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TNO report

TNO 2021 R12503-UK

Framework for Assessing Ecological and Cumulative Effects 2021 (KEC 4.0) – marine mammals

This report provides an approved English translation by Pete Thomas of the original report TNO 2021 R12503 'Kader Ecologie en Cumulatie 2021 (KEC 4.0) – zeezoogdieren'.

In case of differences in interpretation between the English and Dutch versions of this report, the original Dutch version shall prevail.

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Abstract

With the publication of the 2030 Offshore Wind Energy Roadmap on 27 March 2018, the government presented the planned roll-out for the further realisation of offshore wind energy for the period 2024 through to 2030. This 2030 Roadmap included the timetable and the selection of certain designated wind energy areas for the period leading up to 2030. As with the wind energy areas defined previously in the 2023 Roadmap, the Framework for Assessing Ecological and Cumulative Effects (KEC) for this roadmap was used to investigate the situation of marine mammals, and harbour porpoises in particular, to determine whether there is enough ecological latitude to implement the planned roll-out. Recent EU agreements make it necessary to raise the target for the contribution of renewable energy to the total requirement by 2030 (to 55% instead of 49%). Some of the original plans for the roll-out in 2030-2040 of 27 GW of additional installed capacity will therefore have to be implemented earlier. To meet the reduction target of 55% by 2030, 10 GW of windfarm capacity will be needed in addition to the wind farms that have already been planned and completed, which have a combined capacity of some 10 GW. The government must therefore designate new wind energy areas in order to be in a position to realise additional wind farms in the period prior to 2030. For the purpose of selecting those areas, search areas have been selected where development is expected to be possible within that time frame.

An update of the KEC is necessary for the wind farms in these newly selected areas. In this update, the analysis of the cumulative effects of the construction of the wind farms in these areas have, in addition to harbour porpoises, taken harbour and grey seals into consideration. No ecological standard is available for the two seal species at present. As a working standard, the same ecological standard used for harbour porpoises has been adopted:
With the construction of offshore wind farms, the populations of harbour porpoises, harbour seals and grey seals on the Dutch Continental Shelf (DCS) must be maintained at a minimum of 95% of the present level with a high degree of certainty (>95%) (in other words, the probability of a population reduction ≥ 5% must be ≤ 5%).

This report sets out the results of the study of the cumulative effects of the construction of offshore wind farms in the period 2016-2030, including three calculation variants for the impact of the accelerated construction of wind farms in the Dutch section of the North Sea on marine mammals. The results are compared with the effects of wind farm construction in the international North Sea. As in the KEC 3.0 (2019), the steps in the 2015 staged procedure have been updated on the basis of the most recent knowledge where necessary. The same staged procedure has been used for seals as for harbour porpoises, and the steps have been further elaborated with respect to the background report accompanying the KEC 1.0 by Heinis & de Jong et al. (2015).

The results of the calculations show that the accelerated construction of offshore wind energy in the period 2016-2030 is possible only if the sound standard

proposed in the KEC 3.0 of SELss[1] (750 m) = 168 dB re 1 $\mu Pa^2 s$ is made stricter. That is because, with this sound standard, there is a 5% probability that the number of harbour porpoises on the DCS will fall by 6-8%. This exceeds the ecological standard adopted for harbour porpoises. The results of the calculations also show that no cumulative effects on seals may be expected as result of the accelerated construction of offshore wind energy. The ecological working standard for seals will therefore not be exceeded. Given the assumptions used and a sound standard of SELss (750 m) = 168 dB re 1 $\mu Pa^2 s$, permanent effects on the hearing of harbour porpoises and seals can be excluded. If a single universal sound standard is assumed of SELss (750 m) = 160 dB re 1 $\mu Pa^2 s$ for the construction of the IJmuiden Ver ('old' 2030 Roadmap) plus search areas for the acceleration and the sound standards set out in the site decisions for the wind farms planned in the Energy Agreement, it has been calculated for the scenarios described in this report that, for the entire period up to and including 2030, the probability is higher than 95% that the harbour porpoise population on the DCS will decline by no more than 2.3-2.9%. This means that, as a result of the construction of offshore wind farms in the period 2016-2030, there is a high degree of certainty that the harbour porpoise population will remain at a level of at least 97% of the current average population.

The calculations were based on worst-case principles. The margin of uncertainty can be significantly reduced by conducting further research. This may lead to smaller calculated effects for harbour porpoises.
The main uncertainties are:

- The non-inclusion of the frequency-dependent sensitivity of hearing when calculating the effects of sound on behaviour, whether mitigated or not;
- The 'interim' nature of the Interim PCoD model used; the further development of this model is required to determine the cumulative effects of disturbance more accurately;
- The 'home range' of individual harbour porpoises in the Dutch section of the North Sea;
- Seasonal variation in the distribution of harbour porpoises in the Dutch section of the North Sea.

In addition, the application of alternative, low-noise techniques will result in smaller calculated effects.

[1] SELss (750 m) is the unweighted broadband sound exposure level generated by a single piling strike (*Single Strike Sound Exposure Level*) at 750 m from the piling location (in other words, the source of the sound).

Contents

Foreword

The Aanvullend Ontwerp Programma Noordzee 2002-2027 (Additional Draft North Sea Programme 2022-2027), which was made available for public inspection on 9 November 2021, contains a description of the Dutch government's stronger ambitions for the development of offshore wind energy through to 2030. The document identified new search areas in addition to the wind energy areas designated in the original 2030 Offshore Wind Roadmap. The present report looks at whether this accelerated development of offshore wind energy through to 2030 is possible without exceeding the ecological standard set for marine mammals. It sets out the underlying arguments for the marine mammals component of the Framework for Assessing Ecological and Cumulative effects (KEC) 4.0 and it updates the relevant part of the KEC 3.0.

The study was conducted at TNO in partnership with HWE (Floor Heinis, reporting) by Christ de Jong (analysis, reporting), Sander von Benda-Beckmann (analysis, Interim PCoD modelling, reporting), Bas Binnerts and Paul de Krom (underwater sound modelling) and Victor Oppeneer (Interim PCoD modelling). As part of the project, Geert Aarts and Sophie Brasseur of Wageningen Marine Research drew up new density maps for harbour seals and grey seals based on the available data from tagged seals. Those maps were then used by TNO in the calculations. Pete Thomas translated the original Dutch version of the report into English. Frans-Peter Lam led the project. During the study, there were two consultation meetings with the Marine Mammals and Underwater Sound Working Group at which the adopted approach and the results of the analyses were discussed. The working group consists of specialists from Rijkswaterstaat, the Ministry of Agriculture, Nature and Food Quality and the Ministry of Defence, and researchers from Wageningen Marine Research, Utrecht University and Seamarco. Peter Beerens was responsible for quality control at TNO.

The project was supervised by Martine Graafland (of Rijkswaterstaat Zee en Delta) on behalf of the client, Rijkswaterstaat Water, Traffic & Environment (WVL). She was also the point of contact for all information about the scenario and the calculation variants. Within Rijkswaterstaat, Martine Graafland was supported by Niels Kinneging and other members of the Wozep-team. An earlier version of this report has been reviewed both nationally (relevant ministries, including Rijkswaterstaat) and internationally. The comments have been incorporated in this final version of the report.

1 Introduction

1.1 Background

In recent decades, the knowledge about, and understanding of, the potential effects of piling sound on the marine mammals (harbour porpoises, seals) that are dominant in the North Sea have increased significantly. That knowledge has been included in the 'Framework for Assessing Ecological and Cumulative Effects' (KEC). This assessment framework includes an approach for determining and assessing the cumulative effects of the impulsive underwater sound produced during construction on important populations of marine mammals (KEC 1.0, underwater sound section: Heinis & de Jong, 2015).

The Dutch national Energy Agreement, which was signed in 2013, provided for the development of wind farms in the wind energy areas of Borssele, Hollandse Kust (south) and Hollandse Kust (north) in the period prior to 2023. The effects of underwater sound from wind farm construction in these areas were assessed using KEC 1.0 and the minor update in 2016 (KEC 2.0), which included an ecological standard for the acceptable level of impact on the harbour porpoise population.

With the publication of the 2030 Offshore Wind Energy Roadmap on 27 March 2018, the government presented the planned roll-out for the further realisation of offshore wind energy for the period 2024 through to 2030. This roadmap included the timetable and the selection of certain designated wind energy areas for the period leading up to 2030. The site decisions for the development of offshore wind energy in these areas will also have to be assessed using the KEC. The KEC from 2016 was updated for this purpose so that the three new wind energy areas Hollandse Kust (west), Ten noorden van de Waddeneilanden and IJmuiden Ver were also included. This update, KEC 3.0, was published in early 2019 (www.noordzeeloket.nl/functies-gebruik/windenergie-zee/ecologie/cumulatie/kader-ecologie/). It incorporated the results of recent research and the latest insights in the field of the effects of impulsive underwater sound. It also set limits for the levels of underwater sound produced during construction (sound standard) to ensure that the ecological standard determined previously for harbour porpoises will not be exceeded.

Recent EU agreements make it necessary to raise the target for the contribution of renewable energy to the total requirement by 2030 (to 55% instead of 49%). Some of the original plans for the roll-out in 2030-2040 of 27 GW of additional installed capacity will therefore have to be implemented earlier. To meet the reduction target of 55% by 2030, at least 10 GW of windfarm capacity will be needed in addition to the wind farms that have already been planned and completed, which have a combined capacity of some 10 GW. In addition, there is an as-yet-unplanned remainder of 0.7 GW that will be needed to meet the 49% reduction target. The '2022-2027 North Sea Programme' has therefore set aside space for 10 GW + 0.7 GW of extra installed capacity for 2030. The additional 17 GW will be included in a later, partial revision of the 2022-2027 North Sea Programme in order to meet the overall target of 27 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). Search areas have been selected where development is expected to be possible within that time frame. The areas being considered for that purpose are shown in Table 1.1 below, together with the wind energy areas from the Energy Agreement and the original 2030 Roadmap, the cumulative effects of which were assessed using KEC 1.0/2.0 and KEC 3.0 respectively. The location of the wind energy areas in Table 1.1 and other as yet undesignated search areas for wind energy development can be found in Figure 1.1.

The cumulative effects determined in accordance with the KEC approach will also have to be determined for the wind farms in these newly designated areas. In addition to an update of the offshore wind scenarios, a number of improvements to the KEC procedure have been implemented. For example, the methodology has been extended in order to include the effects on populations of harbour seals and grey seals, more recent data on population densities in the North Sea have been used and the determination of the number of animals disturbed around a piling location has been improved by using new dose-effect relationships instead of the discrete threshold for disturbance used in previous KEC versions.

Table 1.1 Wind energy areas on the DCS where construction activities have begun or may begin in the period 2016-2030.

Wind energy area/site	**Size (MW)**	**Operational**	
Borssele III/IV	2 x 366	2019	KEC 1.0/2.0
Borssele I/II	2 x 376	2020	KEC 1.0/2.0
Borssele V	2 x 9.5	2020	KEC 1.0/2.0
Hollandse Kust (South) I/II	2 x 385	2021	KEC 1.0/2.0
Hollandse Kust (South) III/IV	2 x 385	2022	KEC 1.0/2.0
Hollandse Kust (North)	700	2022	KEC 1.0/2.0
Hollandse Kust (West) VI/VII	1,400	2024	KEC 3.0
Ten noorden van de Waddeneilanden	700	2026	KEC 3.0
IJmuiden Ver	4,000	2027	KEC 3.0
Hollandse Kust (West) southern section	700	2028	KEC 4.0, this report
IJmuiden Ver (North)	2,000	2028	KEC 4.0, this report
Search area 5 (East)	4,000	2029	KEC 4.0, this report
Search area 2 (North)	4,000	2030	KEC 4.0, this report
Search area 1 (South)	2,000	2030	KEC 4.0, this report
Search area 1 (North)	4,000	2030	KEC 4.0, this report
Areas to be selected	Total approximately 11 GW	2030-2040	KEC x.x

1.2 Objective

The objectives of the KEC 4.0 for the underwater sound component and marine mammals are:

- To update the steps in the staged procedure adopted in the KEC 1.0/2.0 and the KEC 3.0 to determine the cumulative effects of the realisation of offshore wind energy on the harbour porpoise, harbour seal and grey seal populations.

- To update the density maps for harbour porpoises, harbour seals and grey seals in the North Sea.
- On the basis of the updated steps, to calculate the cumulative effects of the realisation of offshore wind energy on the populations of the three marine mammal species in the period 2016-2030 (wind energy areas in the KEC 3.0 and the acceleration variants).
- The derivation of an acceptable level of impact on the populations of harbour and grey seals (ecological standard) and the submission of the results to the competent authority (Ministry of Agriculture, Nature and Food Quality).
- Research into the effects on populations of different sound standards for wind farms to be built in the period up to and including 2030 for which no sound standards have yet been adopted in site decisions; the imposition of a sound standard will ensure that the ecological standard for populations of harbour porpoises, harbour seals and grey seals is not exceeded.

1.3 Scope

The construction of wind farms in the Netherlands is based on the agreements in the Energy Agreement and the 2030 Roadmap[2], as well as three calculation variants supplied by Rijkswaterstaat for the possible acceleration of construction activity in the years 2027 through to 2030. An overview of the wind farms and wind energy search areas in the different variants can be found in Table 1.2.

As in the KEC 3.0, this KEC 4.0 for marine mammals has, in addition to the sound from piling for the construction of the wind turbines in the wind farms included in Table 1.2, taken the following sources of impulsive sound into account:

- Sound produced during the geophysical surveys prior to the construction of the wind farms and for the purposes of the routing of the cables; the associated effects have been looked at separately but not included in an integrated way in the calculation of effects on populations (see also Section 3.4);
- Piling sound generated during the construction of the transformer platforms;
- Piling sound generated by the construction of wind farms in the non-Dutch section of the North Sea; this is particularly relevant for harbour porpoises because it has been assumed that the harbour porpoises on the DCS are part of the larger North Sea population.

[2] See https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/windenergie-op-zee

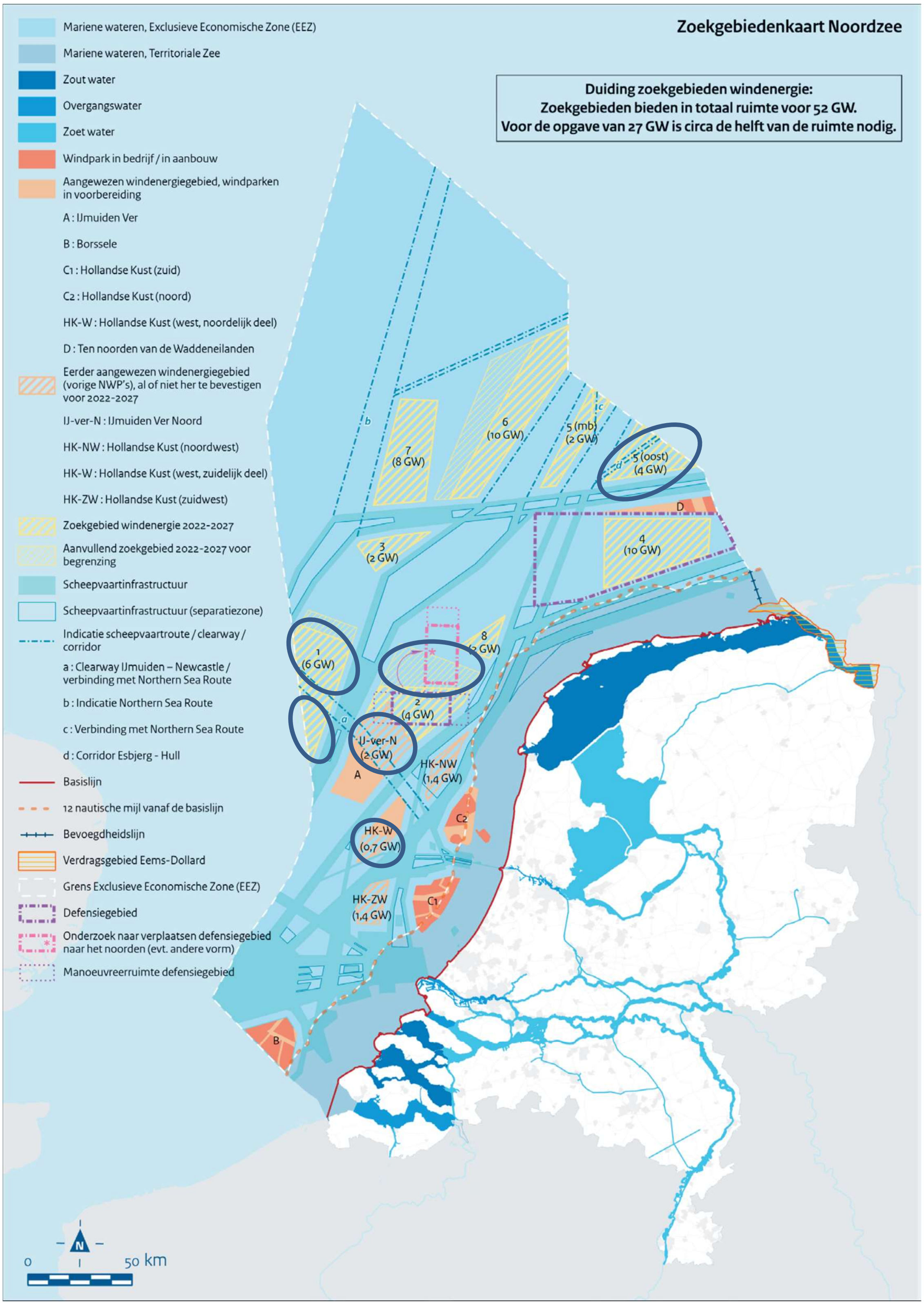

Figure 1.1 Realised wind farms and search areas for wind energy on the DCS, map from '2022-2027 Draft North Sea Programme' (Ministry of Infrastructure and Water Management, March 2021). Blue ovals: search areas for which calculations have been made in this KEC 4.0 (see also Table 1.1).

Table 1.2 Wind farms from the Energy Agreement/2030 Roadmap and search areas for the acceleration of the realisation of offshore wind energy in the period 2027-2030 in three variants. See Figure 1.1 for the location of completed and planned wind farms and the search areas for the acceleration.

Energy Agreement and old 2030 Roadmap	**Variants for 2027-2030 (acceleration – 2030)**		
	I	**II**	**III**
Borssele III/IV	Hollandse Kust (West) southern section	Hollandse Kust (West) southern section	Hollandse Kust (West) southern section
Borssele I/II	IJmuiden Ver (North)	IJmuiden Ver (North)	IJmuiden Ver (North)
Borssele V	Search area 5 (East)	Search area 5 (East)	Search area 5 (East)
Hollandse Kust (South) I/II	Search area 2 (North)	Search area 2 (North)	Search area 2 (North)
Hollandse Kust (South) III/IV		Search area 1 (South)	Search area 1 (South)
Hollandse Kust (North)			Search area 1 (North)
Hollandse Kust (West) VI/VII			
Ten noorden van de Waddeneilanden			
IJmuiden Ver			
approx. 10 GW	**10.7 GW**	**12.7 GW**	**16.7 GW**

The calculations for the KEC 4.0 look exclusively at the cumulative effects on harbour porpoises, harbour seals and grey seals of impulsive sound produced by the construction of offshore wind farms. The following sources of underwater sound have therefore not been included:

- Impulsive sound produced during seismic exploration for the extraction of oil and gas; this factor has, theoretically, been present up to a certain level for years; the calculations of the effects on the population are implicitly taken into account in the Interim PCoD model by the selected population-dynamic parameters[3];
- Military sonar systems due to the fact that these systems make only a very limited contribution to the total amount of underwater sound in the Dutch part of the North Sea (Ministry of Infrastructure and the Environment 2012; Ainslie et al., 2009);
- The sound from the clearance of ordnance because this is always a short sound burden in which hearing damage is a more important aspect than disturbance (see, for example, Aarts et al., 2016);
- Sound produced during the installation of turbine foundations using techniques other than piling (including vibropiling or blue piling). Results from pilot projects have shown that a substantial sound reduction can be achieved with these techniques (see review by Verfuss et al., 2019). Although techniques of this kind are promising, they have not yet been applied in practice for offshore wind (see also Chapter 5, Uncertainties and Gaps in Knowledge);
- 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 (see also

[3] The Dutch government is developing a staged procedure that can be used to test any additional seismic activity that exceeds a certain baseline level. This will allow an assessment for permit purposes, if necessary subject to certain conditions.

Chapter 5, Uncertainties and Gaps in Knowledge); 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);

- Sound from the Acoustic Deterrent Devices (ADD) used prior to piling. These are used to drive marine mammals located a short distance from the piling location far enough away to prevent the risk of permanent hearing damage (PTS). This disturbance lasts a shorter time and results in smaller disturbance distances than those caused by piling, which means that this effect is cancelled out by the effects of the piling;
- Sound produced during the decommissioning of wind farms; 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 (see Chapter 5, Uncertainties and Gaps in Knowledge).

1.4 Approach

As explained above, the intention behind the KEC is to assess the future development of offshore wind on the basis of a given ecological standard. If this ecological standard is exceeded, restrictions are imposed on the activity (in this case a maximum permissible sound level). The KEC therefore provides an insight into possible exceedances of ecological standards but it is not a framework for the issuing of permits for individual projects. To calculate the effect of impulsive sound on the population, different steps (intermediate variables) must be used, each of which is associated with individual uncertainties. The steps and the associated uncertainty levels – the ‘staged procedure’ – have been described in Heinis & de Jong et al. (2015). For the purposes of this new KEC 4.0, the steps will not change but the calculation of each stage has been adjusted when the results of new studies and recent insights relating to effect relationships justify doing so.

For the harbour porpoise and the grey seal, all the steps in the staged procedure have been quantified as well as possible. That involved the use of insights acquired during EIA procedures, new distribution maps produced in the context of the KEC 4.0 and the latest literature on the relationships between the development of offshore wind and the impact on seals. An ecological standard was proposed in June 2021 for both seal species for the purpose of assessing the possible cumulative effects of the development of offshore wind energy. This standard, which is comparable to the ecological standard for harbour porpoises, was used as the ‘working standard’ in the calculations for the KEC 4.0. The relevant grounds have been set out in the memorandum in Annex A to this report.

On the basis of the new insights relating to the effect relationships, improvements were first implemented in the KEC procedure. The new procedure was then applied to the wind farms in the Energy Agreement (Borssele, Hollandse Kust (South) and Hollandse Kust (North)) and the three new wind energy areas Hollandse Kust (West), Ten noorden van Waddeneilanden and IJmuiden Ver. The calculations for the new wind energy areas were initially performed using the sound standard – SEL_{SS} (750 m) = 168 dB re 1 μPa^2s – derived in the KEC 3.0 for the wind energy areas in the 2030 Roadmap. That resulted in a picture of the potential to accelerate the construction of wind farms in the period 2027-2030 within the current system of standards, while incorporating the latest insights. On the basis of the underlying assumptions that were adopted, it was found that this potential was not present for harbour porpoises. An investigation was therefore also conducted into whether accelerated construction with a stricter sound standard *is* possible.

1.5 Report structure

After this first chapter, which describes the background, objective, scope and general approach, Chapter 2 describes and updates the steps in the staged procedure for determining and assessing the cumulative effects of the construction of offshore wind farms on marine mammals. In Chapter 3, the updated procedure is applied to the determination of the cumulative effects of the construction of offshore wind farms on the populations of harbour porpoises, harbour seals and grey seals in the North Sea in the period 2016-2030. That chapter presents the results of the calculations for the period in question for three variants relating to the accelerated construction of offshore wind farms in the Dutch sector of the North Sea in an international scenario. Chapter 4 describes how the effects calculated in Chapter 3 can be reduced and it describes the effect of a further reduction in sound production on the harbour porpoise population. Uncertainties and gaps in knowledge are described in Chapter 5 and Chapter 6 sets out the principal conclusions. The report also includes a list of references and eight annexes.

2 The determination of the cumulative effects of the development of offshore wind on marine mammals

2.1 Overview of the steps in the staged procedure

To determine the cumulative effects of impulsive sound on harbour porpoises and seals due to the construction of offshore wind farms, a staged procedure was developed for the KEC 1.0 to quantify the various steps in the effect chain (Heinis & de Jong et al., 2015). This staged procedure was used again in KEC 3.0 to quantify and assess effects on the harbour porpoise population (Heinis & de Jong et al., 2019). In KEC 4.0, the staged procedure once again constitutes the underlying principle for the quantification of the cumulative effects of impulsive sound on harbour porpoises, harbour seals and grey seals. The assumption in that respect is that there will be no permanent effects on hearing (*Permanent Threshold Shift,* PTS) because these effects – even supposing they could occur – can be eliminated by preventive measures (see Section 2.8 for the underlying arguments). The following steps have been defined (Figure 2.1):

1. The calculation of a realistic worst case for the propagation of sound resulting from a single pile-driving strike for each wind farm; this calculation is based on information about the source strength, local factors (including bathymetry and bed 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 of the sound;
2. The calculation of the size of the area disturbed by impulsive sound for each wind farm. The calculated sound propagation and a threshold value or dose-effect relationship for the occurrence of a significant behavioural change are the determining factors here;
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 in each season;
4. The calculation of the number of animal 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 model (version 5.2);
6. The assessment of the estimated population reduction and appraisal with reference to the ecological target set by the government for harbour porpoises (Ministry of Economic Affairs and Climate & Ministry of Infrastructure and the Environment 2016 a, b) and seals (see the advisory report submitted to the Ministry of Agriculture, Nature and Food Quality in Annex A).

In the sections that follow here, the different steps in the staged procedure for harbour porpoises and seals are discussed in more detail and a description is given of the improvements that have been made with respect to the KEC 3.0 version on the basis of recent insights and research results.

2.2 Calculation of sound propagation

The aim of calculating the sound propagation is to estimate how many harbour porpoises and seals may be affected by the sound levels during piling and by geophysical research activities. These effects may manifest themselves in the form of a behavioural response, such as faster breathing and swimming away from the source of the sound, or in the form of a physiological effect on hearing in which animals suffer a temporary (TTS: temporary threshold shift) or permanent (PTS: permanent threshold shift) impairment of hearing as a result of prolonged exposure to increased sound levels.

As in the KEC 3.0, the Aquarius 4 model, which was further developed in the context of the Offshore Wind Energy Programme (WOZEP)[4] was used for the calculation of sound propagation in the KEC 4.0. See Annex B 'Modelling piling sound' and de Jong et al. (2018) for further details relating to the modelling approach that was adopted.

The use of the Aquarius 4 model results in calculation results for broadband sound that are a good match for the broadband sound levels measured in the field (de Jong et al., 2018). The calculations are based on the scenarios supplied by Rijkswaterstaat. To calculate the effects on marine mammals, Aquarius 4 generated underwater sound maps.

[4] For more information about WOZEP (in Dutch), see https://zoek.officielebekendmakingen.nl/kst-33561-26.html and www.noordzeeloket.nl/functies-gebruik/windenergie/ecologie/wind-zee-ecologisch-programma-wozep/

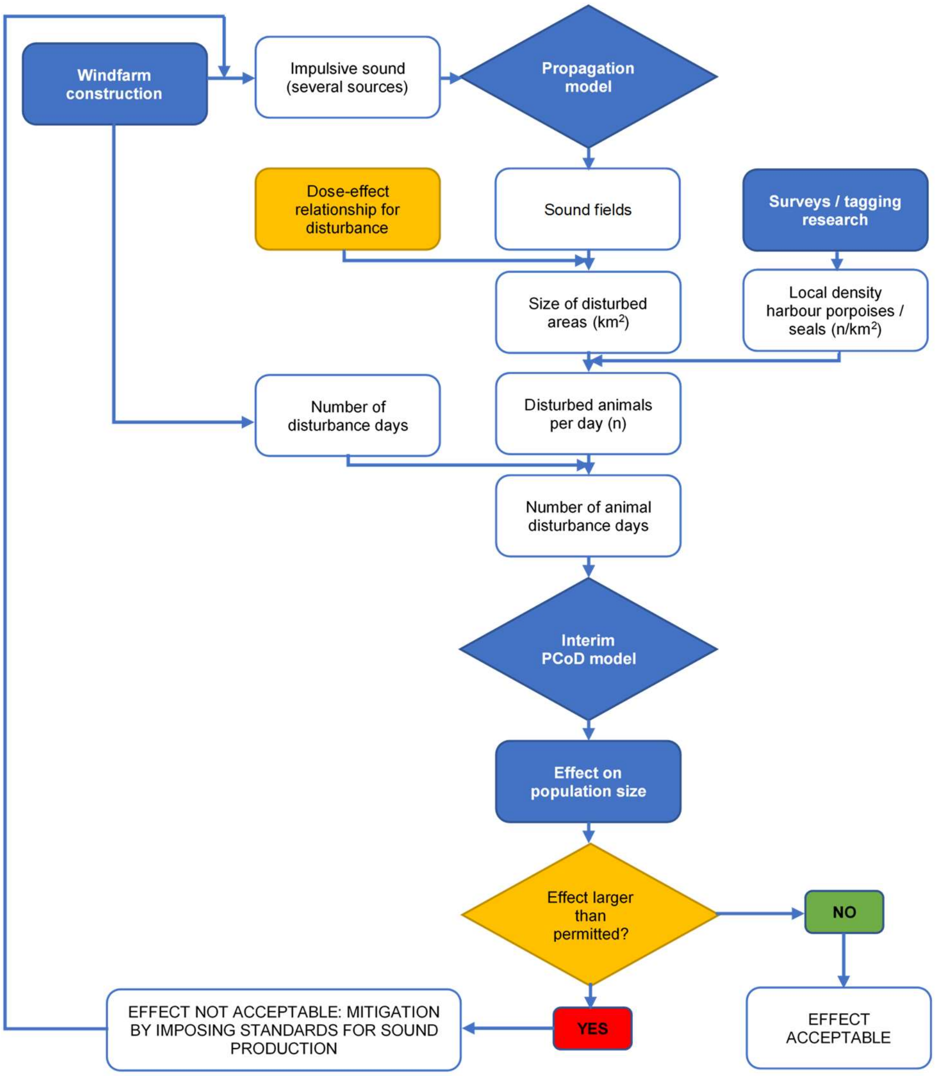

Figure 2.1 Schematic representation of the steps in the staged procedure for determining and assessing the cumulative effects of impulsive underwater sound on harbour porpoises and seals during the construction of wind farms.

2.3 Dose-response relationship

Relationships between the sound level (unweighted broadband Single Strike Sound Exposure Level) and the occurrence of a significant behavioural response[5] were derived as much as possible from recent peer-reviewed literature. It was assumed here that the sound energy from a single, maximum, piling strike determines the possible occurrence of a significant behavioural change (disturbance). By contrast with previous KECs, a dose-response relationship was used rather than a discrete threshold value of SEL_{SS} = 140 dB re 1 $\mu Pa^2 s$ for the calculations in the KEC 4.0. This means that the calculations take into account differences in the probability of the disturbance of animals that are close to the piling location at the start of the piling activities, where the sound level is higher, and animals that are further away.

[5] Behaviour with a score of 5 or higher on the behavioural response severity 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).

In the case of harbour porpoises, this relationship was estimated on the basis of observations around piling activities in the Netherlands, Germany and Scotland (see, among others, Geelhoed et al., 2018, Brandt et al., 2018, Graham et al., 2019) and the relationship for seals was estimated on the basis of Kastelein et al. (2011), Russell et al. (2016), Whyte et al. (2020) and Aarts et al. (2018). The relationships used for harbour porpoises, harbour seals and grey seals are shown in Figure 2.2 (see Annex C for more details about the derivation of the relationships).

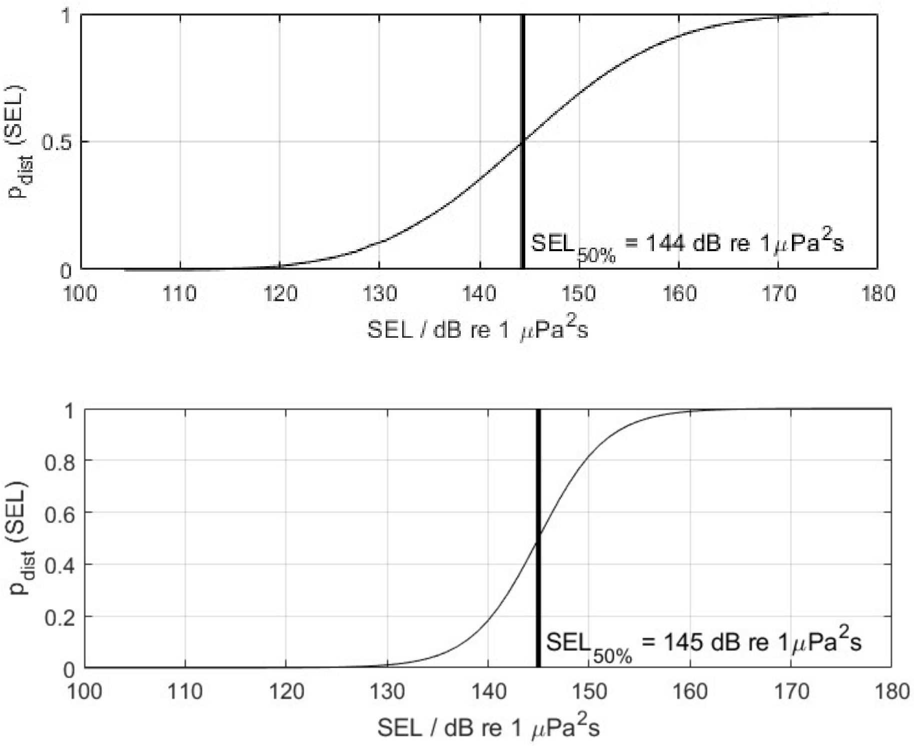

Figure 2.2 Relationships between sound dose (Single Strike Sound Exposure Level) and probability of occurrence of a behavioural response in harbour porpoises (above) and seals (below). On the basis of a comparison of observations from Russell et al. (2016) and Whyte et al. (2020) for harbour seals and from Aarts et al. (2018) for grey seals, it is assumed that the responses of harbour and grey seals are comparable. The vertical line and the $SEL_{50\%}$ value shown in the figures indicate at which SEL there is a 50% probability of the animals being disturbed.

2.4 Surface area disturbed by impulsive sound

The area around the piling location in which animals may be disturbed by the piling sound was calculated using the underwater sound maps generated with the Aquarius 4 model showing the propagation of sound resulting from a single piling strike (SEL_{SS}). Examples of sound maps for harbour porpoises and seals can be found in Figure 2.3. On the basis of the relationships shown in Figure 2.2, an *effective disturbance area* for harbour porpoises, harbour seals and grey seals can be calculated for each wind energy area (see Annex C for further explanation). In the case of the IJmuiden Ver (North) wind energy area shown in Figure 2.3, this is 1344 km^2 for harbour porpoises and 358 km^2 for seals.

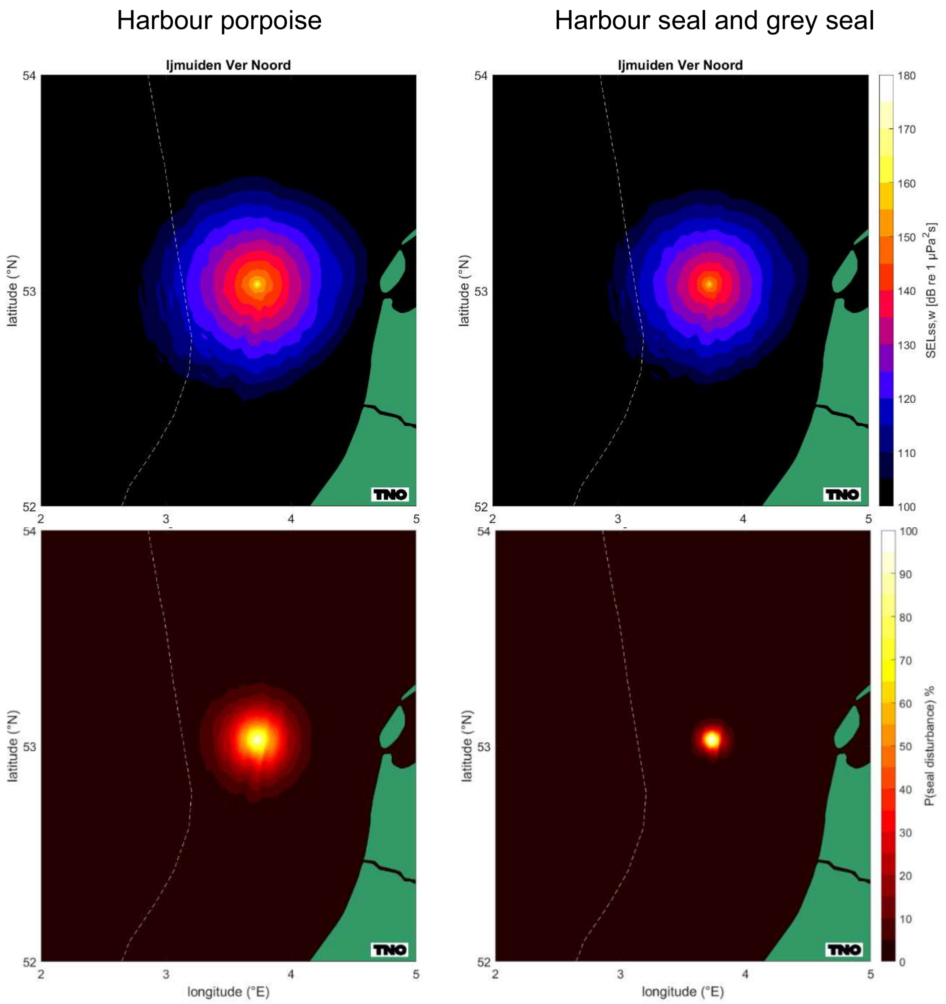

Figure 2.3 Calculated distribution of SEL_{SS} during piling involving the application of a sound standard of 168 dB re 1 μPa^{2}s in wind energy area IJmuiden Ver (North) (top) and the percentage probability of disturbance (bottom) for harbour porpoises (left) and seals (right). The same dose-response relationship has been assumed for harbour seals and grey seals (see Annex C for further details). The white dashed line is the UK-Dutch border.

2.5 Calculation of the number of disturbed animals

The number of animals disturbed per piling day and per wind energy area was calculated for the three species by calculating the probability of a behavioural response (disturbance) for each point in the sound map (see Section 2.3), and multiplying it by the area of the grid cell around the point and by the local estimate of the density of animals at this point. The values obtained in this way were then totalled. The implicit assumption here is that, during the piling work for one foundation (approx. 2 hours), there is limited movement of animals to or through the disturbed area and that the density returns to normal again by the time the next foundation is driven. For a discussion of the sensitivity of the model outcomes to disregarding animal movement during piling, the reader is referred to Annex D.

For **harbour porpoises**, the local density was derived from the map drafted by Gilles et al. (2020) for Rijkswaterstaat (Figure 2.4). This is an update of the summer density map for harbour porpoises by Gilles et al. (2016), supplemented with data

from the 2016 SCAN-III survey and annual summer counts from Belgium, the Netherlands (by Wageningen Marine Research), Germany and Denmark during the period 2014 – 2019. The KEC 4.0 is based on this map because it takes the result of counts (primarily aerial counts) into consideration alongside the variables that determine habitat suitability. The map therefore gives a more reliable estimate of the average numbers of harbour porpoises. On the basis of this map, an average size of the North Sea population of 373,310 animals has been calculated. In the Dutch part of the North Sea, this concerns an average of 62,771 animals, i.e. 17% of the total.
Due to the lack of up-to-date maps for the other seasons, it was assumed for the purposes of this study that the average distribution map from Gilles et al. (2020) applies to the entire year (see also Chapter 5, Uncertainties and Gaps in Knowledge).

To make an estimate of the number of seals on the DCS that are disturbed when piling starts, the composite maps from Aarts et al. (2021) were adopted for the purposes of the KEC 4.0. Those maps model, on the basis of all the available tagging data, the density of harbour seals and grey seals for each month (see Aarts et al. 2016 for a description of the methods). The maps for the month of July are shown in Figure 2.5 as an example. The average density per season (spring = March-May, summer = June-August, autumn = September-November and winter = December-February) was used in the calculations. The annual average is 55,418 harbour seals and 19,559 grey seals on the maps shown in the figure. On the Dutch part, there are 18,363 harbour seals and 14,787 grey seals, which is 33% and 76% of the total respectively.

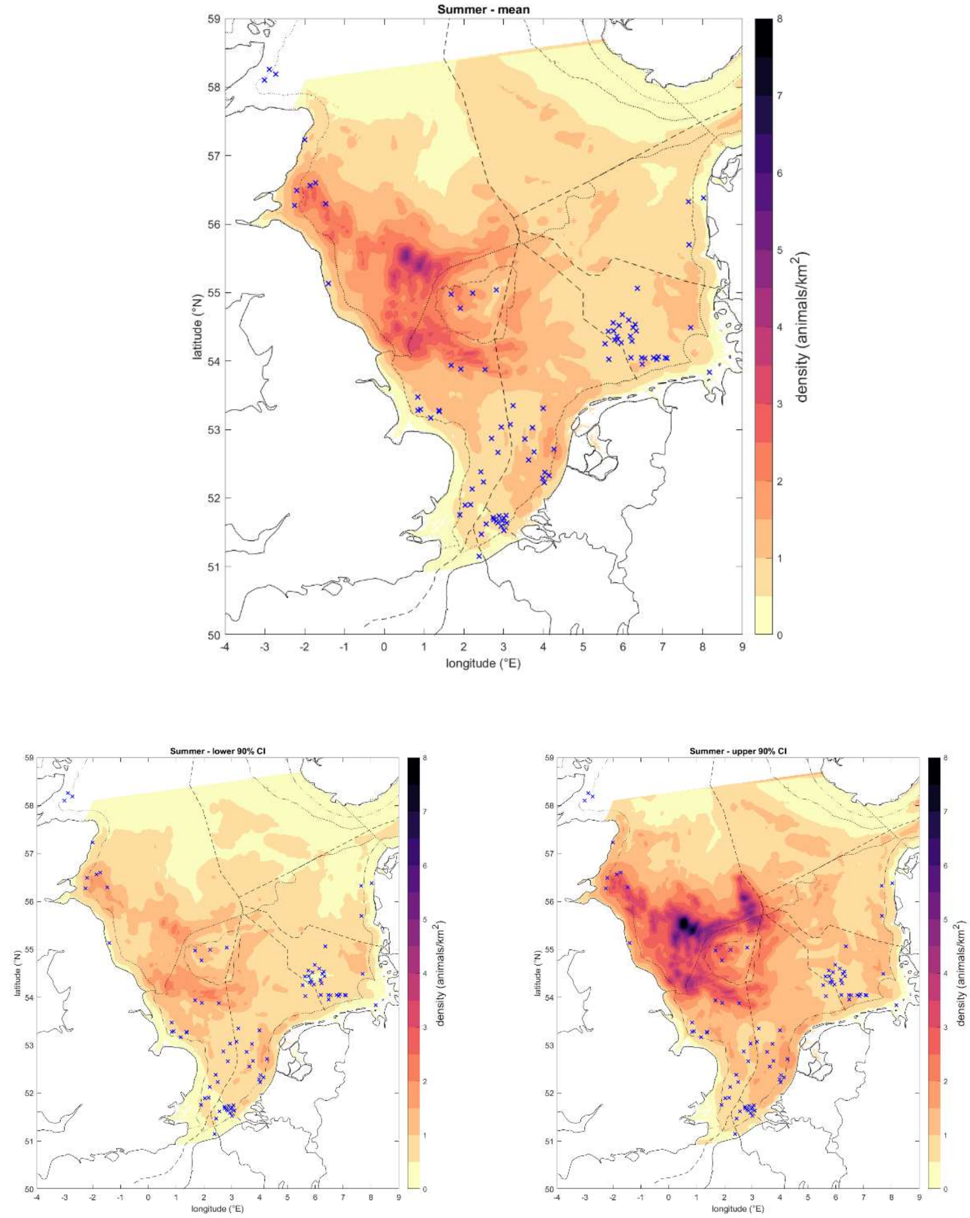

Figure 2.4 Estimate of harbour porpoise density in the southern North Sea during the period 2014-2019 (after: Gilles et al., 2020). The three maps show the calculated mean density (top), and the lower and upper limits of the 95% confidence interval (bottom, left and right, respectively). Crosses: the selected sites in each wind farm/wind energy area for which calculations were made.

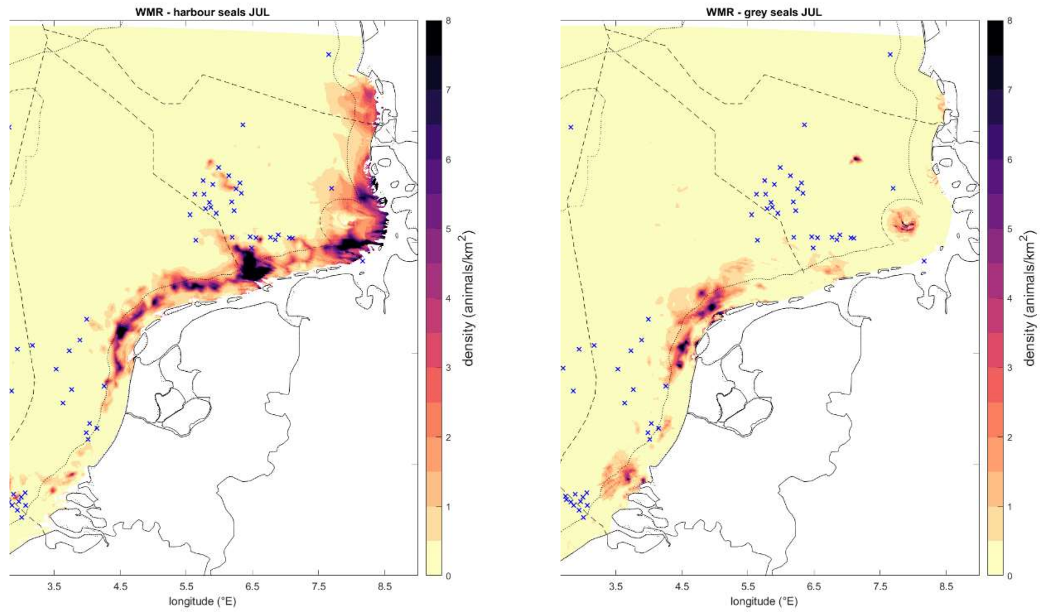

Figure 2.5 Estimate of the mean density of harbour seals (left) and grey seals (right) in July (after Aarts et al., 2021).

2.6 Determining the effects on the population

To determine the effects of piling sound on marine mammal populations, the approach developed in the context of the KEC (Heinis & de Jong et al., 2015) and updated in 2018 (Heinis & de Jong et al., 2019) was used as the basis for the wind farms in the 2030 Roadmap and the calculation variants for the acceleration. Improvements that were introduced for the KEC 4.0 have been described in the previous sections. For the determination of the possible effects of piling sound on marine mammals, the effects on behaviour have been adopted as the criterion and it has been assumed that mitigation measures (the use of 'slow start' and sound standards, where appropriate in combination with Acoustic Deterrent Devices) will prevent permanent effects on hearing (PTS).

It was decided to use the Interim Population Consequences of Disturbance (PCoD) model from the SMRU/St. Andrews University (Harwood et al., 2013) for the three marine mammal species. The approach underpinning this model is used internationally (NRC 2005; New et al., 2014), which means that not only the method but also the results are internationally comparable (see Intermezzo *Calculating the effects of disturbance on populations of marine mammals*). The Interim PCoD 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 and reproductive success (the *vital rates*). The relationship was derived by consulting experts in a formal expert elicitation process since monitoring data for the development of a full PCoD model (cf. New et al., 2014) are lacking. 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 results were incorporated in version 5.0 of the iPCoD model, which was released for general use in March 2019 (http://www.smruconsulting.com)[6]. The calculations for the KEC 4.0 used the latest version of the iPCoD model (version 5.2).

The total number of **animal disturbance days** was calculated by multiplying the number of animals that may be disturbed on one day by the number of **disturbance days**. The iPCoD model assumes that each day of piling (irrespective of the duration of piling) will result in a six-hour disturbance for all harbour porpoises inside the disturbance contour. A longer disturbance duration of 24 hours was assumed in the model for seals, despite agreement by the experts during the expert elicitation that this leads to the duration of disturbance being overestimated. For example, Russell et al. (2016) have shown that harbour seals are disturbed for a much shorter period of time (approx. 4 hours: duration of piling + 2 hours).

Intermezzo: Calculating the effects of disturbance on populations of marine mammals

Another model, DEPONS (Disturbance Effects on the harbour POrpoise population in the North Sea), estimates the effects of disturbance resulting from piling sound on the harbour porpoise population on the basis of the movement and behaviour of individual harbour porpoises (Agent-Based Modelling, ABM, or Individual-Based Modelling, IBM). This model was not yet available at the time of the KEC 1.0 (Van Beest et al., 2015, Nabe-Nielsen et al., 2014). A first version for general application became available in April 2017. An update to that version has since been released and it can be downloaded from depons.au.dk.

In addition to safeguarding international comparability, an important reason for working with the Interim PCoD model in the case of harbour porpoises is the lack of data for the southern section of the North Sea relating to the movement and behaviour of individuals in space and time. Data of this kind are available for seals and the energetic consequences of an interruption in foraging options on the basis of the location and diving data can, in principle, be calculated (see, for example, New et al., 2014 and Costa 2012). A model using these data and focusing on the calculation of the cumulative effects of impulsive sound on seal populations is being developed (WMR, G. Aarts c.s.) but it is not yet available.

Effects on populations of harbour seals and grey seals have therefore, as in the case of harbour porpoises, been determined with the most recent version of the Interim PCoD model.

2.7 Effect assessment and appraisal on the basis of the ecological standard

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. In the permit procedure for sites I and II of the Borssele wind energy area, an ecological standard for harbour porpoises – namely an acceptable level of impact – was adopted, in part on the basis of the recommendations from the EIA Commission, for the wind farms in the Energy Agreement with a corresponding system of sound standards. The relevant principles have been set out in the 2016 KEC update (Ministry of Economic Affairs & Ministry of Infrastructure and the Environment 2016b). The guiding

[6] A beta version of the updated Interim PCoD model was already used in 2018 for the KEC 3.0 calculations of the cumulative effects on the harbour porpoise population (see Heinis et al., 2019).

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 certainty (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.

The KEC 3.0 and KEC 4.0 are based on the same ecological standard for harbour porpoises (i.e. the acceptable level of impact) as in 2016. This means that the reduction of the harbour porpoise population estimated with a high degree of certainty as a result of the construction of wind farms on the DCS in the period leading up to 2030 may not exceed 5% (and that it must preferably be less). In consultations with the Ministry of Agriculture, Nature and Food Quality on 9 June 2021, it was proposed for the purposes of the KEC 4.0 that there should be an assessment of any cumulative effects on populations of harbour seals and grey seals based on the same ecological standard as the standard for harbour porpoises (see Annex A). The Ministry has acknowledged that this is a safe limit and proposes using this standard as a working standard in the KEC 4.0 rather than adopting it at the present time.

The following ecological standard has therefore been adopted as one of the underlying assumptions in the KEC 4.0:
“With the construction of offshore wind farms, the populations of harbour porpoises, harbour seals and grey seals on the DCS must be maintained at a minimum of 95% of the present level with a high degree of certainty (>95%) (in other words, the probability of a population reduction of more than 5% may not exceed 5%).”

If the ecological standard for harbour porpoises or seals are expected to be exceeded, wind farms may be constructed only if mitigating measures are taken that ensure the ecological standards will be met. The Dutch government has set a limit for this purpose on the maximum amount of underwater sound that may be produced.

2.8 Effects of impulsive sound on hearing (PTS)

2.8.1 Guiding principles

The KEC 1.0 described how to calculate whether animals are at risk of a permanent increase in the hearing threshold (PTS). An effect on hearing of this kind could occur when animals are exposed to the sound of multiple piling strikes.

The total sound dose (cumulative SEL) is calculated taking into account the avoidance behaviour of the animal, with the observed SELss decreasing with increasing distance from the piling location. The swimming scenario used has been revised and adapted in the KEC 4.0:

- In KEC 1.0, it was assumed that animals swim very quickly to the water surface, where sound levels are lower, during the first two observed piling strikes. This assumption was not supported by observations. In the meantime, tagging studies have indicated that a harbour porpoise actually dives to the bed when disturbed by the approach of a ship (Wisniewska et al., 2018). In the absence of better information about disturbance behaviour, it was decided to assume a worst-case approach in which animals always continue to swim at the depth at which the SELss is the highest.

- When piling starts, the animals are located at a distance R_n from the piling location.
- When the exposure level (SELss) at that location exceeds the threshold for avoidance behaviour, the animal swims in a straight line away from the piling location during piling.
- A swimming speed of 2 m/s was assumed for the harbour porpoise on the basis of Kastelein et al. (2018).
- A swimming speed of 2 m/s was adopted for seals in line with the maximum speed assumed in AgentSeal (Chudzinska et al., 2021) and observed by WMR in the Borndiep (Brasseur & Aarts, 2019).
- Animals stop swimming as soon as they reach a point at a distance from the piling location at which the SELss as a result of 1 piling strike is lower than or equal to the threshold value at which avoidance occurs.

To determine whether an animal is at risk of PTS, the cumulative exposure dose (SEL_{CUM}) is calculated for the time taken to drive a foundation pile. This takes into account the piling scenario (the variation of the hammer blow energy during piling) and the swimming scenario, depending on the distance from the piling location where the animal is located when piling starts. In line with the US National Marine Fisheries Service technical manual for determining effects on marine mammal hearing (NMFS 2016) and the scientific publication by Southall et al. (2019), the SEL_{CUM} weighted for the animal's hearing sensitivity is calculated and compared with a frequency-weighted threshold value for cumulative sound exposure that results in PTS.

2.8.2 *Worst-case scenario for calculations*

The consequences of the updated assumptions for the calculation of the probability of PTS were studied with a specimen calculation for a worst-case scenario. The search area with the largest water depth (Search area 5, water depth 39 m, animals swimming away in a northerly direction) was considered for this purpose because this is where the propagation loss of the piling sound is the lowest. Furthermore, this worst-case calculation does not take into account a possible ‘slow start’ in which the hammer blow energy and hammer frequency are slowly raised to the maximum value. Table 2.1 provides an overview of the main input data for this calculation.

Table 2.1 Data for the worst-case scenario for the calculation of the probability of PTS.

Parameter	**value**
Search area	5
Location (lat, lon, WGS84)	54.2506 N; 5.556 E
Water depth	39 m
Sound standard: unweighted broadband SEL_{SS}(750m)	168 dB re 1 μPa^{2}s
Piling scenario	35 strikes / minute, max. 5000 even strikes
Disturbance distance for harbour porpoises	29.7 km
Disturbance distance for seals	10.6 km
Swimming speed for harbour porpoises	2 m/s
Swimming speed for seals	2 m/s

2.8.3 *Result of worst-case calculations*

Figure 2.6 shows the calculated exposure dose as a function of the distance of the animals from the piling location when piling starts. Figure 2.6a shows that animals are at risk of hearing impairment (PTS) when they are at a relatively short distance from the piling location (550 m or less for seals and 1.2 km for harbour porpoises) and do not swim away during exposure to the sound of a series of strikes (more than 350 for harbour porpoises and more than 1250 for seals). Due to the work at the piling location prior to piling, it is unlikely that animals will be so close to that location. In combination with the worst-case assumptions that there is no slow start and that the animals do not engage in avoidance behaviour, the probability of PTS in a harbour porpoise or seal is already small. Figure 2.6b shows that the probability of PTS is eliminated entirely when it is assumed that the animals swim away from the piling sound (avoidance behaviour). In that case, the cumulative exposure dose does not exceed the PTS thresholds for harbour porpoises and seals anywhere.

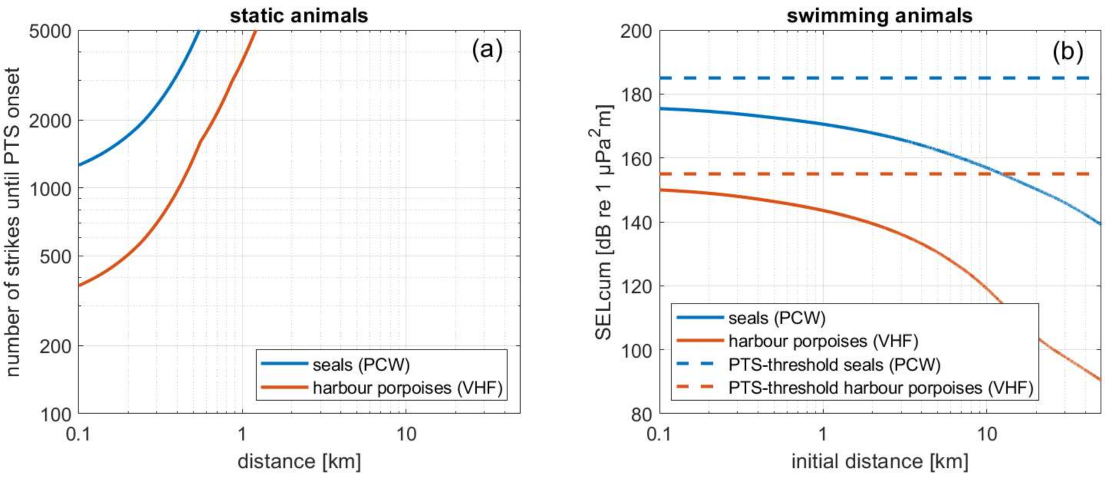

Figure 2.6 (a) Number of piling strikes after which the cumulative sound exposure dose (SEL_{CUM}, vhf-weighted for harbour porpoises and pcw-weighted for seals) for static animals exceeds the PTS threshold value, and (b) cumulative exposure dose for swimming animals compared with the PTS threshold values. Both for the worst-case scenario considered here (see Table 2.1).

2.8.4 *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 of piling for the construction of offshore wind farms, provided that the underwater sound is limited to the sound standard SEL_{SS} (750m) = 168 dB re 1 μPa²s, or lower. This conclusion is partly attributable to recent scientific insights (Southall et al., 2019) that the occurrence of damage to hearing when there is exposure to underwater sound depends on the frequency-dependent hearing sensitivity of the animals.

3 Scenarios and results of calculations

3.1 Scenarios

For this KEC (4.0) study, Rijkswaterstaat has drawn up national and international scenarios for the construction of offshore wind farms. The scenarios were established in a meticulous process and after consultation.

- The international scenario relates to the completed and planned construction of wind farms in the southern North Sea in the years 2016 through to 2030. Information was obtained from the 'SEANSE' study (see https://www.msp-platform.eu/practices/testing-ceaf-common-environmental-assessment-framework-seanse-case-studies-impact) and from the website of 4C Offshore (see https://www.4coffshore.com/).
- The 2023 and 2030 roadmaps (see https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/windenergie-op-zee) as well as three calculation variants supplied by Rijkswaterstaat for the possible acceleration of construction activity in the years 2027 through to 2030 (see Figure 1.1 and Table 1.2 for an overview of the Dutch areas and the three variants) were adopted as the basis for the consideration of the construction of Dutch wind farms.

For the purposes of KEC modelling, the scenario includes the following data for each wind farm:

- the maximum capacity to be installed;
- the surface area of the farm;
- the number of turbines (= maximum installed capacity divided by capacity per turbine);
- the year in which the construction of the wind farm begins.

An overview map showing the wind farms considered in this study can be found in Figure 3.2. There are 90 wind farms with a total installed capacity of 77.5 GW (6,384 turbines/piling days). By comparison, the KEC 3.0 assumed a considerably smaller international scenario and a total installed capacity of 48.8 GW and 74 wind farms (5,229 turbines/piling days). Figure 3.1 below shows the construction of the various wind farms over the years.

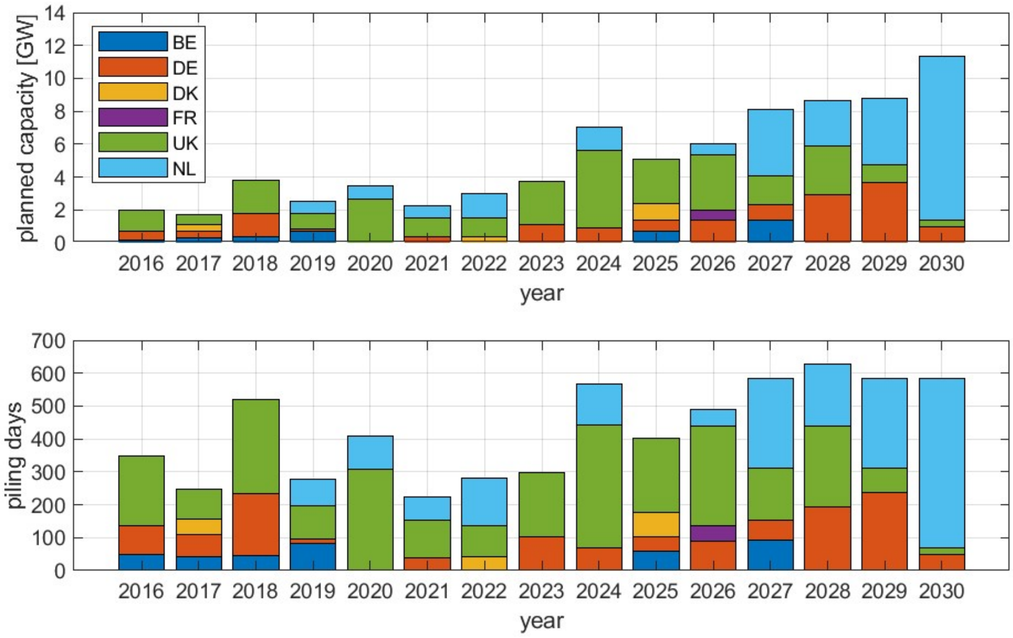

Figure 3.1 Maximum installed capacity per year (GW, top figure) and number of piling days for the completed and planned construction of wind farms in the North Sea in the years 2016 through to 2030 (bottom figure). The colours show the national contributions of the North Sea countries. For the Netherlands, these figures include the plans from calculation variant III (16.7 GW).

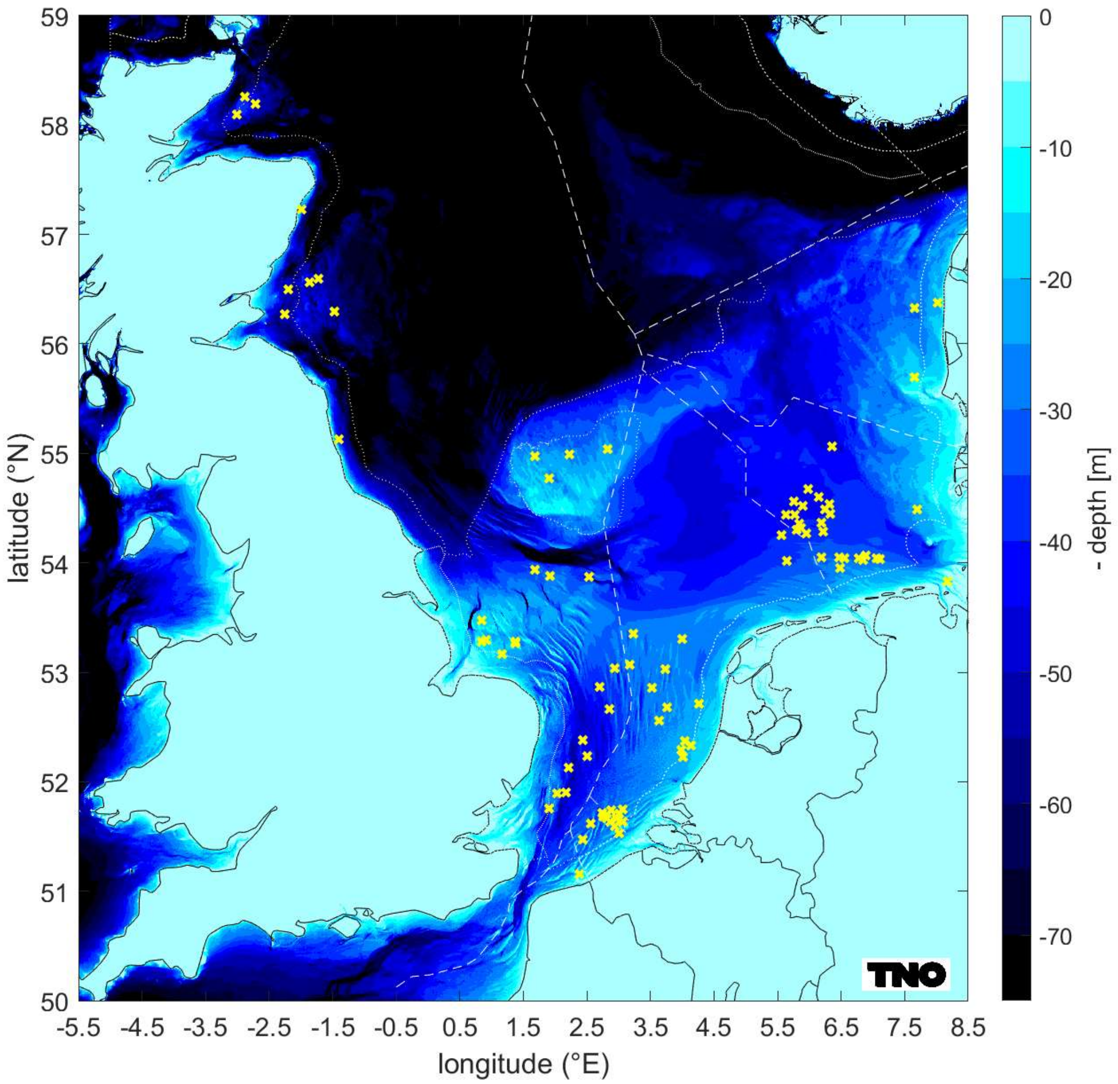

Figure 3.2 Overview map showing the locations (yellow crosses) and search areas (yellow contours) of the completed and planned construction of wind farms on the DCS and adjacent areas in the years 2016 through to 2030.

3.2 Underlying assumptions for the calculations

The input data for the calculations of the underwater sound produced during the piling activities are based on the following assumptions:

- For each wind energy search area, the Aquarius 4 model developed by TNO was used to calculate the sound propagation for a single location (see Annex B for underlying assumptions for input data). For the farms constructed by other countries, the coordinates provided by Rijkswaterstaat were used. For the Dutch farms, it was decided to adopt the centroid of the area contours supplied in shape files by Rijkswaterstaat as the piling location (Figure 3.3).
- For the wind farms covered by the Energy Agreement – in other words, Borssele, Hollandse Kust (South) and Hollandse Kust (North), the sound standard imposed in the site decisions was adopted; for the wind farms in the 'old' 2030 Roadmap and the calculation variants for the acceleration, a sound standard of SEL_{SS} (750 m) = 168 dB re 1 μPa^2s was used. This was also the approach adopted in the site decisions for the wind energy areas Hollandse

Kust (West) and Ten noorden van de Waddeneilanden from the 'old' 2030 Roadmap.
- In the case of the farms constructed by other countries, the calculation of sound propagation was based on the sound standard applicable in the country concerned.
- All turbines are on monopiles; alternative foundation types and techniques, and 'floating' wind farms have not been taken into consideration.
- Where data about turbine capacity are lacking, the calculations assume 12 MW turbines between now and 2025 and 15 MW turbines after 2025 with pile diameters of 5.5 m and 7.5 m respectively.

For the piling of the foundations for the transformer platforms:
- until 2027 and for Hollandse Kust (West – South), one platform will be installed for every 750 MW (maximum);
- with effect from 2027 (IJmuiden Ver (North) and search areas 1, 2 and 5), one platform for every 2000 MW (maximum);
- Six piles with a diameter of 3 m are driven for a transformer platform. Two platform piles are driven in one day.

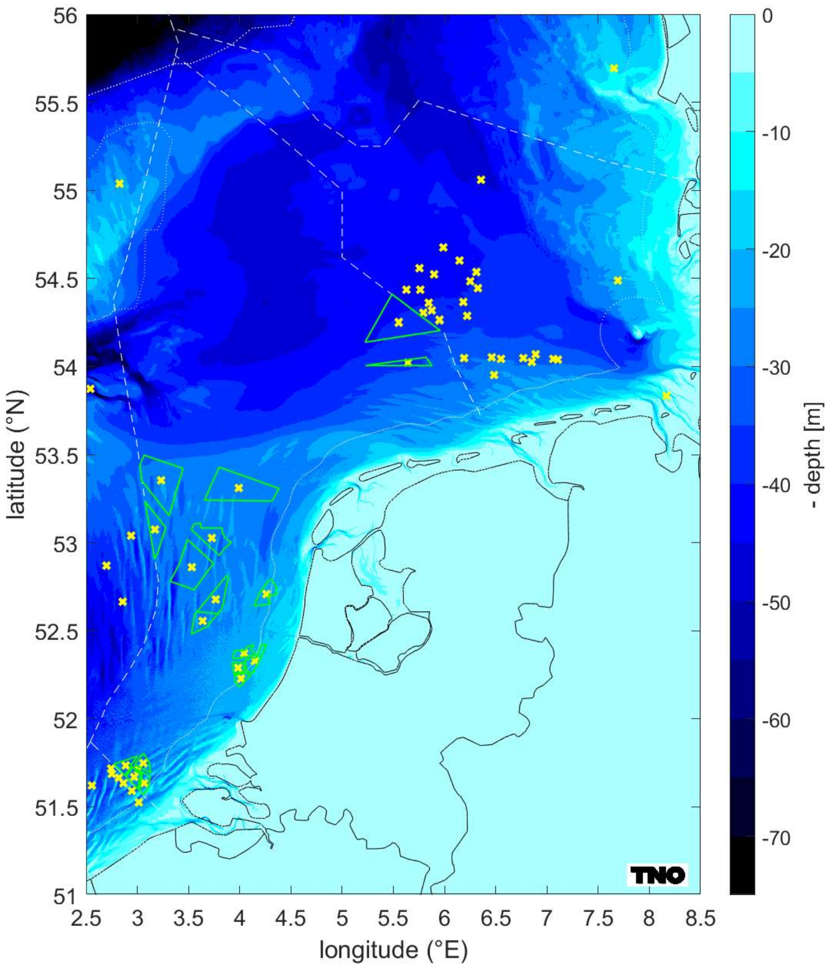

Figure 3.3 Overview map showing the locations (yellow crosses) and search areas (yellow contours) of the completed and planned construction of wind farms on the DCS and adjacent areas in the years 2016 through to 2030.

3.3 Scheduling of scenarios for Interim PCoD model

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 or underlying assumptions:

- From the Excel file supplied by Rijkswaterstaat: starting date and number of piles;
- Piling can take place all year round (no winter break);
- Because only the first year is known, a random starting date has been adopted[7];
- It has been assumed in all cases that an average of two piles are driven every three days;
- The transformer platforms will be installed one year before the construction of the wind turbines (this factor has been considered only for the Dutch wind farms).

The calendar established on the basis of these assumptions can be found in Figure 3.4. A more detailed overview is given in Annex E.

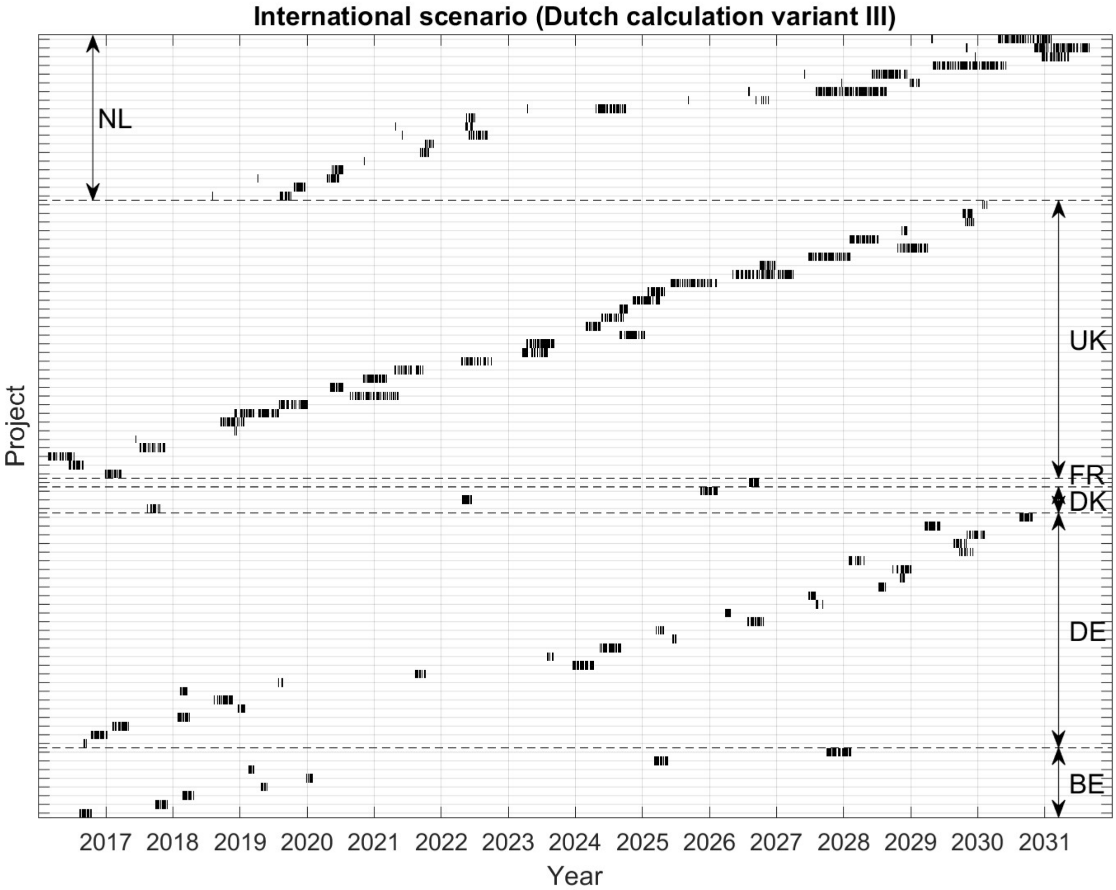

Figure 3.4 Calendar of impulse days for piling foundations in the period 2016-2030 in the North Sea. Calculation variant III (16.7 GW, see Table 1.2) was adopted for the Netherlands. Piling for the foundations of the transformer platforms has also been included for the Netherlands in this calendar.

[7] No attempt has been made to include the current construction schedules of wind farms that have already been completed in the modelling.

Table 3.1 provides an overview of the total installed capacity and the number of days of piling for wind turbine foundations in the North Sea in the period 2016-2030 for each country. By comparison with the study for the KEC 2019, in which calculations were made for the same period, 2016-2030, the number of piling days assumed in the study for the installation of turbine foundations is 1,155 higher (22%). This is because more wind farms are expected to be built than a few years ago, particularly in Germany, the Netherlands and the United Kingdom.

Table 3.1 Installed capacity and number of days on which there will be piling for the installation of wind turbine foundations in the period 2016-2030 in Belgium (BE), Denmark (DE), Germany (DE), the Netherlands (NL) and the United Kingdom (UK) on the basis of the underlying assumptions stated above.

2016-2030	Installed capacity (MW)	Proportion	Number of piles (turbines)*	Proportion
Total	**77,484**		**6,384**	
BE	3,650	5%	370	6%
FR	598	1%	46	1%
DK	1,751	2%	165	3%
DE	15,319	20%	1,244	19%
NL (calculation variant III)	26,543	34%	1,762	28%
UK	29,623	38%	2,797	43%

* For the Dutch wind farms, the scenario includes 114 extra piling days for the installation of foundations for the transformer platforms.

3.4 Results of calculations

3.4.1 Harbour porpoise

Effects of the piling of foundations for wind turbines and transformer platforms

An example of the distribution of sound relevant for harbour porpoises during piling for the construction of wind turbines, as calculated by TNO, can be found for the IJmuiden Ver (North) wind energy area in Figure 3.5 (top left). The sound distribution calculation assumes that a sound standard of SEL_{SS} = 168 dB re 1 μPa^{2}s is applied at 750 m and that this standard is met exactly. The remaining panels in the figure provide an impression of the intermediate steps used to calculate the number of disturbed harbour porpoises per piling day (sum of the number of disturbed harbour porpoises in the bottom right panel). This is calculated on the basis of the propagation of the piling sound (the sound map, top left), the dose-response relationship (% of disturbed harbour porpoises per calculation point, top right) and the average harbour porpoise density per calculation point (bottom left). It has been calculated that approximately 1,300 harbour porpoises are disturbed on a day of piling for a turbine foundation. That number is slightly lower for the piling of the smaller foundations for the TenneT platforms: approximately 1,190 harbour porpoises.

The calculated cumulative effects of the construction of wind farms, including the construction of the Tennet platforms, on the harbour porpoise population of the North Sea and the DCS in the period 2016-2030, including the three calculation variants for the acceleration, can be found in Table 3.2.

Table 3.2 Estimate of the impact of the construction of offshore wind farms on the harbour porpoise population on the DCS in the period 2016-2030, including calculation variants for the acceleration (see Figure 1.1 and Table 1.2 for wind energy areas and the calculation variants). Sound standard: SEL_{SS} (750 m) = 168 dB re 1 $\mu Pa^2 s$ for wind energy areas in the 'old' 2030 Roadmap + wind energy search areas for acceleration (see Annex H for the animal disturbance days per wind farm on the DCS). Other sound standards in accordance with site decisions or applicable regulations (wind farms of other countries).

	Variant III	**Variant II**	**Variant I**
Installed capacity 2016-2030	10	10	10
Additional installed capacity 2016-2030	16.7 GW	12.7 GW	10.7 GW
Number of harbour porpoise disturbance days, international	25.0×10^6	24.8×10^6	24.6×10^6
Number of harbour porpoise disturbance days, NL contribution	2.6×10^6	2.4×10^6	2.2×10^6
Population reduction, international without NL	44,464	44,464	44,464
Population reduction, NL contribution	3,955	3,752	4,728
Population reduction (% of DCS population)	**6.3%**	**6.0%**	**7.5%**

The results show the following:

- The effect of the underwater sound produced by piling for the construction of wind farms on the harbour porpoise population on the DCS (estimated at 62,771 animals) is not negligible for the three calculation variants: the estimated population reduction[8] is between 6% and 7.5% of the number of harbour porpoises on the DCS.
- The three calculation variants produce different results with respect to the effects on the harbour porpoise population: the number of harbour porpoise disturbance days increases with the increase in installed capacity but this is not reflected in the results of the calculations with the Interim PCoD model (the calculation with the smallest variant leads to the largest effect). The reason for this is that the statistical Interim PCoD model does not lend itself well to the highly precise (> 95% confidence) calculation of the relatively small differences between the development of the undisturbed population and the disturbed population over a longer period of time. The probability of a population decline in the undisturbed population is therefore not 0 either, despite the fact that the population is expected to be stable on average (see Annex F for a more detailed discussion of this question). However, the results of the calculations show that, based on the worst-case assumptions adopted, there is more than 95% certainty that the number of harbour porpoises on the DCS will decline by no more than between 6 and 7.5%.

[8] This reduction is not due to direct mortality in harbour porpoises (resulting from exposure to the sound) but to the fact that fewer fertile females are born, either because fewer young are born due to the energetic level of mothers being too low or because the mortality in animals < 1 year of age is higher due to a reduction in fitness. Experts agree that disturbance will not, in any case, cause mortality in juvenile animals (> 1 year) or adult females.

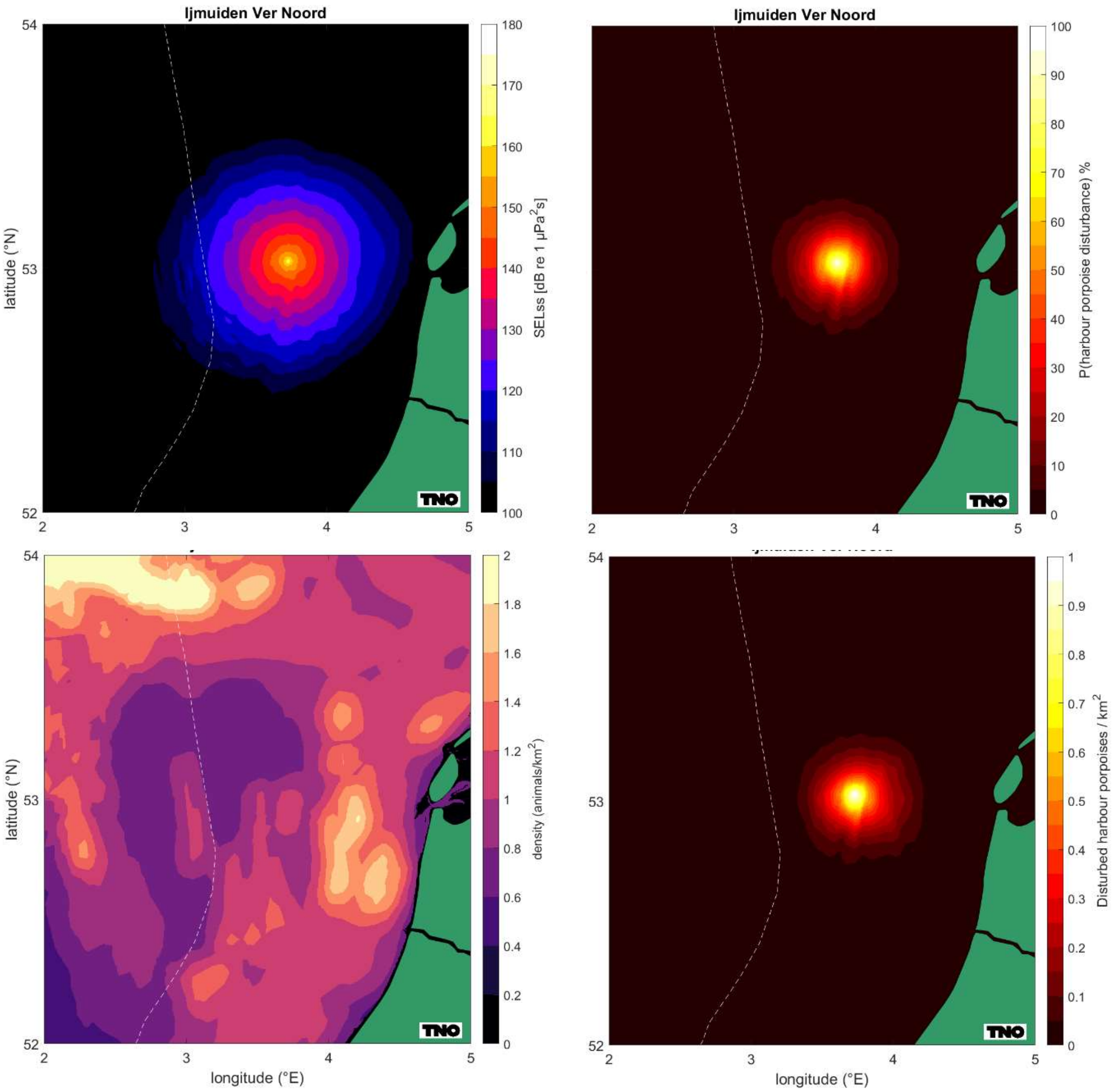

Figure 3.5 Calculated distribution of SEL_{SS} during piling with a sound standard of 168 dB re 1 μPa^2s (750 m) at a representative pile position in the IJmuiden Ver (North) wind energy area (top left), the percentage of disturbed harbour porpoises derived from the dose-response relationship in Figure 2.2 (top right), harbour porpoise density in summer based on Gilles et al., 2020 (bottom left) and number of harbour porpoises disturbed per km^2 due to piling at this location (bottom right).

Effects of impulsive sound during geophysical surveys

The calculations do not include the potential population effects of the geophysical surveys conducted prior to the construction of the wind farms and cable routes. On the basis of the assumptions used previously in the KEC 3.0, separate calculations were made (see Annex G for the underlying assumptions). These are indicative calculations to provide an impression of the relative importance of the effects of the geophysical surveys compared with those of piling sound. Assumptions have been made about the surface areas under investigation and the length of cable routes, which may be different during the preparations for the construction of the wind farm. The potential effects of the geophysical survey for each project must therefore be calculated more precisely in the permit procedures.

It emerges from the results of the indicative calculations shown in Table 3.3 that:

- The total number of harbour porpoise disturbance days due to the surveys for the Dutch wind farms is a maximum of 2.4% of the number of harbour porpoise disturbance days attributable to piling;
- The increase in the calculated 5% probability of a reduction in the population on the DCS is negligible (from 6.3% to 6.5%).

Table 3.3 Calculated harbour porpoise disturbance days (hpdd) resulting from geophysical surveys for the construction of wind farms on the DCS in the period 2016-2030 (calculation variant III = maximum variant).

Activity	**Time**	**System**	**Disturbed area per day (km^2)**	**hpdd NL farms 2016-2030 (calculation variant III)**
Global survey of the wind energy area	5 years before construction	Sparker	~ 84 km^2	22,664
Detailed survey of wind energy area	1 year before construction	Sparker	~ 84 km^2	22,664
Global survey of cable route	2 years before construction	Sub-bottom profiler	~ 36 km^2	8,148
Detailed survey of cable route	1 year before construction	Sub-bottom profiler	~ 36 km^2	8,148
			Total	**61,622**

3.4.2 Seals

The disturbance contour for seals is smaller than for harbour porpoises during the period in which piling takes place around the piling location. An example of the distribution of sound relevant for harbour seals during piling for the construction of wind turbines, as calculated by TNO, can be found for the IJmuiden Ver (North) wind energy area in Figure 3.6 (top left). This sound distribution assumes the application of a sound standard of SEL_{SS} = 168 dB re 1 μPa^2s at 750 m. The remaining panels in the figure provide an impression of the intermediate steps used to calculate the number of disturbed harbour seals per piling day (sum of the number of disturbed harbour seals in the bottom right panel). This is calculated on the basis of the propagation of the piling sound (the sound map, top left), the dose-response relationship (% of disturbed seals per calculation point, top right) and the average harbour seal density per calculation point (bottom left). For a day in the winter season (December - February) when a turbine foundation is driven, it has been calculated that approx. 20 harbour seals will be disturbed.

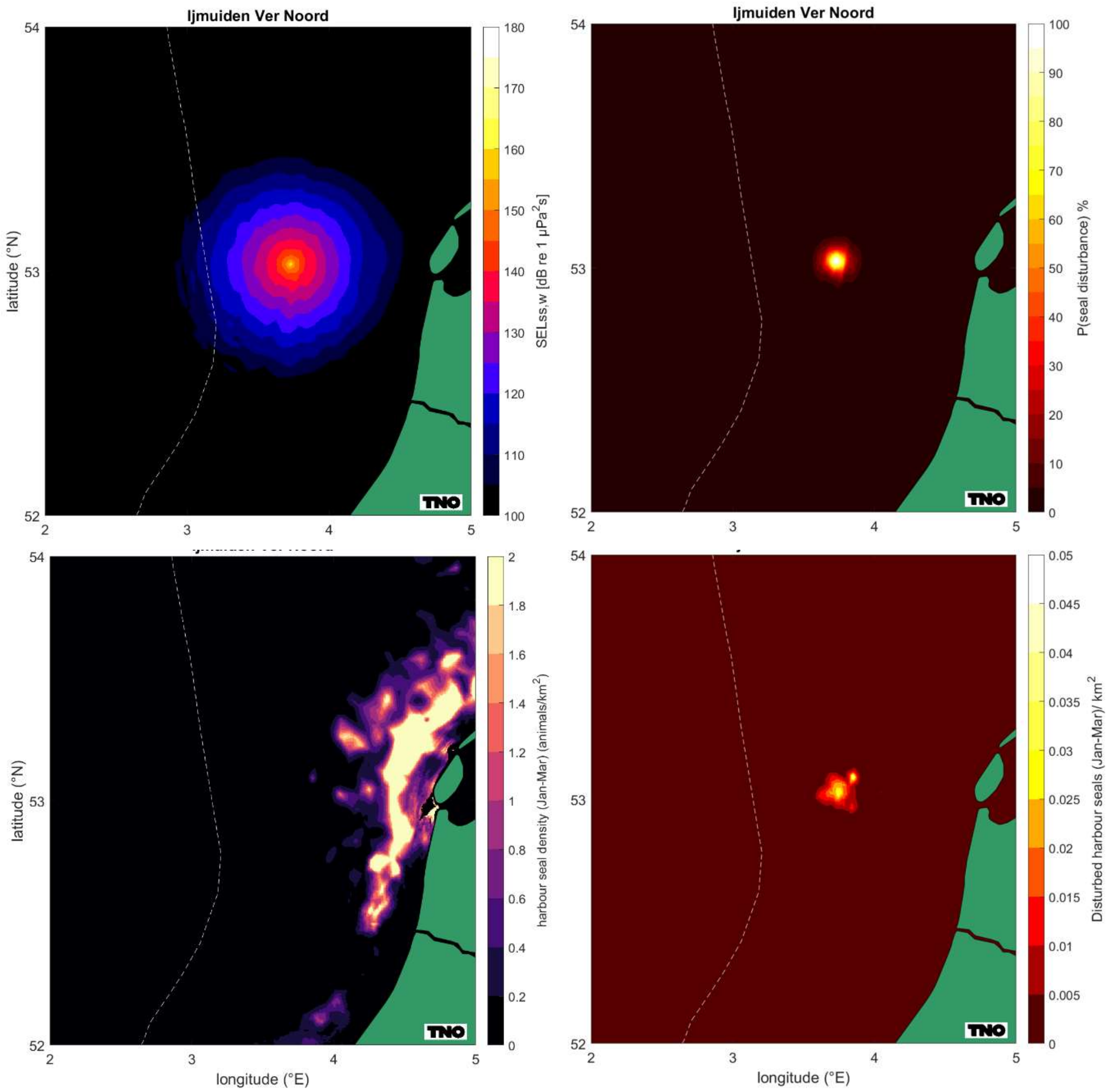

Figure 3.6 Calculated distribution of SEL_{SS} during piling with a sound standard of 168 dB re 1 μPa^2s (750 m) at a representative pile position in the IJmuiden Ver (North) wind energy area (top left), the percentage of disturbed seals (top right) derived from the dose-response relationship in Figure 2.3, harbour seal density in winter based on Aarts et al., 2021 (bottom left) and number of harbour seals disturbed per km^2 due to piling at this location (bottom right).

The calculated cumulative effects of the construction of wind farms on the harbour and grey seal populations on the DCS in the period 2016-2030, including the three calculation variants for the acceleration, are included in Table 3.4 and Table 3.5.

The results show that, on the basis of the assumptions used, an acceleration in the roll-out of offshore wind in the period 2016-2030 will have no negative effects on the populations of harbour and grey seals, even if the total number of animal disturbance days as a result of conducting geophysical surveys were to double. No cumulative effects are likely to be found in these calculations since the probability of a seal being disturbed over a period of several days is very small[9]. This is because, at the locations where wind farms are planned, seal density is very low and therefore the likelihood of a seal being disturbed over a period of several days is also low. It should be noted that the calculations are based on the assumption that the probability of an individual seal being disturbed is the same for all individuals in the population. In the worst-case assumption that a much smaller part of the population may be disturbed and that animals always go to the same location (high level of site fidelity), the probability of a seal being disturbed several times will increase. Because a situation of this kind involves a negligible proportion of the entire population, there will still be no impact on the population as a whole.

Table 3.4 Estimate of the impact of the construction of offshore wind farms on the population of harbour seals on the DCS in the period 2016-2030, including calculation variants for the acceleration (see Figure 1.1 and Table 1.2 for wind energy areas and the calculation variants, and Annex H for the animal disturbance days per wind farm on the DCS).

	Variant III	**Variant II**	**Variant I**
Installed capacity 2016-2030	10	10	10
Number of animal disturbance days in old 2030 Roadmap	92×10^3	92×10^3	92×10^3
Additional installed capacity 2016-2030 (acceleration)	16.7 GW	12.7 GW	10.7 GW
Number of animal disturbance days due to acceleration	48×10^3	45×10^3	44×10^3
Population reduction (% of DCS population)	**0%**	**0%**	**0%**

Table 3.5 As in Table 3.4 for grey seals.

	Variant III	**Variant II**	**Variant I**
Installed capacity 2016-2030	10	10	10
Number of animal disturbance days in old 2030 Roadmap	58×10^3	58×10^3	58×10^3
Additional installed capacity 2016-2030 (acceleration)	16.7 GW	12.7 GW	10.7 GW
Number of animal disturbance days due to acceleration	24×10^3	22×10^3	21×10^3
Population reduction (% of DCS population)	**0%**	**0%**	**0%**

[9] In the Interim PCoD model, the number of disturbance days determines the level of the effect on vital rates (survival and reproductive success). See Section 2.6 and Annex F.

4 Limiting effects with additional measures

4.1 Overview of possibilities

There are various options for reducing the negative effects of underwater sound on marine mammals during the construction of offshore wind farms. The analyses have shown that the number of animal disturbance days determines the size of the impact on the population. The calculations performed for the KEC 4.0 have shown that permanent effects on hearing (PTS: *permanent threshold shift*) can be excluded.

The number of animal disturbance days is calculated by multiplying the number of animals disturbed by the underwater sound by the number of impulse days. The number of animals disturbed is calculated by multiplying the area disturbed by sound by the local marine mammal density. Effects can therefore be mitigated by:

1 reducing the area disturbed by sound and/or
2 conducting the piling in a season with a relatively low density of marine mammals and/or
3 reducing the number of disturbance days (= the number of foundations) or
4 using a different technique for foundations that produces less sound (such as vibropiling, blue piling, or screw piling).

1. The size of the disturbed area can be limited by:

- limiting the propagation of piling sound further by using measures to mitigate sound (mantles, bubble screens, etc.);
- selecting areas with relatively shallow water depths for the construction of wind farms. The sound will not then travel as far.

2. Piling when the density of marine mammals is low

The recent map from Gilles et al. (2020) estimating density during the summer season was used for **harbour porpoises** for the KEC 4.0. Previous research by Geelhoed et al. (2011) and more recent research by Soldaat & Poot (2019) have shown that there can be large differences in animal distribution between seasons. However, it is not possible to determine on the base of the data whether there are systematic differences between seasons that are similar from year to year (see also Chapter 5 Uncertainties and Gaps in Knowledge).

On the basis of the maps produced by Aarts et al. (2021), seasonal variations for **harbour and grey seals** can be considered. These variations have been included in the calculations and this has shown that the cumulative effects of the construction of wind farms in the North Sea can be excluded in all cases.

3. Reducing the number of disturbance days

The construction of a wind farm with a small number of relatively large turbines requires a higher piling energy than the construction of a wind farm with a larger number of smaller turbines. However, when a single universal sound standard is applied, the energy used for piling does not, in principle, affect the size of the area disturbed because sound levels are not allowed to exceed these values at a distance of 750 m from the piling location. If it is decided to install a smaller number of relatively large turbines, it will of course be more difficult to comply with the prevailing sound standard. Since there is no difference between the different variants with respect to the size of the area disturbed, the effects of a wind farm with a smaller number of relatively large turbines will always be more favourable for marine mammals than those of a wind farm with more, smaller, turbines. Obviously, when opting for a particular size of wind turbine, other species, such as birds and bats, must also be taken into account.

4. Application of alternative foundation techniques
Non-impulsive sound during the installation of turbine foundations using techniques other than piling (vibropiling, screw piles or blue piling) may produce less disturbance. Results from pilot projects have shown that a possibly substantial sound reduction can be achieved with these techniques (see review by Verfuss et al., 2019). Although some techniques are promising, they have not yet been applied in practice for offshore wind.

4.2 Cumulative effects of offshore wind in 2016-2030 when a stricter sound standard is applied

In Section 3.4, it was concluded that it is impossible to rule out that the ecological standard of a maximum reduction of 5% (certainty > 95%) in the population on the DCS **may be exceeded for harbour porpoises**. It was assumed here that a sound standard of SEL_{SS} (750 m) = 168 dB re 1 $\mu Pa^2 s$ is applied for the wind farms in the 2030 Roadmap, including the additional construction of 10-16 GW of installed capacity. **There are no effects on harbour and grey seals on the DCS** and the ecological working standard will not therefore be exceeded.

Looking at the possibilities listed in Section 4.1 for limiting the effects on marine mammals during the construction of wind farms, the further reduction of disturbance by limiting sound propagation is the only option that can lead to a significant reduction in the calculated effects in the period 2016-2030. To establish a picture in this respect, calculations have been made assuming the application of a sound standard of SEL_{SS} (750 m) = 160 dB re 1 $\mu Pa^2 s$ for the construction of wind farms in the IJmuiden Ver wind energy area ('old' 2030 Roadmap) and the wind energy search areas for accelerated construction (see Table 1.1). Germany has been using this sound standard for several years (BMU 2013) and so we propose it as a realistically achievable, more stringent, sound standard. The calculated number of harbour porpoise disturbance days will therefore decrease by 1.0-1.2 million (45-47% of the Dutch contribution given a sound standard of SEL_{SS}(750 m) = 168 dB re 1 $\mu Pa^2 s$).

The calculated cumulative effects of wind farm construction on the North Sea and DCS harbour porpoise populations in the period 2016-2030, including the three acceleration calculation variants, can be found in Table 4.1. The results show that, if a sound standard of SEL_{SS} (750 m) = 160 dB re 1 $\mu Pa^2 s$ is applied in the IJmuiden Ver wind energy area and the acceleration areas, the estimated population reduction will, depending on the calculation variant, be between 2.3% and 2.9% of the number of harbour porpoises on the DCS with a high level of certainty (>95%). This means that the ecological standard in place **will not be exceeded** (and allows for future developments).

Table 4.1 Estimate of the impact of the construction of offshore wind farms on the harbour porpoise population on the DCS in the period 2016-2030, including calculation variants for the acceleration (see Figure 1.1 and Table 1.2 for wind energy areas and the calculation variants). Sound standard: SEL_{SS} (750 m) = 160 dB re 1 $\mu Pa^2 s$ for the wind energy area IJmuiden Ver + wind energy search areas for acceleration (see Annex H for the animal disturbance days per wind farm on the DCS). Other sound standards in line with site decisions.

	Variant III	**Variant II**	**Variant I**
Installed capacity 2016-2030	10	10	10
Additional installed capacity 2016-2030	16.7 GW	12.7 GW	10.7 GW
Number of harbour porpoise disturbance days, international	23.9×10^6	23.8×10^6	23.7×10^6
Number of harbour porpoise disturbance days, NL contribution	1.4×10^6	1.3×10^6	1.2×10^6
Population reduction, international without NL	44,464	44,464	44,464
Population reduction, NL contribution	1,797	1,624	1,410
Population reduction (% of DCS population)	**2.9%**	**2.6%**	**2.3%**

5 Uncertainties and gaps in knowledge

5.1 Procedure for determining population effects

Each step of 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). An overview:

Quantification of source sound and sound propagation

- Despite the fact that significant improvements have been made in the Aquarius 4 model with respect to the description of the physics of the radiation and propagation of sound (de Jong et al., 2019), the quantitative forecasting of the SEL_{SS} remains uncertain. This is particularly true of the high-frequency component of the sound, but this is of no importance 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 establish even more confidence and obtain 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 locality 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.

Dose-response relationship for disturbance/changes in behaviour

- For the time being, the calculations for harbour porpoises do not take hearing sensitivity as a result of the frequency into account. It is reasonable to assume that the application of an SEL value weighted with the frequency sensitivity of harbour porpoise hearing provides a better prediction of the behavioural response. However, the data available at the time of drafting the KEC 4.0 did not allow for clear conclusions to be drawn about the necessity to adopt this approach. Tougaard et al. (2015) pointed out some time ago that frequency weighting with a filter based on the inverse of the audiogram would be a suitable approach for determining effects. The US National Marine Fisheries Service has endorsed this position and has already implemented frequency weighting in their technical guidance for determining effects on the hearing of marine mammals (NMFS 2016). However, the data are still inadequate to implement frequency weighting for behavioural effects and disturbance. In the case of projects where piling sound is mitigated by the use of bubble screens, the application of frequency weighting when determining harbour porpoise behavioural disturbance could result in smaller predicted disturbance areas because the sound in frequencies relevant to harbour porpoises is attenuated better (Dähne et al., 2017).

Quantification of the number of disturbed animals

- For harbour porpoises, the KEC 4.0 has used the map in Gilles et al. (2020), 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 conducted in Danish waters, making more information available about individual animals (e.g. Sveegaard 2011, Nielsen et al., 2018). However, this gap will not be remedied in the short term for the southern section of the North Sea. This makes it difficult to provide a more precise estimate of the number of animals affected at different times of the year.

- For seals, seasonal variations in distribution were taken into account but not the effects of the site fidelity of seals, which is probably stronger 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 suffer disturbance in that case. Annex D discusses the potential effects of animal movement on the results of the Interim PCoD model for seals.

Extrapolating the effects on individual harbour porpoises to population effects (iPCoD)

- The size of the vulnerable subpopulation of harbour porpoises is one of the parameters in the *interim Population Consequences of Disturbance* (iPCoD) model. The KEC 4.0 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 (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) a recent publication has shown that the home range of harbour porpoises can be quite large (Nielsen et al., 2018). The sensitivity of the model results to the size of the vulnerable subpopulation for three different sizes was investigated for the Dutch scenario for the KEC 1.0 (Heinis & de Jong et al., 2015). These analyses showed that the size of the vulnerable subpopulation starts to play a role when there is a calculated population reduction of about half the size of the vulnerable subpopulation. The total effect is limited to about 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 therefore reduces the risk of underestimating effects.
- Extrapolation of harbour porpoise disturbance to effects on vital rates.
  The iPCoD model was thoroughly updated and improved in 2018. The determination of the relationship between disturbance and vital rates for harbour porpoises draws on a state-of-the-art energy budget model developed by the University of Amsterdam in collaboration with the University of St. Andrews. The model calculations clearly show that, in many cases, harbour porpoises can compensate for a temporary loss of foraging opportunities. However, it is not yet clear whether and, if so, why the areas where the highest densities are seen are the most suitable areas. Are the survival chances of harbour porpoises that are driven out of an area of this kind actually adversely affected and how are seasonal variations in numbers linked to variations in food availability?

- 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 sound?
- 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, Sparling et al., 2007), the effect on the population could be estimated by combining an *agent-based* model (see, for example, Nabe-Nielsen et al., 2014) with a Dynamic Energy Budget. Wageningen Marine Research 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. Once again here, it was assumed that all seals present on the DCS belong to the vulnerable subpopulation. Furthermore, it was 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).

5.2 Other uncertainties

- Applicability of alternative installation techniques. Results from pilot projects have shown that a substantial sound reduction can be achieved with techniques other than piling such as vibropiling or blue piling (see review by Verfuss et al., 2019). Although techniques of this kind are promising, they have not yet been applied in practice for offshore wind. One of the reasons is that it is not yet certain whether the monopile is anchored as firmly when one of these techniques is used as when it is driven (‘axial bearing capacity’). There is also uncertainty about the applicability of these techniques in deeper water. Moreover, data on the nature of the sound produced (frequency content and levels) are still largely lacking for vibrohammers.
- 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 are 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 (4-6 piles) probably takes more time than piling a single monopile foundation. If that takes several days, the number of harbour porpoise disturbance days and therefore the calculated effect on the population will also increase. This possible underestimation of the effect is considerably smaller than the overestimation of the effects of the very large (> 50 km) effect distances in deeper waters calculated in this study that do not correspond to the observed effect distances.

- Continuous sound produced, in particular by ships, during the construction and operational phases. Results of recent research suggest 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 (ADD), which prevent the occurrence of PTS. However, at various wind farms, reduced activity of harbour porpoises around the piling location 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 the sound of ships (and particularly the sound of 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 ships). All these activities result in shorter disturbance distances than the distances caused by non-mitigated piling sound. A very recent study reported that ship sound disturbed harbour porpoises at distances of approx. 4 km (Benhemma-Le Gall et al., 2021). However, the available quantitative data are insufficient to arrive at any conclusions about the possible population effects of sound associated with the construction and operation of wind farms. 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).
- 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 remove the monopiles in a sustainable and cost-effective way. The hydraulic extraction of monopiles is one of the new methods for removing 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 Conclusions

- Provided that sound production is adequately attenuated during construction, the accelerated development of offshore wind energy through to 2030 will, according to the updated KEC procedure, not have any unacceptable cumulative effects on the populations of harbour porpoises, harbour seals and grey seals on the DCS: the ecological standards that have been adopted will not be exceeded.
  - The results of the calculations show that, based on the assumptions used and the best available knowledge at the time of the study, none of the scenarios studied for seals will have an impact on the populations of harbour seals and grey seals. The calculations for the wind farms in the Dutch section of the North Sea are based on the sound standards adopted in site decisions and on a sound standard of SEL_{SS} (750 m) = 168 dB re 1 $\mu Pa^2 s$ for the wind energy areas in the ‘old’ 2030 Roadmap, and the search areas added for the acceleration. In case of the other wind farms (in other countries), the approach assumes the current legislation regarding the production of underwater sound during the construction of wind farms.
  - For harbour porpoises, the calculations show that applying a sound standard of SEL_{SS} (750 m) = 168 dB re 1 $\mu Pa^2 s$ to the construction of the wind farms in the ‘old’ 2030 Roadmap + the acceleration leads to the ecological standard being exceeded. With a sound standard of SEL_{SS} (750 m) = 160 dB re 1 $\mu Pa^2 s$ for the IJmuiden Ver wind energy area and the wind energy areas for the acceleration, this is not the case and the calculations indicate a population reduction of 2.3-2.9% with 95% certainty. This conclusion hardly changes at all if the effects of geophysical surveys are included.
- The calculations show that up to approximately 16 GW of additional capacity can be installed on top of the approximately 10 GW previously assessed in KECs 1.0 – 3.0, provided a sound standard of SEL_{SS} (750 m) = 160 dB re 1 $\mu Pa^2 s$ is applied for the IJmuiden Ver wind energy area and the search areas for the acceleration.
- The calculations were based on worst-case assumptions: the margin of uncertainty can be reduced significantly by conducting further research; this may lead to smaller calculated effects for harbour porpoises.
- In addition, the application of alternative, quieter techniques will result in smaller calculated effects.

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8 Signature

The Hague, January 2022

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A Ecological effect standard for seals

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Datum: 3 juni 2021

Betreft: Ecologische effectnorm zeehonden (ALI - *Acceptable Level of Impact*)

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1 Achtergrond

In hoofdstuk 4 van deelrapport B van de eerste versie van het Kader Ecologie en Cumulatie (KEC 1.0) is een mogelijke aanpak voor het bepalen van effecten van de realisatie van windenergie op zee op populaties van gewone en grijze zeehonden beschreven. Daarin is voorgesteld om de stappen uit de redeneerlijn voor bruinvissen direct te vertalen naar zeehonden, maar verder niet in het KEC uit te werken. Er kon namelijk worden beredeneerd dat de verwachte effecten van de aanleg van de in het KEC 1.0 beoordeelde Nederlandse windparken op de zeehondenpopulaties minder groot zouden zijn dan op de bruinvispopulatie. Dit was vooral gebaseerd op het feit dat de gemiddelde dichtheid van bruinvissen op de onderzochte windenergiegebieden hoger is dan die van zeehonden. In de update 2018 van het KEC is deze lijn voortgezet (KEC 3.0). In de MERren en PBs die aan de kavelbesluiten voor de windenergiegebieden uit het Energieakkoord en de Routekaart Wind op Zee 2030 ten grondslag liggen, zijn mogelijke effecten op zeehonden echter wel berekend en op hoofdlijnen beoordeeld. In alle gevallen is op grond van waargenomen dichtheden van zeehonden in de windenergiegebieden en tijdelijkheid van de effecten geconcludeerd dat significante effecten op de populaties niet zouden optreden. Mogelijke effecten van verstoring door het constructiegeluid op de *vital rates* van gewone en grijze zeehonden en de eventuele doorvertaling naar effecten op de populatieomvang zijn in deze studies echter niet bepaald.

In de KEC 4.0 update wordt de redeneerlijn voor het berekenen van de effecten van de realisatie van windenergie op zee op de populaties van gewone en grijze zeehonden weer opgepakt. De voorgestelde aanpak uit KEC 1.0 zal, mede op basis van de ervaringen in de MER/PB-studies worden geactualiseerd. Voor het kwantificeren van effecten op de populatie zal gebruik worden gemaakt van het Interim PCoD model, waarvan in 2019 ook voor zeehonden een volledige update is gepubliceerd. Ten behoeve van het KEC 4.0 zullen dus, net als voor bruinvissen, effecten van de constructie van windparken op zee op de populaties van gewone en grijze zeehonden worden berekend. Dit maakt het ook mogelijk om de resultaten van deze berekeningen te toetsen aan een, nog op te stellen ecologische effectnorm voor zeehonden.

Het is de bedoeling dat het bevoegd gezag als onderdeel van het KEC 4.0 een norm stelt aan de acceptabele impact van de aanleg van de windparken op de beide zeehondensoorten. Hierna wordt daarvoor op grond van een aantal overwegingen een voorstel gedaan.

1

2 Advies voor een acceptabele effectnorm voor zeehonden

Op 27 mei j.l. is een overleg met de Werkgroep Zeezoogdieren en Onderwatergeluid geweest, waarin ook de acceptabele effectnorm voor zeehonden aan de orde kwam. In dit overleg is voorgesteld om van dezelfde norm uit te gaan als voor bruinvissen op grond van de overwegingen in onderstaande tabel, mede omdat er geen zwaarwegende redenen lijken te zijn om een andere, strengere of soepelere norm te hanteren. In het werkgroepoverleg zijn geen argumenten naar voren gebracht om van een andere norm uit te gaan.

Soort	Landelijke Svl	Populatietrend	
		Nederland	Internationaal
Bruinvis	Gunstig	Stabiel	Stabiel
Gewone zeehond	Gunstig	Stabiel/groeiend	Stabiel?
Grijze zeehond	Gunstig	Groeiend	Groeiend

Het betekent dat voor bruinvissen, gewone en grijze zeehonden de volgende norm voor een acceptabel ecologisch effect zou gaan gelden:
"Door de aanleg van windparken op zee moeten populatie van bruinvissen, gewone zeehonden en grijze zeehonden op het NCP met grote zekerheid (>95%) op minimaal 95% van de huidige omvang blijven (ofwel: de kans dat de populatiereductie ≥ 5% moet ≤ 5% zijn)."

B Modelling underwater sound

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

- the 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, mantles, etc.),
- water depth (bathymetry) around the pile,
- 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 (in other words, the number of variations to be calculated). The uncertainty in the calculated sound propagation should, in theory, decrease when more detailed information is available. The models have been validated to only a limited extent (PAWP, Luchterduinen, Gemini) 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 OWEP, see de Jong et al. (2018).
- The Aquarius 4 model calculations result in a sound propagation in terms of the third band spectrum of the SELss in the vicinity of the pile as a function of distance and depth.
- As a measure for quantifying the possible disturbance of harbour porpoises, we use, in line with the KEC 1.0 - KEC 3.0, the unweighted broadband value for the calculated SELss.
- We select the maximum value of the SELss over the water depth. In Aquarius 4, the SELss as a function of depth is calculated in 10 equidistant steps and the maximum is then selected.

Hammer

Hammer type and energy are selected at a late stage of the design process. For this study it has been 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. On the basis of information provided by TenneT, a maximum hammer energy of 2000 kJ has also been assumed for the driving of the smaller piles (2–3m) for the jacket foundations of the platforms.

The Aquarius 4 model uses an idealised model of the hammer (Deeks & Randolph 1993) 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 will not be 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
- Monopile wall thickness (API formula): $t = 0.01D + 6.35 \times 10^{-3}$ m
- Anvil mass = ram mass = hammer energy * (1 ton/20 kJ)
- Contact stiffness 20 GN/m

Mitigation

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

It will 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 piling will be reduced by a constant value so that it complies precisely with the sound standard at 750 m from the pile. See Annex E for an overview of the sound standards used in each project.

- DE: sound standard SEL (750m) = 160 dB re 1 μPa^{2}s
- BE standard Lzp(750m) = 185 dB re 1 μPa^2 (according to “Omschrijving van Goede Milieutoestand & vaststelling van Milieudoelen voor de Belgische mariene wateren”, http://www.vliz.be/en/imis?module=ref&refid=220232). On the basis of Lippert et al. (2015) and data from Luchterduinen and Gemini, this can be stated in global terms as a standard where SEL (750m) = 160 dB re 1 μPa^{2}s
- NL standard SEL (750m) per search area, as adopted in site decisions and calculated in the same way (using the approximation formula from the KEC report for the relationship between harbour porpoise disturbance days and population decline) for the farms dating from after the SER agreement.

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 calculations on the basis of the calculated sound distribution for non-mitigated piling. 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.

Locations

The scenarios provided by Rijkswaterstaat state a central location for each planned wind farm. For the wind farms in other countries, the locations provided by Rijkswaterstaat were used. For the Dutch farms, it was decided to adopt, as the piling location, the centroid of the area contours supplied in shape files by Rijkswaterstaat. This does not necessarily result in a realistic worst case everywhere 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.

Sediment

In the Aquarius models, the sediment is modelled as an equivalent uniform liquid (without shear stiffness or layers). The Wozep study has shown that this assumption results at low frequencies in a good match with the U8 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): density ρ = 2086 kg/m^3, sound velocity c = 1797 m/s, and absorption α = 0.88 dB/λ at a sound velocity in water of 1500 m/s.
- Absorption decreases ($\sim f^{1.8}$) below 250 Hz.
- These values were used for all locations.

Wind

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.

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C Derivation of dose-response relationship

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 & Thomas (2019) emphasise the importance of applying dose-response relationships when estimating the number of animals potentially affected, and state that applying a discrete threshold may lead to inaccurate estimates. In the KEC 4.0, it was therefore decided to use dose-response relationships instead of the thresholds for disturbance used in KEC 1.0-3.0.

A dose-effect relationship describes the probability of an animal being disturbed (response) as a function of the sound dose to which the animal is exposed. 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 expressed with a logistic function (the ‘S-Curve’).

$$\mathrm{P_{resp}}(\mathrm{SEL_{SS}}) = \frac{1}{1+\exp(-a+b\times\mathrm{SEL_{SS}})} \qquad \text{(C-1)}$$

Here, $\mathrm{P_{resp}}$ is the probability of disturbance and $\mathrm{SEL_{SS}}$ (unweighted broadband) the exposure dose. a and b are model parameters used to fit the function to available data.

Harbour porpoises

The data from which a dose-effect relationship for the disturbance of harbour porpoises by piling can be derived are scarce. In the KEC 3.0, it was decided to adopt a discrete threshold for disturbance (SEL_{SS} = 140 dB re 1 μPa^{2}s) on the basis of data from a SEAMARCO playback study (Kastelein et al., 2013) and a German field study (Diederichs et al., 2014). This was also in line with the German *Schallschutzkonzept* (BMU 2013). An extensive study of the effects of piling on harbour porpoises looking at the first seven wind farms in German waters (Brandt et al., 2018) concluded that “*Declines were found at sound exposure levels exceeding 143 dB re 1 μPa^{2}s (the sound exposure level exceeded during 5% of the piling time, SEL_{05}) and up to 17 km from piling*”. In the calculations for the KEC 3.0 (Heinis et al., 2019), the disturbance areas were determined both on the basis of a threshold value of SEL_{ss} = <u>140</u> dB re 1 μPa^{2}s (unweighted and broadband) and for a value of <u>143</u> dB re 1 μPa^{2}s (unweighted and broadband).

Graham et al. (2019) derived a dose-response relationship for the disturbance of harbour porpoises by piling sound from measurements made during the construction of the Beatrice wind farm in the UK. The relationship is expressed in their paper as a function of an ‘audiogram-weighted’ SEL_{SS} but a dose-effect relationship based on unweighted SEL_{SS} was also presented at the INPAS Symposium in Amsterdam (June 2018), see Figure C.1.

In the KEC 4.0, it was decided to adopt, as the worst-case scenario, the dose-effect relationship derived by Graham et al. (2019) for the response of harbour porpoises to the turbine foundation that was piled first. Possible habituation, leading to a reduced probability of disturbance when there are successive piling days, has been disregarded as a precautionary measure.

The experimental curve in Graham et al. (2019) can be approximated reasonably with a logistic function (in accordance with B3-1) with the parameters $a = -21.3947$ and $B = 0.1482$, see Figure C.2. This curve corresponds in broad terms with the observations of Brandt et al. (2018).

In Figure C.3, this dose-response relationship is applied to the measured underwater sound from piling for the construction of the Gemini wind farms. The dose-response relationship predicts a 50% probability of disturbance at a distance of 40.3 km from the pile being driven. The effective disturbance distance based on the integral of the area under the dose-response curve is 48 km. By comparison with the observations of Geelhoed et al. (2018), who concluded that harbour porpoises avoided piling locations up to a distance of 15 to 25 km, this is a conservative estimate. It should be noted that, during the driving of a single foundation pile (which takes several hours), harbour porpoises cannot swim more than 10 to 20 km.

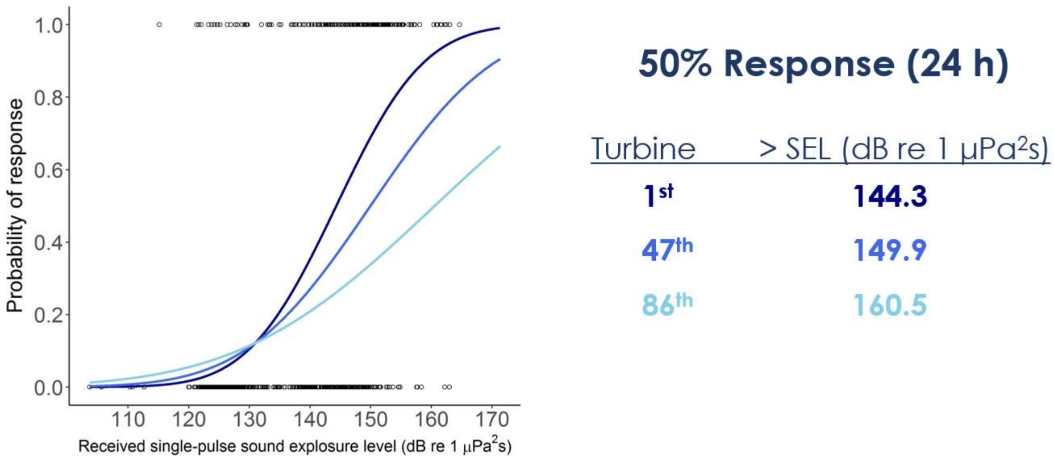

Figure C.1 Dose-response relationship for the disturbance of harbour porpoises by piling sound derived from measurements during the construction of the Beatrice wind farm in the UK (Graham et al., 2019), as presented at the INPAS Symposium (Amsterdam, June 2018). The three curves for the piling of the 1st, 47th and 86th turbine foundations indicate that the probability of a response declined slowly during the construction of the farm.

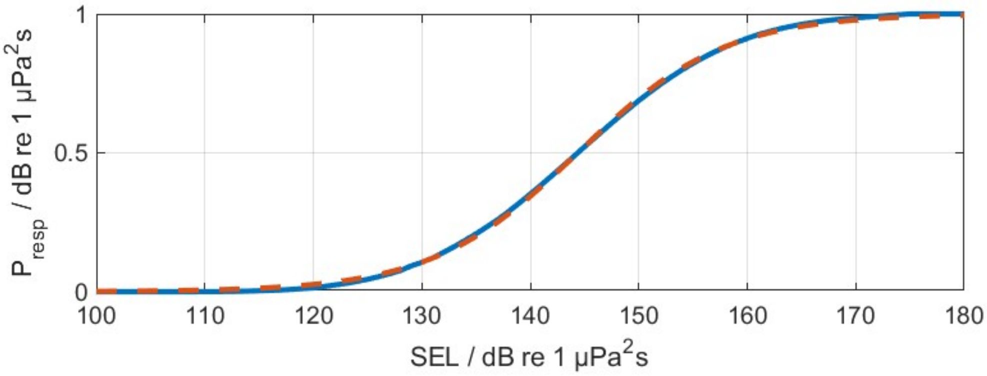

Figure C.2 Dose-response relationship for the disturbance of harbour porpoises by piling sound: probability of disturbance P_{dist} as a function of the unweighted broadband SELss. The solid line was taken from Graham et al.; the dashed line was calculated using the functional description (cf. B3-1). $\boldsymbol{P_{resp}}(\boldsymbol{SEL_{SS}} = 144\ dB) = 50\%$

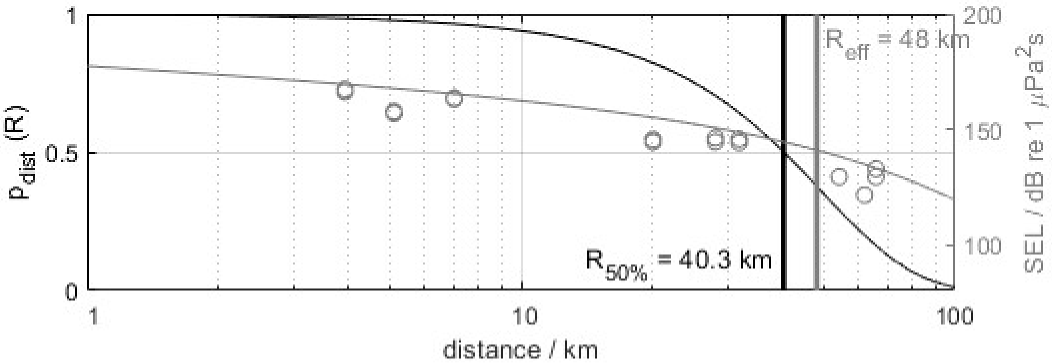

Figure C.3 Probability of disturbance of harbour porpoises by piling sound as a function of distance from the pile derived from the dose-response relationship and measured unweighted broadband SEL_{SS} at different distances from the pile during the construction of the Gemini wind farm (grey trend line has been fitted to the measurement points shown as ‘o’).

Seals

The monitoring data from which a dose-effect relationship for disturbance by piling can be derived are also scarce for seals. In the KEC 3.0, it was decided to adopt a discrete threshold for disturbance (SEL_{SS} = 145 dB re 1 μPa^{2}s, M weighted broadband in accordance with Southall et al., 2007) on the basis of data from a playback study (SEAMARCO, 2011).

For the KEC 4.0, the observations of Russell et al. (2016) and Whyte et al. (2020) were used to estimate a dose-response relationship for harbour seals. Those researchers saw a decrease in the number of harbour seals when exposed to SEL_{SS} = 142 – 151 dB re 1 μPa^{2}s. This would seem to be reasonably consistent with the observations of Aarts et al. (2018) for grey seals. They also 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 small probability of disturbance starting at exposure to SEL_{SS} = 144 – 150 dB re 1 μPa^{2}s. Because of the correspondence between the observations of the responses of harbour seals and grey seals, the same dose-response relationship for the two species is being assumed for the time being.

Figure C.4 shows the assumed dose-response function for seals. It is centred around the threshold of 145 dB assumed previously and the bandwidth is comparable with the observations expressed by a logistic function (in line with B3-1) with the parameters $a = -43.5$ and $B = 0.3$.
Figure C.5 applies this dose-response relationship to the measured underwater sound from piling for the construction of the Gemini wind farms. The dose-response relationship predicts a 50% probability of disturbance at a distance of 26.1 km from the pile being driven. The effective disturbance distance based on the integral of the area under the dose-response curve is 30.9 km.

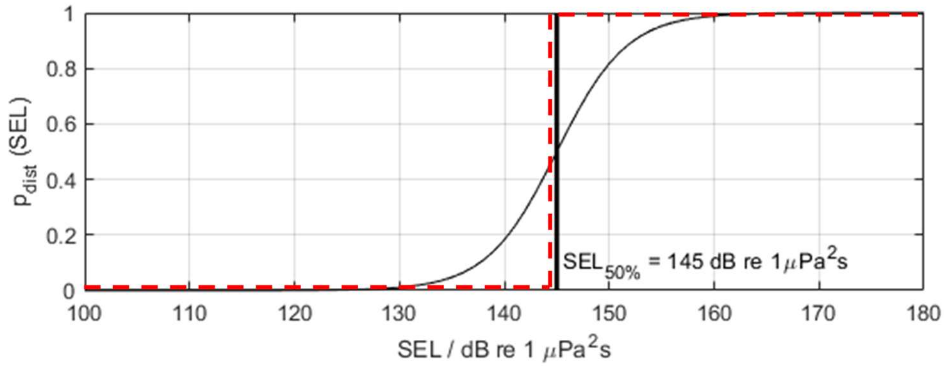

Figure C.4 The relationship derived for the purposes of the KEC 4.0 between the sound dose and significant behavioural response for harbour seals and grey seals. The red dashed line shows the discrete threshold assumed in the KEC 3.0 (SELss = 145 dB re 1 μPa²s).

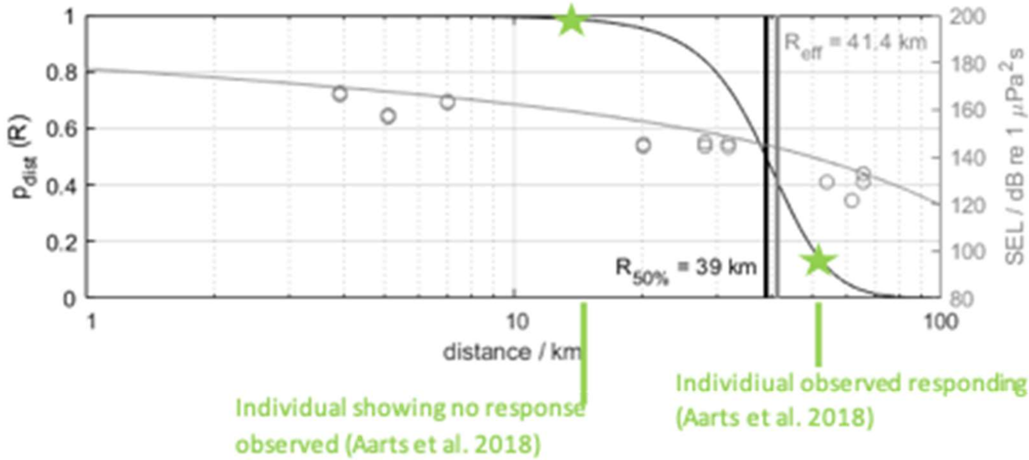

Figure C.5 Probability of disturbance of seals by piling sound as a function of distance from the pile derived from the dose-response relationship and measured unweighted broadband SEL_{SS} at different distances from the pile during the construction of the Gemini wind farm (grey trend line has been fitted to the measurement points shown as 'o').

Calculation of disturbance area and number of disturbed animals

The effective animal disturbance area A_{dist} was calculated for the three species by calculating the probability of disturbance $\mathrm{P}_{\mathrm{dist,n}}(\mathrm{SEL}_{\mathrm{SS}})$ for each point in the sound map, multiplying it by the area $\mathrm{d}A_n$ of the grid cell around the point and then producing a total for all points in the sound map:

$$A_{\mathrm{dist}} = \sum_n \mathrm{P}_{\mathrm{dist,n}}(\mathrm{SEL}_{\mathrm{SS}}) \times \mathrm{d}A_n \qquad \text{(C-2)}$$

The number of animals disturbed N_{dist} per piling day per location was calculated for the three species by calculating $\mathrm{P_n}(\mathrm{SEL}ss)$ for each point in the sound map (see Section 2.3), multiplying it by the area $\mathrm{d}A_n$ of the grid cell around the point and by the local estimate of the density D_n of animals at this point (from the animal distribution maps interpolated to the same grid as the sound maps) and then producing a total for all points in the map:

$$N_{\mathrm{dist}} = \sum_n \mathrm{P}_{\mathrm{dist,n}}(\mathrm{SEL}_{\mathrm{SS}}) \times D_n \times \mathrm{d}A_n \qquad \text{(C-3)}$$

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D Effects of animal movement on the model outcome from the iPCoD model

Calculation of number of disturbed animals and animal disturbance days
The KEC approach consists of two steps that can be affected by animal movements:
1 the disregarding of the influx of animals during piling;
2 the accumulation of disturbance.

The discussion that follows here looks at how these two assumptions affect the outcomes of the iPCoD model.

1. Disregarding the influx of animals during piling
The approach estimates the number of animals disturbed per day by each operation (such as wind farm construction). This is done by multiplying the average animal density at a given location by the probability of disturbance. This probability is predicted using a dose-effect relationship that links the modelled single-strike SELss to a probability of disturbance (see Annex C). The underlying assumption is that no animals move into the area disturbed by sound during construction, and that the number of animals disturbed can therefore be estimated by multiplying the density by the disturbed area. This assumption disregards the potential influx of new animals during piling operations on that day.

A Matlab simulation gives an idea of the size of the underestimation. We distinguish between three scenarios for this purpose:
1 Static animals: only the animals present in the disturbed area at the start of the piling operation will be disturbed. That is what we have always implicitly assumed until now; during the piling, no ‘new’ animals will enter the area and there will be no disturbance of animals that would wish to enter the area but do not do so because of the sound.
2 Animals swimming freely: all random animals swimming around that are present in the vicinity of the disturbance area during piling and that can swim into the area temporarily affected by sound will be disturbed. In this scenario, the animals swim at a constant speed and change direction randomly in each time step. Disturbance does not affect swimming.
3 Migrating animals: all animals swimming through the disturbance area during piling will be disturbed. In this scenario, the animals swim at a constant speed, all in the same direction. Disturbance does not affect swimming.

For example:
- Density: 1 animal per square kilometre
- Swimming speed: 2 m/s
- Effective disturbance distance (see Annex C for explanation): 26 km
- Duration of piling: 3 hours
- Time step: 6 minutes

The number of potentially disturbed animals in the three scenarios is, respectively (for one run of the scenario): 1) 2156, 2) 2519, 3) 3293.
At an effective disturbance distance of 10 km (which is more realistic for seals), the numbers are: 1) 292, 2) 418, 3) 698.

The results of these indicative calculations indicate that, in this respect, our current estimate of the number of disturbed animals per day based on Scenario 1, in other words the scenario we have assumed in the study, is not conservative. The underestimation is largest for the smaller disturbance distances, and for migrating animals (scenario 3). For the largest disturbance distance, the maximum error is a factor of 1.5; for the smaller distance representative for seals, it is a factor of 2.5. It is assumed above that all animals that have been present in the disturbed area at any time during piling (period of 3 hours) will be disturbed. Observations have shown that a response of seals to piling can lead to a reduction in foraging efficiency and/or temporarily swimming away from the piling location. Available data indicate that these responses in seals are seen primarily during piling and that the animals quickly return to normal behaviour once piling stops. It is therefore reasonable to assume that animals swimming into the area later on will be disturbed for a shorter period of time. The total number of animals may therefore be larger because of animals swimming around (up to a factor of approx. 2.5). The only question is whether the iPCoD expert judgment is representative for these shorter disturbance times.

2. Accumulation of disturbance

The iPCoD model calculates which modelled animals are disturbed each day. The total number of days of disturbance days a year determines the reduction in vital rates. The relationship between accumulated disturbance days and the probability of reproduction and survival are based on expert judgement. In the iPCoD model, modelled animals are collected randomly every day from a larger population, the vulnerable subpopulation. That population can be selected in such a way that only specific animals use a particular area and this subpopulation will be more likely to enter the disturbed area more often. At present, it has been decided to use the entire population. This means that the probability of an individual being disturbed several times is lower but that more individuals may be disturbed for shorter periods of time.

Due to the location of their resting locations in combination with their action radius, seals will use a more restricted area, as result of which animals may be exposed more frequently than is currently assumed. In the calculation below, we look at the sensitivity of the number of disturbance days per modelled animal, depending on the size of the assumed subpopulation (Figure D.1).

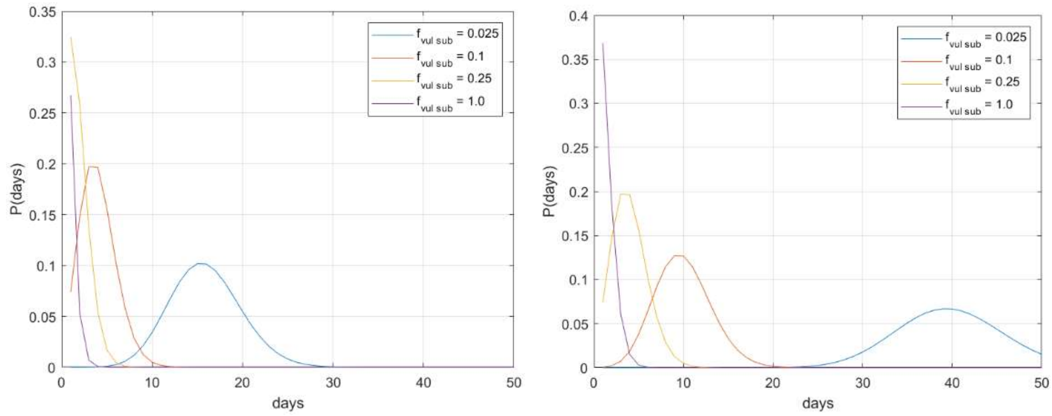

Figure D.1 Calculation with a single wind farm, in which 20 animals a day are typically disturbed relative to a subpopulation. The probability of an animal being disturbed several times was calculated here using a binomial distribution in which the probability of being disturbed on each day is $p_{dist} = N_{dist}/N_{subpop} = 20 / (f_{vul\ sub} * N_{DCS})$. Where N_{DCS}= 18,363 the total number of harbour seals on the DCS. The second calculation (on the right) if the total number of disturbed animals a day is larger by a factor of 2.5 (see calculation above).

If only a vulnerable subpopulation of 2.5% of the total population were to be disturbed, this would result in a significant number of days of disturbance in that part of the population by comparison with the expert judgement (see the figures taken from Booth et al., 2019, below). This is an effect on a small part (2.5%) of the population. The other 97.5% of the DCS population is not adversely affected.

B)

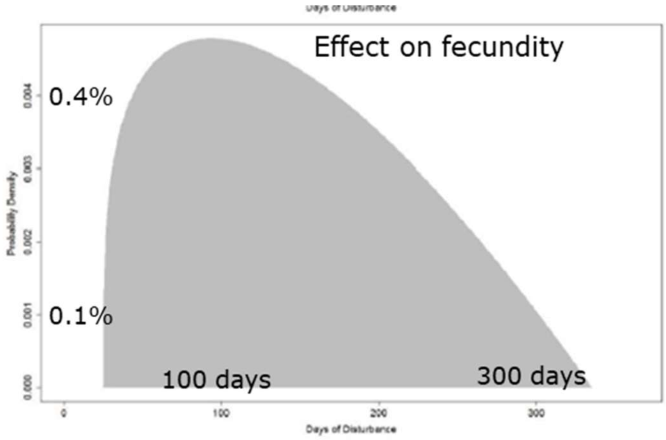

Figure 10 - Probability distributions showing the consensus of the EE for the effect of disturbance on harbour seal fertility- A) the number of days of disturbance a pregnant female could 'tolerate' before disturbance has any effect on fertility and B) the number of days required to reduce the fertility of the same individual to zero.

B)

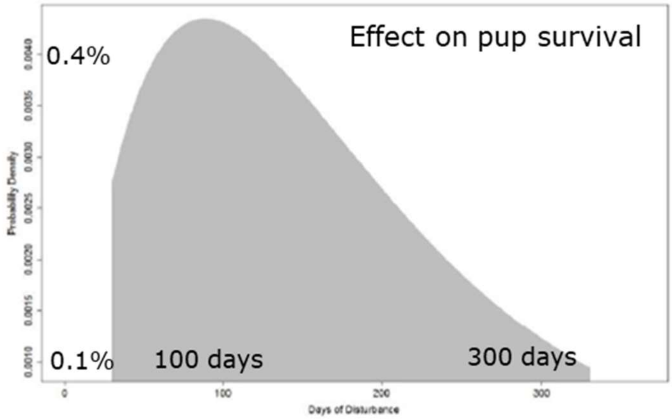

Figure 12 - Probability distributions showing the consensus of the EE for the effect of disturbance on harbour and grey seal 'weaned of the year' survival - A) the number of days of disturbance such a seal could 'tolerate' before it has any effect on survival and B) the number of days required to reduce the survival of the same individual to zero.

Effects of possible underestimation on the results of calculations

The iPCoD calculations for the piling scenarios for the North Sea wind farms between 2016 and 2030 did not predict any effect on populations of harbour and grey seals. In order to obtain an impression of what level of disturbance would have an effect on the population, a test scenario was defined for the seals in which 1000 seals a day are disturbed.

Scenarios for 100 and 200 piling days (in one year) were run for this purpose. This therefore means 100,000 and 200,000 animal disturbance days a year respectively. In both cases, the iPCoD calculation for this generic scenario does not result in effects on the seal population. Population reduction 0.

Compare: the maximum number of piling days a year in our scenario is 540 for the DCS (median 85) and the maximum number of animal disturbance days a year is ~33000 (median ~2000).

E Scenario

Scenario Seals	Name	Country	Expected start of construction	Sound standard: unweighted SEL_{SS} at 750 m (dB re 1 μ Pa^2s)	Max capacity in MW	MW Turbine	Number of turbine monopiles	Number of platform piles
+	Nobelwind	BE	2016	160	165	3	50	0
+	Rentel	BE	2017	160	309	7	42	0
+	Norther	BE	2018	160	370	8	44	0
+	Seamade (SeaStar)	BE	2019	160	252	8	30	0
+	Seamade (Mermaid)	BE	2019	160	235	8	28	0
+	Northwester 2	BE	2019	160	219	10	23	0
+	Princess Elisabeth – Noordhinder Noord – 2023 Tender	BE	2025	160	700	12	59	0
-	Princess Elisabeth – Fairybank/ Noordhinder Zuid – 2025 Tender	BE	2027	160	1400	15	94	0
-	Nordergründe	DE	2016	160	111	6	18	0
+	Veja Mate	DE	2016	160	402	6	67	0
+	Merkur	DE	2017	160	396	6	66	0
+	Borkum Riffgrund 2	DE	2018	160	450	8	56	0
+	Deutsche Bucht	DE	2018	160	252	8	31	0
+	Hohe See	DE	2018	160	497	7	71	0
+	Trianel Windpark Borkum II	DE	2018	160	203	6	32	0
+	Albatros	DE	2019	160	112	7	16	0
+	Kaskasi	DE	2021	160	342	9	38	0
+	Borkum Riffgrund 3	DE	2023	160	900	11	81	0
+	Gode Wind 3	DE	2023	160	242	11	22	0
+	EnBW He Dreiht	DE	2024	160	900	10	70	0
+	N-3.7	DE	2025	160	225	15	15	0
+	N-3.8	DE	2025	160	433	15	29	0
+	N-7.2	DE	2026	160	930	15	62	0
+	N-8.4	DE	2026	160	425	15	28	0
+	N-3.5	DE	2027	160	420	15	28	0
+	N-3.6	DE	2027	160	480	15	32	0
+	N-6.6	DE	2028	160	630	15	42	0
+	N-6.7	DE	2028	160	270	15	18	0
+	N-9.1	DE	2028	160	1000	15	67	0
+	N-9.2	DE	2028	160	1000	15	67	0
+	N-10.1	DE	2029	160	1000	15	57	0
+	N-10.2	DE	2029	160	700	15	47	0
+	N-9.3	DE	2029	160	1000	15	67	0
+	N-9.4	DE	2029	160	1000	15	67	0
+	N-13-3	DE	2030	160	1000	20	50	0
+	Horns Rev 3	DK	2017	160	407	8	49	0
-	Vesterhav Nord/Syd	DK	2022	160	344	8	41	0
-	Thor – 2020 Tender	DK	2025	160	1000	16	75	0

Scenario Seals	Name	Country	Expected start of construction	Sound standard: unweighted SEL_{SS} at 750 m (dB re 1 μ Pa^2s)	Max capacity in MW	MW Turbine	Number of turbine monopiles	Number of platform piles
-	L'éolien en mer région Dunkerque (troisième appel d'offres)	FR	2026	-	598	16	46	0
-	Dudgeon	UK	2016	-	402	6	67	0
-	Galloper	UK	2016	-	353	6	56	0
-	Race Bank	UK	2016	-	573	6	91	0
-	Beatrice	UK	2017	-	588	7	84	0
-	Blyth Offshore Demonstrator Phase 1	UK	2017	-	42	8	5	0
-	Aberdeen Offshore Wind Farm (EOWDC)	UK	2018	-	93	9	11	0
-	East Anglia ONE	UK	2018	-	714	7	102	0
-	Hornsea Project One	UK	2018	-	1218	7	174	0
-	Moray East	UK	2019	-	950	10	100	0
-	Hornsea Project Two	UK	2020	-	1386	8	165	0
-	Neart na Gaoithe	UK	2020	-	448	8	54	0
-	Triton Knoll	UK	2020	-	857	10	90	0
-	Seagreen	UK	2021	-	1140	10	114	0
-	Dogger Bank A	UK	2022	-	1200	13	95	0
-	Dogger Bank B	UK	2023	-	1200	13	95	0
+	East Anglia Hub – THREE	UK	2023	-	1400	14	100	0
+	Dogger Bank C	UK	2024	-	1200	14	95	0
-	East Anglia Hub – ONE North	UK	2024	-	800	14	58	0
-	Moray West	UK	2024	-	950	15	85	0
-	Seagreen 1A	UK	2024	-	360	10	36	0
-	Sofia	UK	2024	-	1400	14	100	0
-	East Anglia Hub – TWO	UK	2025	-	900	14	65	0
+	Norfolk Vanguard	UK	2025	-	1800	20	158	0
+	Hornsea Project Three	UK	2026	-	2400	11	231	0
-	Inch Cape	UK	2026	-	1000	15	72	0
+	Norfolk Boreas	UK	2027	-	1800	20	158	0
-	Berwick Bank	UK	2028	-	2300	20	115	0
-	Dudgeon Extension	UK	2028	-	402	20	115	0
-	Sheringham Shoal Extension	UK	2028	-	317	20	16	0
-	North Falls	UK	2029	-	504	15	34	0
-	Race Bank Extension	UK	2029	-	573	15	38	0
-	Five Estuaries	UK	2030	-	353	20	18	0
+	Borssele 3	NL	2019	164/170/172	366	10	39	6
+	Borssele 4 – Blauwwind	NL	2019	164/170/172	366	10	39	0
+	Borssele 1	NL	2020	163/169/171	376	8	47	6
+	Borssele 2	NL	2020	163/169/171	376	8	47	0
+	Borssele Site V –Two towers	NL	2020	164/170/172	19	10	2	0

Scenario Seals	Name	Country	Expected start of construction	Sound standard: unweighted SEL_{SS} at 750 m (dB re 1 μ Pa^2s)	Max capacity in MW	MW Turbine	Number of turbine monopiles	Number of platform piles
+	Hollandse Kust Zuid Holland I	NL	2021	167/173/ 175	385	11	35	6
+	Hollandse Kust Zuid Holland II	NL	2021	167/173/ 175	385	11	35	0
+	Hollandse Kust Noord (Tender 2019)	NL	2022	166/170/ 174	700	11	69	6
+	Hollandse Kust Zuid Holland III	NL	2022	167/173/ 175	385	11	35	6
+	Hollandse Kust Zuid Holland IV	NL	2022	167/173/ 175	385	11	35	0
+	Hollandse Kust West (Tender 2020/2021)	NL	2024	168	1400	12	117	12
+	Ten noorden van de Waddeneilanden – (Tender 2022)	NL	2026	168	700	15	47	6
+	IJmuiden Ver	NL	2027	168	4000	15	267	12
+	Hollandse Kust West zuidelijke punt	NL	2028	168	700	15	47	6
+	IJmuiden Ver Noord	NL	2028	168	2000	15	134	6
+	Search area 5 (East original)	NL	2029	168	4000	15	267	12
+	Search area 1 (South)	NL	2030	168	2000	20	100	6
+	Search area 1 (North)	NL	2030	168	4000	20	200	12
+	Search area 2 (North)	NL	2030	168	4000	20	200	12

Seasonal sound standards apply for January-May, June-August and September-December in the Dutch wind farms (2019-2022).

Number of days on which there will be piling for the installation of wind turbine foundations in the period 2016-2030 in Belgium (BE), Denmark (DK), Germany (DE), the Netherlands (NL) and the United Kingdom (UK) on the basis of the underlying assumptions stated in Section 3.2.

	BE	DE	DK	FR	NL	UK	total	% total
2016	50	85	0	0	0	214	**349**	**5%**
2017	42	66	49	0	0	89	**246**	**4%**
2018	44	190	0	0	0	287	**521**	**8%**
2019	81	16	0	0	78	100	**275**	**4%**
2020	0	0	0	0	96	309	**405**	**6%**
2021	0	38	0	0	70	114	**222**	**3%**
2022	0	0	41	0	139	95	**275**	**4%**
2023	0	103	0	0	0	195	**298**	**5%**
2024	0	70	0	0	117	374	**561**	**9%**
2025	59	44	75	0	0	223	**401**	**6%**
2026	0	90	0	46	47	303	**486**	**8%**
2027	94	60	0	0	267	158	**579**	**9%**
2028	0	194	0	0	181	246	**621**	**10%**
2029	0	238	0	0	267	72	**577**	**9%**
2030	0	50	0	0	500	18	**568**	**9%**
total	**370**	**1244**	**165**	**46**	**1762**	**2797**	**6384**	
% total	**6%**	**19%**	**3%**	**1%**	**28%**	**44%**		

F Statistics in the iPCoD model

Interim PCoD (version 5.2)
The KEC analysis of the effects of underwater sound from piling for offshore wind farms on marine mammal populations used the most recent version (version 5.2) of the *interim Population Consequences of Disturbance* (iPCoD) model (see http://www.smruconsulting.com/). The iPCoD model calculates marine mammal population trends using a 'Leslie Matrix' model. The effect of disturbance resulting from piling sound on population parameters ('calf and juvenile survival' and 'fertility') is taken into consideration here on the basis of expert elicitation.

Scenario
For this study, scenarios were considered for the disturbance of the North Sea harbour porpoise population resulting from the sound of wind farm construction by countries around the North Sea in the years 2016 through to 2030. Convergence was examined in more detail for one reference scenario (including the acceleration variant III for the Dutch wind farms, with an underwater sound standard SEL_{SS} (750m) = 168 dB re 1 μPa^{2}s from 2023 onwards). The effect of disturbance is determined by comparing calculations of harbour porpoise population trends with and without disturbance.

Evolution of the harbour porpoise population
The model calculations assume a relatively low adult survival rate (0.85) in order to factor in effects like bycatch, and relatively high fecundity (0.96). The average size of the North Sea harbour porpoise population was estimated on the basis of the recent density map drawn up by Gilles et al. (2020) at 373,310 individuals, 62,771 of which (17%) are on the DCS, see Table F.1.

Table F.1 Harbour porpoise densities (individuals/km^2) according to Gilles et al. (2021).

	-95% C.I.	**average**	+95% C.I.
North Sea population	272,390	**373,310**	508,860
DCS population	53,288	**62,771**	79,209
	20%	**17%**	16%

Figure F.1 shows how the undisturbed harbour porpoise population in the North Sea evolves from 2016 through to 2042 according to the iPCoD model. The statistical modelling means that the uncertainty of the calculated population size increases with the years. In this model, there is a maximum 5% probability that the population will be reduced by 36% in 2042 and a 50% probability that the population will be reduced by 2%. In 2031 (the first year after the construction scenario), these decreases are 28% (5% probability) and 1% (50% probability) respectively.

Figure F.2 shows how the harbour porpoise population disturbed by underwater sound from windfarm construction will develop from 2016 through to 2042 according to the iPCoD model. There is a maximum probability of 5% that the population in 2042 will be reduced by 49% and a 50% chance that it will be reduced by 4%. In 2031 (the first year after the construction scenario), these decreases are 41% (5% probability) and 3% (50% probability) respectively.

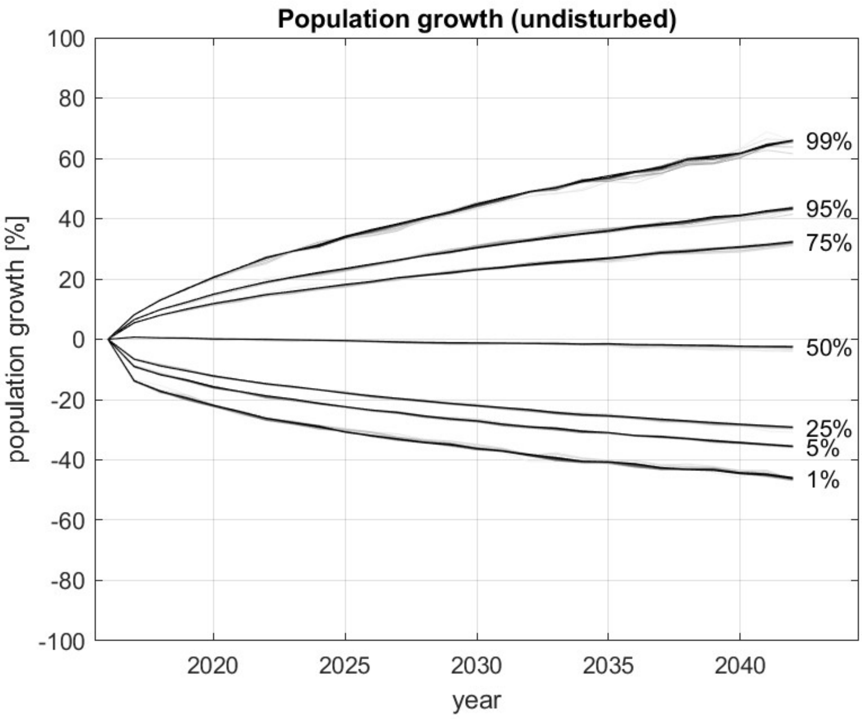

Figure F.1 Percentiles for the change in the <u>undisturbed</u> harbour porpoise population in the North Sea according to the Interim PCoD model. Curves were plotted for each percentile with grey shading increasing from white to black for the cumulative result of 1,000 to 20,000 model calculations in steps of 1,000.

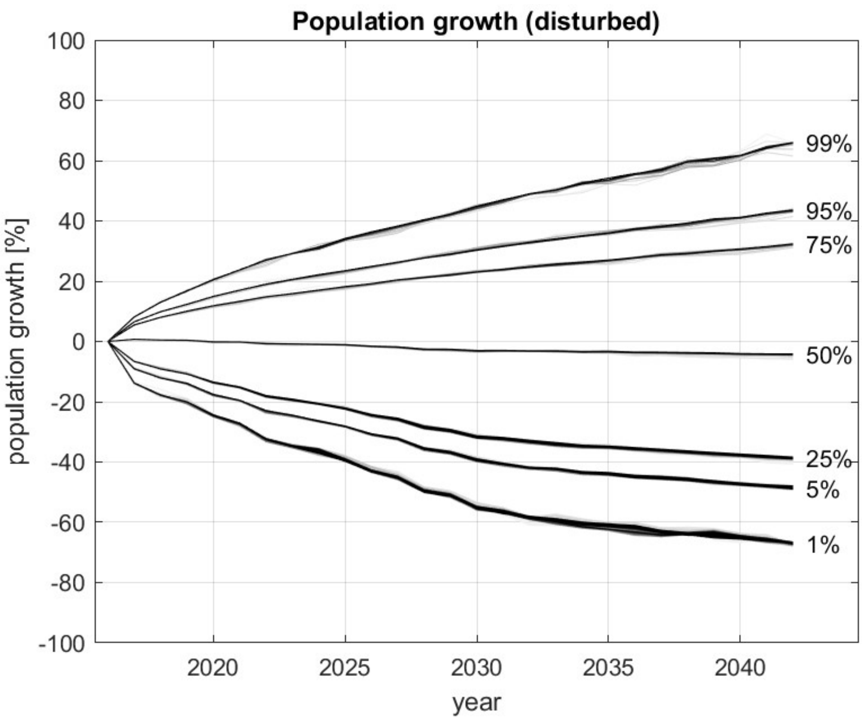

Figure F.2 Percentiles for the change in the harbour porpoise population <u>disturbed by piling sound</u> in the North Sea according to the Interim PCoD model. Curves were plotted for each percentile with grey shading increasing from white to black for the cumulative result of 1,000 to 20,000 model calculations in steps of 1,000.

Probability of disturbance
The probability of a harbour porpoise in the North Sea being disturbed on a given day by the underwater sound of piling for the construction of the wind farms is determined in the iPCoD model on the basis of the ratio of the number of potentially disturbed animals around the locations where piling is taking place on that day and the proportion of the population that could be in that area at any point in time (in other words, the vulnerable subpopulation). The KEC analyses assumed that this vulnerable subpopulation for harbour porpoises and seals corresponds to the total population. In that case, the probability of a harbour porpoise being disturbed in the reference scenario is a maximum of 8%. Figure F.3 shows that the probability is considerably lower on most days of the year. For example, the probability is less than 2% on 290 days a year.

Probability of disturbance lasting several days
During the iPCoD expert elicitation (Booth et al., 2019), the effect of disturbance lasting several days on the vital rates of the harbour porpoise population was estimated. Because the iPCoD model assumes that the probability of an animal being disturbed is independent of the prior history, the probability of an animal being disturbed on several days a year follows from the product of the probabilities of disturbance on the individual days. This means that the probability of disturbance lasting several days decreases sharply with the number of days. In the hypothetical worst-case scenario that the probability of disturbance on all days is equal to 8% (=8/100), the probability of disturbance during N days will then be equal to $(8/100)^N$.

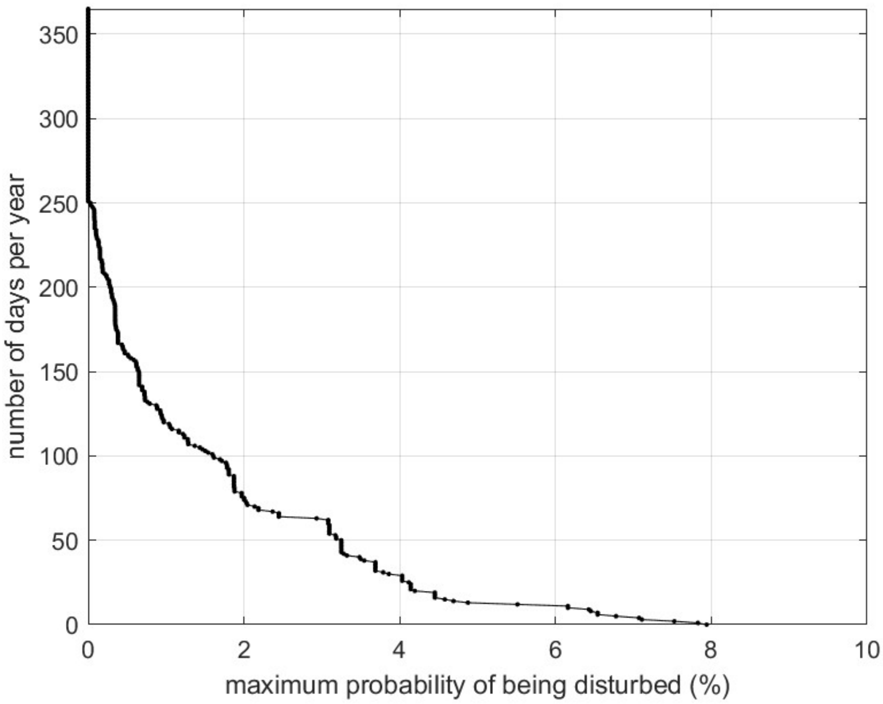

Figure F.3 The number of days a year on which the maximum probability of harbour porpoises being disturbed by piling occurs, in the reference scenario.

If a smaller vulnerable subpopulation were to be selected in the iPCoD model, assuming that the area in which piling takes place is important for a part of the population for some reason, the probability of disturbance lasting several days increases for that subpopulation. This means that the piling would have a larger effect on a part of the population. The KEC 1.0 study (Heinis et al., 2015) looked at the sensitivity of the iPCoD results to the size of the vulnerable subpopulation. It was concluded at the time that opting for a smaller vulnerable subpopulation results in a smaller effect on the total population. In order to avoid the risk of underestimating the effects, the KEC 4.0 study therefore uses the maximum vulnerable subpopulation for the calculations.

The iPCoD model accounts for uncertainty in the estimated probability of disturbance by multiplying it by a lognormal uncertainty distribution $\frac{1}{x\sigma\sqrt{2\pi}}\exp -\frac{1}{2}\left(\frac{\ln x-\mu}{\sigma}\right)^2$, where $\mu = 0$ and $\sigma = 0.25$, see King et al. (2015).

Reduction of harbour porpoise population by underwater sound during construction of offshore wind farms

The government wants 95% certainty that the 'Dutch' part of the harbour porpoise population (on the DCS) will not fall below 95% of the size it would have been without the effect of wind farms (in other words, a 5% probability of a maximum decrease of 5%). The percentiles for the change in the undisturbed population show that the model cannot provide this certainty. In the KEC, this requirement has therefore been stated as a 5% probability of an additional reduction in the DCS harbour porpoise population as a result of underwater sound during the construction of the wind farms of no more than 5%.

For the undisturbed population, the iPCoD model calculates a 5% probability of a reduction in the North Sea population in 2042 of 132,891 animals (36%), see Figure F.1. If there is disturbance as a result of the construction of the wind farms, the model calculates that there is a 5% probability of a reduction in the North Sea population of 182,017 animals (49%), see Figure F.2.

Figure F.4 shows the additional reduction of the harbour porpoise population due to underwater sound during the construction of the wind farms according to the iPCoD model. The curves show the differences for the percentiles from Figure E.1 and Figure E.2. There is a maximum 5% probability of an additional 13% reduction in the population decline and a 50% probability of an additional reduction of 2%.

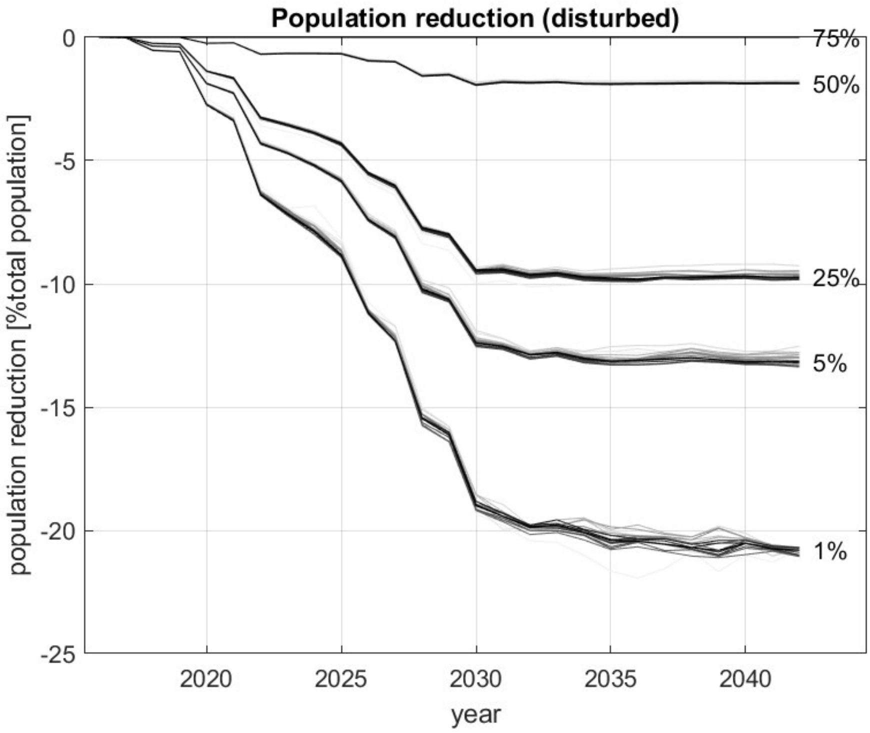

Figure F.4 Percentiles for the additional reduction in the harbour porpoise population disturbed by piling in the North Sea according to the iPCoD model. Curves were plotted for each percentile with grey shading increasing from white to black for the cumulative result of 1,000 to 20,000 model calculations in steps of 1,000.

Convergence

Figure F.5 shows the change in the 5th percentile of the undisturbed population in 2042 as a function of the number of model calculations. All the iPCoD simulations of the various scenarios for KEC 4.0 considered the results of 10,000 model calculations and the population reduction (5% percentile) averaged over the years 2032 through to 2042. Figure F.6 shows the effect of the number of model calculations on the calculated population reduction. These figures show the following:

- The model results do not clearly converge when the number of model calculations is raised to 20,000; from 10,000 model calculations onwards, the lines continue to fluctuate around an average of ~500 individuals. The results also suggest that the calculated reduction may deviate in the order of ~1000 individuals from the values given on the basis of 10,000 model calculations (in other words, ~0.3% of the North Sea population and ~2% of the calculated additional reduction of 48,419 individuals).
- The variation in the calculated reduction of the disturbed population over the years 2032 through to 2042 is virtually independent of the number of model calculations: the standard deviation is 416 ± 34 individuals, less than 1% of the calculated additional reduction of 48,419 individuals (for 10,000 model calculations).

Conclusion

As a result of the aim of 95% certainty, and looking at the 5% percentile of the statistical distribution of calculated population trends, the estimates of the possible population reduction are conservative but not very accurate (in the order of ~1000 individuals).

Extrapolation to the DCS population

The decision to define an ecological standard in the KEC for the acceptable level of impact of the construction of the wind farms on the harbour porpoise population on the DCS results in additional uncertainty in the calculation results. The effect of the Dutch wind farms on the total harbour porpoise population is calculated on the basis of the difference between, on the one hand, the calculated percentiles for population reduction in an international scenario including the DCS farms and, on the other, the percentiles of the population reduction in an international scenario that excludes the DCS farms. Here, therefore, two figures with an uncertainty of the order of ~1000 animals are subtracted from each other. The resulting 'Dutch contribution' to the population reduction is then compared with the DCS population, see Figure F.7. The calculated 5% percentile of the DCS population reduction varies from 5% to 7%.

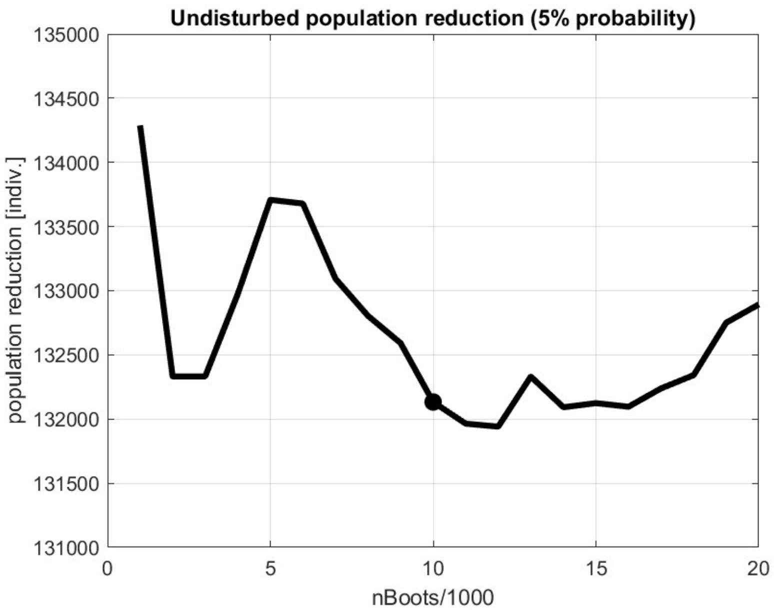

Figure F.5 Effect of the number of model calculations ('nBoots', from 1,000 to 20,000, in steps of 1,000) on the 5% percentile of the calculated reduction of the undisturbed population: reduction of the number of individuals in 2042.
The black dot represents the reduction calculated with nBoots = 10,000.

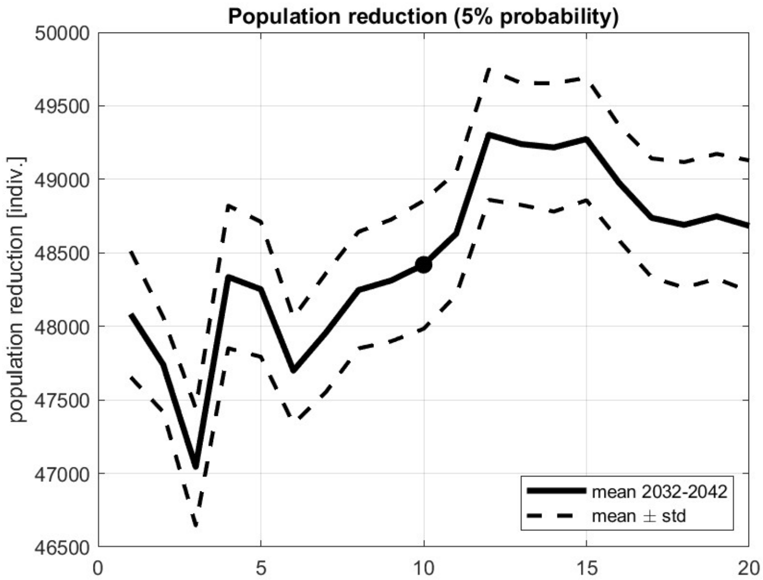

Figure F.6 Effect of the number of model calculations (‘nBoots’, from 1,000 to 20,000, in steps of 1,000) on the 5% percentile of the calculated population reduction (number of individuals) from 2032 through to 2042 (mean and standard deviation). The black dot represents the reduction calculated with nBoots = 10,000.

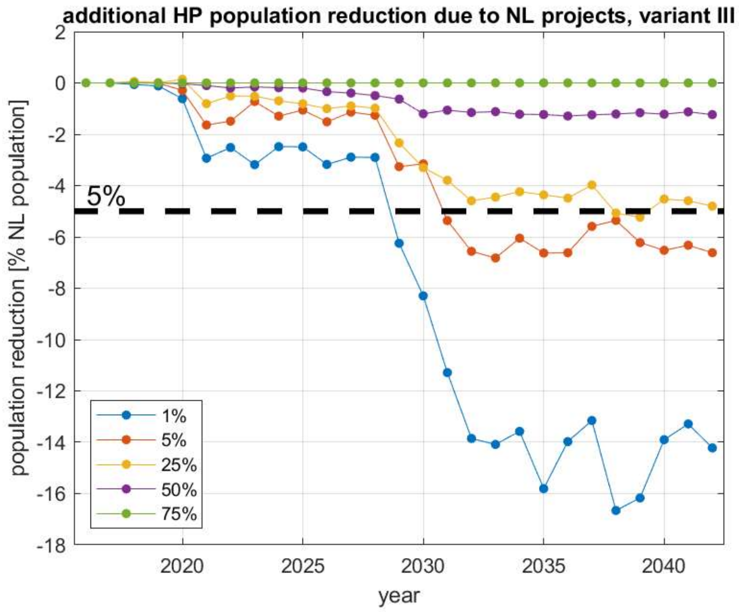

Figure F.7 Percentiles of the calculated reduction (percentage of the DCS population) from 2032 through to 2042 (mean and standard deviation) for the reference scenario (including acceleration variant III for the Dutch wind farms). The black dashed line shows the acceptable level of reduction (5%) required with a high degree of certainty (5% percentile).

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G Geophysical surveys

Scenario description
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 bed 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.

The calculations assume that the scenario for the geophysical survey consists of four sub-scenarios:
1 Global survey of the area of the future wind farm;
2 Detailed survey of the locations of the future turbines, platforms and infield cables;
3 Global survey of the cable route;
4 Detailed survey of the cable route.

1) Global survey of the area of the future wind farm:
- A geophysical survey covers about 10 km^2 per day and it continues 24 hours a day (unless there is bad weather and during the monthly crew changeover, which we disregard in this study). The number of days per farm = surface covered by geophysical survey divided by 10 (km^2).
- It is assumed that this survey will be conducted in the five years prior to the construction of the wind farm (in other words, the installation of the wind turbines).
- The work is done with a multibeam, a sidescan sonar, a magnetometer, a sub-bottom profiler and a multi-channel sparker, depending on the different objectives involved. The use of a sparker is assumed as the worst-case scenario, resulting in effect distances of 3 km (see below, 'Estimate of effect distances for geophysical instruments').
- No location-specific acoustic calculations were performed; it is assumed that 10 km^2 a day is scanned, with an estimated maximum disturbance distance (in the case of a sparker) of ~3 km. For a rectangular scanning area, that results in a disturbance area of ~84 km^2 a day.

2) Detailed survey of the locations of the future turbines, platforms and infield cables:
- Typically conducted 1 to 2 years before the construction of the farm (as in the case of Gemini). The assumption here is that the survey is conducted one year before construction.
- Other assumptions are those used for the global surveys (1).

3) Global survey of the cable route:
- This is a survey of the route from the wind energy area to land. Assumptions have been made here about the position of the platform and the landing, and therefore the length of the route, which will probably not correspond to what has been or will be realised in practice. In addition, a survey of the location of the platform(s) is planned, in particular for obstacles (sidescan sonar, bathymetry) and magnetic contacts (for 'unexploded ordnance', otherwise known as UXO).

- The total surveyed area is estimated as the number of kilometres of cable multiplied by a strip width. This width depends on the number of cables and distance to the farm (estimated values in Table G.3).
- This survey is typically conducted two years before the construction of the wind farm.
- It involves the use of a magnetometer, a sidescan sonar, a sub-bottom profiler, and a singlebeam and multibeam echo sounder. A multi-channel sparker may not be needed if the sub-bottom profiler can provide enough information down to the burial depth of the cables (1–2 metres) plus the height of the sand waves (location-specific) and it is not included here because very deep bed penetration is not required. Here, we adopted an effect distance typical for the sub-bottom profiler of 1 km (see Table G.5).
- No location-specific acoustic calculations were performed; it is assumed that 10 km2 a day is scanned, with an estimated maximum disturbance distance (with the sub-bottom profiler) of ~1 km (see below, ‘Estimate of effect distances for geophysical instruments’). For a rectangular scanning area, this results in a disturbance area of ~30-36 km^2 a day (depending on the route).

4) Detailed survey of the cable route:

- The route from the search area to land is estimated as the number of kilometres of the route multiplied by a strip around the cable (approximately 100 metres around the cable). Assumptions were made about the position of the platform and the landing and therefore the length of the cable route (see above).
- This survey is conducted one year before the construction of the wind farm using a magnetometer, a sidescan sonar, a sub-bottom profiler, and a single-beam and multibeam echo sounder because very deep bed penetration is not required. Here, we adopted an effect distance typical for the sub-bottom profiler of 1 km (see Table G.5). Limited penetration is needed for the largest area; deeper penetration is needed in the order of 10 metres between the coast and the 3 km line only.
- No location-specific acoustic calculations were performed; it was assumed that 10 km^2 is scanned a day, with an estimated maximum disturbance distance (with a sub-bottom profiler) of ~1 km. Any effect of sparker deployment in the last 3 km, the coast and in and around the vicinity of the platforms has been disregarded. For a rectangular scanning area, that results in a disturbance area of ~36 km^2 a day.

The above scenarios lead to the following for each farm (Table G.1) and each platform/cable route (Table G.2).

Table G.1 Geophysical survey by farm.

Time	**Activity**	**Disturbance area per day (km^2)**
5 years before construction	Global survey area wind farm and platforms	84
1 year before construction	Detailed survey of the locations of the future turbines and platforms	84

Table G.2 Geophysical survey by cable route.

Time	Activity	Disturbance area per day (km²)
2 years before construction	Global survey of the cable route	36
1 year before construction	Detailed survey of the cable route	36

It is assumed that the number of animal disturbance days is the same for the global and detailed surveys. Estimates for the cable routes depend on the distance to land and the type of cable connection (AC or DC).
The values used to estimate the number of harbour porpoise disturbance days resulting from the surveys are shown in Tables G.3 and G.4 below.

Using the above assumptions, the total estimated number of harbour porpoise disturbance days for the scenario for the four geophysical surveys for the Dutch search areas for offshore wind is 61,622 (from Tables G.3 and G.4). This corresponds to approximately 3% of the estimated total number of harbour porpoise disturbance days due to piling during the construction of the farms (approximately 2.7 million).

Table G.3 Estimated value for harbour porpoise disturbance days caused by a geophysical survey of the search areas calculated on the basis of the assumed parameters for these surveys given in the table.

Search area	Surface area	Number of survey days	Disturbance area per day (km²)	Density in spring (ind/km²)	harbour porpoise disturbance days
Borssele 3	61	6	84	0.71	365
Borssele 4 – Blauwwind	61	6	84	0.71	362
Borssele 1	56	6	84	0.80	375
Borssele 2	56	6	84	0.73	344
Borssele Site V -Two towers	1	0.1	84	0.75	4
Hollandse Kust Zuid Holland I	52	5	84	1.12	488
Hollandse Kust Zuid Holland II	52	5	84	1.07	469
Hollandse Kust Noord (Tender 2019)	94	9	84	1.42	1,121
Hollandse Kust Zuid Holland III	54	5	84	1.04	471
Hollandse Kust Zuid Holland IV	54	5	84	1.08	491
Hollandse Kust West – (Tender 2020/2021)	140	14	84	1.09	1,284
Ten noorden van de Waddeneilanden – (Tender 2022)	70	7	84	0.80	472
IJmuiden Ver	400	40	84	0.95	3,184
Hollandse Kust West zuidelijke punt	70	7	84	1.07	631
IJmuiden Ver Noord	200	20	84	0.97	1,627
Search area 2 (South)	400	40	84	1.02	3,435
Search area 5 (East original)	400	40	84	0.77	2,595
Search area 1 (South)	200	20	84	0.80	1,337
Search area 2 (North)	400	40	84	1.07	3,610
				total	22,664

Table G.4 Estimated value for harbour porpoise disturbance days caused by a geophysical survey of the cable route for the search areas calculated on the basis of the estimated distances from the transformer platforms to land and the associated assumed parameters for these surveys given in the table. It is assumed that the two cables follow the same route[10].

Transformer platform	**Length of route to land (km) (estimate)**	**Route width (km) – estimate**	**Area of route (km²)**	**number of km² surveyed per day**	**Number of survey days**	**Disturbance area per day (km²)**	**Density in spring (ind/km²)**	**harbour porpoise disturbance days**
Borssele 1&2	61	1.2	73	10	7	36	0.71	187
Borssele 3&4	68	1.2	82	10	8	36	0.71	209
HK-ZH I&II	48	1.2	58	10	6	36	0.71	147
HK N	20	1.2	24	10	2	36	0.71	61
HK-ZH III&IV	40	1.2	48	10	5	36	0.71	123
HKW alpha & beta	87	1.2	104	10	10	36	0.71	534
TNW	120	1.2	144	10	14	36	0.97	503
IJmuiden Ver alpha & beta	200 × 2	1.2	240	10	24	36	0.71	1,227
HKW-Z	80	1.2	96	10	10	36	0.71	245
IJmuiden Ver Noord	200	1.2	240	10	24	36	0.71	613
Search area 2 (South alpha & beta)	200 × 2	1.2	240	10	24	36	0.71	1,227
Search area 5 (East alpha & beta)	133 × 2	1.2	160	10	16	36	0.97	1,115
Search area 1 (South)	238	1.2	286	10	29	36	0.71	730
Search area 2 (North alpha & beta)	200 × 2	1.2	240	10	24	36	0.71	1,227
							total	8,148

Estimate of effect distances for geophysical instruments

Geotechnical surveys are conducted to prepare for the construction of the wind farms. They draw on a range of acoustic sources such as multibeam and sidescan sonars, sub-bottom profilers and sparkers. The source strength and frequency range of the survey signals are very different from those of piling sound. On the basis of global information about the acoustic sources in combination with a threshold value weighted with the frequency sensitivity of harbour porpoise and seal hearing, an estimate was made of the disturbance distance for different types of systems used in these surveys (see below ‘Acoustic properties of geophysical surveys’). These resulting impact distances are summarised in Table G.5 below.

[10] The calculations assume that the two cables follow the same route and that the surface area only counts once. If it is assumed that the cables are at some distance from each other and that the area therefore needs to be doubled, the total estimated number of harbour porpoise disturbance days for the scenario for the four geophysical surveys is estimated at 72,280 instead of the 61,622 stated here. This corresponds to approximately 4% (instead of 2.4%) of the total number of harbour porpoise disturbance days due to piling during farm construction, which is still a negligible contribution.

Table G.5 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.

System type	System example	Maximum estimated effect distance	
		Harbour porpoise	**Seals**
Multibeam echo sounder:	Kongsberg EM2040 Dual Head, Dual Swath / Dual Ping – Frequency 400 kHz	Above threshold for harbour porpoise hearing; No significant sub-harmonics; expected effect distances negligible	Above threshold for seal hearing; No significant sub-harmonics; expected effect distances negligible
Sidescan sonar:	Edgetech 4200 300/600 – Frequency: 239 kHz (LF) and 555 kHZ (HF)	Above threshold for harbour porpoise hearing; No significant sub-harmonics; expected effect distances negligible	Above threshold for seal hearing; No significant sub-harmonics; expected effect distances negligible
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 distances between 1 and 2 km as a result of the primary frequency of the source at 100 kHz (see Figure G.1)	Primary frequency not easily heard by seals; at secondary frequencies, the expected effect distance is negligible
Sparker Single-channel	GSO 200-tip sparker (assumed operated at 500 J)	Maximum effect distances between 1 and 2 km on the basis of estimates (see Figure G.1)	Maximum effect distances between 1 and 2 km on the basis of estimates (see Figure G.1)
Sparker Multi-channel	GSO 360-tip Sparker seismic source + 2000 J PSU (operated at 900 J)	Maximum effect distances between 3 and 4 km on the basis of estimates; (see Figure G.1).	Maximum effect distances between 3 and 4 km on the basis of estimates (see Figure G.1)

These estimates of the maximum effect distance are uncertain for various reasons. For the estimation of the thresholds for disturbance of harbour porpoises and seals as well as for the noise levels limited data were available. These estimates are, therefore, based on rough assumptions. Because insufficient public information was available during the development of KEC 4.0 to improve the estimates, the same disturbance distances were used as in KEC 3.0.

Acoustic properties of geophysical surveys

The multi-beam echosounders and sidescan sonars used during geophysical surveys emit high-frequency signals (> 200 kHz) which are not audible to harbour porpoises and seals. Measurements of this type of system indicate that hardly any acoustic energy is emitted at lower frequencies (see, for example, Crocker et al., 2018). The sources that cause significant sound levels at frequencies audible to harbour porpoises and seals are the sub-bottom profilers and sparkers.

A sub-bottom profiler that is typically used, a ‘parametric sub-bottom profiler’, generates low-frequency (~10 kHz) sound by simultaneously emitting several high-frequency (~100 kHz) sounds. Using high frequencies results in a very directional, downward, low-frequency beam (~3-6 degrees -3 dB beam width). Leaflets from suppliers of parametric sub-bottom profiler providers indicate that the source level (SL) is in the main frequencies range (85–125 kHz) > 240 dB re 1 μPa·m. The source levels at the low frequencies are around 202 dB re 1 μPa·m. This corresponds to a typical 30–40 dB reduction in the source level of the secondary frequencies in a parametric sonar (Moffet & Melen 1977). A typical SL = 240 dB re 1 μPa·m at 100 kHz is assumed here to estimate the effect distances. For the secondary frequencies, an SL = 202 dB re 1 μPa·m is assumed at 10 kHz. Typical pulse lengths for the sub-bottom profiler are in the order of

t_{pulse} ~ 0.04-30 ms. Here, a source level energy (SLE) in the main beam is assumed of SLE = SL + 10*log10(T_{puls} / 1s) dB ~ 187 dB re 1 μPa^2·m^2·s. For the horizontally propagated sound (which is propagated effectively and can result in disturbance), another 60 dB is subtracted here because of the high directionality of this source.

Sparkers are systems that generate air bubbles by means of electrical discharges to ‘tips’. This produces an air bubble, which generates a broadband impulse sound, typically with higher frequencies than the sound of the airguns often used for seismic surveys. Typical source levels can be found in Crocker et al. (2018). The source level depends on the power used and the bandwidths are quite broad: SLE ~ 167-181 dB re 1 μPa^{2}m^{2}s (500 J) and SLE ~ 179-186 dB re 1 μPa^{2}m^{2}s (900 J). This analysis is based on the maximum values stated. The bandwidths of the generated pulse are BW_{-3dB} ~ 1.2-1.9 kHz (500 J), and BW ~ 3.2 kHz (1000 J) (Crocker et al., 2018). These signals are roughly approximated in the calculations below by assuming a signal of 1 kHz with the above SLE. We assume that directionality is comparable with a single airgun pulse.

Threshold values for the disturbance of behaviour were derived from a review of disturbance thresholds conducted as part of WOZEP (de Jong & von Benda-Beckmann 2017) and they are summarised here in Table G.6.

Tabel G.6 SELss threshold values to estimate effect distances for disturbance of harbour porpoises and seals by geophysical sound sources at different frequencies.

	harbour porpoise	**seal**
Frequency / kHz	**SELss / dB re 1 μPa^{2}s**	**SELss / dB re 1 μPa^{2}s**
1	130	130
10	100	100
100	75	75

The propagation loss for these sources in the North Sea is estimated using a cylindrical and a ‘mode-stripping’ regime for a point source (in line with 9.46 from Ainslie 2010), with values representative for a sandy bed (which is typical for the North Sea). The effect distances in Table G.5 correspond to the threshold values shown in Figure G.1.

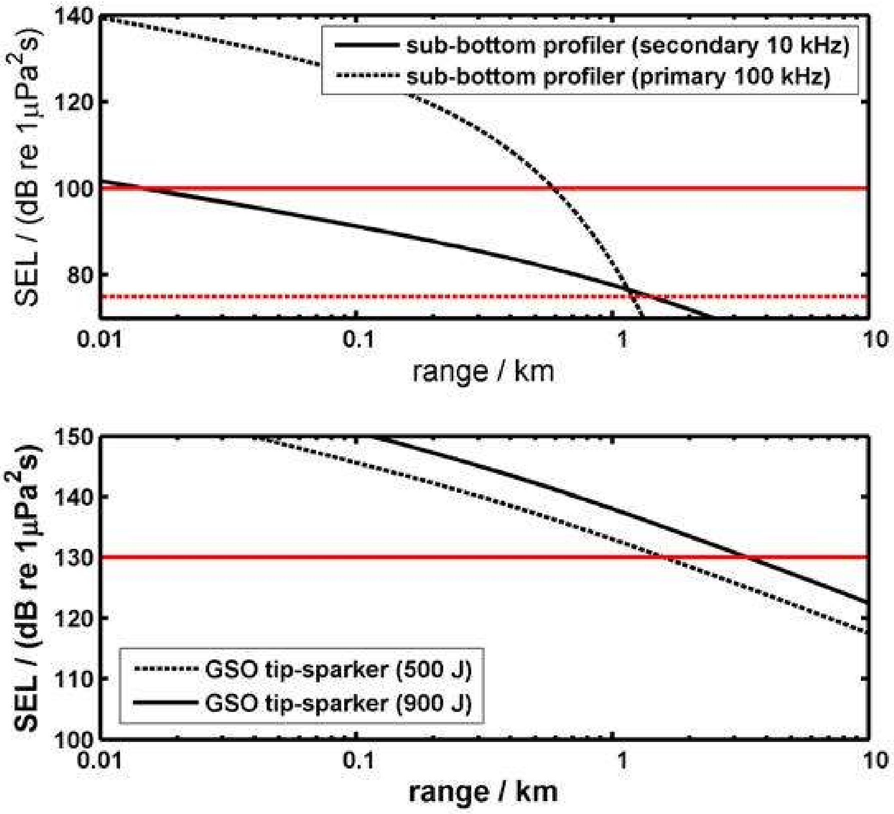

Figure G.1 Single pulse SEL (black lines) as a function of distance to the source for a parametric sub-bottom profiler with the primary frequency (dashed line) and secondary frequency (upper panel) and two types of sparker (lower panel). The red lines show the frequency-dependent disturbance thresholds (from Table G.6).

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H Animal disturbance days for the Dutch wind farms

Harbour porpoises

	Depth m	Standard SELss dB	Disturbance area km^2	Harbour porpoise density km^{-2}	Number of piles	Harbour porpoise disturbance days
Borssele 3	29.9	170	1154	0.7	42	34,500
Borssele 4 – Blauwwind	29.8	170	1625	0.7	39	44,811
Borssele 1	25.8	169	1169	0.8	50	46,623
Borssele 2	32.5	169	768	0.7	47	26,461
Borssele Site V -Two towers	31.4	170	1235	0.7	2	1,852
Hollandse Kust Zuid Holland I	22.2	173	1099	1.1	38	46,301
Hollandse Kust Zuid Holland II	21.2	173	1104	1.1	35	41,545
Hollandse Kust Noord (Tender 2019)	23.6	170	944	1.4	72	96,882
Hollandse Kust Zuid Holland III	21.0	173	994	1.0	38	38,901
Hollandse Kust Zuid Holland IV	20.0	173	880	1.1	35	33,320
Hollandse Kust West – (Tender 2020/2021)	25.5	168	1140	1.1	123	152,976
Ten noorden van de Waddeneilanden – (Tender 2022)	37.2	168	2500	0.8	50	99,296
IJmuiden Ver	25.4	168	1475	0.9	273	380,940
Hollandse Kust West zuidelijke punt	27.6	168	1326	1.1	50	70,709
IJmuiden Ver Noord	25.7	168	1344	1.0	137	178,026
Search area 5 (East original)	25.9	168	3161	0.8	273	663,477
Search area 1 (South)	39.2	168	1628	0.8	103	133,080
Search area 1 (North)	27.3	168	1541	0.8	206	265,286
Search area 2 (North)	26.5	168	1329	1.1	206	293,334

With stricter sound standard for search areas starting after construction in 2027 (IJmuiden Ver and calculation variants for the acceleration).

IJmuiden Ver	25.4	160	653	1.0	267	169,155
Hollandse Kust West zuidelijke punt	27.6	160	597	1.1	50	32,254
IJmuiden Ver Noord	25.7	160	606	1.0	137	79,810
Search area 5 (East original)	25.9	160	571	1.0	273	271,164
Search area 1 (South)	39.2	160	1327	0.8	103	57,464
Search area 1 (North)	27.3	160	713	0.8	206	110,486
Search area 2 (North)	26.5	160	597	1.1	206	134,456

Harbour seals

	Depth m	Standard SELss dB	Disturbance area km^2	Seal density km^{-2}	Number of piles	Seal disturbance days
Borssele 3	29.9	170	299	0.4	42	7,917
Borssele 4 – Blauwwind	29.8	170	401	0.6	42	10,239
Borssele 1	25.8	169	301	0.3	50	3,188
Borssele 2	32.5	169	213	0.2	50	1,947
Borssele Site V -Two towers	31.4	170	318	0.5	5	781
Hollandse Kust Zuid Holland I	22.2	173	424	0.1	38	2,456
Hollandse Kust Zuid Holland II	21.2	173	434	0.1	38	1,119
Hollandse Kust Noord (Tender 2019)	23.6	170	386	0.8	72	33,741
Hollandse Kust Zuid Holland III	21.0	173	414	0.2	38	2,938
Hollandse Kust Zuid Holland IV	20.0	173	370	0.1	38	1,078
Hollandse Kust West – (Tender 2020/2021)	25.5	168	341	0.1	123	1,730
Ten noorden van de Waddeneilanden – (Tender 2022)	37.2	168	483	0.6	50	20,790
IJmuiden Ver	25.4	168	365	0.04	273	4,205
Hollandse Kust West zuidelijke punt	27.6	168	351	0.04	50	502
IJmuiden Ver Noord	25.7	168	358	0.1	137	2,556
Search area 5 (East original)	25.9	168	532	0.1	273	17,636
Search area 1 (South)	39.2	168	377	0.1	103	1,850
Search area 1 (North)	27.3	168	353	0.1	206	2,463
Search area 2 (North)	26.5	168	347	0.3	206	22,939

Grey seals

	Depth m	Standard SELss dB	Disturbance area km^2	Seal density km^{-2}	Number of piles	Seal disturbance days
Borssele 3	29.9	170	299	0.04	42	975
Borssele 4 – Blauwwind	29.8	170	401	0.05	42	795
Borssele 1	25.8	169	301	0.11	50	1,064
Borssele 2	32.5	169	213	0.07	50	690
Borssele Site V -Two towers	31.4	170	318	0.07	5	102
Hollandse Kust Zuid Holland I	22.2	173	424	0.29	38	7,258
Hollandse Kust Zuid Holland II	21.2	173	434	0.27	38	3,862
Hollandse Kust Noord (Tender 2019)	23.6	170	386	0.56	72	23,078
Hollandse Kust Zuid Holland III	21.0	173	414	0.29	38	4,500
Hollandse Kust Zuid Holland IV	20.0	173	370	0.50	38	6,582
Hollandse Kust West – (Tender 2020/2021)	25.5	168	341	0.06	123	2,318
Ten noorden van de Waddeneilanden – (Tender 2022)	37.2	168	483	0.08	50	2,200
IJmuiden Ver	25.4	168	365	0.04	273	4,518
Hollandse Kust West zuidelijke punt	27.6	168	351	0.04	50	685
IJmuiden Ver Noord	25.7	168	358	0.06	137	2,843
Search area 5 (East original)	25.9	168	532	0.10	273	4,396
Search area 1 (South)	39.2	168	377	0.03	103	1,155
Search area 1 (North)	27.3	168	353	0.03	206	1,711
Search area 2 (North)	26.5	168	347	0.18	206	13,251