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TNO report

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Testing CEAF in SEANSE case studies - Impact of piling for wind farms on North Sea harbour porpoise population

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Summary

The environmental subgroup under Support Group 1 on Marine Spatial Planning in the framework of the implementation of the Political Declaration on energy cooperation between the North Seas Countries develops a common environmental assessment framework (CEAF) for assessing ecological cumulative effects of offshore renewable energy development. One of the proposed framework approaches, in this case a modelling tool to quantitatively assess cumulative impacts of piling for offshore wind farm construction on the harbour porpoise population, has been tested within the Strategic Environmental Assessment North Sea Energy as an aid for Maritime Spatial Planning (SEANSE) project, co-funded by the EU's European Maritime and Fisheries Fund and participating countries (Denmark, France, Germany, Netherlands and Scotland).

This report describes the details of the staged procedure and illustrates the procedure by application to three hypothetical scenarios for North Sea offshore wind development between 2016 and 2038.

Contents

List of terms and abbreviations

Aquarius	TNO modelling framework for underwater sound, including models for marine pile driving sound.
BE	Belgium
CEAF	Common Environmental Assessment Framework
DCS	Dutch section of the Continental Shelf
DE	Germany
DK	Denmark
E&W (Ministry of)	Infrastructure and Water Management
EIA	Environmental impact assessment
EZK (Ministry of)	Economic Affairs and Climate
HPDD	Harbour porpoise disturbance days: the number of impulse days per wind farm multiplied by the number of disturbed harbour porpoises per impulse day.
Impulse day	A day on which impulsive sound is produced (at any given time).
iPCoD	Interim PCoD model.
KEC	Framework for Assessing Ecological and Cumulative Effects (in Dutch: Kader Ecologie en Cumulatie).
LNV (Ministry of)	Agriculture, Nature and Food Quality
NL	Netherlands
PCoD	Population Consequences of Disturbance
Potential biological removal (PBR)	Potential Biological Removal, a term used for setting limits to the additional mortality (caused by human activity) with the aim of the sustainable maintenance of a population.
PTS	Permanent Threshold Shift
QoI	Quantity of Interest
RWS	Rijkswaterstaat (Agency of Dutch Ministry of E&W)
SCANS	Small Cetaceans in European Atlantic waters and the North Sea
SEANSE	Strategic Environmental Assessment North Sea Energy as an aid for Maritime Spatial Planning
SEL (Sound Exposure Level)	10 times $\log_{10}$ of the ratio of the integral of the square of the sound pressure squared during a defined interval of time (or during a defined event) to the reference value $E_0 = 1\ \mathrm{Pa^2s}$.
SELss	Sound exposure level of a single impulsive sound (SS stands for 'single strike')
SMRU	Sea Mammal Research Unit (University of Saint Andrews)

TNO	Netherlands Organisation for Applied Scientific Research
UK	United Kingdom
Vital rates	In general, the probabilities of survival and reproduction used in the population dynamic models. In the Interim PCoD model, disturbance by impulsive sound affects only the probability of mortality in young, weaned and unweaned animals in their first year of life and the probability of adult females producing offspring.
Vulnerable sub-population	The part of the population that may be disturbed by impulsive sound from a specific project. The size of the vulnerable sub-population is linked to the mobility of the animals: how many different animals could be inside the disturbance area during the course of the project?
Wozep	Offshore Wind Ecological Programme (in Dutch: Wind op zee ecologisch programma)

1 Introduction

A staged procedure to quantify the effects of marine piling noise on marine mammal populations, specifically on harbour porpoises, was developed by an expert group (Heinis et al. 2015 & 2019), for environmental impact assessments and appropriate assessments for future Dutch offshore wind energy projects.

The North Sea countries are cooperating (on a voluntary basis) to develop a *Common Environmental Assessment Framework* (CEAF) for assessing ecological cumulative effects of plans and projects with regard to offshore renewable energy development. One of the proposed framework approaches, in this case a modelling tool to quantitatively assess cumulative impacts of piling for offshore wind farm construction, is tested within the *Strategic Environmental Assessment North Sea Energy as an aid for Maritime Spatial Planning* (SEANSE) project (RWS, November 2018). The SEANSE project is co-funded by the EU's European Maritime and Fisheries Fund, see https://www.msp-platform.eu/projects/strategic-environmental-assessment-north-seas-energy-seanse, and participating countries (Denmark, France, Germany, Netherlands and Scotland). It started in early 2018 and will be finalized in the beginning of 2020.

The following scenarios for North Sea offshore wind development are formulated for SEANSE:

- Scenario 1: the wind farms which are expected to be in operation in 2023.
- Scenario 2: the wind farms which are expected to be in operation in 2030.
- Scenario 3: including windfarm developments expected to take place after 2030, as far as already identified by the governments of the participating countries.

This report describes the details of the staged procedure (Chapter 2) and illustrates the procedure by application to the SEANSE scenarios (Chapters 3 to 4). Chapter 5 provides an assessment of the uncertainties associated with the procedure.

2 Procedure to determine the cumulative effects of impulsive underwater sound on the harbour porpoise population

2.1 Overview of the procedure

The cumulative effects of wind farm development in the North Sea on the harbour porpoise population were assessed by applying the procedure that was developed by an expert group (Heinis et al. 2015). In this procedure, the various stages in the effect chain, that can be discerned are quantified. In 2018, improvements were made, using recent insights and research (Heinis et al. 2019). The stages in the effect chain, as shown in Figure 1 in schematic form, can be distinguished:

1. The calculation of a realistic worst case scenario in the propagation of sound due to a single strike for each wind farm; this calculation is based on information about the source sound level, local environmental factors (including bathymetry and seabed structure) and knowledge about how sound propagates in water.
2. The calculation of the size of the area disturbed by impulsive sound (piling events) for each wind farm; this is determined by the calculated sound propagation and a threshold value, possibly frequency-weighted, for the occurrence of a significant behavioural change, such as for example avoidance of the area.
3. The calculation of the number of harbour porpoises disturbed by sound on the basis of the calculated disturbed areas multiplied by the local density of harbour porpoises relevant to the season.
4. The calculation of the number of harbour porpoise disturbance days on the basis of the number of disturbed animals per day multiplied by the number of disturbance days.
5. The estimation of the possible impact on the population using the Interim PCoD[1] model.
6. The assessment of the estimated population reduction and appraisal with reference to an ecological target. This last step not part of SEANSE.

In the sections that follow, the different stages in the procedure that has been used in the SEANSE project are described in more detail.

2.2 Sound propagation

The sound propagation by pile-driving was calculated with the Aquarius 4 model, that was developed by TNO in the context of the Offshore Wind Energy Programme (Wozep)[2] (see Appendix A 'Modelling piling sound' & de Jong et al. 2019). The most important characteristics of this model are:

- Aquarius 4 contains a line-source model that includes the properties of the hammer and pile; this means that the effect of the pile diameter, the pile-driving energy and the mass/stiffnesses of the pile and hammer are incorporated into the model.

[1] Population Consequences of Disturbance.
[2] See https://zoek.officielebekendmakingen.nl/kst-33561-26.html (in Dutch) and https://www.noordzeeloket.nl/en/functions-and-use/offshore-wind-energy/

- Hammer type and energy are selected at a late stage of the design process. For this study it is assumed that all wind turbines are placed on monopile foundations that are struck with a hammer energy of 2000 kJ for the foundations of turbines up to 12 MW and a hammer energy of 4000 kJ is assumed for the piling of the monopiles for turbines larger than 12 MW, see Appendix A.1.
- In various countries (DE, NL, BE, DK), a sound mitigation standard will be used in the coming years for pile-driving, usually in terms of a maximum permissible unweighted broadband SELss at a distance of 750 m from the pile. This sound standard is processed in the Aquarius calculations on the basis of the calculated sound distribution for unmitigated pile-driving. A constant value is then subtracted from this sound distribution (unweighted broadband SELss) for each project that ensures that the SELss (maximum value over the water depth) at 750 m from the pile is less than or equal to the sound standard in all directions. Any effect on the shape of the spectrum as a result of the selected mitigation measure is therefore not included in the calculations.
- Aquarius 4 contains a range-dependent normal mode propagation model, in which the sediment is modelled as a semi-infinite fluid.
- Non-linear absorption in the sediment is assumed below a frequency of 250 Hz based on the available literature and the Gemini U8 pile measurements (see Binnerts et al. 2016 and de Jong et al. 2019).
- On the basis of a model validation study (Binnerts et al. 2016) it was concluded that the available models for wind losses resulted in an overestimation of the propagation loss. Therefore it was decided to rely on a worst-case assumption in which the effect of additional propagation losses due to wind is disregarded (de Jong et al. 2019).

The use of the Aquarius 4 model results in a reliable calculation of the broadband Single Strike Sound Exposure Levels (SELss) that has been validated against measurements at various distances from the piling location in the field (de Jong et al. 2019). The calculations are based on a realistic worst case scenario for the hammer, pile and environment parameters (see Appendix A).

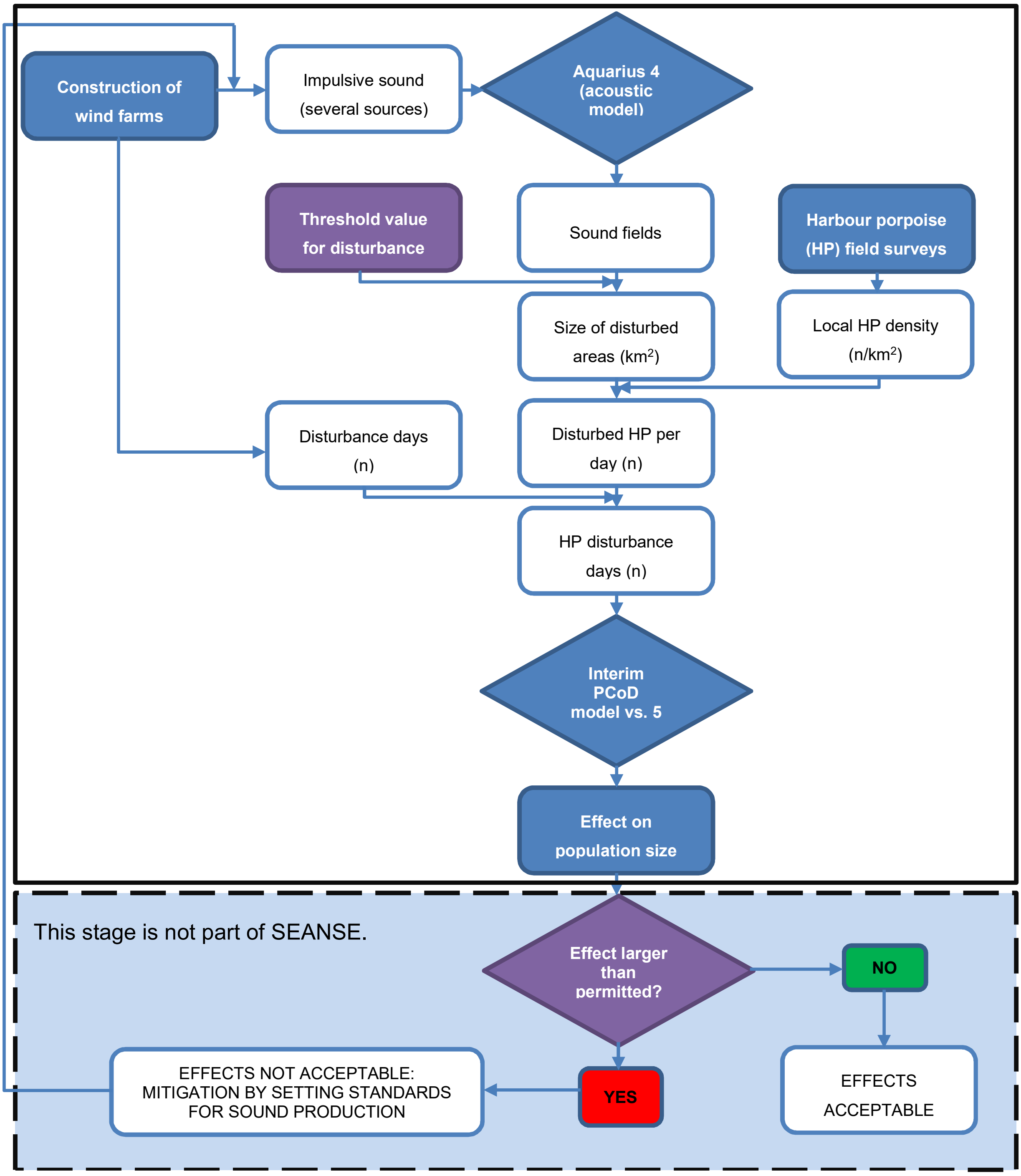

Figure 1 Schematic representation of the stages in the staged procedure for determining and assessing the cumulative effects of impulsive underwater sound on harbour porpoises during the construction of wind farms. The version numbers of models are mentioned as applied in this project and can change as new versions of models become available.

2.3 Determining the size of the affected area

2.3.1 Relevant effect parameters

As a result of the developments associated with offshore wind energy and the associated monitoring and research programmes, we have learnt more in recent years about the effects of impulsive sound on marine animals. This is knowledge acquired both in the field and in laboratory conditions about the effect of the sound on the behaviour and the hearing of individual animals (particularly harbour porpoises). See for instance the publications of Kastelein et al. (2013, 2015), Diederichs et al. (2014) and Dähne et al. (2013). The effects on individual harbour porpoises can have an impact on the population size, for example because foraging abilities are impaired, with a knock-on negative effect on survival chances or reproductive success because of the animal's condition. Changes in behaviour can also have acute effects on the chances of survival, for example if young animals lose their mothers Miller et al. (2012).

The procedure for assessing the cumulative effects of offshore wind farm construction on harbour porpoises has been based on the latest research results. When assessing the cumulative effects of the wind farm development in the North Sea, it is assumed that behavioural effects (i.e avoidance) will have fitness consequences for the individual and therefore influence the population. The effects on hearing and any knock-on effects of temporary or permanent threshold shifts in the hearing ability (TTS and PTS) on foraging and fitness and therefore on the population are not taken into account (see arguments below).

The arguments for disregarding **TTS** are as follows:

- TTS onset contours are smaller than the maximum avoidance contours, which means that the number of harbour porpoises with hearing that is temporarily affected is smaller than the number of harbour porpoises disturbed.
- 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 has emerged that the shift is limited to a relatively small band of low frequencies (Kastelein et al. 2015). A statistically significant TTS was found only at frequencies of 4 kHz and 8 kHz, and not at the higher measured frequencies (16 kHz and 125 kHz, the echo-location frequency) and the lower frequency (2 kHz). It is striking that, at frequencies in which most of the sound energy of the delivered piling sound is located, namely the 600 – 800 Hz frequency band, there is no TTS. These observations are important for the assessment of the ecological relevance of a predicted hearing threshold shift. A temporary shift in the low-frequency range of the hearing spectrum is probably much less relevant for harbour porpoises in terms of foraging than it is in the high-frequency range. High-frequency sounds of about 125 kHz and the audibility of those sounds are essential in this species for locating prey (using echo location).
- If mitigation measures are implemented to prevent PTS (see below), all the harbour porpoises that may be affected with TTS will recover their hearing in full (with the vast majority of them doing so within a few hours after leaving the area affected or after piling ceases).

As for the possible effects of **PTS**, it has been assumed that the risk of exposing porpoises to PTS will be prevented by mitigation measures. At present, this is safeguarded by means of a regulation in the existing permits by different nations. It emerges from the calculations made for various wind farms on the Dutch continental shelf that the distance at which harbour porpoises could suffer PTS is relatively small (even when no sound mitigation measures have been taken). At these distances, the effect can probably be prevented by piling with a 'soft start' and by using an 'acoustic deterrent device' (ADD)[3] that drive harbour porpoises away to a distance outside the PTS contour line. Furthermore, it is unlikely that the effects of PTS in the lower frequency bands (< 10 kHz) have a large effect on survival or reproductive success of harbour porpoises. This was concluded in a recent workshop with marine mammal experts for the update of the transfer functions in the Interim PCoD model (Booth et al. 2019).

2.3.2 *Threshold values for disturbance*

In the past few years, relatively large amounts of research data have become available that can be used to derive threshold values for disturbance. These data come from research in both controlled conditions and from field studies. In the present study, a threshold value for disturbance of SEL_{ss} = 140 dB re μPa²s (unweighted, broadband) is assumed[4]. This value lies between a value of 136 dB re 1 μPa²s derived from the results of controlled experiments in quiet conditions by Kastelein et al. (2013) and a value of 144 dB re 1 μPa²s derived from the results of field research during the construction of the German Borkum West II wind farm (Diederichs et al. 2014). Bearing the recent results of Brandt et al. (2018) in mind, we consider the selected threshold value of 140 dB re 1 μPa²s a precautionary choice.

2.3.3 *Disturbance area*

The size of the area disturbed by impulsive sound is estimated on the basis of the calculated propagation of the sound of a single piling strike and the threshold value for disturbance. The disturbance area is determined by the contour where the threshold value for disturbance is exceeded at the maximum SEL_{SS} in the water column (worst-case scenario). The effect of wind has not been included (see § 2.2 and Appendix A for the underlying arguments). Further, it is assumed that all harbour porpoises present inside the disturbance contour are equally disturbed as there is no information available that will allow differentiation of duration of disturbance based on the initial position of a harbour porpoise. There is also no information available about the likelihood of same individuals or new ones returning to the area after one piling event is concluded.

Figure 2 shows two examples of sound maps with the contours for the areas inside which the limit value of 140 dB re 1 μPa²s is exceeded. The difference in the extent of the disturbed area is attributable to the application of a noise limit in one case (left panel) and unmitigated piling in the other case (right panel).

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[3] Because ADDs produce sound in another frequency range than piling sound, the possibility of cumulative effects on porpoise hearing, such as an increase in TTS as a result of the cumulative exposure to piling and sound of ADD's, is negligible.

[4] This is probably a worst-case assumption as the results of the extensive study of Brandt et al. (2018) suggest. Looking at the effects of pile-driving of the first seven wind farms in German waters on harbour porpoises, they concluded that '*Declines were found at sound exposure levels exceeding 143 dB re 1 μPa²s (the sound exposure level exceeded during 5% of the piling time, SEL_{05}) and up to 17 km from piling*'.

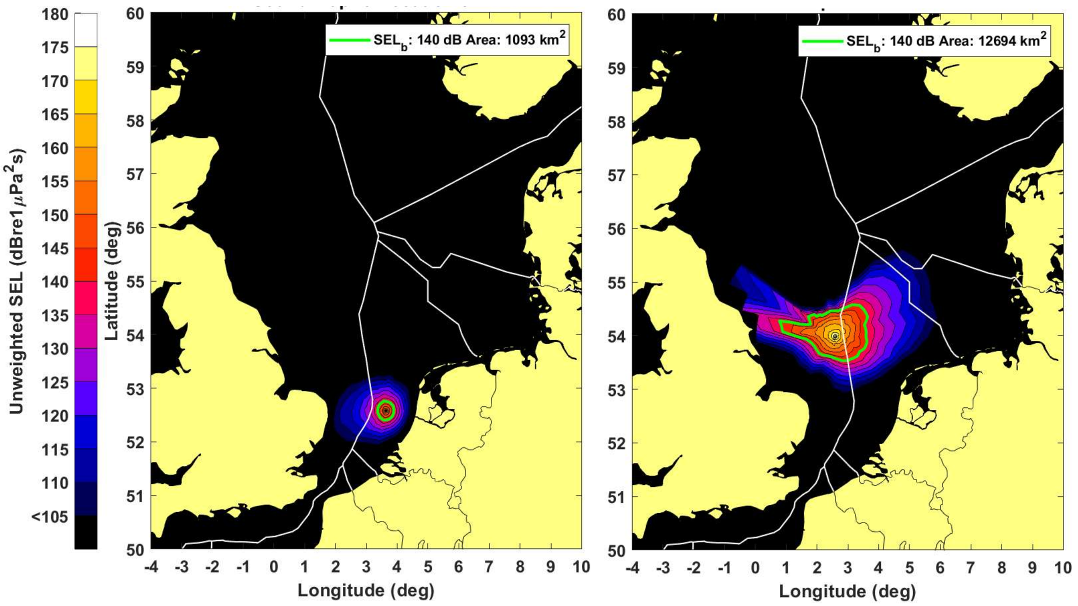

Figure 2 Examples of sound maps (left: Hollandse Kust (West II) and right: Hornsea Project Three) with contours in green for the sound levels at which the limit value of 140 dB for disturbance of harbour porpoises is exceeded. Mitigation of piling sound (left panel; noise limit SEL_{ss}(750 m) = 168 dB re $\mu Pa^2 s$) results in a much smaller disturbance area than unmitigated piling (right panel). The asymmetric shape of the disturbance area in the right panel is caused by the bathymetry.

Comments:

1 It is reasonable to assume that the application of a SELss value weighted with the frequency sensitivity of harbour porpoise's hearing provides a better prediction of the behavioural response, but there is as yet no international or national consensus in this respect.
2 Although it should, in principle, be possible to include a more realistic dose-response curve, as opposed to the current '100% disturbance if SEL > threshold', however this has not been considered further in this project.

2.4 Number of disturbed harbour porpoises

The number of animals potentially disturbed is calculated by multiplying the disturbance area by the local harbour porpoise density for the season in which the pile-driving takes place.

The local density of harbour porpoises is estimated on the basis of the best available data from aerial and shipboard surveys (such as Hammond et al. 2017 and Geelhoed et al. 2018) and from habitat-based density models (such as Gilles et al. 2016). Annual variations in the seasonal distribution can be applied in future studies when such information becomes available.

2.5 Harbour porpoise disturbance days

The total number of harbour porpoise disturbance days is calculated by multiplying the number of animals that may be disturbed on one day by the number of pile driving days. In the current approach, one disturbance day is interpreted, for the assessment of the effects on vital rates, as a disturbance of 6 hours and therefore also a 6-hour interruption of foraging (see §2.6).

2.6 Effect on population

The possible effects of disturbance by impulsive sound on the harbour porpoise population are calculated using the Interim PCoD model that was developed by SMRU/University of St. Andrews (Harwood et al. 2014; King et al. 2015, http://www.smruconsulting.com/products-tools/pcod/ipcod/).

In this study, we applied Interim PCoD version 5b[5], which is a complete update of the previous versions based on the expert elicitation of 2013 incorporating the results of the new expert elicitation workshops of February and June 2018 (Booth et al. 2019). The workshop in June 2018 focused on the experts' opinions relating to the effects of disturbance on the vital rates of harbour porpoises, see the text box below for an example from this workshop about the effects of disturbance by impulsive sound on vital rates.

Example of expert elicitation judgment (Booth et al. 2019)
The objective of an expert elicitation is to construct a probability distribution to accurately represent the knowledge and beliefs of an expert or group of experts regarding a specific Quantity of Interest (QoI). Here the QoI was the effects of disturbance on the probability of survival and probability of a successful birth (fecundity) in different stage classes of harbour porpoise. The Sheffield Elicitation Framework (SHELF) approach was used in the expert elicitation workshop (Oakley and O'Hagan 2016). For each QoI, which has a true value (which is unknown, and which we will call 'X'), each expert was asked to provide their individual judgements regarding a number of parameters, i.e. the plausible limits, median, lower and upper quartiles. The exact structure of each question was agreed with experts in advance of the elicitation and all required definitions were specified and agreed in advance.

The experts were then asked to input their personal judgements into a web-interface form and to send the data to the facilitator (via the form). The judgements were then input into SHELF and distributions were fitted to each individual expert judgement with the best statistical fit (determined in SHELF as the distribution with the lowest sum of squares value). The facilitator then presented the anonymised individual judgements of all experts together to the group (Figure a). During the process, the mechanisms experts had considered in making their individual judgements were discussed among the group.
Following this, the group was asked to reach a 'group consensus' judgement (in the form of a probability distribution). It is important to note here (and stated clearly to experts), that there was no expectation that the experts would reach complete agreement on a probability distribution for a particular QoI. That is because it is unlikely that there is one single distribution that would be accepted as perfectly representing the opinion of all experts. Instead, we asked experts to discuss and agree upon a distribution representing the reasoned opinions of a theoretical external observer, called a Rational Impartial Observer (or RIO). The RIO would not have identical views to any one of the experts but would instead find some merit in all the differing arguments or justifications – and give some weight to each.

The statistical analyses used to estimate the parameters of the relationships required by the Interim PCoD model from the results of this 'effects of disturbance' elicitation are described

[5] John Harwood (SMRU) has confirmed that version 5b is virtually equal to the new release of Interim PCOD (http://www.smruconsulting.com/products-tools/pcod/ipcod/). The only changes are that the latest release includes the results from last year's expert elicitation for harbour seals and grey seals, and some minor modifications in the way small populations (<1000 individuals) are simulated.

by Donovan et al. (2016).

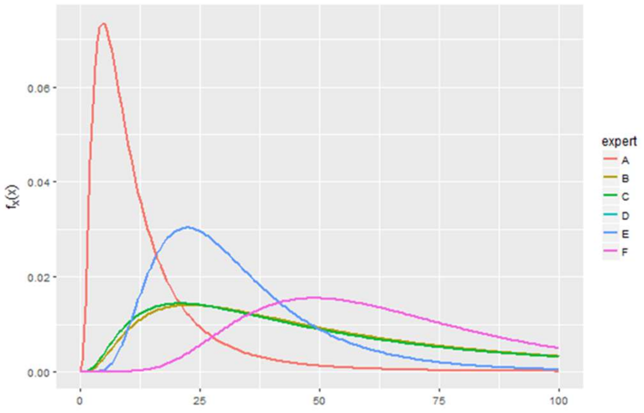

Figure a Theoretical example of individual judgements fitted in SHELF 3.0

In the elicitation distributions were generated that provide information on two parameters:

- Firstly, estimates (and associated uncertainty) on the number of days of disturbance that an individual can 'tolerate' before it has any effect in its vital rates. That is, how many days of disturbance would an individual need to experience before a specific vital rate was reduced at all.
- Secondly, estimates (and associated uncertainty) of the number of days of disturbance the same individual would need to experience to reduce the vital rate to zero (i.e. for survival this means death; for fecundity, this means no chance of producing a viable offspring).

In order to achieve this, the experts were asked to provide judgements on two separate questions for each harbour porpoise-vital rate combination to capture estimates for the above parameters.

For harbour porpoises, the elicitation focused on the effects of disturbance on calf survival (covering the period post-weaning) and fecundity (= the probability of a successful birth). Juvenile (> 1 year old) and mature female survival were agreed to be unlikely to be significantly affected by disturbance (as by this developmental stage they are considered to be relatively robust).

The results of the 2018 workshop on the effects of disturbance on the fecundity of harbour porpoise are described below. Experts explored the different possible mechanisms by which harbour porpoise fecundity could be impacted by disturbance and agreed that only the energetic considerations are conceivable. As the final third of the year is the most critical (the end of the lactation period for mothers and the beginning of new pregnancies), only in scenarios where animals received repeated exposure throughout the year this would result in significant impacts on fecundity. Experts also agreed that it was very unlikely an animal would terminate a pregnancy early as typically the energy reserves of the mother tend to be sufficient (*i.e.* close to the target level) at this time of year.

Following individual judgements they were presented to the group and experts explored and achieved a group (RIO) consensus as shown below in Figure b.

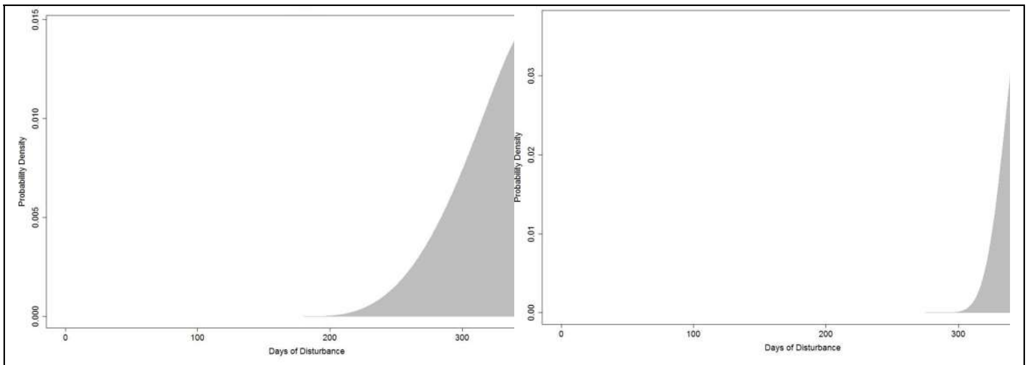

Figure b Probability distributions showing the consensus of the expert elicitation for the effect of disturbance on harbour porpoise fecundity: the number of days of piling a pregnant female could ‘tolerate’ before it has any effect on fecundity (left panel) and the number of days required to reduce the fecundity of the same individual to zero (right panel). N.B. The experts’ judgements were based on the assumption that, on average, the behaviour of the animals classified as being disturbed on one day of piling will be altered for 6 hours, and that no feeding will take place during this time.

In their assessment of the effects of disturbance resulting from piling sound on the vital rates of harbour porpoises, the experts assumed that pile-driving of one foundation would result in a disturbance of 6 hours (rather than the 24 hours concluded during the previous elicitation process). The experts were able to draw on the results of calculations using an energetic model for harbour porpoises developed by the University of St. Andrews in collaboration with the University of Amsterdam to form their opinion about the effect of disturbance on the vital rates. This model drew on the most recent data collected by SEAMARCO and the monitoring programme for the GEMINI wind farm (Kastelein et al. 2018, Kastelein et al. 2019).

The calculations with the Interim PCoD model (version 5b) were based on the following additional assumptions:

- Total harbour porpoise population in the North Sea: 350,000 (based on Hammond et al. 2002, Hammond et al. 2013, Hammond et al. 2017, Gilles et al. 2016).
- *Vulnerable sub-population*: 350,000 animals (equal to the total North Sea population)[6] because (1) there are no clear indications that there are sub-populations in the harbour porpoise population in the North Sea that have identifiable home ranges, (2) a recent publication shows that the home range of harbour porpoises can be quite large (Nielsen et al. 2018) and (3) the total duration of the scenario to be examined is relatively long at 15 years.
- Relatively low adult survival of 0.85, to incorporate the effects of bycatch, and relatively high fecundity of 0.96.
- The Interim PCoD calculations assume that the harbour porpoise population distribution and size is not density dependent. This means that the population

[6] The sensitivity of the modelling results to the size of the vulnerable sub-population for three different sizes was investigated for the development of windfarms at sea in the Netherlands (Heinis et al. 2015). These analyses showed that the vulnerable sub-population will play a role starting at population declines that are in the order of magnitude of about half the vulnerable sub-population. The total effect is limited to about 80% of the size of the vulnerable sub-population.

will not recover from an effect once it has occurred, such as a decline due to the activities associated with the construction of wind farms. In the latest version of the Interim PCoD model (versions 5), an option has been built in to take into account density-dependent population development. However, it appears that there is not yet enough knowledge to implement this in a meaningful way.

3 Scenario for North Sea offshore wind development (2016-2032) and planned scenario (2030-2038).

Scenarios for the current and planned offshore wind developments were provided to TNO in the file ‘31146751.0002 scenarios 10July19.pdf’, supplied by Rijkswaterstaat, with input from the SEANSE partners. This describes the location of these developments with a starting date and a number of piles. This overview has been used to create a scenario for the calculations presented in this report. The table is included in Appendix B.

We emphasize that this scenario cannot yet be considered to represent reality for North Sea wind farm development. It should be viewed as a first attempt to demonstrate the procedure to determine the cumulative effects of impulsive underwater sound on the harbour porpoise population at a North Sea scale.

The following scenarios for North Sea offshore wind development have been included:

- Scenario 1: the wind farms which are expected to be in operation in 2023.
- Scenario 2: the wind farms which are expected to be in operation in 2030[7].
- Scenario 3: including windfarm developments expected to take place after 2030, as far as already identified by the governments of the participating countries.

Because of the uncertainties affecting the timetable for the future construction of wind farms in the North Sea, assumptions had to be made when drawing up the construction scenarios. The calendars for the Interim PCoD model were generated on the basis of the following information and underlying assumptions:

- All turbines are assumed to be mounted on a single monopile.
- It was assumed in all cases that two piles are driven every three days.
- No piling during the winter months (December, January, February).
- A random starting date was selected between 1 March and 1 August.
- The actual start dates for the piling projects are unknown, hence start dates were generated such that the piling for each project was distributed over a maximum of two years.
- When an overview had been drawn up of all the construction activities in the North Sea, it emerged that an unrealistically large number of farms were sometimes due to be built at the same time and that the required capacity is probably lacking. It has therefore been assumed that a maximum of six pile-drivers will be available at the same time for the construction of wind farms in the North Sea, two of which will be used in the Netherlands. Construction work was assumed to begin first on farms with the first starting time; the others were postponed until the completion of an ongoing project. As a result of this procedure, the construction period for some of the wind farms of Scenario 2 was extended until the end of 2032.

[7] As a result of the applied procedure to generate the piling calendar, the construction period for some of the wind farms of Scenario 2 was extended until the end of 2032.

Note that the algorithm to generate the calendar was applied for all piling projects in the three scenarios, starting from 2016. The actual piling scenario of the projects that have already been completed is not taken into account by the algorithm and no attempts have been made to make the scenarios more realistic.

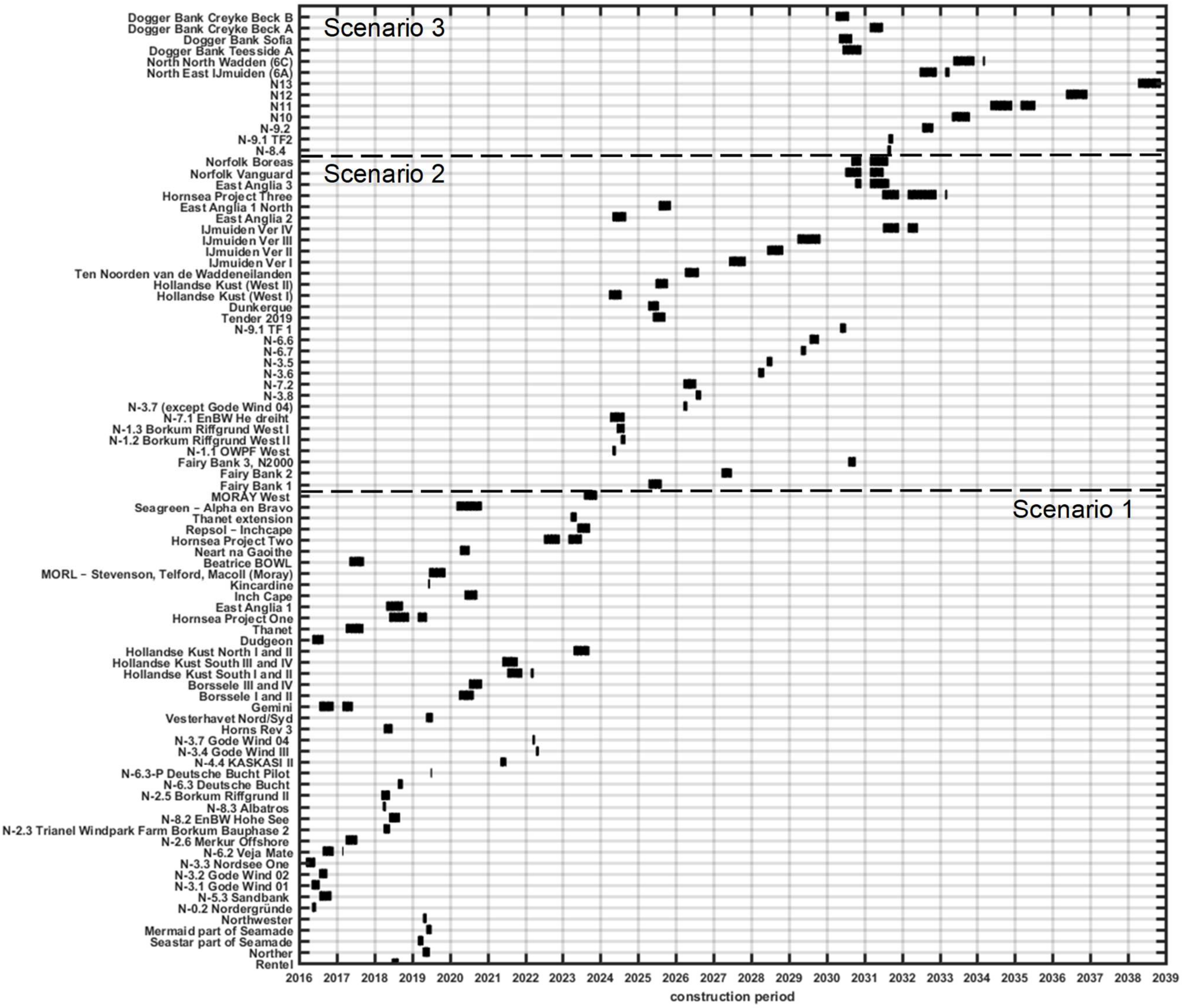

Figure 3 Overview of the assumed construction periods for the various projects in the calculated scenario for wind farm construction on the North Sea from 2016 until 2038.

Figure 4 shows the installed wind power per North Sea country and per year for the proposed scenarios 1 to 3. This illustrates that the modelled development is not evenly distributed over years and countries.

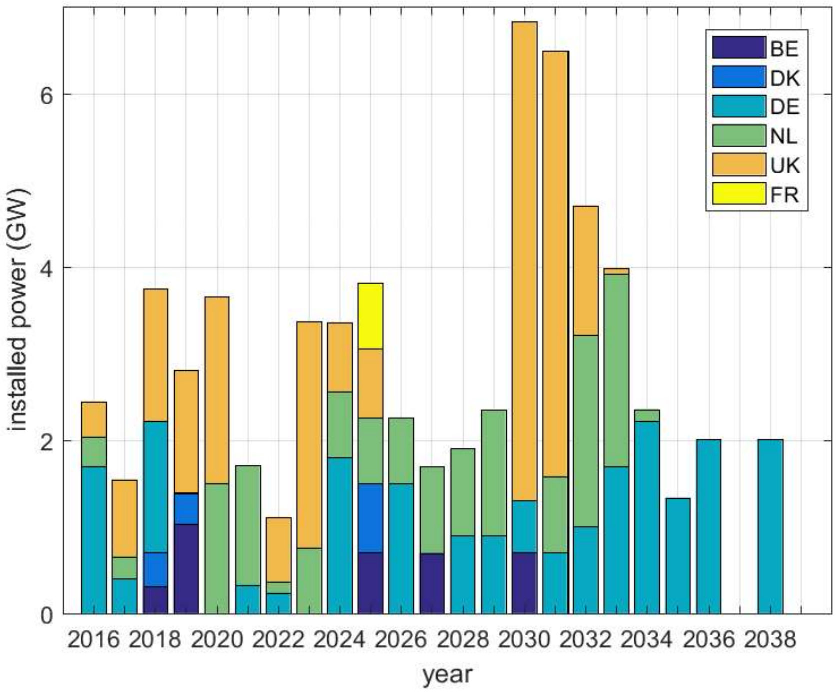

Figure 4 Installed wind power in GW per North Sea country and per year for the proposed scenario.

3.1 Porpoise density

For this example study, the local density of harbour porpoises was estimated on the basis of the available data from aerial and shipboard surveys (Hammond et al. 2017, Geelhoed et al. 2018) and from habitat-based density models (Gilles et al. 2016). Six areas were identified, and the seasonal density of harbour porpoises was estimated using the following method for each of those areas:

- For some areas, summer values (July) were first derived using Table 6 in Hammond et al. (2017) and Table 7 in Geelhoed et al. (2018).
- Spring and autumn values were then calculated on the basis of the ratio of summer values to spring and autumn values from Table 4 in Gilles et al. (2016).
- For the Dutch wind farms Hollandse Kust and IJmuiden Ver and UK farms offshore East Anglia: average values for the years 2010-2017, for study area D (Delta) as defined in Figure 1 in Geelhoed et al. (2018).
- For part of the German wind farms and the Dutch wind farm Ten Noorden van de Waddeneilanden: average values for the years 2010-2017, for study area C (Frisian Front) as defined in Figure 1 in Geelhoed et al. (2018).
- For Belgian wind farms, UK wind farm Thanet, Dutch Borssele wind farms and French Dunkerque wind farm: values for section L as defined in Figure 1 in Hammond et al. (2017).
- For the Danish wind farms and eastern German wind farms: values for section M as defined in Figure 1 in Hammond et al. (2017, SCANS-III).
- For UK wind farms Dudgeon, North of Norfolk (Hornsea) and Dogger Bank: values for section O as defined in Figure 1 in Hammond et al. (2017).

- For UK wind farms offshore Scotland: values for section R as defined in Figure 1 in Hammond et al. (2017).

The estimated seasonal density of harbour porpoises on the basis of the above method is shown in Table 1. The six areas are indicated in Figure 5, overlaying the distribution of wind farm locations included in the scenario described in Chapter 3.

It is recognized that the distribution of harbour porpoises is variable over the years, however for this example it was assumed that the same seasonal densities apply for all years in the scenario. Annual variations can be applied in future studies when such information is available.

Table 1 Estimated local harbour porpoise population densities by area and season.

		Individuals/km^2		
Area		**Spring**	**Summer**	**Autumn**
1	NL Holl. coast + IJmuiden Ver, UK East Anglia	0.721	0.698	0.444
2	BE, NL Borssele, UK Thanet, FR	0.628	0.607	0.386
3	DE (part), NL Ten Noorden van de Waddeneilanden	0.812	0.785	0.500
4	DK + DE (part)	0.286	0.277	0.176
5	UK Dudgeon, Hornsea, Dogger Bank	0.918	0.888	0.565
6	UK Scotland	0.619	0.599	0.381

NL = Netherlands, UK = United Kingdom, BE = Belgium, DE = Germany, DK = Denmark, FR = France.

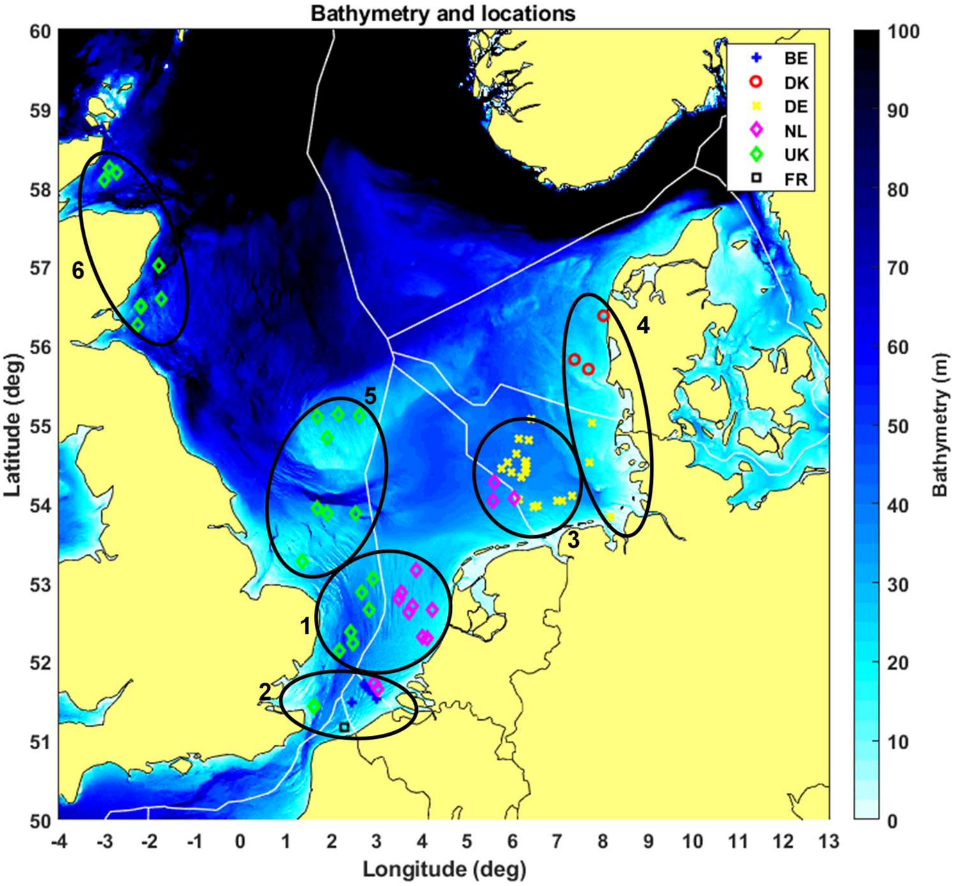

Figure 5 Location of the wind farms in areas for determining the local density of harbour porpoises. See Table 1 for description of numbers.

4 Results

The staged approach to determine the cumulative effects of impulsive underwater sound on the harbour porpoise population is applied for the example scenario (Chapter 3), with the following stages:

1. Aquarius 4 calculations of piling sound (SELss) distribution, for one characteristic pile location per project (“realistic worst case”, i.e. deep and furthest from shore).
2. Calculation of the size of the area in which the calculated SELss exceeds the threshold value (140 dB re 1 μPa^2s) for porpoise disturbance.
3. Calculation of the number of harbour porpoises disturbed by sound, by multiplying the calculated size of the disturbed areas with the local density of harbour porpoises by season.
4. Calculation of the number of *harbour porpoise disturbance days*, by multiplying the number of disturbed animals per day with the number of piling days.
5. Estimation of the possible impact on the population using the Interim PCoD model.

4.1 Harbour porpoise disturbance area

The calculated disturbance areas per project (resulting from stages 1 and 2) are presented in Appendix C.1.

4.2 Harbour porpoise disturbance days

The calculated numbers of *harbour porpoise disturbance days* per project (resulting from stages 1 to 4) are presented in Appendix C.2.

Figure 6 provides an overview of piling days and calculated number of harbour porpoise disturbance days per North Sea country and per year. This illustrates that the proposed scenario is not evenly distributed over the countries and over the years. It also illustrates that the UK projects have by far the largest contribution to the harbour porpoise disturbance days.

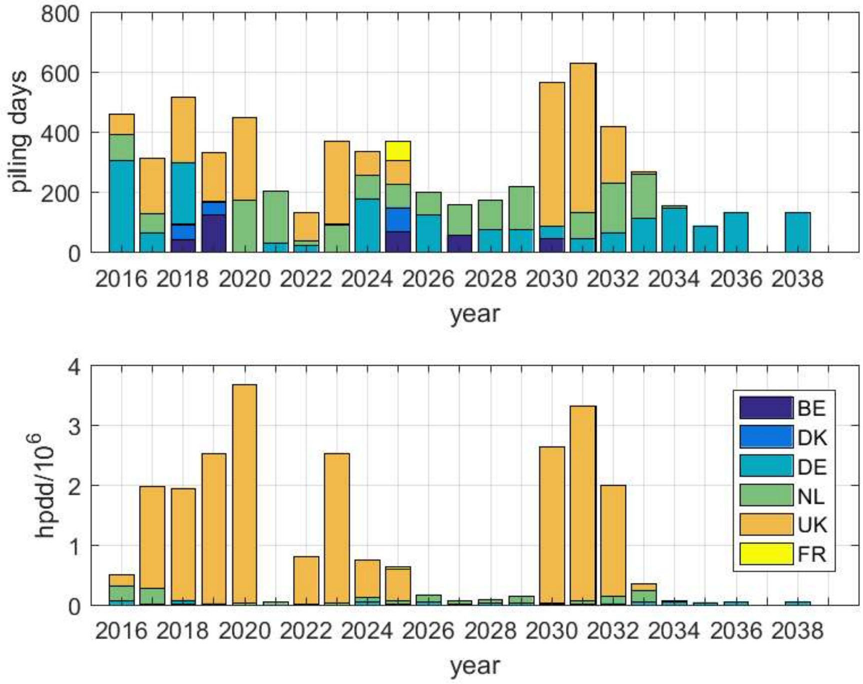

Figure 6 Number of piling days (upper graph) and calculated number of *harbour porpoise disturbance days* (lower graph) per North Sea country and per year for the proposed scenario.

4.3 Harbour porpoise population consequences of disturbance by piling sound

Interim PCoD model calculations (stage 5) have been carried out for the offshore wind development scenarios as described in Chapter 3. The piling calendar for each scenario is followed by ten years without disturbance. These ten extra years are included to allow for a stable statistical estimation of the total effect of the scenarios on the porpoise population. They are not to be interpreted as part of the piling scenario. The population effects calculated for these years are determined by the baseline vital rates for a stable population, because there is no disturbance by piling sound and the population model does not incorporate density dependence.

The probability of a population reduction due to the piling scenarios is quantified by the 5%, 10% and 50% (median) percentiles from a large set of statistical calculations of the difference between the disturbed and undisturbed populations.

Figure 7 presents an example of the calculated population development for scenarios 1 to 3 (up to 2038). The percentiles (%) indicate the probability of exceeding the calculated additional population reduction. This results in a 5% probability of a population reduction by 13% and a 50% probability of a population reduction by 2%. The reduction is displayed cumulatively and increases steeper in years after higher construction activity to finally stabilize over the ten years without disturbance after 2038.

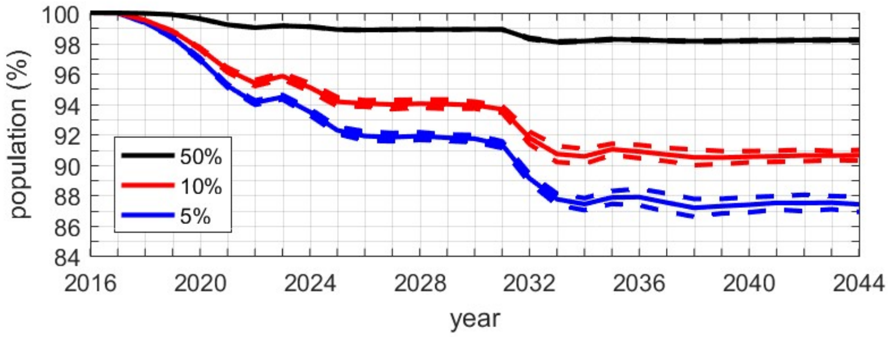

Figure 7 Interim PCoD predictions of the 5%, 10% and 50% percentiles of the development of the size of the North Sea harbour porpoise population over the years due to the example scenario 1-3 for offshore wind development (2016-2038), expressed as a percentage of the population (350,000 animals). The dashed lines indicate one standard deviation below and above the mean predicted reduction.

The total population reduction is then calculated as the average over the ten extra years after the completion of the scenario (in this example 2039 until 2049,). 10,000 Interim PCoD model runs have been performed. Each run corresponds to individual realization of the statistical dose-response curves that describe the effect of disturbance on the vital rates (see Section 2.6). From each model run we store the difference the calculated sizes of the disturbed and undisturbed population. This difference is the additional population reduction due to disturbance, compared with the natural reduction or growth. Figure 8 illustrates that the resulting cumulative average of the modelled additional population reduction stabilizes after about 4,000 runs. Finally, the average and the standard deviation over the results after runs 4,000 to 10,000 are reported.

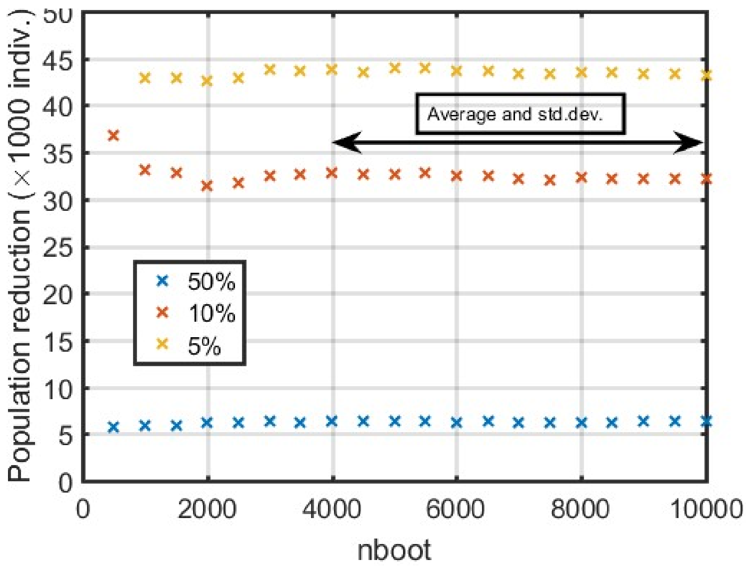

Figure 8 Calculated percentiles 5%, 10% and 50% (= median) of the additional population reduction as a result of the activities in the years 2016 to 2032 (scenarios 1 to 2), determined as an average of the calculated differences between the undisturbed and disturbed populations for the years 2033 to 2042 as a function of the number of model runs (nboot).

The results of the Interim PCoD calculations are summarized in Table 2 and Table 3. In these tables, the results for the scenarios 1 to 3 (North Sea wind development 2016-2038) are compared with the combined results for scenarios 1 and 2 (2016-2032).

Table 2 Results of the Interim PCoD calculations for the scenarios 1-2 (2016 – 2031) and scenarios 1-3 (2016-2038). The percentiles (%) indicate the probability of exceeding the calculated additional population reduction.

Scenario	Piling days	Porpoise disturbance days	Percentiles of the average additional population reduction (individuals)			Standard deviation (individuals)		
			5%	10%	50%	5%	10%	50%
1-2	5,287	22,024,744	37,019	27,613	4,994	603	367	86
1-3	6,645	24,395,903	44,080	32,735	6,248	275	241	85

Table 3 Relative results of the Interim PCoD calculations for the scenarios 2 (2016 – 2031) and 3 (2016-2034).

Scenario	Percentiles of the average additional population reduction (percent of North Sea population of 350,000 individuals)			Standard deviation (percent of calculated mean population reduction)		
	5%	10%	50%	5%	10%	50%
1-2	11%	8%	1%	2%	1%	2%
1-3	13%	9%	2%	1%	1%	1%

The example scenario 3' wind farm development for the years 2031-2038 adds 1,358 piling days (+26%), resulting in 2,371,159 additional porpoise disturbance days (+11%). As a consequence, there is a 5% probability that the North Sea porpoise population (350,000 individuals) experiences an additional decline from 312,981 (=350,000-37,019; 10% reduction) after 2032 to 305,920 (13% reduction) after 2038. The models predict a 50% probability of a maximum population reduction of 2% after 2038.

In the KEC study (Heinis et al. 2019) it was found that the additional porpoise disturbance by the underwater sound from piling for transformer platforms and from geophysical surveys increased the total number of harbour porpoise disturbance days for the development of Dutch wind farms between 2020 and 2030 by about 10%. A linear extrapolation of the observed trend (1% increase in porpoise disturbance days results in a further population reduction with 1%), would then result in a 5% probability that the porpoise population for scenario 3 of wind farm construction between 2016 and 2038 declines to 301,512 (14% reduction) after 2039.

4.4 Effect of the distribution of disturbance days over the years

The Interim PCoD model predicts the population decline as a function of the number of harbour porpoise disturbance days per year. The model is based on the assumption that disturbance by piling sound affects calf survival and adult female fecundity. Consequently, the population reduction lags at least one year behind the exposure, as illustrated by the distribution of harbour porpoise disturbance days and the resulting population decline per year in Figure 9.

The variable number of windfarms constructed over the years is reflected in the variable number of porpoise disturbance days over the years as seen in Figure 9a.The resulting annual population reduction is depicted in Figure 9b. The annual population decline is not linearly proportional with the number of disturbance days in the previous year. The effect on fecundity in particular increases strongly when a threshold of about 200 disturbance days is exceeded (see Section 2.6, text box, Figure b). Those years of higher impact are also reflected in the cumulative population reduction in Figure 9c as a steeper reduction.

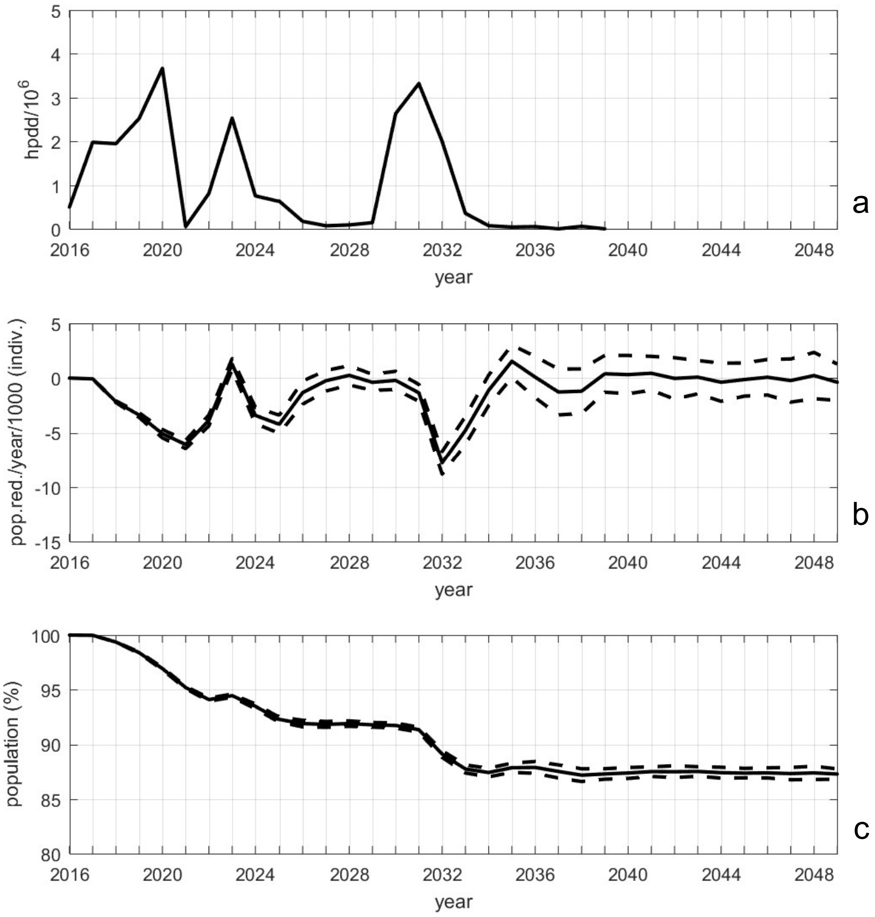

Figure 9 Calculated number of harbour porpoise disturbance days ('hpdd'; a) per year for the proposed scenario 1-3 and the population reduction ('pop.red', 5% probability) calculated by the Interim PCoD model, as reduction per year (b) and cumulative effect over the years on the population size (c). The solid lines give the mean and the dashed lines the mean plus and minus one standard deviation of the results from the 6,000 model runs.

To investigate the effect of the distribution over the years, an additional generic scenario has been constructed, with approximately the same total number of harbour porpoise disturbance days, over the same period (2016-2039), but then uniformly distributed over the years, assuming two parallel projects per year

The results of the Interim PCoD calculations for this 'uniform' scenario are shown in Figure 10 and summarized in Table 4 and Table 5. This shows that the predicted 5th probability population reduction is not very sensitive to the distribution over the years (in this comparison). The median (50%) population effect, however, is substantially smaller for the uniform distribution of the exposure over the years.

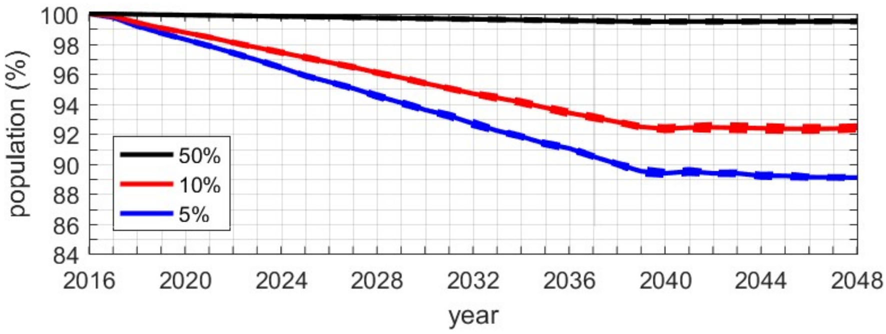

Figure 10 Interim PCoD predictions of the 5%, 10% and 50% percentiles of the cumulative reduction of the North Sea harbour porpoise population over the years due to a uniformly distributed scenario for offshore wind development (2016-2039), expressed as a percentage of the population (350,000 animals)

Table 4 Results of the Interim PCoD calculations for scenario 1-3 (2016-2039), from Table 2, compared with a generic 'uniform' scenario in which approximately the same total number of harbour porpoise disturbance days is uniformly distributed over the same period.

Scenario	Piling days	Porpoise disturbance days	Percentiles of the average additional population reduction (individuals)			Standard deviation (individuals)		
			5%	10%	50%	5%	10%	50%
1-3	6,645	24,395,903	44,080	32,735	6,248	275	241	85
'uniform'	11,592	24,401,160	37,497	26,639	1,780	560	157	21

Table 5 Relative results of the Interim PCoD calculations for scenario 1-3 (2016-2039), from Table 2, compared with a generic 'uniform' scenario in which approximately the same total number of harbour porpoise disturbance days is uniformly distributed over the same period.

Scenario	Percentiles of the average additional population reduction (percent of North Sea population of 350,000 individuals)			Standard deviation (percent of calculated population reduction)		
	5%	10%	50%	5%	10%	50%
1-3	13%	9%	2%	1%	1%	1%
'uniform'	11%	8%	0.5%	1%	1%	1%

4.5 Effect of the calculation of the disturbance areas

The current approach is based on the simplified assumption that all porpoises are disturbed by piling sound when they are exposed to an unweighted, broadband single-strike sound exposure level that exceeds the assumed threshold $SELss = 140$ dB re 1 $\mu Pa^2 s$, and none when that threshold is not exceeded. More realistic dose-response functions would be needed for a more accurate estimate of the number of animals affected (Tyack and Thomas, 2019), but such functions are not readily available for the disturbance of porpoises by piling noise.

For some projects without mitigation in deeper parts of the North Sea, the calculated disturbance areas based on these simplified assumption are very large (corresponding with effective disturbance ranges up to 108 km, see the table in Appendix C.1). There is no known evidence that animals respond to piling sound at such large distances.

To test the effect of the calculated disturbance on the predicted consequences of the North Sea piling scenarios on the porpoise population, Rijkswaterstaat has proposed an alternative test case in which the disturbance area for all projects is calculated from a uniform disturbance range of 26 km, independent of the actual location and the local environmental properties. This corresponds with a disturbed area of 2124 km^2 for all projects. This area is generally larger than the areas calculated for projects in which mitigation is required (DE, DK, BE, NL) and smaller than the areas calculated for projects in which no mitigation is required (UK, FR).

The resulting number of harbour porpoise disturbance days when this area is applied to the scenarios 1 to 3 is presented in the table in Appendix C.2 next to the disturbance days for the calculated disturbance area per project. The total number of harbour porpoise disturbance days for the scenarios 1 to 3 when assuming a fixed disturbance range of 26 km for all projects is 62% smaller than when the calculated disturbance radius per project is used, see Table 6.

With the lower estimation of the cumulative harbour porpoise disturbance days, the resulting estimation of population reduction is lower as well. In this adapted scenario there is a 5% probability of a population reduction by 4% after the completion of scenario 3 for wind farm construction between 2016 and 2038.

Table 6 Results of the Interim PCoD calculations for the scenarios 1-3 (2016-2039), for the calculated disturbance area per project and an assumed fixed disturbance area for all projects. The percentiles (%) indicate the probability of exceeding the calculated additional population reduction.

Scenario	Piling days	Porpoise disturbance days	Percentiles of the average additional population reduction (individuals)			Standard deviation (individuals)		
			5%	10%	50%	5%	10%	50%
Calculated area	6,645	24,395,903	44,080	32,735	6,248	275	241	85
Fixed area	6,645	9,227,371	12,745	8,427	141	65	46	1

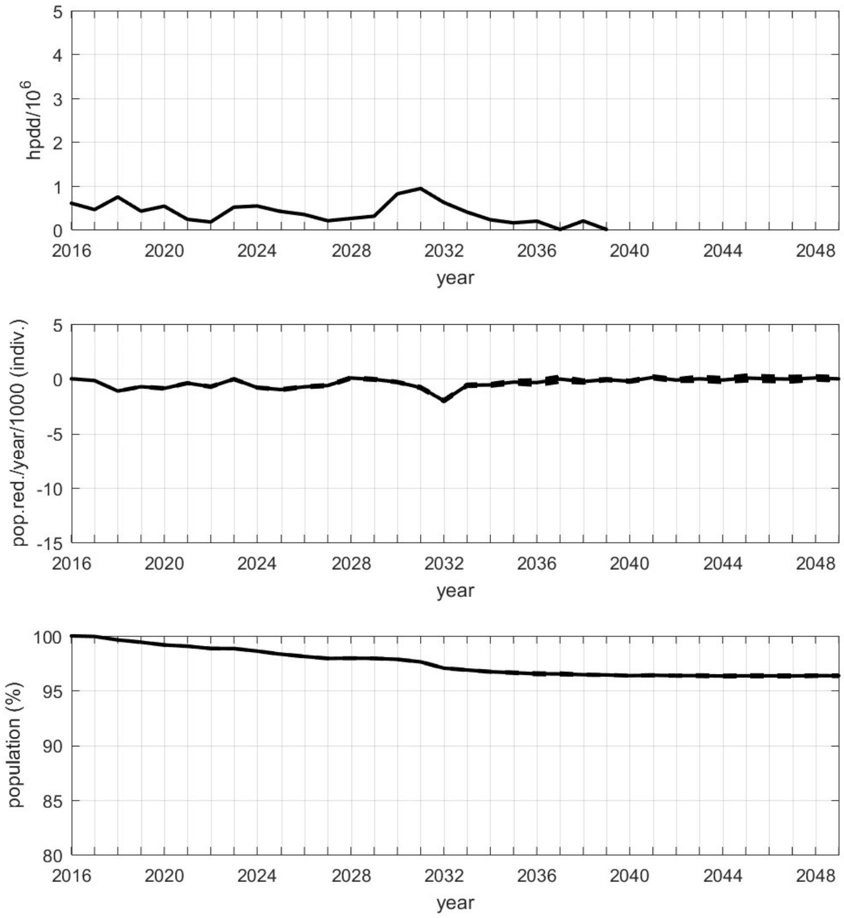

Figure 11 calculated number of harbour porpoise disturbance days ('hpdd'; upper graph) per year for the proposed scenario 1-3 ***for a uniform disturbance range of 26 km*** and the 5th percentile of the population reduction ('pop.red') calculated by the Interim PCoD model, as reduction per year (middle graph) and cumulative effect over the years on the population size (lower graph). The solid lines give the mean and the dashed lines the mean plus and minus one standard deviation of the results from the 6,000 model runs.

Table 7 Relative results of the Interim PCoD calculations, see Table 6.

Scenario	Percentiles of the average additional population reduction (percent of North Sea population of 350,000 individuals)			Standard deviation (percent of calculated population reduction)		
	5%	10%	50%	5%	10%	50%
Calculated area	13%	9%	2%	1%	1%	1%
Fixed area	4%	2%	0.04%	1%	1%	1%

5 Uncertainties in the various steps of the procedure

The staged procedure used here can be considered as a way forward to improve the assessment of the (cumulative) impact of impulsive noise on the populations of marine mammals, applied to harbour porpoises as a case study. However, since assumptions are made in each of step of the procedure uncertainties will occur. One should, therefore, be aware of the uncertainties in every step and report these. Transparency about the way the outcomes are determined and how they could be interpreted is critical in order to gain international acceptance as well as meaningful applications in licensing / granting (space for) offshore wind energy developments / projects.

There is a level of uncertainty, or a bandwidth, in the quantification of each of the steps in the procedure with the associated selected parameter. That level of uncertainty can be caused by a more or less known variation in the selected parameter value but also by the fact that little, and sometimes almost nothing, is known about the parameter in question (this is a 'knowledge gap'). An overview of the uncertainties or knowledge gaps for each of the values computed is given below:

1 <u>Quantification of sound source and propagation</u>
In spite of significant improvements in the description of the physics of the piling sound radiation and propagation in the updated Aquarius 4 model (de Jong et al. 2019), the quantitative prediction of the SELss remains uncertain, in particular for the high frequency content. The Aquarius 4 modelling results showed good agreement with unweighted broadband SELss measured during the construction of a Dutch wind farm (Gemini, U8 pile), but further validation of the model for a wider range of scenarios (both for different pile-hammer configurations and different environmental conditions) is required to obtain confidence in the predicted levels.

2 <u>Threshold values for disturbance/changes in behaviour</u>
   a The calculated effect distances are highly dependent on the discrete threshold value selected[8]. The current approach relies on this simplified approach and does not account for more realistic dose-reponse functions (Tyack and Thomas, 2019), because such functions are not available for the disturbance of porpoises by piling noise. Results from various studies under controlled conditions and in the field have shown that threshold values for disturbance could be between (broadband and unweighted) SELss 136 and 145 dB re 1 $\mu Pa^2 s$ (Kastelein et al. 2013; Diederichs et al. 2014; Brandt et al. 2018). The most extensive study was done by Brant et al. (2018). They looked at the effects of pile-driving on harbour porpoises during the construction of the first seven wind farms in German waters. In their study, a significant decline of harbour porpoise presence was found at broadband and unweighted sound exposure levels exceeding 143 dB re 1 $\mu Pa^2 s$.

[8] The term 'discrete threshold value' is used because it indicates the boundary between 'no disturbance at all' and any other form of disturbance defined as **all** responses with a score of 5 or more on the scale of Southall et al. (2007). By contrast with a dose-effect relationship in which the probability of the occurrence, or the level, of an effect gradually increases in line with the exposure level (in other words, the dose).

Hence, the threshold value chosen in the present study should be considered precautionary (at least, under similar conditions). If a higher threshold value is assumed in the calculations, e.g. SELss = 143 dB re 1 μPa^2s (broadband and unweighted), the disturbance area and therefore also the number of harbour porpoise disturbance days is considerably smaller (30 - 40%, see Heinis et al. 2019).

b For the time being, the calculations for harbour porpoises do not take hearing sensitivity as a function of the frequency into account. It is reasonable to assume that the application of a SELss value weighted with the frequency sensitivity of harbour porpoises' hearing provides a better prediction of the behavioural response. However, the available data are too limited to draw firm conclusions about the need for incorporating frequency weighting. Nevertheless, Tougaard et al [2015] have proposed that 'frequency weighting with a filter function approximating the inversed audiogram might be appropriate when assessing impact', and the US National Marine Fisheries Service decided that there was sufficient evidence to implement frequency weighting in its technical guidance for assessing the onset of noise induced hearing loss in marine mammals (NMFS, 2018). Application of frequency weighting in the assessment of porpoise behavioural disturbance would lead to much smaller (less conservative) predicted disturbance areas for projects in which the piling sound is mitigated with bubble screens, because these are more effective for reducing the weighted SELss than the unweighted SELss (Dähne et al. 2017).

3 <u>Quantification of the number of disturbed animals</u>
The bandwidth around the estimates of the local porpoise densities is approximately 50%. Furthermore, not much is known about any possible season-dependent migration patterns, site fidelity, and possible sex- and age-specific variations in these factors. Although tagging studies are taking place in Danish waters that are generating more information about individual animals (Sveegaard, 2011; Nielsen et al. 2018), this gap will not be remedied for the North Sea in the short term. This makes it difficult to provide a more precise estimate of the number of animals affected at different times of the year.

4 <u>Vulnerable sub-population</u>
In the present study it was assumed that the size of the vulnerable sub-population (used as input parameter for the Interim PCoD model) equals the full size of the total North Sea population (350,000), mainly because there are no clear indications that there are sub-populations in the harbour porpoise population in the North Sea and because Nielsen et al. (2018) showed that the home range of harbour porpoises can be quite large. The sensitivity of the modelling results to the size of the vulnerable sub-population for three different sizes was investigated for the Dutch scenario in 2015 (Heinis et al. 2015). These analyses showed that the vulnerable sub-population will play a role starting at population declines that are in the order of magnitude of about half the vulnerable sub-population. The total effect was limited to about 80% of the size of the vulnerable sub-population. This also means that the calculated population reduction will increase with the size of the vulnerable sub-population at higher values. Although choosing a large vulnerable sub-population may lead

to unrealistic scenarios, because the modelling is not spatially explicit, it reduces the risk of underestimating the potential impact.

5 Extrapolation of animal disturbance to effects on vital rates
The Interim PCoD model has been updated in 2018 and the transfer functions linking disturbance to vital rates of harbour porpoises were improved considerably, using a state-of-the-art energy model, see Booth et al. (2019). This model showed clearly that harbour porpoises can, in many cases, compensate for lost foraging opportunities as a result of disturbance. However, it is not yet entirely clear if the areas where the highest population densities are recorded are the most suitable habitats. Are the survival chances of harbour porpoises that are driven out of an area of this kind actually adversely affected and to what extent are seasonal variations in population levels linked to variations in the availability of food supplies?

6 Assumptions in Interim PCoD model about population development and demographic parameters
In the calculations with the Interim PCoD model it is assumed that the harbour porpoise population is stable and that demographic development does not depend on the population 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 population-density-dependent effects on demographic developments in order to arrive at a more realistic estimate of changes in the population in 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 sound?

7 Scenario definition
The quality of the available information about the offshore wind development scenario to which the staged approach is applied also determines the reliability of the predicted effects on the porpoise population. More accurate information about the piling projects leads to more confidence in the predicted population effects.

The presented staged approach allows for including many details, such as locations of individual piles, piling dates, properties of piles, hammers an environment, that were not available for the example scenarios in this study.

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7 Signature

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A Modelling piling sound

The underwater sound propagation for driving a representative foundation pile (turbine and platform) was calculated for each location. Sound generation and propagation depends on:

- type of hammer, mass of the hammer and hammer strike energy
- anvil mass and contact stiffness
- diameter, wall thickness and material of the pile
- length of the pile in the water and in the bed
- mitigation measure (bubble screen, mantle, etc)
- water depth (bathymetry) around the pile
- sea bed properties around the pile (density, sound velocity and absorption)
- wind speed/wave height.

In recent years, TNO has developed a suite of Aquarius computing models to calculate underwater sound propagation around a pile. The model version selected from that suite depends on the available information and the complexity of the calculation (number of variations to be calculated). The uncertainty in the calculated sound propagation should, in theory, decrease when more accurate and complete information is available. The models have been validated to only a limited extent (data from measurements during the construction of the Princess Amalia, Luchterduinen and Gemini wind farms) and the results of those studies show that we are not yet in a good position to quantify this uncertainty because we cannot adequately distinguish between the contributions of the various parameters (see the list above) to uncertainty.

- For the piling sound calculations in this study, the Aquarius 4 model was used that was further developed in the context of Wozep, see de Jong et al. (2019).
- The Aquarius 4 model calculations result in a spatial distribution of the piling sound in terms of the one-third octave (base-10) band spectrum of the SELss in the surroundings of the pile as a function of distance and depth.
- As a measure for quantifying the possible disturbance of harbour porpoises, it uses, in accordance with the KEC staged procedure, the unweighted broadband value for the calculated SELss.
- The maximum value of the SELss over the water depth is used. In Aquarius 4, the SELss as a function of depth is calculated in 10 steps spread equally from the seabed to the water surface and the maximum is then selected.

A.1 Hammer

Hammer type and energy are selected at a late stage of the design process. For this study it is assumed, at the request of Rijkswaterstaat, that, in all cases, the wind turbines are placed on monopile foundations that are struck with an estimated maximum hammer energy of 2000 kJ. Turbine capacity is expected to increase over the years. A maximum hammer energy of 4000 kJ is assumed for the piling of the monopiles for turbines larger than 12 MW. The largest hammer currently used by IHC delivers 4000 kJ (maximum pile diameter 7.5 m).

The Aquarius 4 model uses an idealised model of the hammer (Deeks & Randolph 1994) that requires data about the kinetic energy of the hammer, the hammer and anvil masses and the contact stiffness between the hammer and anvil. An analysis of all possible hammer types has not been included in the present study due to the lack of sufficiently detailed data. The hammer (IHC S-2000) used for Gemini was adopted as the starting point for determining the ultimate parameters:

- Turbines of 12 MW or less: pile diameter D = 5.5 m, 2000 kJ hammer energy.
- Turbines of 15 MW: pile diameter D = 7.5 m, 4000 kJ hammer energy.
- Platform piles: pile diameter D = 3 m, 2000 kJ hammer energy.

Other parameters:

- Monopile wall thickness (API, 1984 formula): $t = 0.01D + 6.35e^{-3}\ \mathrm{m}$.
- Anvil mass = ram mass = hammer energy * (1 ton/20 kJ).
- Contact stiffness 20 GN/m.

A.2 Mitigation

In various countries (DK, NL, BE), a sound mitigation standard will be used in the coming years for pile-driving, usually in terms of a maximum permissible unweighted broadband SELss at a distance of 750 m from the pile.

It will be left to the builders to determine how they will meet this standard. The modelling will therefore not be based on a specific solution: the calculated sound propagation (SELss) for unmitigated pile-driving is reduced by a constant value so that it just complies with the sound limit at 750 m from the pile.

- BE limit Lzp(750m) = 185 dB re 1 μPa^2 (according to Belgische staat, 2012). Based on Lippert et al. 2015 and data from the Luchterduinen and Gemini wind farms, this can be stated in global terms as equal to a sound limit SEL(750m) = 160 dB re 1 μPa^2.
- NL standard SELss(750m) per wind energy area, as adopted in site decisions and calculated in the same way (using the calculated relationship between harbour porpoise disturbance days and population decline) for the farms dating from after the SER agreement. After 2023, the sound limit is fixed to SELss(750m) = 168 dB re 1 μPa^2s for all NL projects.
- In Denmark the cumulative sound exposure level (SEL_{cum}) of animals is used as acoustic indicator which needs to be limited to 190 dB re 1μPa^2s for a complete pile driving sequence[9]. To incorporate in our calculations the corresponding need to apply mitigation measures, we have tentatively assumed that this corresponds with a sound limit SEL(750m) = 160 dB re 1 μPa^2, similar to the German sound limit.

Because the builders are free to choose the measures they implement to comply with the sound standard, the sound standard is processed in the Aquarius

[9] See e.g. Energinet.dk , Marine mammals and underwater noise in relation to pile driving – Working Group 2014, Document no. 13/93456-1246, 21.01.2015, and Energinet.dk, Marine mammals and underwater noise in relation to pile driving - Revision of assessment, Document no. 15/11973-34, 21 December 2015.

calculations on the basis of the calculated sound distribution for unmitigated pile-driving. A constant value was subtracted from this sound distribution (unweighted broadband SELss) for each project that ensures that the SELss (maximum value over the water depth) at 750 m from the pile is less than or equal to the sound standard in all directions. Any effect on the shape of the spectrum as a result of the selected mitigation measure is therefore not included in the calculations.

A.3 Locations

The scenarios provided by Rijkswaterstaat (RWS) state a central location for each planned farm. This does not necessarily result in a realistic worst case for the calculated disturbance area. That worst case will generally be seen at the greatest depth in the farm and at the largest distance offshore. For each farm, therefore, a 'realistic worst-case' location in the vicinity of the given central point was selected on the basis of the bathymetry.

A.4 Sound Propagation

The Aquarius 4 shallow water propagation model uses a proprietary implementation of a normal mode model, based on the KrakenC normal mode solver (Porter, 2001). The range-dependent bathymetry is incorporated via an adiabatic coupling (Jensen et al, 2011).

The sound speed and density in the water columns are uniform across the depth and the sediment is modelled as an equivalent uniform liquid (without shear stiffness or layering).

The Wozep validation study (Binnerts et al, 2016) has shown that this assumption results at low frequencies in a good match with measurement data, provided that a frequency-dependent absorption in the sediment is taken into account. The following choices were made:

- ‘Medium sand' parameter values (Ainslie 2010, Table 4.18) $\rho = 2086\ \mathrm{kg/m^3}, c = 1797\ \mathrm{m/s}$, and $\alpha = 0.88\ \mathrm{dB}/\lambda$ and a sound velocity in the water of 1500 m/s.
- Decreasing absorption ($\sim f^{1.8}$) below 250 Hz.

Because of uncertainty about the reliability of the modelling of the extra propagation loss resulting from the disturbance of the water surface by wind and waves, it has been decided to adopt a cautious approach and omit this effect from the Aquarius 4 calculations, in other words to assume a wind speed of 0 m/s.

B Scenarios

B.1 Project overview

The following scenarios for North Sea offshore wind development are considered:

- Scenario 1: the wind farms which are expected to be in operation in 2023.
- Scenario 2: the wind farms which are expected to be in operation in 2030.
- Scenario 3: . including windfarm developments expected to take place after 2030, as far as already identified by the governments of the participating countries.

The table below presents the proposed projects. The first column indicates which project belongs to which scenario.

Scenario	Modelling id	Name	Country	Expected start of construction	Max capacity in MW	MW Turbine	Number of monopiles
1	1	Rentel	BE	2018	309	7	44
1	2	Norther	BE	2019	370	8	44
1	3	Seastar part of Seamade	BE	2019	246	8	29
1	4	Mermaid part of Seamade	BE	2019	246	8	29
1	5	Northwester	BE	2019	219	9.5	23
1	6	N-0.2 Nordergründe	DE	2016	111	6	18
1	7	N-5.3 Sandbank	DE	2016	288	4	72
1	8	N-3.1 Gode Wind 01	DE	2016	330	6	55
1	9	N-3.2 Gode Wind 02	DE	2016	252	6	42
1	10	N-3.3 Nordsee One	DE	2016	332	6	54
1	11	N-6.2 Veja Mate	DE	2016	402	6	67
1	12	N-2.6 Merkur Offshore	DE	2017	396	6	66
1	13	N-2.3 Trianel Windpark Farm Borkum Bauphase 2	DE	2018	200	6	32
1	14	N-8.2 EnBW Hohe See	DE	2018	497	7	71
1	15	N-8.3 Albatros	DE	2018	112	7	16
1	16	N-2.5 Borkum Riffgrund II	DE	2018	448	8	56
1	17	N-6.3 Deutsche Bucht	DE	2018	260	8.4	31
1	18	N-6.3-P Deutsche Bucht Pilot	DE	2019	17	8.4	2
1	19	N-4.4 KASKASI II	DE	2021	325	10	33
1	20	N-3.4 Gode Wind III	DE	2022	110	10	11
1	21	N-3.7 Gode Wind 04	DE	2022	132	10	13
1	22	Horns Rev 3	DK	2018	400	8	50
1	23	Vesterhavet Nord/Syd	DK	2019	344	8	43
1	24	Gemini	NL	2016	600	4	150
1	25	Borssele I and II	NL	2020	752	8	94
1	26	Borssele III and IV	NL	2020	752	9.5	79
1	27	Hollandse Kust South I and II	NL	2021	752	8	94

Scenario	Modelling id	Name	Country	Expected start of construction	Max capacity in MW	MW Turbine	Number of monopiles
1	28	Hollandse Kust South III and IV	NL	2021	752	8	94
1	29	Hollandse Kust North I and II	NL	2023	760	8	95
1	30	Dudgeon	UK	2016	402	6	67
1	31	Thanet	UK	2017	300	3	100
1	32	Hornsea Project One	UK	2018	1,218	7	174
1	33	East Anglia 1	UK	2018	714	7	102
1	34	Inch Cape	UK	2020	700	10	72
1	35	Kincardine	UK	2019	50	8.4	6
1	36	MORL – Stevenson, Telford, Macoll (Moray)	UK	2019	1,116	9.5	100
1	37	Beatrice BOWL	UK	2017	588	7	84
1	38	Neart na Gaoithe	UK	2020	450	7	54
1	39	Hornsea Project Two	UK	2022	1,386	8	173
1	40	Repsol – Inchcape	UK	2023	784	10	78
1	41	Thanet extension	UK	2023	340	10	34
1	42	Seagreen – Alpha en Bravo	UK	2020	1,050	7	150
1	43	MORAY West	UK	2023	850	10	85
2	44	Fairy Bank 1	BE	2025	700	10	70
2	45	Fairy Bank 2	BE	2027	700	12	58
2	46	Fairy Bank 3, N2000	BE	2030	700	15	47
2	47	N-1.1 OWPF West	DE	2024	240	10	24
2	48	N-1.2 Borkum Riffgrund West II	DE	2024	240	10	24
2	49	N-1.3 Borkum Riffgrund West I	DE	2024	420	10	42
2	50	N-7.1 EnBW He dreiht	DE	2024	900	10	90
2	51	N-3.7 (except Gode Wind 04)	DE	2026	225	12	19
2	52	N-3.8	DE	2026	375	12	31
2	53	N-7.2	DE	2026	900	12	75
2	54	N-3.6	DE	2028	480	12	40
2	55	N-3.5	DE	2028	420	12	35
2	56	N-6.7	DE	2029	270	12	23
2	57	N-6.6	DE	2029	630	12	52
2	58	N-9.1 TF 1	DE	2030	600	15	40
2	59	Tender 2019	DK	2025	800	10	80
2	60	Dunkerque	FR	2025	750	12	63
2	61	Hollandse Kust (West I)	NL	2024	760	10	76
2	62	Hollandse Kust (West II)	NL	2025	760	10	76
2	63	Ten Noorden van de Waddeneilanden	NL	2026	760	10	76
2	64	IJmuiden Ver I	NL	2027	1,000	10	100
2	65	IJmuiden Ver II	NL	2028	1,000	10	100
2	66	IJmuiden Ver III	NL	2029	1,450	10	145
2	67	IJmuiden Ver IV	NL	2030	1,450	10	145
2	68	East Anglia 2	UK	2024	800	10	80
2	69	East Anglia 1 North	UK	2025	800	10	80
2	70	Hornsea Project Three	UK	2030	2,400	8	300

Scenario	Modelling id	Name	Country	Expected start of construction	Max capacity in MW	MW Turbine	Number of monopiles
2	71	East Anglia 3	UK	2030	1,200	8	150
2	72	Norfolk Vanguard	UK	2030	1,800	10	180
2	73	Norfolk Boreas	UK	2030	1,800	10	180
3	74	N-8.4	DE	2031	300	15	20
3	75	N-9.1 TF2	DE	2031	400	15	27
3	76	N-9.2	DE	2032	1,000	15	67
3	77	N10	DE	2033	1,700	15	113
3	78	N11	DE	2034	3,550	15	237
3	79	N12	DE	2036	2,000	15	134
3	80	N13	DE	2033	3,420	15	228
3	81	North East IJmuiden (6A)	NL	2032	2,000	15	133
3	82	North North Wadden (6C)	NL	2033	2,000	15	133
3	83	Dogger Bank Teesside A	UK	2030	1,200	10	120
3	84	Dogger Bank Sofia	UK	2030	1,200	15	80
3	85	Dogger Bank Creyke Beck A	UK	2030	1,200	15	80
3	86	Dogger Bank Creyke Beck B	UK	2030	1,200	15	80

The following table provides an overview of the installed power (in MW) per country according to this international scenario:

Scenario	1	2	3	Total	
Installed capacity (MW)	20,662	25,330	19,750	65,742	
BE	1,390	2,100	-	3,490	5%
FR	-	750	-	750	1%
DK	744	800	-	1,544	2%
DE	4,212	5,700	10,950	20,862	32%
NL	4,368	7,180	4,000	15,548	24%
UK	9,948	8,800	4,800	23,548	36%

C Porpoise disturbance

C.1 Porpoise disturbance area

The table below presents per project the calculated area A (km^2) around the pile in which the SELss exceeds the 140 dB re 1 μPa^{2}s disturbance threshold for harbour porpoises. It also gives an ‘equivalent’ porpoise disturbance range R, calculated as $R = \sqrt{A/\pi}$ (km).

The table also presents the national sound limits (‘norm’) that have been applied for projects in Germany and The Netherlands. Currently, the United Kingdom does not require piling sound mitigation. For lack of information concerning the situation in Denmark, piling sound mitigation has not (yet) been applied for the Danish wind farms.

Scenario	Modelling id	Name	Country	Norm (SELss at 750 m, in dB re 1 μPa^{2}s)	Harbour porpoise disturbance area (km^2)	Harbour porpoise equivalent disturbance range (km)
1	1	Rentel	BE	160	224	8.4
1	2	Norther	BE	160	166	7.3
1	3	Seastar part of Seamade	BE	160	232	8.6
1	4	Mermaid part of Seamade	BE	160	324	10.2
1	5	Northwester	BE	160	291	9.6
1	6	N-0.2 Nordergründe	DE	160	13	2.0
1	7	N-5.3 Sandbank	DE	160	234	8.6
1	8	N-3.1 Gode Wind 01	DE	160	432	11.7
1	9	N-3.2 Gode Wind 02	DE	160	433	11.7
1	10	N-3.3 Nordsee One	DE	160	433	11.7
1	11	N-6.2 Veja Mate	DE	160	483	12.4
1	12	N-2.6 Merkur Offshore	DE	160	339	10.4
1	13	N-2.3 Trianel Windpark Farm Borkum Bauphase 2	DE	160	341	10.4
1	14	N-8.2 EnBW Hohe See	DE	160	489	12.5
1	15	N-8.3 Albatros	DE	160	487	12.5
1	16	N-2.5 Borkum Riffgrund II	DE	160	384	11.1
1	17	N-6.3 Deutsche Bucht	DE	160	487	12.5
1	18	N-6.3-P Deutsche Bucht Pilot	DE	160	488	12.5
1	19	N-4.4 KASKASI II	DE	160	265	9.2
1	20	N-3.4 Gode Wind III	DE	160	421	11.6
1	21	N-3.7 Gode Wind 04	DE	160	429	11.7
1	22	Horns Rev 3	DK	160	207	8.1

Scenario	Modelling id	Name	Country	Norm (SELss at 750 m, in dB re 1 μPa^2s)	Harbour porpoise disturbance area (km^2)	Harbour porpoise equivalent disturbance range (km)
1	23	Vesterhavet Nord/Syd	DK	160	193	7.8
1	24	Gemini	NL		5,027	40.0
1	25	Borssele I and II	NL	163	285	9.5
1	26	Borssele III and IV	NL	163	486	12.4
1	27	Hollandse Kust South I and II	NL	165	511	12.8
1	28	Hollandse Kust South III and IV	NL	165	482	12.4
1	29	Hollandse Kust North I and II	NL	165	559	13.3
1	30	Dudgeon	UK		2,852	30.1
1	31	Thanet	UK		5,700	42.6
1	32	Hornsea Project One	UK		12,552	63.2
1	33	East Anglia 1	UK		12,170	62.2
1	34	Inch Cape	UK		17,018	73.6
1	35	Kincardine	UK		11,783	61.2
1	36	MORL – Stevenson, Telford, Macoll (Moray)	UK		36,549	107.9
1	37	Beatrice BOWL	UK		27,925	94.3
1	38	Neart na Gaoithe	UK		14,488	67.9
1	39	Hornsea Project Two	UK		12,838	63.9
1	40	Repsol – Inchcape	UK		19,996	79.8
1	41	Thanet extension	UK		5,685	42.5
1	42	Seagreen – Alpha en Bravo	UK		30,299	98.2
1	43	MORAY West	UK		15,361	69.9
2	44	Fairy Bank 1	BE	160	240	8.7
2	45	Fairy Bank 2	BE	160	240	8.7
2	46	Fairy Bank 3, N2000	BE	160	332	10.3
2	47	N-1.1 OWPF West	DE	160	384	11.1
2	48	N-1.2 Borkum Riffgrund West II	DE	160	384	11.1
2	49	N-1.3 Borkum Riffgrund West I	DE	160	385	11.1
2	50	N-7.1 EnBW He dreiht	DE	160	492	12.5
2	51	N-3.7 (except Gode Wind 04)	DE	160	449	12.0
2	52	N-3.8	DE	160	449	12.0
2	53	N-7.2	DE	160	491	12.5
2	54	N-3.6	DE	160	446	11.9
2	55	N-3.5	DE	160	449	12.0
2	56	N-6.7	DE	160	495	12.6
2	57	N-6.6	DE	160	715	15.1
2	58	N-9.1 TF 1	DE	160	578	13.6
2	59	Tender 2019	DK	160	261	9.1
2	60	Dunkerque	FR		815	16.1
2	61	Hollandse Kust (West I)	NL	168	1,062	18.4
2	62	Hollandse Kust (West II)	NL	168	1,093	18.7

Scenario	Modelling id	Name	Country	Norm (SELss at 750 m, in dB re 1 μPa^2s)	Harbour porpoise disturbance area (km^2)	Harbour porpoise equivalent disturbance range (km)
2	63	Ten Noorden van de Waddeneilanden	NL	168	2,042	25.5
2	64	IJmuiden Ver I	NL	168	1,072	18.5
2	65	IJmuiden Ver II	NL	168	1,072	18.5
2	66	IJmuiden Ver III	NL	168	1,194	19.5
2	67	IJmuiden Ver IV	NL	168	1,194	19.5
2	68	East Anglia 2	UK		11,370	60.2
2	69	East Anglia 1 North	UK		12,026	61.9
2	70	Hornsea Project Three	UK		12,694	63.6
2	71	East Anglia 3	UK		11,056	59.3
2	72	Norfolk Vanguard	UK		10,884	58.9
2	73	Norfolk Boreas	UK		7746	49.7
3	74	N-8.4	DE	160	554	13.3
3	75	N-9.1 TF2	DE	160	578	13.6
3	76	N-9.2	DE	160	585	13.6
3	77	N10	DE	160	585	13.6
3	78	N11	DE	160	576	13.5
3	79	N12	DE	160	568	13.4
3	80	N13	DE	160	625	14.1
3	81	North East IJmuiden (6A)	NL	168	1,108	18.8
3	82	North North Wadden (6C)	NL	168	2,263	26.8
3	83	Dogger Bank Teesside A	UK		5,773	42.9
3	84	Dogger Bank Sofia	UK		6,926	47.0
3	85	Dogger Bank Creyke Beck A	UK		2,472	28.1
3	86	Dogger Bank Creyke Beck B	UK		8,564	52.2

C.2 Harbour porpoise disturbance days

The table below presents the assumed porpoise density (animals/km^2) per season per project location and the calculated total number of *harbour porpoise disturbance days* (i.e. the number of piling days per wind farm multiplied by the number of disturbed harbour porpoises per piling day), based on the assumed piling calendar (Figure 3), the porpoise density per season (see also Table 1) and the calculated disturbance area (Section C.1).

Scenario	Modelling id	Name	Country	Porpoise density in spring (Mar-May; ind/km^2)	Porpoise density in summer (Jun-Aug; ind/km^2)	Porpoise density in fall (Sep-Nov; ind/km^2)	Harbour porpoise disturbance days: Based on calculated disturbance area (C.1)	Harbour porpoise disturbance days: Based on a 26 km disturbance range
1	1	Rentel	BE	0.628	0.607	0.386	5,984	56,716
1	2	Norther	BE	0.628	0.607	0.386	4,549	58,291
1	3	Seastar part of Seamade	BE	0.628	0.607	0.386	4,234	38,686
1	4	Mermaid part of Seamade	BE	0.628	0.607	0.386	5,737	37,561
1	5	Northwester	BE	0.628	0.607	0.386	4,209	30,682
1	6	N-0.2 Nordergründe	DE	0.286	0.277	0.176	72	10,850
1	7	N-5.3 Sandbank	DE	0.286	0.277	0.176	3,624	32,920
1	8	N-3.1 Gode Wind 01	DE	0.812	0.785	0.500	18,885	92,825
1	9	N-3.2 Gode Wind 02	DE	0.812	0.785	0.500	12,189	59,729
1	10	N-3.3 Nordsee One	DE	0.812	0.785	0.500	18,996	93,039
1	11	N-6.2 Veja Mate	DE	0.812	0.785	0.500	17,460	76,656
1	12	N-2.6 Merkur Offshore	DE	0.812	0.785	0.500	17,889	112,131
1	13	N-2.3 Trianel Windpark Farm Borkum Bauphase 2	DE	0.812	0.785	0.500	8,864	55,168
1	14	N-8.2 EnBW Hohe See	DE	0.812	0.785	0.500	27,177	117,980
1	15	N-8.3 Albatros	DE	0.812	0.785	0.500	6,320	27,584
1	16	N-2.5 Borkum Riffgrund II	DE	0.812	0.785	0.500	17,472	96,544
1	17	N-6.3 Deutsche Bucht	DE	0.812	0.785	0.500	8,668	37,762
1	18	N-6.3-P Deutsche Bucht Pilot	DE	0.812	0.785	0.500	766	3,334
1	19	N-4.4 KASKASI II	DE	0.286	0.277	0.176	2,460	19,727
1	20	N-3.4 Gode Wind III	DE	0.286	0.277	0.176	1,320	6,677
1	21	N-3.7 Gode Wind 04	DE	0.286	0.277	0.176	1,599	7,891
1	22	Horns Rev 3	DK	0.286	0.277	0.176	2,920	30,065
1	23	Vesterhavet Nord/Syd	DK	0.286	0.277	0.176	2,291	25,398
1	24	Gemini	NL	0.812	0.785	0.500	517,354	218,551
1	25	Borssele I and II	NL	0.628	0.607	0.386	16,484	122,831
1	26	Borssele III and IV	NL	0.628	0.607	0.386	18,490	80,726
1	27	Hollandse Kust South I and II	NL	0.721	0.698	0.444	27,234	113,142
1	28	Hollandse Kust South III and IV	NL	0.721	0.698	0.444	27,826	122,697
1	29	Hollandse Kust North I and II	NL	0.721	0.698	0.444	36,614	139,124
1	30	Dudgeon	UK	0.918	0.888	0.565	170,816	127,194

Scenario	Modelling id	Name	Country	Porpoise density in spring (Mar-May; ind/km²)	Porpoise density in summer (Jun-Aug; ind/km²)	Porpoise density in fall (Sep-Nov; ind/km²)	Harbour porpoise disturbance days: Based on calculated disturbance area (C.1)	Harbour porpoise disturbance days: Based on a 26 km disturbance range
1	31	Thanet	UK	0.628	0.607	0.386	340,000	126,678
1	32	Hornsea Project One	UK	0.918	0.888	0.565	1,727,269	292,280
1	33	East Anglia 1	UK	0.721	0.698	0.444	810,530	141,413
1	34	Inch Cape	UK	0.619	0.599	0.381	682,708	85,188
1	35	Kincardine	UK	0.619	0.599	0.381	42,348	7,632
1	36	MORL – Stevenson, Telford, Macoll (Moray)	UK	0.619	0.599	0.381	1,790,900	104,050
1	37	Beatrice BOWL	UK	0.619	0.599	0.381	1,359,220	103,369
1	38	Neart na Gaoithe	UK	0.619	0.599	0.381	477,602	70,021
1	39	Hornsea Project Two	UK	0.918	0.888	0.565	1,732,499	286,644
1	40	Repsol – Inchcape	UK	0.619	0.599	0.381	875,244	92,949
1	41	Thanet extension	UK	0.628	0.607	0.386	121,380	45,356
1	42	Seagreen – Alpha en Bravo	UK	0.619	0.599	0.381	2,472,816	173,332
1	43	MORAY West	UK	0.619	0.599	0.381	564,465	78,025
2	44	Fairy Bank 1	BE	0.628	0.607	0.386	10,340	91,310
2	45	Fairy Bank 2	BE	0.628	0.607	0.386	8,698	76,832
2	46	Fairy Bank 3, N2000	BE	0.628	0.607	0.386	7,496	47,920
2	47	N-1.1 OWPF West	DE	0.812	0.785	0.500	7,488	41,376
2	48	N-1.2 Borkum Riffgrund West II	DE	0.812	0.785	0.500	7,224	40,008
2	49	N-1.3 Borkum Riffgrund West I	DE	0.812	0.785	0.500	12,684	70,014
2	50	N-7.1 EnBW He dreiht	DE	0.812	0.785	0.500	35,244	152,082
2	51	N-3.7 (except Gode Wind 04)	DE	0.812	0.785	0.500	6,935	32,756
2	52	N-3.8	DE	0.812	0.785	0.500	10,912	51,677
2	53	N-7.2	DE	0.812	0.785	0.500	29,547	127,761
2	54	N-3.6	DE	0.812	0.785	0.500	14,480	68,960
2	55	N-3.5	DE	0.812	0.785	0.500	12,320	58,345
2	56	N-6.7	DE	0.812	0.785	0.500	9,168	39,310
2	57	N-6.6	DE	0.812	0.785	0.500	23,691	70,349
2	58	N-9.1 TF 1	DE	0.812	0.785	0.500	18,355	67,421
2	59	Tender 2019	DK	0.286	0.277	0.176	5,431	44,315
2	60	Dunkerque	FR	0.628	0.607	0.386	31,780	82,782
2	61	Hollandse Kust (West I)	NL	0.721	0.698	0.444	57,416	114,788
2	62	Hollandse Kust (West II)	NL	0.721	0.698	0.444	51,038	99,157
2	63	Ten Noorden van de Waddeneilanden	NL	0.812	0.785	0.500	124,083	129,029
2	64	IJmuiden Ver I	NL	0.721	0.698	0.444	62,016	122,867
2	65	IJmuiden Ver II	NL	0.721	0.698	0.444	62,832	124,484
2	66	IJmuiden Ver III	NL	0.721	0.698	0.444	109,235	194,310
2	67	IJmuiden Ver IV	NL	0.721	0.698	0.444	105,413	187,499
2	68	East Anglia 2	UK	0.721	0.698	0.444	633,558	118,315
2	69	East Anglia 1 North	UK	0.721	0.698	0.444	531,036	93,766

Scenario	Modelling id	Name	Country	Porpoise density in spring (Mar-May; ind/km^2)	Porpoise density in summer (Jun-Aug; ind/km^2)	Porpoise density in fall (Sep-Nov; ind/km^2)	Harbour porpoise disturbance days: Based on calculated disturbance area (C.1)	Harbour porpoise disturbance days: Based on a 26 km disturbance range
2	70	Hornsea Project Three	UK	0.918	0.888	0.565	2,890,146	483,588
2	71	East Anglia 3	UK	0.721	0.698	0.444	1,067,370	205,003
2	72	Norfolk Vanguard	UK	0.721	0.698	0.444	1,204,250	234,959
2	73	Norfolk Boreas	UK	0.721	0.698	0.444	869,074	238,242
3	74	N-8.4	DE	0.812	0.785	0.500	6,962	26,685
3	75	N-9.1 TF2	DE	0.812	0.785	0.500	8,463	31,094
3	76	N-9.2	DE	0.812	0.785	0.500	25,109	91,119
3	77	N10	DE	0.812	0.785	0.500	46,479	168,713
3	78	N11	DE	0.812	0.785	0.500	97,108	357,986
3	79	N12	DE	0.812	0.785	0.500	51,019	190,730
3	80	N13	DE	0.812	0.785	0.500	57,548	195,329
3	81	North East IJmuiden (6A)	NL	0.721	0.698	0.444	86,011	164,864
3	82	North North Wadden (6C)	NL	0.812	0.785	0.500	201,322	188,914
3	83	Dogger Bank Teesside A	UK	0.918	0.888	0.565	501,416	184,474
3	84	Dogger Bank Sofia	UK	0.918	0.888	0.565	490,854	150,532
3	85	Dogger Bank Creyke Beck A	UK	0.918	0.888	0.565	180,188	154,848
3	86	Dogger Bank Creyke Beck B	UK	0.918	0.888	0.565	618,680	153,440

Totals:

	Piling days	Harbour porpoise disturbance days based on calculated disturbance area (C.1)	Harbour porpoise disturbance days based on 26 km disturbance range
Total	6,645	24,395,903	9,227,371
BE	344	51,247	437,998
FR	63	31,780	82,782
DK	173	10,642	99,778
DE	1,866	644,497	2,732,532
NL	1,590	1,503,368	2,122,983
UK	2,609	22,154,369	3,751,298