porpoises and seals. A comparison of measured sound levels with disturbance criteria for harbour porpoises (Figure D.3) suggests that disturbance up to a distance of approximately 3 km could occur, which is consistent with (Pace, Robinson, Lumsden, & Martin, 2021). The effect distance for seals is estimated at approximately 700 m.

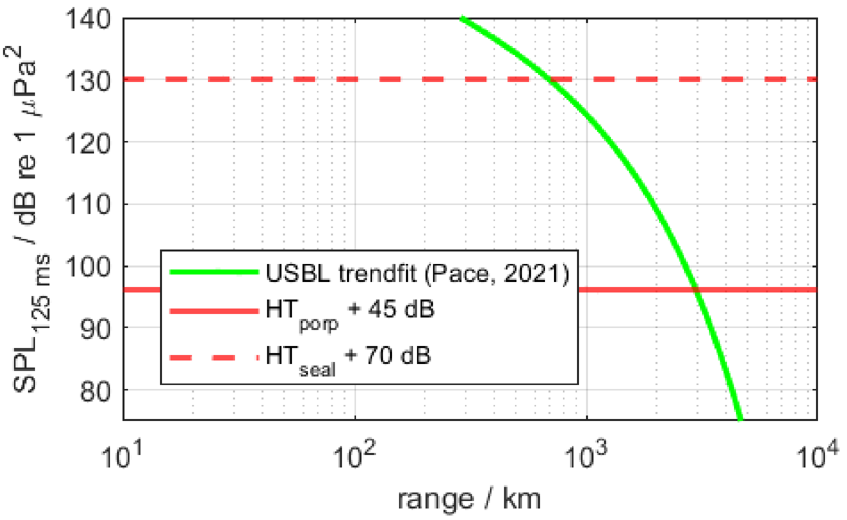

Figure D.3: Trend fit of measured SPL for a USBL beacon at a frequency around 25 kHz, and disturbance thresholds for harbour porpoises (red solid line) and seals (red dotted line).

D.2.2 Sub-bottom profiler

A typical 'parametric sub-bottom profiler' generates low-frequency (~10 kHz) sound by simultaneously emitting several high-frequency (~100 kHz) sounds. See, for example (Westervelt, 1963). Using high frequencies results in a very narrow, downward beam (~3-6 degrees -3 dB beam width). Information from suppliers of parametric sub-bottom profilers indicates that the source level (SL) in the direction of the sound beam around the main frequencies (85-125 kHz) exceeds 240 dB re 1 μPa×m, averaged over the pulse length. The source level at the low frequencies is around 202 dB re 1 μPa×m. Typical pulse lengths for the sub-bottom profiler are in the order of t_{pulse} ~ 0.04 – 30 ms. This corresponds to a typical 30-40 dB reduction in the source level of the secondary frequencies in a parametric sonar (Moffet & Mellen, 1977). The energy source level (SL_E; dB re 1 μPa^2×m^2×s) for the longest pulses (30 ms) in the main beam is therefore (SL_E = SL + 10*log10(t_{pulse} / 1s) dB) approximately 225 dB around the main frequencies and approximately 187 dB at the low frequency. The strong directional dependence of the source means that the horizontally radiated sound (which propagates effectively and can lead to disturbance) will be substantially (approximately 60 dB) lower.

Recent acoustic measurements on the North Sea from a parametric SBP provide a picture of typical sound levels produced by sub-bottom profilers (Pace, Robinson, Lumsden, & Martin, 2021). Comparisons of measured sound levels with disturbance criteria for harbour porpoises suggest that disturbance up to a distance of approximately 700 m could occur (Pace, Robinson, Lumsden, & Martin, 2021). For seals, the effect distances are negligible for this source given the lower sensitivity.

D.2.3 Sparkers

Sparkers are systems that generate bubbles by means of electrical discharges to ‘tips’. The implosion of the bubbles produces a broadband impulsive sound with higher frequencies than the sound of the airguns often used for seismic surveys. Typical source levels (SL_E) can be found in (Crocker, et al., 2019). The source levels depend on the electrical power used and the bandwidths are quite broad: SL_E ~ 167-181 dB re 1 $\mu Pa^2 m^2 s$ with 500 J electrical power and SL_E ~ 179-186 dB re 1 $\mu Pa^2 m^2 s$ with 900 J. Recent studies also provide field measurements that are consistent with estimated SL_E in the field for sparkers used in shallow water and on sandy beds (Halvorsen & Heaney, 2018). The GSO-360 (900 J) is the most commonly used system for the monitoring of wind farms in Dutch waters. Recent acoustic recordings of this system in the North Sea (Pace, Robinson, Lumsden, & Martin, 2021) show that this system has an ESL of approximately 167 dB 1 $\mu Pa^2 m^2 s$. This corresponds to the lowest ESL stated for two other types of sparker systems in (Crocker, et al., 2019). Offshore measurements of the systems in (Crocker, et al., 2019) also found higher ESL for these other types of sparker (Halvorsen & Heaney, 2018). The absence of a clear trend for ESL with power (J) may be explained by the fact that the source power of sparker systems has proven to be sensitive to the ‘load power peak’ (Li, et al., 2024). As a result, a stronger relationship can be expected with the speed of the discharge than with the absolute power (Li, et al., 2024).

This analysis is based on the measured spectra for the GSO-360 from (Pace, Robinson, Lumsden, & Martin, 2021) because this type of system is the one that is mainly used for the monitoring of Dutch wind farm areas. Comparisons of measured sound levels with disturbance criteria for harbour porpoises suggest that disturbance up to a distance of approximately 2 km could occur (Pace, 2021). If we extrapolate the measured spectrum at 2 km in Pace (2021) with Aquarius 3 for conditions in the Danish North Sea and compare them with the disturbance thresholds used here, the estimated maximum effect distance for harbour porpoises is slightly larger (3.8 km) than the 2 km in Pace (2021) (Figure 3-3). The estimated effect distances for seals are approximately 500 m (Figure D.6).

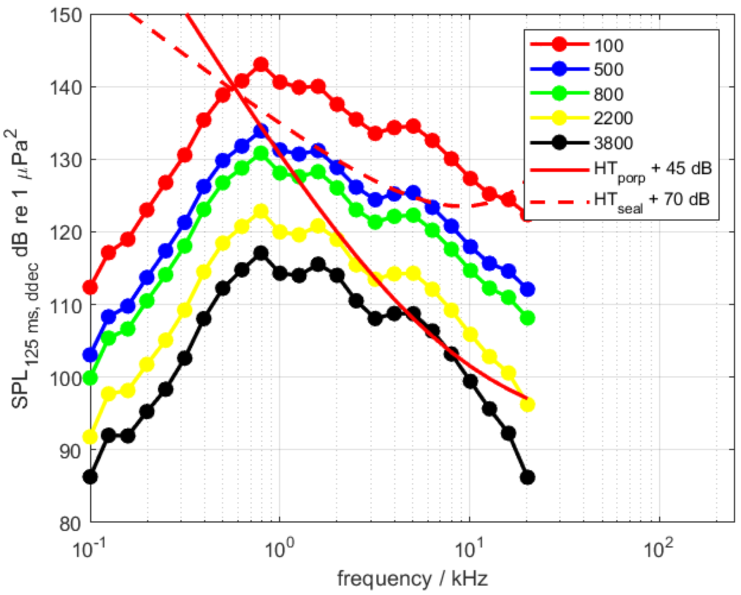

Figure D.4: Modelled spectra for a GSO-360 sparker based on extrapolation of the measured spectrum at 2.2 km (Pace, Robinson, Lumsden, & Martin, 2021) with the Aquarius 3 propagation model for different distances. A comparison with the disturbance thresholds used for harbour porpoises (red line), and seals (dotted red line) gives disturbance distances of approximately 3.8 km (harbour porpoise) and 500 m (seal).

Appendix E
UXO clearance

This study assumes estimates for future wind farms based on an review conducted by Arcadis on behalf of Rijkswaterstaat (Dinjens, 2024). That review defines two different scenarios: a worst case, and the most likely scenario. For the most likely scenario, it has been assumed that a different array of explosives (fewer artillery shells) will be found at locations further offshore. This assumption would seem to be consistent with the types of UXO found in German waters. The most likely scenario from the Arcadis report has therefore been assumed.

A number of locations not yet included in the Arcadis report have been included for the KEC 5.0. Construction in these locations has not been considered in the KEC 5.0 scenario based on the 2030 Supplementary Roadmap. However, UXO surveys and clearance prior to construction have. The assumption for these northern sites (Doordewind II and III, and Search Area 6/7) is that only bombs or mines are present (similar assumption as for Doordewind). For the farms that have already been cleared (Borssele and HKN), the Arcadis report states only the total number of clearance operations. In the case of Borssele, numbers by type have been estimated in line with Table 12 in (Dinjens, 2024). The same assumption was made for Hollandse Kust Zuid as for Hollandse Kust Noord (near the coastline, with higher numbers of artillery shells).

On the basis of estimates made by Rijkswaterstaat in consultation with industry, an update of the area to be surveyed for each location has been provided (Table E.1). UXO clearance also takes place along cable routes. The expected UXO numbers per location has been changed with respect to the Arcadis study (Dinjens, 2024) on the basis of these surface areas. The same density and distribution of UXO types have been assumed for the cable routes as for the related wind farm.

Table E.1: Estimated numbers of different types of UXO cleared per wind farm location based on the most likely estimates from (Dinjens, 2024), scaled in line with the surface area covered by UXO surveys in each area with the associated cable routes.

	Area / km²	Aerial bombs	Mines	Artillery shells	Torpedoes	Depth charges	Unknown	Total
Borssele Site I-V	256	23	6	0	2	2	8	41
Hollandse Kust Zuid Site IV	224	7	8	21	3	3	10	51
Hollandse Kust Noord Site V	99	3	4	11	2	2	5	28
Hollandse Kust West Sites VI & VII	161	5	2	0	1	1	2	11
IJmuiden Ver	637	21	6	0	2	2	3	33
Nederwiek	986	40	10	0	3	3	16	73
Doordewind Site I	614	21	61	0	0	0	0	83
Hollandse Kust West Site VIII	82	3	1	0	0	0	1	5
Ten Noorden van de Waddeneilanden	86	3	8	0	0	0	0	11
Doordewind Site II	744	26	74	0	0	0	0	100
Lagelander	412	14	4	0	2	2	5	27
Area 6/7	600	21	60	0	0	0	0	81
	Total	188	244	32	15	15	50	544
	Percentage	35%	45%	6%	3%	3%	9%	

Recent studies of explosive detonations in the North Sea have shown that some types of explosives (artillery shells, mines and torpedoes) regularly fail to detonate completely because they have been corroded by salt water (apart from the donor charge used to initiate detonation) (Robinson et al. 2022; Lepper et al. 2024). The amount of corrosion is determined to a major extent by the type, the wall thickness and the composition of the casing used in the explosive (Den Otter et al., 2024). Most aerial bombs have a thick casing. Estimates of the corrosion of these bombs suggest that this type of explosive will not be affected. The estimate therefore assumes that 100% of the aircraft bombs will explode completely and that this will happen with 50% of the remaining types of explosive. In the case of the explosives that do not detonate, it has been assumed that the donor charge used for the detonation will have a minimal effect. This assumes that a donor charge of 1 kg will be used for explosives with a net equivalent weight (NEG) < 15 kg and a donor charge of 12 kg will be used for larger explosives.

Table E.2 provides an overview of estimated distances in the wind farms (Table E.1) within which animals are at risk of auditory trauma (see Section 4.6.1) when exposed to the sound and shock wave from various types of explosive.

Table E.2: Effect distances and areas (with ranges in brackets) within which harbour porpoises and seals are at risk of 'auditory trauma' (L_E > 203 dB re 1 μPa²s) for different types of explosive (NEW = net equivalent weight of the explosive, including the mass of the donor charge applied for the detonation).

Type	NEW (kg)	harbour porpoises / seals	
		R_{TRAUMA} (km)	A_{TRAUMA} (km²)
Donor charge (small)	1	0.0 (0.0 – 0.0)	0 (0 – 0)
Donor charge (large)	12	0.0 (0.0 – 0.1)	0 (0 – 0)
Aerial bomb			
37 kg	48	0.3 (0.2 – 0.4)	0 (0 – 0.6)
101 kg	113	0.7 (0.5 – 1.1)	1 (1 – 4)
238 kg	250	1.3 (1.0 – 2.2)	6 (3 – 15)
500 kg	512	2.4 (2.1 – 4.6)	20 (13 – 65)
1102 kg	1114	4.1 (3.5 – 8.0)	57 (38 – 203)
Mine	239	1.3 (1.0-2.0)	6 (4 – 13)
Artillery shell	10	0.0 (0.0 – 0.0)	0 (0 – 0)
Torpedo	301	1.5 (1.1 – 2.4)	7 (4 – 19)
Depth charge	121	0.7 (0.6 – 1.1)	2 (1 – 4)
Unknown	15	0.0 (0.0 – 0.0)	0 (0 – 0)

Table E.3 provides an overview of estimated PTS distances in the wind farms (Table E.1) for the various types of explosive in the wind farms and for harbour porpoises and seals.

Table E.3: Effect distances and areas (with ranges in brackets) within which harbour porpoises and seals are at risk of PTS ($L_{E,VHF}$ > 155 dB re 1 μPa²s and $L_{E,PCW}$ > 185 dB re 1 μPa²s) for different types of explosives (NEW = net equivalent weight of the explosive, including the mass of the donor charge applied for the detonation).

		harbour porpoises		seals	
Type	NEW (kg)*	R_{PTS} (km)	A_{PTS} (km²)	R_{PTS} (km)	A_{PTS} (km²)
Donor charge (small)	1	0.7 (0.6 - 0.9)	2 (1 – 2)	0.0 (0.0 – 0.0)	0 (0 – 0)
Donor charge (large)	12	2.0 (1.8 - 2.1)	12 (10 – 14)	0.0 (0.0 – 0.0)	0 (0 – 0)
Aerial bomb					
37 kg	48	3.2 (3.0 - 3.4)	32 (28 - 35)	0.3 (0.2 – 0.4)	0 (0 – 0.6)
101 kg	113	4.1 (3.9 - 4.4)	53 (49 - 60)	0.7 (0.5 – 1.1)	1 (1 – 4)
238 kg	250	5.2 (4.9 - 5.5)	86 (75 - 96)	1.3 (1.0 – 2.2)	6 (3 – 15)
500 kg	512	6.4 (6.0 - 6.8)	129 (113 - 145)	2.4 (2.1 – 4.6)	20 (13 – 65)
1102 kg	1114	7.9 (7.2 - 8.5)	198 (163 - 225)	4.1 (3.5 – 8.0)	57 (38 – 203)
Mine	239	5.2 (4.8 - 5.5)	83 (73 - 94)	1.3 (1.0-2.0)	6 (4 – 13)
Artillery shell	10	1.9 (1.8 - 2.0)	11 (10 - 13)	0.0 (0.0 – 0.0)	0 (0 – 0)
Torpedo	301	5.5 (5.2 - 5.9)	96 (84 - 108)	1.5 (1.1 – 2.4)	7 (4 – 19)
Depth charge	121	4.2 (4.0 - 4.5)	56 (51 - 62)	0.7 (0.6 – 1.1)	2 (1 – 4)
Unknown	15	2.2 (2.0 - 2.3)	15 (13 - 17)	0.0 (0.0 – 0.0)	0 (0 – 0)

To estimate the number of harbour porpoises at risk of trauma or PTS, the average animal density for each wind farm area has been assumed, including the associated cable routes.

Table E.4: The estimated number of harbour porpoises affected by blast trauma (SEL > 203 dB re 1 μPa²s) or PTS (SEL_{VHF} > 155 dB re 1 μPa²s) depending on the assumed disturbance distance of the ADD (R_{ADD} = 18 and 7 km respectively). For reference purposes, the numbers that apply if there is no mitigation are also shown.

	Area / km²	# harbour porpoises with blast trauma			# harbour porpoises with PTS		
		with ADD (R_{ADD}=18 km)	with ADD (R_{ADD}=7 km)	no ADD	with ADD (R_{ADD}=18 km)	with ADD (R_{ADD}=7 km)	no ADD
Borssele Site I-V	256	0	0	68	237	249	1410
Hollandse Kust Zuid Site IV	224	0	0	55	241	247	1485
Hollandse Kust Noord Site V	99	0	0	37	162	166	993
Hollandse Kust West Sites VI & VII	161	0	0	24	108	112	580
IJmuiden Ver	637	1	1	77	345	361	1812
Nederwiek	986	1	1	105	449	474	2646
Doordewind Site I	614	16	29	464	533	545	3007
Hollandse Kust West Site VIII	82	0	0	11	53	56	279
Ten Noorden van de Waddeneilanden	86	2	2	62	76	78	424
Doordewind Site II	744	2	3	234	783	798	4058
Lagelander	412	2	2	71	234	245	1317
Area 6/7	600	2	3	222	743	758	3856
Totaal		**26**	**41**	**1430**	**3963**	**4090**	**21866**

The relatively large numbers for Doordewind are attributable to the estimated large number of sea mines in combination with the relatively large water depth, resulting in large effect distances.

A further increase in the effect distance for the ADD does not benefit harbour porpoises. However, deploying the ADD for longer does so because it results in a larger swimming distance. Table E.5 shows that, according to the proposed calculation method, the number of harbour porpoises affected by a UXO detonation is significantly smaller if the ADD is deployed for sixty, rather than thirty, minutes before the detonation. A further extension of the deployment time to 120 minutes results in a relatively small reduction.

Table E.5: The estimated number of harbour porpoises affected by blast trauma (SEL > 203 dB re 1 μPa²s) or PTS (SEL_{VHF} > 155 dB re 1 μPa²s) given an assumed disturbance distance R_{ADD} = 7 km if the ADD is deployed 30, 60 and 120 minutes prior to the UXO detonation and given an assumed swimming speed away from the detonation of 1.5 m/s.

	Area / km2	# harbour porpoises with blast trauma			# harbour porpoises with PTS		
		30 min.	60 min.	120 min.	30 min.	60 min.	120 min.
Borssele Site I-V	256	0	0	0	249	24	22
Hollandse Kust Zuid Site IV	224	0	0	0	247	13	11
Hollandse Kust Noord Site V	99	0	0	0	166	7	6
Hollandse Kust West Sites VI & VII	161	0	0	0	112	9	8
IJmuiden Ver	637	1	0	0	361	33	30
Nederwiek	986	1	0	0	474	47	44
Doordewind Site I	614	29	23	23	545	22	21
Hollandse Kust West Site VIII	82	0	0	0	56	5	4
Ten Noorden van de Waddeneilanden	86	2	0	0	78	3	3
Doordewind Site II	744	3	2	2	798	30	28
Lagelander	412	2	1	1	245	22	20
Area 6/7	600	3	2	2	758	29	27
Totaal		**41**	**28**	**28**	4,090	242	224

The maximum animal density per wind farm area was used for seals. Although the density of seals closer to shore is higher, the corresponding surface area of cable routes is small by comparison with the total area of the wind farm and cable route.
The levels of exposure to explosive sound are lower almost everywhere than the criteria for PTS in the case of both grey and harbour seals (Southall, et al., 2019). Because there are no observations of seals exposed to explosions, it is unclear how valid these criteria are in this case. It was decided to adopt a cautious approach and use the criteria in which blast trauma has been observed in harbour porpoise cadavers (SEL > 203 dB re 1 μPa²s).

Table E.6: The estimated number of seals affected by blast trauma (SEL > 203 dB re 1 µPa²s) depending on the assumed disturbance distance of the ADD (R_{ADD} = = = 1 km). For reference purposes, the numbers that apply if there is no mitigation are also shown.

	Area / km²	# harbour seals with blast trauma		# grey seals with blast trauma	
		with ADD (R_{dist}=1 km)	no ADD (ref)	with ADD (R_{dist}=1 km)	no ADD (ref)
Borssele Site I-V	256	35	44	7	9
Hollandse Kust Zuid Site IV	224	7	8	18	20
Hollandse Kust Noord Site V	99	21	24	14	16
Hollandse Kust West Sites VI & VII	161	3	3	2	2
IJmuiden Ver	637	10	12	5	7
Nederwiek	986	19	22	4	5
Doordewind Site I	614	238	238	24	24
Hollandse Kust West Site VIII	82	1	1	1	1
Ten Noorden van de Waddeneilanden	86	84	90	9	9
Doordewind Site II	744	57	61	11	12
Lagelander	412	18	21	11	13
Area 6/7	600	23	24	23	24
	Total	516	548	128	141

Seals benefit little if the ADD is deployed for longer. They do benefit from an increase in the effect distance of the ADD.

Appendix F
Number of disturbed animals by project

F.1 Piling

F.1.1 Harbour porpoises

Table F.1: Harbour porpoise disturbance days (HPDD) by project on the basis of acoustic calculations using the Aquarius 4 model, with the dose-effect relationship from the KEC 4.0 (Graham et al. 1st pile), and the average harbour porpoise densities per location from (Gilles, Ramirez-Martinez, Nachtsheim, & Siebert, 2020). Projects starting after 2031 have not been counted (0 harbour porpoise disturbance days). The ‘effective disturbance distance’ for each project is the effective radius of a circular area with an area equal to the calculated disturbance area. The ‘effective harbour porpoise density’ for each project is the ratio of the calculated number of harbour porpoises disturbed to the calculated disturbance area.

No.	Country	Name	Year	Number of piles	SELss standard dB	Effective disturbance	# harbour porpoises disturbed per day	Effective harbour porpoise density (km^{-2})	HPDD
1	BE	Nobelwind	2016	25	160	13	334	0.63	8350
2	BE	Nobelwind	2016	25	160	12	289	0.66	7225
3	BE	Rentel	2017	42	160	11	241	0.66	10122
4	BE	Norther	2018	44	160	10	177	0.62	7788
5	BE	Northwester 2	2019	23	160	13	320	0.62	7360
6	BE	Seamade - Mermaid	2019	28	160	14	373	0.63	10444
7	BE	Seamade - Seastar	2019	30	160	12	282	0.65	8460
8	BE	Noordhinder Noord	2028	47	160	14	345	0.56	16215
9	BE	Princess Elisabeth - (Fairybank/NordHinder)	2028	70	160	12	238	0.56	16660
10	DE	Nordergründe	2016	18	160	3	4	0.20	72
11	DE	Veja Mate	2016	67	160	17	656	0.70	43952
12	DE	Merkur Offshore	2017	66	160	14	545	0.84	35970
13	DE	Nordsee One	2017	54	160	13	443	0.79	23922
14	DE	Borkum Riffgrund 2	2018	56	160	13	467	0.89	26152

No.	Country	Name	Year	Number of piles	SELss standard dB	Effective disturbance	# harbour porpoises disturbed per day	Effective harbour porpoise density (km^{-2})	HPDD
15	DE	Deutsche Bucht	2018	31	160	17	634	0.70	19654
16	DE	EnBW Hohe See	2018	71	160	17	660	0.72	46860
17	DE	Trianel Windpark Borkum	2018	32	160	15	559	0.84	17888
18	DE	Albatros	2019	16	160	17	674	0.72	10784
19	DE	KASKASI II	2021	38	160	11	371	1.02	14098
20	DE	Borkum Riffgrund 3	2023	83	160	15	542	0.80	44986
21	DE	Gode Wind 3	2023	23	160	14	478	0.77	10994
22	DE	EnBW He Dreiht	2024	60	160	19	851	0.72	51060
23	DE	N-3.7	2025	15	160	16	607	0.77	9105
24	DE	N-3.8	2025	29	160	16	644	0.79	18676
25	DE	N-7.2	2026	65	160	19	817	0.73	53105
26	DE	N-3.5	2027	28	160	15	580	0.79	16240
27	DE	N-3.6	2027	32	160	16	633	0.80	20256
28	DE	N-6.6	2027	42	160	19	809	0.71	33978
29	DE	N-6.7	2027	18	160	20	871	0.71	15678
30	DE	N-12.1	2028	100	160	19	929	0.81	92900
31	DE	N-12.2	2028	100	160	19	973	0.82	97300
32	DE	N-9.1	2028	133	160	20	941	0.72	125153
33	DE	N-9.2	2028	133	160	20	972	0.74	129276
34	DE	N-9.3	2028	100	160	20	975	0.75	97500
35	DE	N-10.1	2029	100	160	19	891	0.76	89100
36	DE	N-10.2	2029	25	160	19	874	0.75	21850
37	DE	N-11.1	2029	100	160	19	942	0.83	94200
38	DE	N-11.2	2029	75	160	19	1001	0.87	75075
39	DE	N-12.3	2029	100	160	21	1139	0.85	113900
40	DE	N-13.1	2029	30	160	21	1163	0.87	34890
41	DE	N-13.2	2029	60	160	21	1182	0.87	70920
42	DE	N-13.3	2030	100	160	19	966	0.88	96600
43	DE	N-14.1	2030	100	160	20	1021	0.81	102100
44	DE	N-15.1	2031	100	160	20	975	0.81	97500
45	DE	N-16.1	2032	100	160	20	1045	0.84	0

No.	Country	Name	Year	Number of piles	SELss standard dB	Effective disturbance	# harbour porpoises disturbed per day	Effective harbour porpoise density (km^{-2})	HPDD
46	DE	N-17.1	2032	50	160	20	1010	0.84	0
47	DE	N-18.1	2032	50	160	20	1012	0.84	0
48	DE	N-16.2	2033	100	160	20	1180	0.90	0
49	DE	N-18.2	2033	100	160	20	1056	0.87	0
50	DK	Horns Rev III	2017	49	160	7	113	0.78	5537
51	DK	Vesterhav Nord	2022	23	160	9	100	0.41	2300
52	DK	Vesterhav Syd	2022	18	160	9	175	0.65	3150
53	DK	Thor	2025	72	160	14	350	0.58	25200
54	DK	Nordsøen - Tender 10	2030	50	160	19	828	0.70	41400
55	DK	Nordsøen - Tender 1	2031	50	160	19	785	0.69	39250
56	DK	Nordsøen - Tender 2	2031	50	160	18	597	0.59	29850
57	DK	Nordsøen - Tender 3	2031	50	160	19	697	0.65	34850
58	DK	Nordsøen - Tender 4	2033	50	160	20	820	0.66	0
59	DK	Nordsøen - Tender 5	2033	50	160	19	876	0.76	0
60	FR	Dunkerque	2026	46		15	322	0.46	14812
61	NO	Sørlige Nordsjø	2028	76		79	14910	0.77	1133160
62	UK	Aberdeen Offshore W/F	2016	11		50	8021	1.02	88231
63	UK	Dudgeon	2016	67		24	1877	1.04	125759
64	UK	Galloper	2016	56		44	3616	0.60	202496
65	UK	Methil Demo	2016	1					0
66	UK	Race Bank	2016	91		14	362	0.62	32942
67	UK	Beatrice Offshore Wind Farm	2017	84		53	370	0.04	31080
68	UK	East Anglia ONE	2018	102		55	6976	0.74	711552
69	UK	Hornsea 1 (East)	2018	174		49	13996	1.88	2435304
70	UK	Moray Offshore Windfarm (East)	2019	100		57	648	0.06	64800
71	UK	Blyth Demo Phase 1	2020	5		53	14261	1.62	71305
72	UK	Hornsea Project 2 - Phase 1 (Breesea)	2020	165		53	17632	1.97	2909280
73	UK	Triton Knoll	2020	90		23	1769	1.08	159210
74	UK	Seagreen Phase 1 Windfarm	2021	114		65	18471	1.38	2105694
75	UK	Dogger Bank A	2022	95		27	3864	1.69	367080
76	UK	Neart Na Gaoithe Offshore Wind	2022	54		51	13270	1.64	716580

No.	Country	Name	Year	Number of piles	SELss standard dB	Effective disturbance	# harbour porpoises disturbed per day	Effective harbour porpoise density (km^{-2})	HPDD
77	UK	Dogger Bank B	2023	95		40	10586	2.12	1005670
78	UK	East Anglia THREE	2023	95		56	8275	0.84	786125
79	UK	Dogger Bank C	2024	87		37	5527	1.31	480849
80	UK	East Anglia ONE NORTH	2024	67		59	8336	0.77	558512
81	UK	Seagreen 1A Wind Farm Firth of Forth	2024	36		63	17916	1.44	644976
82	UK	Sofia	2024	100		39	7647	1.59	764700
83	UK	Z1_WDA	2024	60		53	500	0.06	30000
84	UK	East Anglia TWO	2025	75		56	6998	0.70	524850
85	UK	Berwick Bank Firth of Forth	2026	115		72	24629	1.52	2832335
86	UK	Hornsea Project Three (HOW03)	2026	231		57	16787	1.66	3877797
87	UK	Inch Cape Offshore Wind Farm	2026	72		58	16013	1.52	1152936
88	UK	Marr Bank Firth of Forth	2026	93		64	20179	1.55	1876647
89	UK	1_BP Alternative Energy Investments	2027	191		81	25429	1.22	4856939
90	UK	Hornsea Project Four (HOW04)	2027	180		62	25291	2.06	4552380
91	UK	Round 4 Preferred Project 3	2027	100		26	2937	1.34	293700
92	UK	9_Ocean Winds	2028	150		66	1096	0.08	164400
93	UK	Dudgeon Extension	2028	27		26	2145	1.04	57915
94	UK	Five Estuaries	2028	18		53	5741	0.64	103338
95	UK	Norfolk Boreas	2028	100		48	6047	0.84	604700
96	UK	Norfolk Vanguard East And West	2028	200		54	7668	0.85	1533600
97	UK	Round 4 Preferred Project 1	2028	150		42	12827	2.34	1924050
98	UK	Round 4 Preferred Project 2	2028	150		17	1811	1.90	271650
99	UK	Sheringham Shoal Extension	2028	27		20	1007	0.81	27189
100	UK	Bowdun	2029	50		73	17830	1.06	891500
101	UK	North Falls	2029	34		43	3384	0.57	115056
102	NL	Borssele Site III	2019	39	170	19	821	0.71	32019
103	NL	Borssele Site IV	2019	39	170	22	1123	0.71	43797
104	NL	Borssele Site I	2020	47	169	19	920	0.80	43240
105	NL	Borssele Site II	2020	47	169	16	554	0.73	26038
106	NL	Borssele Site V	2021	2	170	20	909	0.75	1818
107	NL	Hollandse Kust Zuid Site I	2021	35	173	19	1218	1.12	42630

No.	Country	Name	Year	Number of piles	SELss standard dB	Effective disturbance	# harbour porpoises disturbed per day	Effective harbour porpoise density (km^{-2})	HPDD
108	NL	Hollandse Kust Zuid Site II	2021	35	173	19	1189	1.07	41615
109	NL	Hollandse Kust Noord Site V	2022	69	170	17	1323	1.43	91287
110	NL	Hollandse Kust Zuid Site III	2022	35	173	18	1023	1.04	35805
111	NL	Hollandse Kust Zuid Site IV	2022	34	173	17	955	1.08	32470
112	NL	Hollandse Kust West Sites VI & VII	2025	108	168	20	1319	1.09	142452
113	NL	IJmuiden Ver Gamma	2027	153	164	17	843	0.96	128979
114	NL	IJmuiden Ver Alpha & Beta	2027	268	164	17	906	0.95	242808
115	NL	Nederwiek Noord	2028	306	164	18	932	0.88	285192
116	NL	Nederwiek Zuid	2028	153	164	18	786	0.78	120258
117	NL	Doordewind	2029	115	164	23	1274	0.74	146510
118	NL	Hollandse Kust West Site VIII	2029	38	164	16	897	1.08	34086
119	NL	Ten Noorden van de Waddeneilanden	2029	53	164	22	1227	0.79	65031
120	NL	Borssele Site III	2018	6	170	18	694	0.72	4164
121	NL	Borssele Site I	2019	6	169	18	825	0.80	4950
122	NL	Hollandse Kust Zuid Site I	2020	6	173	14	713	1.12	4278
123	NL	Hollandse Kust Noord Site V	2021	6	170	15	1033	1.45	6198
124	NL	Hollandse Kust Zuid Site III	2021	6	173	14	601	1.04	3606
125	NL	Hollandse Kust West Sites VI & VII	2024	12	168	18	1149	1.09	13788
126	NL	IJmuiden Ver Gamma	2026	16	164	16	806	0.97	12896
127	NL	IJmuiden Ver Alpha & Beta	2026	32	164	17	868	0.95	27776
128	NL	Nederwiek Noord	2027	32	164	18	878	0.88	28096
129	NL	Nederwiek Zuid	2027	16	164	17	740	0.78	11840
130	NL	Doordewind	2028	16	164	23	1250	0.73	20000
131	NL	Hollandse Kust West Site VIII	2028	6	164	16	870	1.08	5220
132	NL	Ten Noorden van de Waddeneilanden	2028	6	164	21	1100	0.79	6600
								total	44932401

F.1.2 Seals

Table F.2: Seal disturbance days for harbour (HSDD) and grey (GSDD) seals by project on the basis of acoustic calculations using the Aquarius 4 model, with the dose-effect relationship from the KEC 4.0 and the average monthly seal densities per location from (Aarts, 2021). Projects starting after 2031 or outside the seal maps have not been counted. The 'effective disturbance distance' for each project is the effective radius of a circular area with an area equal to the calculated disturbance area. The 'effective seal density' for each project is the ratio of the calculated number of seals disturbed and the calculated disturbance area. See Table F.1 for the number of piles and noise standard for each project.

				Harbour seals			Grey seals		
No.	Country	Name	Effective disturbance distance (km)	number of harbour seals disturbed per day	Effective seal density (km-2)	HSDD	number of grey seals disturbed per day	Effective seal density (km-2)	GSDD
1	BE	Nobelwind	7	88	0.54	2200	6	0.04	150
2	BE	Nobelwind	7	75	0.49	1875	6	0.04	150
3	BE	Rentel	7	19	0.13	798	7	0.05	294
4	BE	Norther	7	18	0.13	792	8	0.06	352
5	BE	Northwester 2	7	85	0.51	1955	7	0.04	161
6	BE	Seamade - Mermaid	8	115	0.59	3220	8	0.04	224
7	BE	Seamade - Seastar	7	55	0.35	1650	6	0.04	180
8	BE	Noordhinder Noord	6	192	1.57	9024	5	0.04	235
11	DE	Veja Mate	9	88	0.33	5896	10	0.04	670
12	DE	Merkur Offshore	8	372	1.78	24552	22	0.11	1452
13	DE	Nordsee One	8	134	0.69	7236	32	0.17	1728
14	DE	Borkum Riffgrund 2	8	679	3.73	38024	39	0.21	2184
15	DE	Deutsche Bucht	9	72	0.28	2232	9	0.04	279
16	DE	EnBW Hohe See	9	307	1.16	21797	10	0.04	710
17	DE	Trianel Windpark Borkum	8	306	1.43	9792	23	0.11	736
18	DE	Albatros	9	684	2.54	10944	9	0.03	144
19	DE	KASKASI II	7	321	2.19	12198	20	0.14	760
20	DE	Borkum Riffgrund 3	8	546	2.61	45318	53	0.25	4399
21	DE	Gode Wind 3	8	337	1.60	7751	23	0.11	529
22	DE	EnBW He Dreiht	11	304	0.82	18240	14	0.04	840
23	DE	N-3.7	10	368	1.25	5520	33	0.11	495
24	DE	N-3.8	10	215	0.72	6235	34	0.11	986
25	DE	N-7.2	11	169	0.47	10985	19	0.05	1235

				Harbour seals			Grey seals		
No.	Country	Name	Effective disturbance distance (km)	number of harbour seals disturbed per day	Effective seal density (km-2)	HSDD	number of grey seals disturbed per day	Effective seal density (km-2)	GSDD
26	DE	N-3.5	9	190	0.70	5320	35	0.13	980
27	DE	N-3.6	10	234	0.80	7488	35	0.12	1120
28	DE	N-6.6	11	174	0.49	7308	18	0.05	756
29	DE	N-6.7	11	162	0.44	2916	13	0.03	234
30	DE	N-12.1	10	232	0.70	23200	7	0.02	700
31	DE	N-12.2	10	185	0.56	18500	6	0.02	600
32	DE	N-9.1	11	203	0.52	26999	16	0.04	2128
33	DE	N-9.2	11	165	0.42	21945	18	0.05	2394
34	DE	N-9.3	11	777	2.02	77700	14	0.04	1400
35	DE	N-10.1	10	926	2.78	92600	8	0.02	800
36	DE	N-10.2	10	1259	3.75	31475	8	0.03	200
37	DE	N-11.1	10	139	0.43	13900	7	0.02	700
38	DE	N-11.2	10	142	0.43	10650	7	0.02	525
39	DE	N-12.3	11	98	0.25	9800	6	0.02	600
40	DE	N-13.1	11	85	0.21	2550	6	0.02	180
41	DE	N-13.2	11	68	0.16	4080	7	0.02	420
42	DE	N-13.3	10	57	0.17	5700	6	0.02	600
43	DE	N-14.1	10	86	0.25	8600	11	0.03	1100
44	DE	N-15.1	10	99	0.30	9900	7	0.02	700
50	DK	Horns Rev III	5	5	0.06	245	1	0.01	49
54	DK	Nordsøen - Tender 10	10	63	0.19	3150	3	0.01	150
78	UK	East Anglia THREE	44	911	0.15	86545	355	0.06	33725
79	UK	Dogger Bank C	28	243	0.10	21141	14	0.01	1218
86	UK	Hornsea Project Three (HOW03)	41	656	0.12	151536	165	0.03	38115
95	UK	Norfolk Boreas	40	868	0.17	86800	186	0.04	18600
96	UK	Norfolk Vanguard East And West	41	852	0.16	170400	253	0.05	50600
102	NL	Borssele Site III	14	302	0.48	11778	39	0.06	1521
103	NL	Borssele Site IV	16	537	0.64	20943	57	0.07	2223
104	NL	Borssele Site I	14	265	0.43	12455	95	0.15	4465

				Harbour seals			Grey seals		
No.	Country	Name	Effective disturbance distance	number of harbour seals disturbed per day	Effective seal density (km-2)	HSDD	number of grey seals disturbed per day	Effective seal density (km-2)	GSDD
105	NL	Borssele Site II	12	92	0.22	4324	38	0.09	1786
106	NL	Borssele Site V	15	334	0.50	668	64	0.10	128
107	NL	Hollandse Kust Zuid Site I	15	120	0.16	4200	279	0.38	9765
108	NL	Hollandse Kust Zuid Site II	16	102	0.13	3570	273	0.36	9555
109	NL	Hollandse Kust Noord Site V	14	553	0.93	38157	357	0.60	24633
110	NL	Hollandse Kust Zuid Site III	15	130	0.18	4550	244	0.34	8540
111	NL	Hollandse Kust Zuid Site IV	14	110	0.17	3740	323	0.51	10982
112	NL	Hollandse Kust West Sites VI & VII	15	107	0.15	11556	70	0.10	7560
113	NL	IJmuiden Ver Gamma	12	70	0.16	10710	40	0.09	6120
114	NL	IJmuiden Ver Alpha & Beta	12	61	0.14	16348	31	0.07	8308
115	NL	Nederwiek Noord	12	64	0.14	19584	13	0.03	3978
116	NL	Nederwiek Zuid	12	90	0.20	13770	17	0.04	2601
117	NL	Doordewind	14	250	0.39	28750	27	0.04	3105
118	NL	Hollandse Kust West Site VIII	11	48	0.12	1824	26	0.07	988
119	NL	Ten Noorden van de Waddeneilanden	14	748	1.14	39644	78	0.12	4134
120	NL	Borssele Site III	13	259	0.51	1554	30	0.06	180
121	NL	Borssele Site I	13	231	0.43	1386	78	0.14	468
122	NL	Hollandse Kust Zuid Site I	11	49	0.13	294	119	0.32	714
123	NL	Hollandse Kust Noord Site V	12	425	0.99	2550	273	0.64	1638
124	NL	Hollandse Kust Zuid Site III	11	69	0.19	414	112	0.31	672
125	NL	Hollandse Kust West Sites VI & VII	14	85	0.15	1020	53	0.09	636
126	NL	IJmuiden Ver Gamma	11	63	0.16	1008	37	0.09	592
127	NL	IJmuiden Ver Alpha & Beta	11	56	0.13	1792	28	0.07	896
128	NL	Nederwiek Noord	11	57	0.14	1824	11	0.03	352
129	NL	Nederwiek Zuid	11	82	0.20	1312	15	0.04	240
130	NL	Doordewind	14	245	0.38	3920	27	0.04	432
131	NL	Hollandse Kust West Site VIII	11	46	0.12	276	25	0.07	150
132	NL	Ten Noorden van de Waddeneilanden	13	657	1.16	3942	62	0.11	372
					total	1416581			295221

F.2 Animal disturbance days caused by geophysical surveys

The following equation is used to calculate the number of animals disturbed by the surveys in the wind farm:

$$\text{HPDD} = \left(\sqrt{\frac{A_{\text{surv,tot}}}{A_{\text{surv,d}}}} + 2R_{\text{dist}}\right)^2 D_{\text{surv}} \cdot \text{n} \tag{E.1}$$

where:
$A_{\text{surv, tot}}$ = total area surveyed (km^2)
$A_{\text{surv, d}}$ = area surveyed per day (km^2)
D_{surv} = duration of survey (days)
n = animal density (#animals / km^2)
R_{dist} = disturbance distance (km) (maximum distance for all deployed sound sources)

The following equation is used to calculate the number of animals disturbed by the surveys of the cable routes:

$$\text{HPDD} = \left(\frac{A_{\text{surv, d}}}{w_{\text{surv}}} + 2R_{\text{dist}}\right) \cdot (w_{\text{surv}} + 2R_{\text{dist}}) \cdot D_{\text{surv}} \cdot \text{n}, \tag{E.2}$$

with the additional parameters:
L_{route}...= length of offshore cable (km)
w_{surv} ...= width of the route (km)

Animal densities along the cable routes were estimated to be approximately equal to the density in the wind farm.

The number of harbour porpoise disturbance days was estimated on the basis of the scenarios and generic disturbance distances. See Tables F.3 and F.4.

Table F.3: Estimated total number of animal disturbance days (DD) as a result of the geophysical surveys (global *and* detailed) of the search areas for Dutch wind farms.

Potential area	harbour porpoise		harbour seal		grey seal	
	density (km^{-2})	DD	density (km^{-2})	DD	density (km^{-2})	DD
Borssele Site III	0.71	360	0.48	60	0.06	8
Borssele Site IV	0.71	360	0.64	81	0.07	9
Borssele Site I	0.80	394	0.43	51	0.15	18
Borssele Site II	0.73	359	0.22	26	0.09	11
Borssele Site V	0.75	15	0.50	2	0.10	0
Hollandse Kust Zuid Site I	1.12	1133	0.16	35	0.38	81
Hollandse Kust Zuid Site II	1.07	1082	0.13	28	0.36	77
Hollandse Kust Noord Site V	1.42	2589	0.93	360	0.60	232
Hollandse Kust Zuid Site III	1.04	1065	0.18	40	0.34	75

Potential area	harbour porpoise		harbour seal		grey seal	
	density (km^{-2})	DD	density (km^{-2})	DD	density (km^{-2})	DD
Hollandse Kust Zuid Site IV	1.08	1106	0.17	38	0.51	112
Hollandse Kust West Sites VI & VII	1.09	3049	0.15	88	0.10	58
IJmuiden Ver Gamma	0.97	10553	0.16	222	0.09	125
IJmuiden Ver Alpha & Beta	0.95	7591	0.14	227	0.07	117
Nederwiek Noord	0.80	18626	0.14	535	0.03	114
Nederwiek Zuid	0.80	6246	0.20	226	0.04	46
Doordewind Site I	0.77	18036	0.39	1354	0.04	139
Hollandse Kust West Site VIII	1.07	1496	0.12	36	0.07	20
Ten Noorden van de Waddeneilanden	0.80	1119	1.14	333	0.12	35
Doordewind Site II*	0.77	11229	0.20	608	0.04	122
Lagelander*	1.02	8151	0.20	500	0.10	300
Area 6/7 subarea 1*	0.92	6394	0.20	125	0.10	125
TOTAL		100951		4975		1822

* Not constructed during the KEC 5.0 planning period, but a geophysical survey of the search area may already have been completed.

Table F.4: Estimated total number of animal disturbance days (DD) as a result of the geophysical surveys (route, UXO, pre-lay and post-lay) of the cable routes for Dutch wind farms.

Platform	harbour porpoise		harbour seal		grey seal	
	density (km^{-2})	DD	density (km^{-2})	DD	density (km^{-2})	DD
Borssele (Site I, II) – Alpha	0.76	5045	0.32	272	0.12	101
Borssele (Site III, IV, V) - Beta	0.72	2852	0.54	493	0.08	68
Hollandse Kust Zuid - Alpha	1.08	5020	0.16	103	0.40	250
Hollandse Kust Zuid - Beta	1.08	4051	0.16	87	0.40	211
Hollandse Kust Noord	1.42	5270	0.93	490	0.60	315
Hollandse Kust West - Alpha	1.09	8083	0.15	139	0.10	92
Hollandse Kust West - Beta	1.09	7740	0.15	134	0.10	89
IJmuiden Ver Alpha	0.95	12399	0.14	228	0.07	117
IJmuiden Ver Beta	0.95	11156	0.14	207	0.07	106
IJmuiden Ver Gamma	0.97	12140	0.16	258	0.09	145
Nederwiek Zuid (Site I)	0.80	13065	0.20	405	0.04	73
Nederwiek Noord (Site II)	0.80	12941	0.17	345	0.04	72
Nederwiek Noord (Site III)	0.80	18075	0.17	475	0.04	104
Ten Noorden van de Waddeneilanden *	0.80	8570	1.14	1466	0.12	154

Platform	harbour porpoise		harbour seal		grey seal	
	density (km^{-2})	DD	density (km^{-2})	DD	density (km^{-2})	DD
Hollandse Kust West (Site VIII) *	1.07	8541	1.07	1053	0.07	69
Doordewind Site I *	0.77	10927	0.39	707	0.04	72
Doordewind Site II *,**	0.77	10927	0.20	362	0.04	72
Doordewind Site III *,**	0.77	13160	0.20	433	0.04	87
Lagelander *,**	1.02	10586	0.20	457	0.10	274
TOTAL		180546		8115		2472

The figures below show the estimated number of animal disturbance days per year.

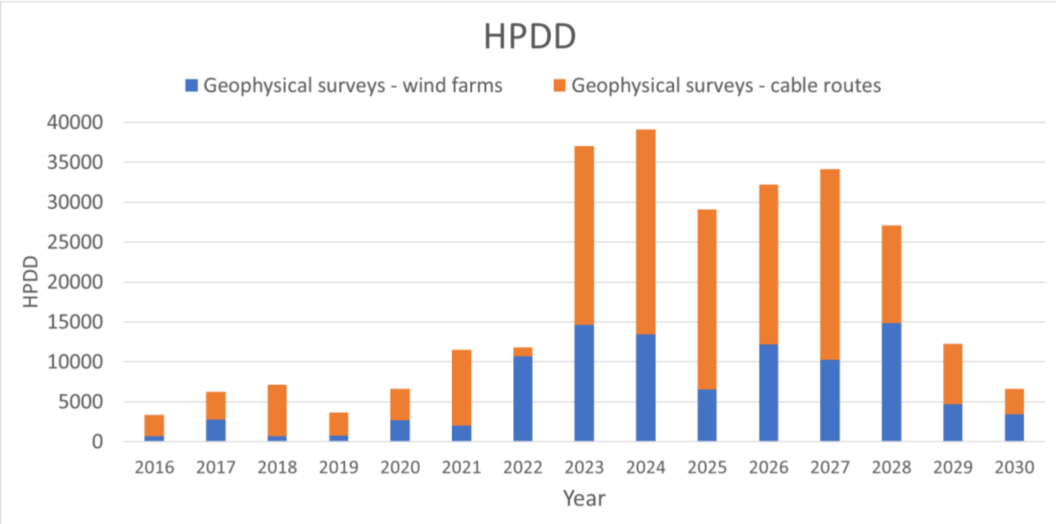

Figure F.1: Calculated number of harbour porpoise disturbance days resulting from geophysical surveys broken down according to the contribution of wind farm areas and cable routes.

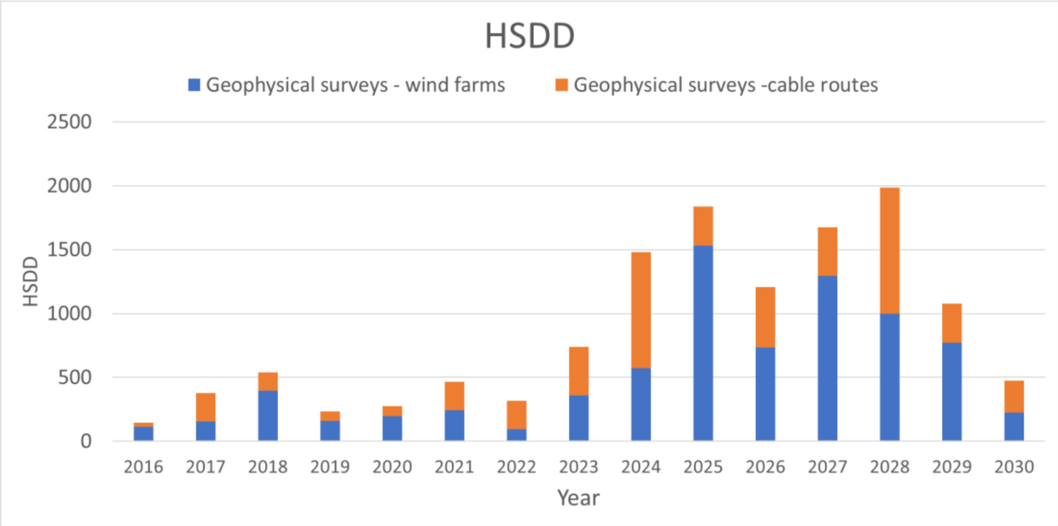

Figure F.2: Calculated number of disturbance days for harbour seals resulting from geophysical surveys broken down according to the contribution of wind farm areas and cable routes.

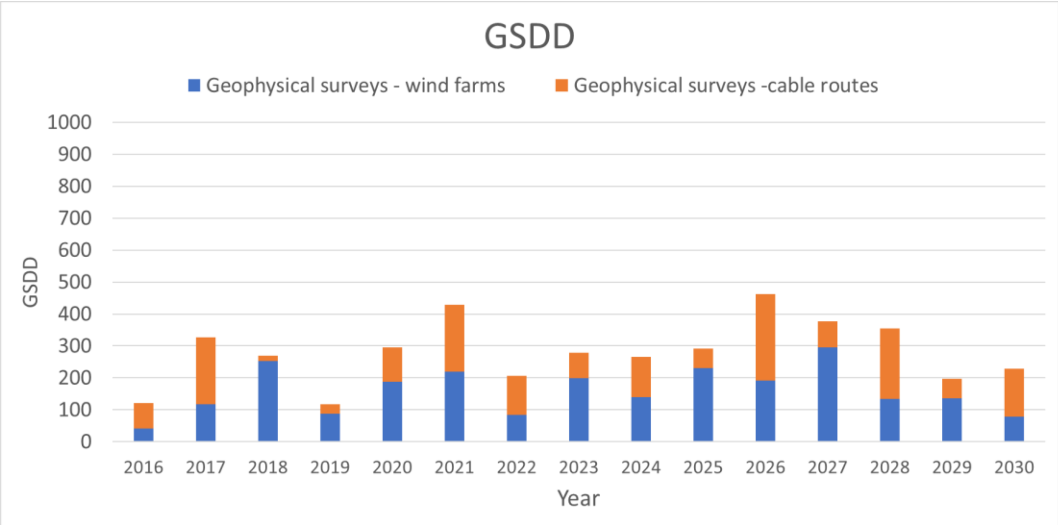

Figure F.3: Calculated number of disturbance days for harbour seals resulting from geophysical surveys broken down according to the contribution of wind farm areas and cable routes.

F.3 ADDs during UXO clearance

Table F.5 shows the calculated number of animal disturbance days due to the deployment of ADDs during UXO clearance. The estimated disturbance area is the same for all areas and so the differences are caused by the number of explosives and the estimated animal density per farm.

The number of animal disturbance days scales with the disturbance area. For a possible harbour porpoise disturbance distance of 18 km, the number of disturbance days is a factor of $(18/7)^2$ higher, in other words a total of approximately 479,000.

Table F.5: Estimated total number of animal disturbance days (DD) resulting from the deployment of ADDs during UXO clearance for the construction of the Dutch wind farms, assuming a disturbance distance of 7.1 km for harbour porpoises and 1 km for seals.

		harbour porpoise	harbour seal	grey seal
Search area	Number of explosives	DD	DD	DD
Borssele Site I-V	41	4703	58	12
Hollandse Kust Zuid Site IV	51	8478	26	64
Hollandse Kust Noord Site V	28	6060	81	52
Hollandse Kust West Sites VI & VII	11	1837	5	3
IJmuiden Ver	33	4950	15	8
Nederwiek	73	8950	35	7
Doordewind Site I	83	9816	102	10
Hollandse Kust West Site VIII	5	844	2	1
Ten Noorden van de Waddeneilanden	11	1337	39	4
Doordewind Site II	100	11893	63	13
Lagelander	27	4219	25	15
Area 6/7	81	11453	25	25
TOTAL	544	74539	477	216

Appendix G

Population effect of disturbance by piling sound

G.1 Interim PCoD 6.0.2 calculations for harbour porpoises

Version 6.0.2 of the interim PCoD model was used for calculations of the effects on the population of harbour porpoises in the North Sea of disturbance by wind farm construction under the KEC 5.0 scenario (Appendix A).

Table G.1: Demographic parameters for harbour porpoises in the North Sea from (Sinclair, Booth, Harwood, & Sparling, August 2024).

	high fertility	low fertility
Population (number of individuals)	373310	373310
DCS population (number of individuals)	62771	62771
birth rate	0.958	0.34
calf survival rate	0.6	0.85
juvenile survival rate	0.85	0.85
adult survival rate	0.85	0.93
Age at which calf becomes independent of its mother	1	1
Age at which an average female gives birth to her first calf	5	5
Population growth	0% / year	0% / year

This is based on the parameters suggested in (Sinclair, Booth, Harwood, & Sparling, August 2024). The 'low fertility' parameters from (Murphy, et al., 2020) correlate well with (IJsseldijk, et al., 2021), who found a pregnancy ratio of 0.34 and an average 'age at sexual maturity' of 4 years.
As can be expected, the undisturbed population develops in line with the international scenarios with and without the NL projects (relative to the total population of 373,310 harbour porpoises in the North Sea). Figure G.1 shows percentiles (based on 20,000 simulations) of the evolution of the undisturbed harbour porpoise population in the North Sea calculated for the two sets of demographic parameters (Table G.1). The spread in the results is slightly lower for low fertility in combination with a lower birth rate than for high fertility.

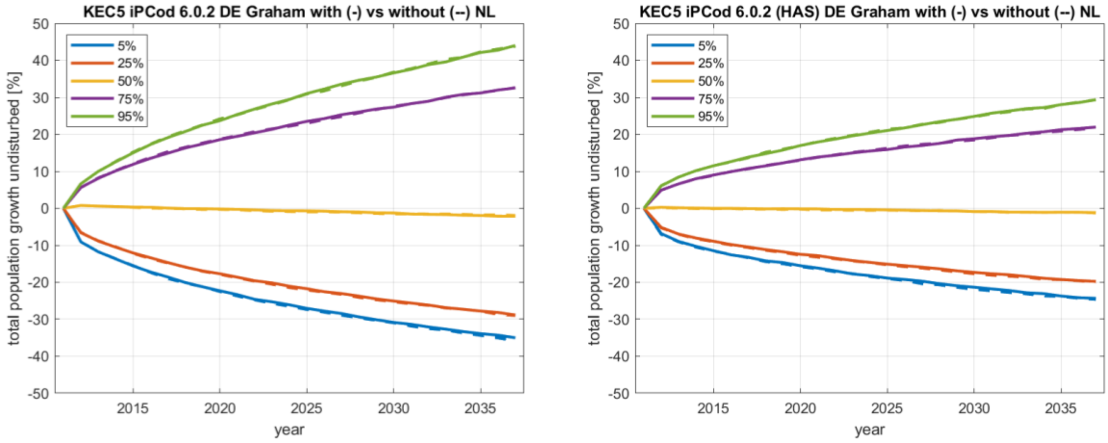

Figure G.1: Percentiles of the evolution of the undisturbed North Sea harbour porpoise population according to the interim PCoD model with high fertility (left) and low fertility parameters (right).

Figure G.2 shows percentiles for population decline resulting from disturbance as calculated by the interim PCoD 6.0.2 model. The calculated population reduction due to disturbance is lower in the case of low fertility than in the case of high fertility. The model calculates the effect of disturbance on the birth rate and survival rate of harbour porpoise calves. The overall effect is smaller with a lower (undisturbed) birth rate.

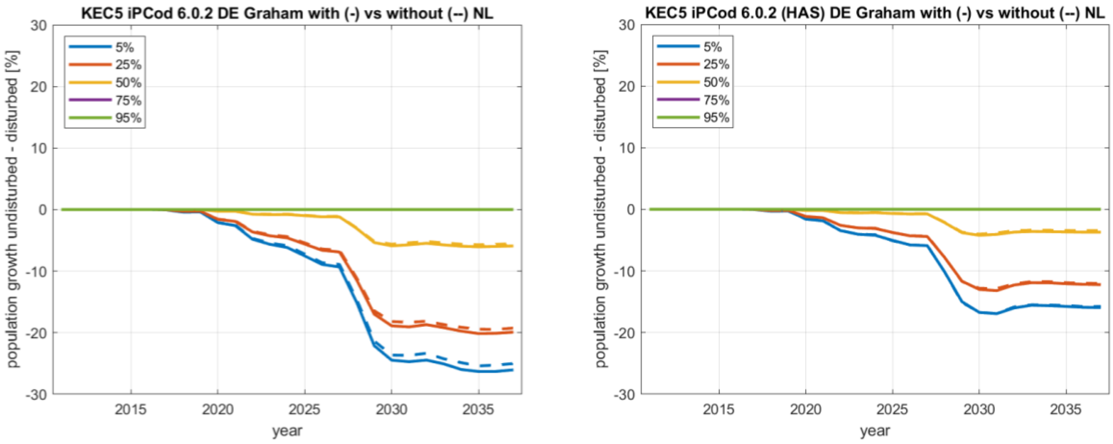

Figure G.2: Percentiles of the additional reduction of the North Sea harbour porpoise population disturbed by piling sound in the KEC 5.0 scenario according to the interim PCoD model with high fertility (left) and low fertility parameters (right). The number of harbour porpoise disturbance days here has been estimated based on the KEC 4.0 dose-effect relationship: 44.9 million harbour porpoise disturbance days for the total international scenario including 1.7 million harbour porpoise disturbance days by the NL projects.

G.1.1 Reducing the maximum disturbance distance

The combination of sound calculations (Aquarius 4) and application of a dose-effect relationship leads to calculated effective disturbance distances of up to ~80 km for projects in the UK where there is no noise mitigation requirement. There are no observations of harbour porpoises responding to sound at such large distances from piling locations. UK effect studies currently assume an effective disturbance distance of 26 km. However, a recent study looking at the installation of seven monopiles (9.5 and 10 m diameter) for the Moray West Offshore Wind Farm (Benhemma-Le Gall, et al., 2024) determined effective disturbance distances of less than 10 km, suggesting that 26 km is probably an overestimate.

Due to the large calculated effect distances, UK projects account for the majority of harbour porpoise disturbance days. To investigate whether a possible overestimation of the effect of UK projects on the harbour porpoise population affects the effect estimate for Dutch projects, interim PCoD calculations were made in which the maximum effective disturbance distance was limited to 26 km. That reduces the total number of harbour porpoise disturbance days for the KEC 5 international scenario to 13.5 million. The calculations assumed 'low fertility' demographic parameters for the harbour porpoise population.

Figure G.3 shows the calculated population decline due to disturbance in the KEC 5.0 scenario with a maximum effective disturbance distance of 26 km, with the 'low fertility' demographic parameters for the harbour porpoise population.

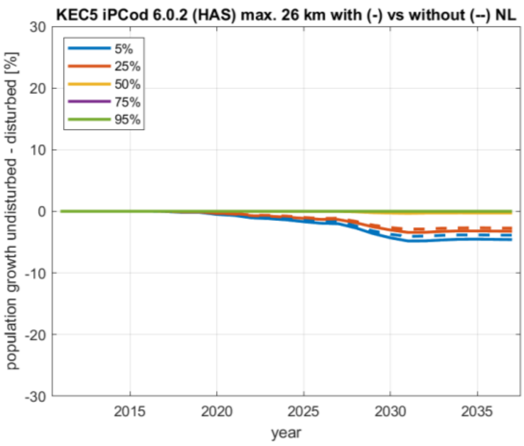

Figure G.3: Percentiles of the additional reduction of the North Sea harbour porpoise population disturbed by piling sound in the KEC 5.0 scenario according to the interim PCoD model with low fertility parameters. The number of harbour porpoise disturbance days here has been estimated based on the KEC 4.0 dose-effect relationship with the maximum disturbance distance being limited to 26 km: 13.5 million harbour porpoise disturbance days for the total international scenario including 1.7 million harbour porpoise disturbance days by the NL projects.

G.1.2 Adjustment of the dose-effect relationship

Applying the Brandt et al. (2018) dose-effect relationship reduces the total number of harbour porpoise disturbance days for the international KEC 5.0 scenario to 20 million and the number of harbour porpoise disturbance days resulting from the NL projects to 0.3 million.

Figure G.4 shows the calculated population decline when the Brandt et al. (2018) dose-effect relationship is applied with the 'low fertility' demographic parameters for the harbour porpoise population.

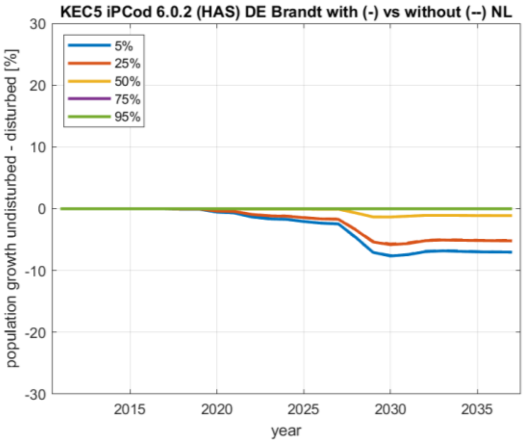

Figure G.4: Percentiles of the additional reduction of the North Sea harbour porpoise population disturbed by piling sound in the KEC 5.0 scenario according to the interim PCoD model with low fertility parameters. The number of harbour porpoise disturbance days here has been estimated based on the Brandt et al. (2018) dose-effect relationship: 20.0 million harbour porpoise disturbance days for the total international scenario including 0.3 million harbour porpoise disturbance days by the NL projects.

Without density dependence (Section G.3), the population reduction stabilises after disturbance ends (from 2031 onwards).

G.1.3 Calculated decline in harbour porpoise population

The final population decline due to the disturbance by piling sound from wind farm construction is determined as the mean and standard deviation over the years 2032-2037 and expressed as a percentage of the harbour porpoise population. Internationally, this is the total population in the North Sea (373,310 harbour porpoises).
Table G.2 provides an overview of the calculated population reduction and harbour porpoise disturbance days for a range of scenarios for which the effect on the harbour porpoise population has been calculated with the interim PCoD (6.0.2).

Table G.2: Calculated reduction of the harbour porpoise population (number of animals; mean ± standard deviation over the years 2032-2037) due to underwater sound from piling for the construction of wind farms in the North Sea in the years 2016 to 2030 for the international scenario (Section 5.1.2) with and without the NL wind farms and applying a range of dose-effect relationships and demographic parameters. (HPDD = harbour porpoise disturbance days)

Scenario	Dose-effect relationship	HPDD / 10^6	population reduction / number of animals			
			high fertility		low fertility	
			50% probability	5% probability	50% probability	5% probability
International	Graham et al. 2018 (1st pile)	44.9	13683 ± 177	58978 ± 661	21858 ± 794	95882 ± 2827
	Brandt et al. 2020	20.0	4049 ± 72	25920 ± 295	6331 ± 267	41901 ± 1363
	Max. 26 km	13.5	1014 ±35	17204 ± 395	1533 ± 55	27171 ± 541
International, without NL projects	Graham et al. 2018 (1st pile)	43.2	12839 ± 138	58514 ± 548	20637 ± 728	92148 ± 2881
	Brandt et al. 2020	19.6	4031 ± 66	25765 ± 314	6372 ± 281	41090 ± 1231
	Max. 26 km	11.8	702 ± 18	14496 ± 262	1076 ± 38	23441 ± 493
contribution NL projects	Graham et al. 2018 (1st pile)	1.7	844 ± 224	464 ± 859	1220 ± 1077	3735 ± 4037
	Brandt et al. 2020	0.3	17 ± 98	155 ± 431	41 ± 388	811 ± 1837
	Max. 26 km	1.7	312 ± 40	2708 ± 474	457 ± 67	3730 ± 732

Because the contribution of the NL projects to the international scenario is relatively small, the estimate of the population reduction due to the NL projects is uncertain, in many cases smaller than the standard deviation.

The contribution of the Dutch projects was determined on the basis of the difference between the simulations with and without the NL projects. The population reduction resulting from the NL projects is, for the purpose of comparison with the ecological standard, expressed as a percentage of the number of harbour porpoises on the Dutch continental shelf (DCS: 62,771 harbour porpoises. See Table 5.7 (Section 5.5.1)). Because of the high level of uncertainty, a proposal for a more robust estimate of the NL contribution can be found in Section 5.5.1.

G.2 Interim PCoD 6.0.2 calculations for seals

Version 6.0.2 of the interim PCoD model was used to calculate the effects on harbour and grey seal populations in the southeastern North Sea of disturbance by wind farm construction in the KEC 5.0 scenario (Appendix A).

Table G.3: Demographic parameters for seals in the North Sea.

	Harbour seals	Grey seals
Population (number of individuals)	55418	19559
DCS population (number of individuals)	18363	14787
Birth rate	0.88	0.84
pup survival rate	0.55	0.222
juvenile survival rate	0.61	0.94
adult survival rate	0.9451	0.94
Age at which pup becomes independent of its mother	1	1
Age at which an average female gives birth to her first pup	4	5
Population growth	0% / year	1% / year

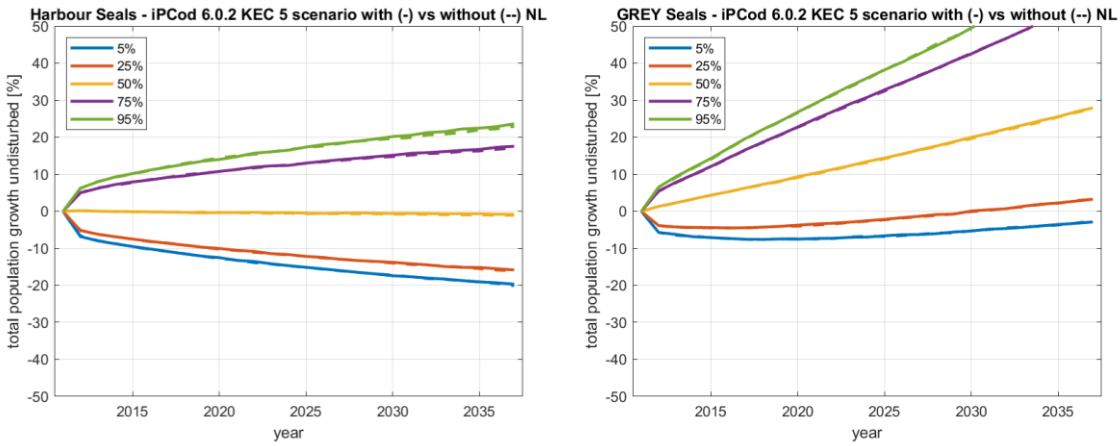

Figure G.5: Percentiles of the evolution of the undisturbed North Sea populations of harbour (left) and grey (right) seals according to the interim PCoD model.

Figure G.6 shows the calculated population reduction (percentage of the population) based on the maximum monthly density (worst case).

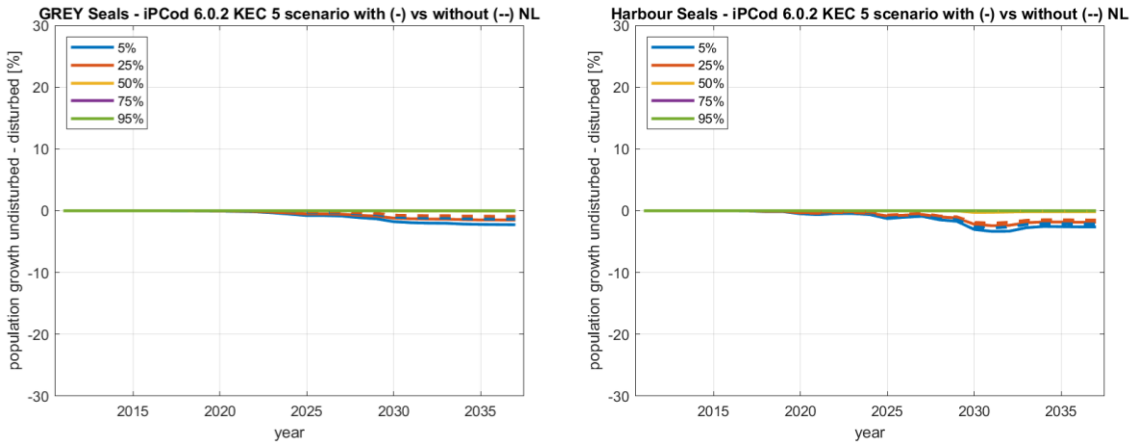

Figure G.6: Percentiles of the additional reduction as a result of piling sound in the KEC 5.0 scenario of the North Sea populations of harbour (left) and grey (right) seals according to the interim PCoD model.

Table G.4 provides an overview of the calculated population reduction and seal disturbance days for a range of scenarios for which the effect on the seal populations has been calculated with the interim PCoD (6.0.2).

Table G.4: Calculated reduction of the seal populations (number of animals; mean ± standard deviation over the years 2032-2037) due to underwater sound from piling for the construction of wind farms in the North Sea in the years 2016 to 2030 for the international scenario (Section 5.1.2) with and without the NL wind farms assuming the highest monthly densities on the project locations ('maximum') and the average density for the year ('average'). (SealDD = seal disturbance days).

Scenario	Species / Density	SealDD / 10^6	population reduction / number of animals	
			50% probability	5% probability
International	Harbour seal / maximum	1.42	86 ± 11	1513 ± 164
	Harbour seal / average	1.15	0 ± 1	574 ± 63
	Grey seal / maximum	0.29	57 ± 4	419 ± 22
	Grey seal / average	0.18	0 ± 1	193 ± 12
International, without NL projects	Harbour seal / maximum	0.57	6 ± 1	1229 ± 114
	Harbour seal / average	0.42	3 ± 1	423 ± 32
	Grey seal / maximum	0.23	4 ± 1	250 ± 17
	Grey seal / average	0.14	0 ± 1	193 ± 12
contribution NL projects	Harbour seal / maximum	0.85	28 ± 11	283 ± 199
	Harbour seal / average	0.73	0 ± 1	151 ± 70
	Grey seal / maximum	0.06	2 ± 1	169 ± 27
	Grey seal / average	0.04	3 ± 1	145 ± 19

Table 5.7 (Section 5.5.1) presents the overview of the calculated population reduction for a range of scenarios for which the interim PCoD (6.0.2) was used to calculate the effect on seal populations, expressed as a percentage of population size, and assuming the highest monthly density at the project locations ('maximum') for the worst case only.

G.3 Density dependence (harbour porpoises)

Inferring a value for "z" in Interim PCoD for north sea harbour porpoises **using the DEB version of iPCoD**

John Harwood, SMRU Consulting, 1 September 2024

The interim PCoD code has an option that allows users to incorporate density dependence in birth rate into the underlying population model. However, empirical data to parameterise the generalized logistic function described by Taylor & DeMaster (1993) are required. This takes the form

$$F_N = F_K + (F_0 - F_K).(1 - (N/K)^z) \qquad \text{Equation 1}$$

where F_N is the probability of giving birth when the population size is N, F_K is the probability of giving birth when the population is at the equilibrium level K, F_0 is the maximum value for the birth rate, and z is a parameter that determines the shape of the relationship between F_N and N. If z<1, most of the changes in F_N occur when $N < K/2$. If z>1, most of those changes occur when $N>K/2$.
Equation 1 can be parameterised if a time series of estimates for population size and birth rate is available. Unfortunately, no such time is available for harbour porpoises in the North Sea. However, Murphy et al. (2015) provided an estimate of 0.34 for the pregnancy rate for this population from samples collected between 1990 and 2012 (line 2 of Table 2). This could be used for F_K if we assume the population is currently stable. Murphy et al. (2015) also found that 19.7% of sexually mature females showed evidence of reproductive failure, suggesting that the maximum value for F (i.e. F_0) is (1 – 0.197) ≃ 0.8.

The dynamic bioenergetic version of iPCoD (iPCoD+DEB - see Chudzińska et al. 2024, Harwood et al. in press) can be used to infer the shape of the relationship between population size and birth rate for harbour porpoises. Density dependence can be incorporated into this model by allowing prey availability to vary with population size (see Hin 2024 for more details). These changes in prey availability result in matching changes in mean birth rate.

Figure 1 shows the outputs from 50 iterations of iPCoD+DEB in which the population was initialised at 50% of carrying capacity and the model was run for 25 years. All populations had reached carrying capacity by the end of the simulation. Most of the changes in birth rate occur when the population is close (within 10%) of carrying capacity.

It is possible to fit a linearised version of Equation 1 to these data if F_0 is set to 0.8. The resulting relationship between F and N/K is shown in green in Figure 1. However, this is an unconvincing representation of the model outputs because predicted birth rates when the population is close to carrying capacity are substantially higher than those generated by the model and the pregnancy rate estimated by Murphy et al. (2015). The red line shows the predictions of Equation 1 if F_K is set to 0.34 and z to 5. This appears to provide a better representation of the changes in birth rate when the population is close to K, which is probably the range of population sizes that are of most interest when iPCoD is being run.

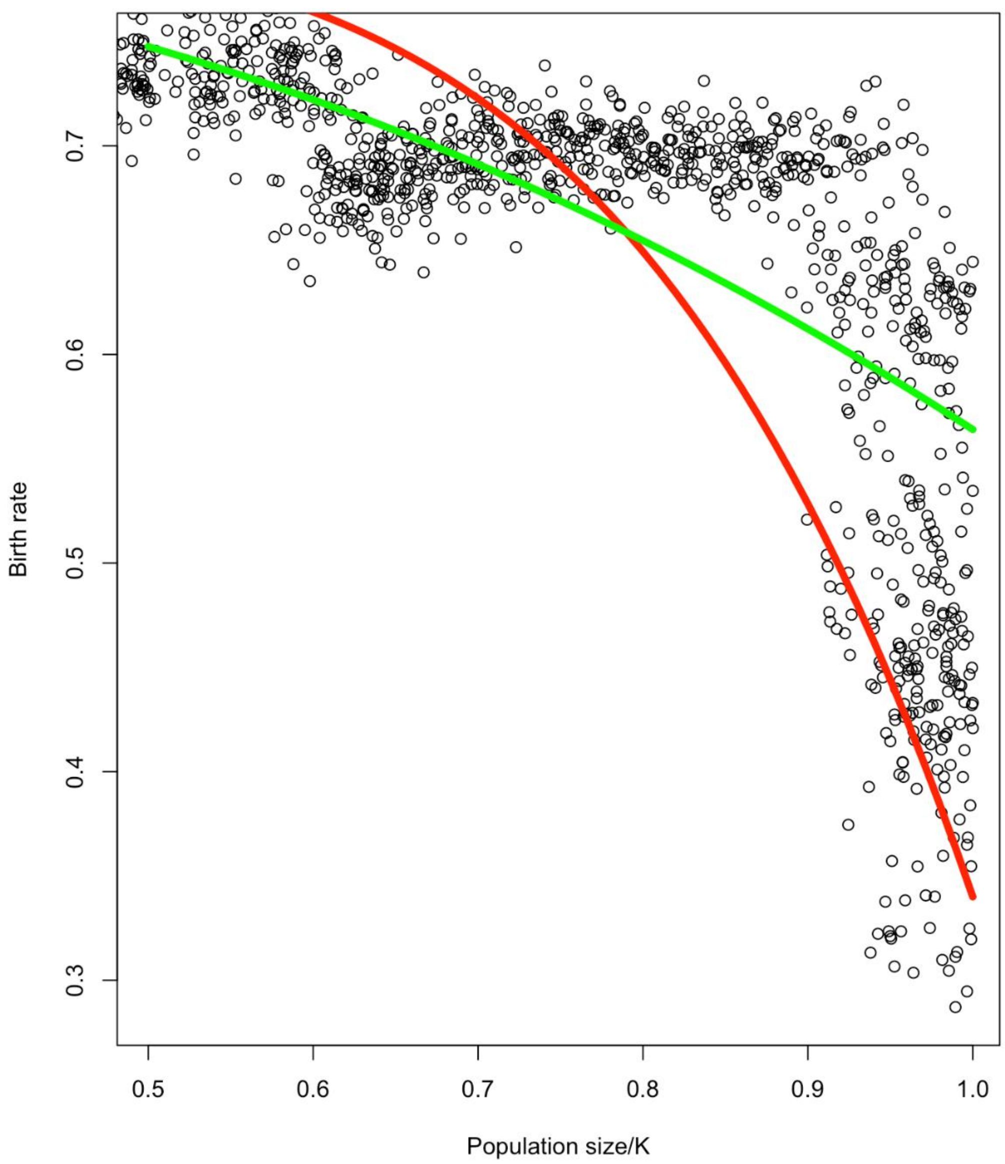

Figure 1. Relationship between birth rate and population size relative to carrying capacity based on 50 runs of the harbour porpoise dynamic energy budget population model (iPCoD+DEB). The red line shows the shape of the density dependent function used in iPCoD if the exponent z is set to 5, Fert_K (birth rate at carrying capacity) to 0.34 and Fert_0 (maximum birth rate) to 0.8. The green line shows the least squares fit to these model outputs with Fert_0 set to 0.8.

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