Assessing the benefit of noise reduction measures during offshore wind farm construction on harbour porpoises

Authors:	Ursula K. Verfuss, Rachael Plunkett, Cormac G. Booth, John Harwood
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1 Executive Summary

To meet the European Union's obligations under the Bern convention, the Council of the European Communities adopted the European Habitats Directive in 1992. The provisions of the Directive require Member States to maintain or restore European Protected Species (EPS), such as the harbour porpoise (*Phocoena phocoena*), at a favourable conservation status and to designate Special Areas of Conservations (SACs). Member states must provide a report on the conservation status of each protected species every six years.

The Southern North Sea possible SAC (pSAC) is one of six pSACs set out for consultation within UK waters for harbour porpoise, for which JNCC and Natural England (2016) set out conservation objectives and advice on activities. To maintain a favourable conservation status for the UK harbour porpoise population, the conservation objectives for this pSAC are to avoid deterioration of the porpoise's habitats or significant disturbance to the porpoise. Disturbance can be caused by noise that is, for example, generated by piling activities during offshore wind farm constructions. JNCC and Natural England (2016) identified piling as an activity that may occur within and/or near to the Southern North Sea pSAC, and considered management actions for the mitigation of noise induced disturbance. One potential mitigation measure is the reduction of piling noise through the use of noise reduction systems installed around a piling site. These have previously been successfully applied in the German North Sea, reducing the area impacted by noise by up to 90% (Diederichs *et al*. 2014).

The investigations presented in this report describe how noise reduction measures may affect the potential impacts of wind farm construction on the North Sea harbour porpoise population. Annex C of the EU habitats directive (European Commission, 2005) advises that a population decline of more than 1% per year within a period specified by the Member States and below the 'favourable reference population' would represent unfavourable conservation status for that population under the Habitats Directive. Therefore the potential population effects of disturbance was expressed as the risk of an annual population decline of 1% or 2%, respectively, and were explored over a period of 36 years in a scenario based on the construction of all wind farms in the UK North Sea that are currently operational, under construction, consented or awaiting approval. A number of different scenarios were conducted, in which the impact of noise was reduced at all wind farms or only those wind farms located within or overlapping with the Southern North Sea pSAC.

The results show that noise reduction measures can clearly help to reduce the risk of a population decline due to the cumulative impacts of wind farm construction. The risk of a 1% population decline due to wind farm construction could be – with the mitigation measures investigated in this project -

reduced by 34% as a minimum but reduction could be up to 96%. The predicted risk decreased with decreasing size of the impact area around a pile and with increasing numbers of wind farms implementing noise mitigation measures during construction. Similar reductions in risk may be achieved by large scale reductions in the impact area at a limited number of construction sites, for example those within a pSAC, or a smaller reduction in the impact area at a large number of sites. Using noise reduction measures in areas with high porpoise densities will be a more efficient measure to reduce the risk of a population decline than applying the same measures in areas of lower porpoise densities. The effectiveness of noise reduction measures was relatively insensitive to the duration of residual disturbance.

2 Introduction

In 1992, the Council of the European Communities adopted the European Habitats Directive to meet the European Union's obligations under the Bern convention[1]. The provisions of the Directive require Member States to introduce a range of measures[2], in order to

- Maintain or restore European Protected Species (EPS) listed in the Annexes at favourable conservation status,
- Contribute to a coherent European ecological network of protected sites by designating Special Areas of Conservation (SACs) for species listed on Annex II,
- Undertake surveillance of species, and
- Assess and report on the conservation status of species listed on the Annexes to the Directive.

Article 17 of the Habitats Directive requires that conservation status reports are provided every six years (Evans and Arvela, 2012). Evans and Arvela (2012) provide guidance on the assessment and reporting of conservation status. Annex C of European Commission (2005) provides a general evaluation matrix for assessing the conservation status of a protected species in each biogeographic region within a member state.

This matrix gives the following definitions for favourable and unfavourable conservation status:

Conservation status is taken as favourable if the:

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[1] The Bern Convention is a binding international legal instrument in the field of nature conservation, covering most of the natural heritage of the European continent (http://www.coe.int/en/web/bern-convention/presentation (accessed 06/06/2016).

[2] Full information can be found under http://jncc.defra.gov.uk/page-1374 (accessed 06/06/2016).

- Range within the biogeographical region concerned is stable (loss and expansion in balance) or increasing AND not smaller than the 'favourable reference range[3]',
- Population size is not lower than the 'favourable reference population[4]' AND reproduction, mortality and age structure do not deviate from normal (if data are available),
- Habitat for the species is sufficiently large in area (and stable or increasing) AND habitat quality is suitable for the long term survival of the species.

Conservation status is taken as unfavourable if the:

- Range has experienced a large decline, equivalent to a loss of more than 1% per year within the period specified by Member States OR is more than 10% below the favourable reference range,
- Population has experienced a large decline, equivalent to a loss of more than 1% per year (this is an indicative value that Member States may deviate from if duly justified) within the period specified by the Member States AND below the 'favourable reference population' OR more than 25% below the favourable reference population OR reproduction, mortality and age structure strongly deviate from normal (if data available),
- Habitat for the species is clearly not sufficiently large in area to ensure the long-term survival of the species OR habitat quality is bad, clearly not allowing long-term survival of the species.

The harbour porpoise (*Phocoena phocoena*) is listed in Annexes II and IV of the Habitats Directive and is therefore a species for which SACs should be designated. In January 2016, JNCC and Natural England released a draft report for comments on the conservation objectives and advice on activities in a possible SAC (pSAC) for the harbour porpoise in the Southern North Sea of the UK (JNCC & Natural England, 2016). One of the conservation objectives outlined is that there is no significant disturbance of the species within the site in order to ensure the integrity of the site and maintain the

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[3] Range within which all significant ecological variations of the habitat/species are included for a given biogeographical region and which is sufficiently large to allow the long term survival of the habitat/species; favourable reference value must be at least the range (in size and configuration) when the Directive came into force; if the range was insufficient to support a favourable status the reference for favourable range should take account of that and should be larger (in such a case information on historic distribution may be found useful when defining the favourable reference range); 'best expert judgement' may be used to define it in absence of other data (from Evans and Arvela 2012).

[4] Population in a given biogeographical region considered the minimum necessary to ensure the long-term viability of the species; favourable reference value must be at least the size of the population when the Directive came into force; information on historic distribution/population may be found useful when defining the favourable reference population; 'best expert judgement' may be used to define it in absence of other data (from Evans & Arvela 2012).

favourable conservation status for the UK harbour porpoise. The report indicates that anthropogenic activities causing underwater noise (such as shipping, drilling, pile driving, underwater explosions, etc.) would be considered as a 'medium' impact relative to other pressures on the UK harbour porpoise population (table 1 of JNCC and Natural England, 2016), i.e. there is some evidence of impact occurring in UK waters (JNCC and Natural England, 2016).

Underwater noise can lead to physical injury, auditory injury (such as a permanent or temporary shift in the hearing threshold - PTS or TTS) and behavioural responses (Southall *et al*. 2007). Movement away from a sound source is one of the most common behavioural responses to underwater noise and can lead to the displacement of a species from a particular area. The fitness costs resulting from behavioural responses may have effects at the population level (New *et al*. 2014).

A number of UK offshore wind farms have been consented to date, of which eleven are located within or overlap with the Southern North Sea pSAC (Figure 1). Construction noise, especially during piling activity, has the potential to cause auditory injury in harbour porpoises (Southall *et al*. 2007; Lucke *et al*. 2009) and may displace porpoises up to several tens of kilometres away from the piling site (e.g. Brandt *et al*. 2011; Dähne *et al.* 2013; Tougaard *et al*. 2006). The duration of this displacement may last from several hours (Tougaard *et al*. 2006) to a few days (Brandt *et al*. 2011). An Environmental Impact Assessment (EIA) has to be conducted in order to obtain consent for a particular wind farm development. These assessments usually include predictions of the potential impact of piling noise on marine mammals in the area of the wind farm. These predictions are often obtained by modelling the noise profile around the sound source and calculating the range at which noise levels are above the threshold level for disturbance or auditory injury. More recent EIAs also provide an estimate of the number of animals predicted to experience auditory injury and behavioural disturbance. The predicted number of impacted animals is often derived by multiplying the size of the impact area by the local animal density (which is obtained from either site specific surveys or published literature such as Hammond *et al*. 2006).

JNCC and Natural England (2016) suggest management options that may be required to reduce the impact of pile driving activities. They highlight that an EPS licence is compulsory for any construction activity carrying a risk of injury or significant disturbance, which requires, at a minimum, the adoption of the JNCC protocol for minimising the risk of injury to marine mammals from piling noise (JNCC, 2010). For piling activities within the Southern North Sea site, or within 26 km of its boundaries, additional management options may be required. These may include measures such as varying the piling schedule, a spatio-temporal limitation of piling, the use of noise reduction systems during piling or the use of low-noise foundations.

Noise reduction systems that can be used during pile-driving have been successfully developed and tested in Germany. For example, Diederichs *et al*. (2014) tested a noise reduction system called a Big Bubble Curtain (BBC) in water depths of 27 to 33 meters at the offshore windfarm Borkum West II in the German North Sea. Two types of the BBC were tested (BBC1 and BBC2) which differed in the jet nozzle hose configurations (nozzle size and distance). They showed that the BBC1 reduced the sound exposure level (SEL) of pile driving by around 8 dB and reduced the behavioural impact radius for harbour porpoise by 55% from 15 km to 6.7 km while the BBC2 reduced the SEL by around 11 dB and the behavioural impact range by 69% from 15 km to 4.6 km. The resulting reductions in the behavioural impact area for harbour porpoise were 80% (from 707 km^2 to 141 km^2) and 90% (from 707 km^2 to 66 km^2) for BBC1 and BBC2 respectively. Verfuss (2014) compared the effectiveness of a number of different noise reduction systems, including BBC, hydro sound damper and casings, and found that they could reduce the SEL by 7 to 18 dB.

In this report, we investigate how the use of noise reduction systems, which reduce the impact area, for all wind farms or for only those wind farms located completely or partially within the pSAC, may change the predicted cumulative effect of wind farm construction on the North Sea harbour porpoise population. In particular, we calculated the risk of a harbour porpoise population decline under a number of different hypothetical construction scenarios, based on all wind farms in the UK North Sea currently operational, under construction, consented or awaiting approval.

3 Methods

3.1 Baseline scenario

A baseline construction scenario was developed, against which the results from scenarios with noise reduction could be compared. This baseline scenario was set up for a defined harbour porpoise population (section 3.3), and a number of UK offshore wind farm projects (section 3.4) constructed over a 24 year period using a hypothetical piling schedule (section 3.6.1). The potential impacts on harbour porpoise considered here were behavioural responses to the pile-driving noise when animals were within the behavioural impact range, and experiencing PTS when animals were within the range of auditory injury but outside the 500 m mitigation range specified in the JNCC protocol (JNCC, 2010). The number of animals within each impact range was retrieved from Environmental Statement documents as described in section 3.6.2. The scenarios were modelled with the interim Population Consequences of Disturbance (iPCoD) framework (section 3.5) to assess the risk of a population decline. Annex C of European Commission (2005) suggest that a population which shows an annual decline in abundance of more than 1% may be considered to have an unfavourable conservation status. We therefore assessed the forecasted risks of an annual decline of 1% and 2% over a 36 year period starting with the year of the first piling activity. Demographic parameters and impact duration were obtained from published literature (section 3.6.3 and 3.6.4).

3.2 Noise reduction scenarios

The effects of four noise reduction scenarios on the risk of a population decline were explored:

1.) All wind farms apply noise reduction methods that result in an 80% reduction of their impact area;

2.) All wind farms apply noise reduction methods that result in a 60% reduction of their impact area;

3.) Only those wind farms whose site boundaries are within, or overlap with a SAC, apply noise reduction methods that result in an 80% reduction of their impact area;

4.) Only those wind farms whose site boundaries are within, or overlap with a SAC, apply noise reduction methods that result in a 60% reduction of their impact area.

The 60% and 80% reduction in impact area corresponds to a 37% and 55% reduction of the corresponding impact ranges. We have chosen an 80% reduction in impact area as this was shown to be a realistic minimum achievement in the German North Sea in water depths up to 33 m (Diederichs *et al*., 2014). To acknowledge the difficult environment of UK waters that may influence the effectiveness of noise reduction systems, we have included a scenario in which the noise reduction is less efficient, (i.e. a 60% reduction in impact area is the best that is achieved in this theoretical scenario).

While we considered geographical differences in harbour porpoise density between wind farm locations (section 3.6.2), we approximated the effectiveness of the noise reduction measures with the assumption that the distribution of the porpoise density within an impact area is uniform. The number of animals present in an impact area will therefore be reduced to the same proportion as the impact area is reduced in size. To put this into practice, the number of animals within an impact range as retrieved for the baseline scenario (section 3.1) was reduced according to the four noise reduction scenarios as described above. All other parameters as described for the baseline scenario were kept constant.

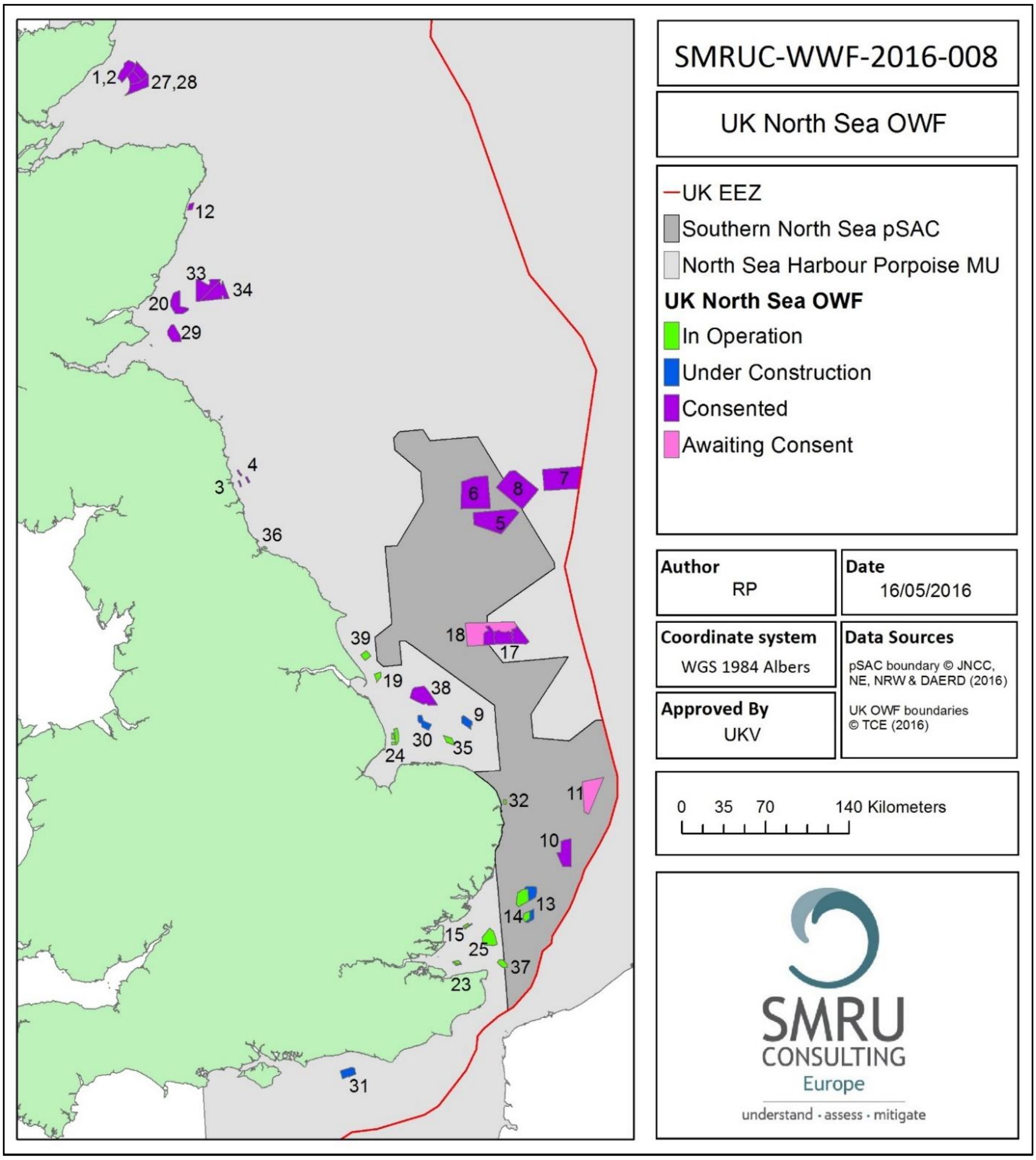

Figure 1. North Sea UK Offshore Wind Farms considered in this project relative to the Southern North Sea pSAC and the North Sea porpoise Management Unit. Numbers serve as identifiers for the specific wind farm developments as listed in Table 1.

3.3 Harbour porpoise population

Construction scenarios were assumed to affect the North Sea harbour porpoise Management Unit (MU), as defined in IAMMWG (2015). The North Sea MU comprises territorial and EEZ waters of the UK, Norway, Sweden, Denmark, Germany, the Netherlands, Belgium and France. It extends from the North Sea into the northern Kattegat via the Skagerrak, and into the English Channel. The boundary of the MU is shown in Figure 1. The estimated abundance of harbour porpoise in the North Sea MU is 227,298 (95% CI: 176,360 - 292,948). The northern and western boundaries of the North Sea MU are arbitrarily defined and there may be interchange with the West Scotland MU (IAMMWG, 2015), however this was not considered in this project.

While this project considered UK windfarm sites only, the entire North Sea MU was considered the most biologically relevant unit for an assessment of potential cumulative impacts. This was implemented due to the fact that the entire North Sea MU would likely be affected by the construction of UK windfarms, given the high mobility and wide home range of harbour porpoises (Evans and Teilmann, 2009) and the long time period of construction considered (i.e. 24 years).

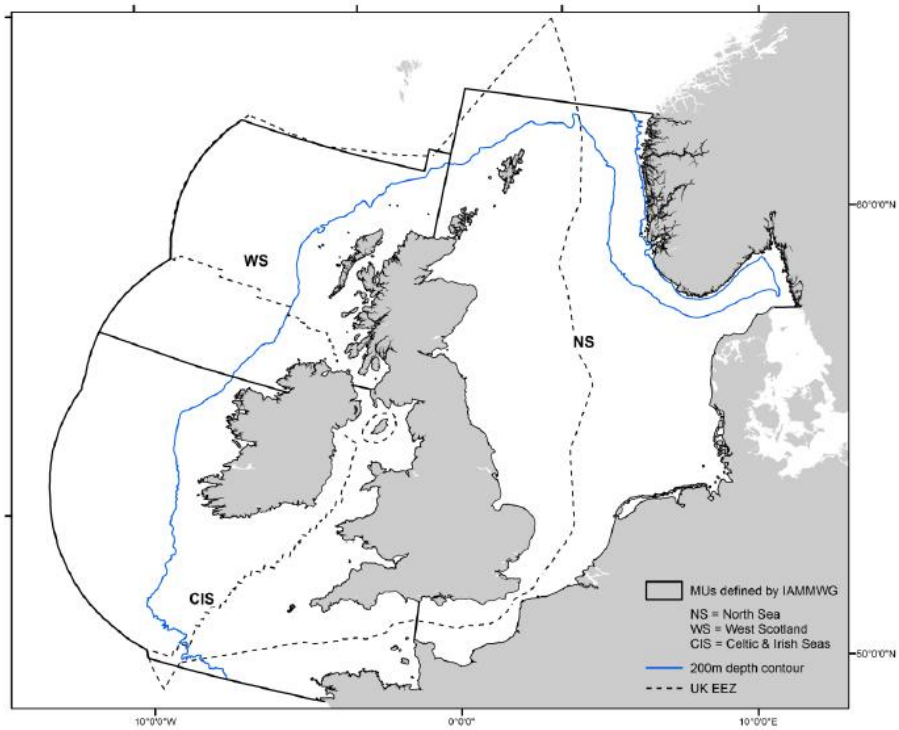

Figure 2. Management units for the harbour porpoise surrounding UK waters as defined by IAMMWG (2015). The current study refers to the North Sea management unit. (Figure from IAMMWG, 2015)

3.4 Offshore Wind Farm sites and related information

We included all UK offshore wind farms that are operational, under construction, consented or awaiting approval and that will lie within the boundaries of the North Sea harbour porpoise MU. This resulted in 39 offshore wind farm developments being included in the simulations (Table 1, Figure 1), with a construction period spanning 24 years from June 2000 to May 2024 (i.e., the potential impact of the construction of all 39 wind farms was considered, including those that Environmental Statements and accompanying documents (from here on referred to as ESs and listed in section 7.2) for these developments were reviewed to obtain relevant information relating to impact assessment and construction to inform the parameters listed below. This was augmented with more recent information collected from news articles and the following public databases:

- www.4coffshore.com,
- www.renewableuk.com,
- Windfarm project specific websites.

Where feasible, the following data on piling activity were extracted from ESs:

- The threshold used to determine the impact range for PTS and behavioural responses,
- The impact range and impact area for PTS and behavioural response,
- The number of porpoise predicted to experience PTS and exhibit a behavioural response as a result of one day of piling, and
- The mean site specific porpoise density (in porpoises per km^2).

Seasonal variation in porpoise density was not considered, because this information was not provided in most of the ESs.

From the wind farm project description, the following data (either actual or proposed) was extracted:

- The start and end date of construction,
- Construction 'down times' between start and end date of construction,
- The foundation type and pile diameter of the foundation, and
- The number of foundations to be piled in the wind farm project area.

Table 1 and Table 2 present the availability of the required data from the individual wind farm ESs. Section 3.6 outlines the procedure that was followed to obtain values for those data that were not available from the individual wind farm ESs.

We identified the following eleven wind farm developments as being within or overlapping with the Southern North Sea pSAC (shown in Figure 1):

- Dogger Bank Creyke Beck A
- Dogger Bank Creyke Beck B
- East Anglia 3
- East Anglia 1
- Greater Gabbard
- Galloper

- Scroby Sands
- Dogger Bank Teeside B
- Hornsea 1
- Hornsea 2
- Thanet

Table 1. UK offshore wind farms considered in this project. Construction start and end dates in italics denotes tentative/uncertain dates which may be subject to change (dates obtained 15/04/2016).

#	Wind Farm	Status	Construc-tion start	Construc-tion end	# Turbines	# Piling days	Foundation Type	Pile Diameter (m)	Year of operation
1	Beatrice	Approved	*2017*	*2018*	84	84	Jacket	2.2	-
2	Beatrice Demo	Operational	2006	2006	2	2	Jacket	1.9	2007
3	Blyth	Operational	2000	2000	2	2	Monopile	3.5	2000
4	Blyth Offshore	Approved	*2017*	*2017*	5	5	Monopile	10	-
5	Dogger Bank Creyke Beck A	Approved	*2020*	*2021*	200	200	Monopile	8 - 10	-
6	Dogger Bank Creyke Beck B	Approved	*2020*	*2021*	200	200	Monopile	8-10	-
7	Dogger Bank Teeside A	Approved	*2021*	*2023*	200	200	Monopile	8	-
8	Dogger Bank Teeside B	Approved	*2021*	*2023*	200	200	Monopile	8	-
9	Dudgeon	Under Construction	2016	*2017*	67	67	Monopile	7 - 7.4	-
10	East Anglia 1	Approved	*2019*	*2020*	102	102	Jacket	1.0 - 2.5	-
11	East Anglia 3	Accepted for examination	*2022*	*2023*	172	172	Monopile	10 - 12	-
12	European Offshore Wind Deployment Centre	Approved	*2017*	*2017*	11	11	Jacket	-	-
13	Galloper	Approved	*2016*	*2017*	56	56	Monopile	7.5	-
14	Greater Gabbard	Operational	2009	2010	140	140	Monopile	up to 6.5	2012
15	Gunfleet Sands I	Operational	2008	2009	30	30	Monopile	4.7	2010
16	Gunfleet Sands II	Operational	2008	2009	18	18	Monopile	4.7	2010
17	Hornsea 1	Approved	*2018*	*2019*	171	171	Monopile	-	-
18	Hornsea 2	Accepted for examination	*2020*	*2022*	258	258	Monopile	-	-
19	Humber Gateway	Operational	2013	2014	73	73	Monopile	4.8	2015
20	Inch Cape	Approved	*2018*	*2019*	110	220	Jacket	-	-
21	Inner Dowsing	Operational	2007	2007	27	27	Monopile	4.8	2009
22	Kentish Flats Extension	Operational	2015	2015	15	15	Monopile	4.3	2015
23	Kentish Flats I	Operational	2004	2004	30	30	Monopile	5	2005
24	Lincs	Operational	2011	2012	75	75	Monopile	4.7	2013
25	London Array	Operational	2011	2012	175	175	Monopile	-	2013
26	Lynn	Operational	2007	2007	27	27	Monopile	4.8	2009

#	Wind Farm	Status	Construc-tion start	Construc-tion end	# Turbines	# Piling days	Foundation Type	Pile Diameter (m)	Year of operation
27	Moray Firth	Approved	*2017*	*2018*	93	93	Jacket	2.5	-
28	Moray Firth	Approved	*2017*	*2018*	93	93	Jacket	2.5	-
29	Neart na Gaoithe	Approved	*2017*	*2018*	64	320	Jacket	5.5 - 6.5	-
30	Race Bank	Approved	*2016*	*2017*	91	91	Monopile	-	-
31	Rampion	Under Construction	2016	*2017*	116	116	Monopile	5.75 - 6.5	-
32	Scroby Sands	Operational	2003	2004	30	30	Monopile	3-3.5	2004
33	Seagreen Alpha	Approved	2018	2021	75	75	Jacket	3	-
34	Seagreen Bravo	Approved	2018	2021	75	75	Jacket	3	-
35	Sheringham Shoal	Operational	2010	2011	88	88	Monopile	4.8	2012
36	Teesside	Operational	2012	2012	27	27	Monopile	5	2013
37	Thanet	Operational	2009	2010	100	100	Monopile	4.1	2010
38	Triton Knoll	Approved	*2018*	*2019*	288	288	Monopile	-	-
39	Westermost Rough	Operational	2014	2014	35	35	Monopile	-	2015

Table 2. Summary of data availability from individual wind farm Environmental Statements.

Information	Parameter	No of wind farms	%
Auditory injury	No. of animals	11	28%
	Impact area or range	21	54%
Behavioural response	No. of animals	10	26%
	Impact area or range	22	56%
Density	Site Specific	11	28%
	Range	8	21%

3.5 Population model

The interim Population Consequences of Disturbance (iPCoD) framework was used to forecast the risk of a harbour porpoise population decline associated with wind farm construction. iPCoD was developed by SMRU Consulting and the University of St Andrews in 2013 to forecast the potential effects on marine mammal populations as a result of disturbance, PTS or collisions that might result from the construction or operation of offshore renewable energy devices. A detailed description of the approach can be found in Harwood *et al*. (2014) and King *et al*. (2015). The iPCoD framework was designed to provide an interim solution to enable decision making given the current paucity of information about the potential effects of these developments on marine mammals (in particular how disturbance and PTS may impact individual survival and reproduction). It should be recognised that this is very much an interim solution to the evaluation of these effects, and that there is an urgent need for additional scientific research to address the knowledge gaps identified by Harwood *et al*. (2014).

The iPCoD framework considers how disturbance may impact both the behaviour and physiology of an individual, and how these responses may affect that individual's vital rates either directly (an acute effect) or indirectly via health (a chronic effect). The parameters for the relationship between behavioural and physiological changes and individual vital rates used in this model were determined by an expert elicitation process (Runge *et al*. 2011; Martin *et al*. 2012) combined with the 4-step interval approach developed by Speirs-Bridge *et al*. (2010). Donovan *et al*. (2016) and Appendix 1 of Harwood *et al*. (2014) describe how this approach was developed and implemented in the iPCoD framework.

3.6 Input Data

The information described in Section 3.4 was used to prepare the input files for iPCoD, which requires a piling schedule indicating on which days and for which wind farm foundations will be piled. In this assessment the total length of the iPCoD simulation was set to 36 years (24 years of construction plus 12 years post construction) in order to assess changes in population status over six 6-year report periods. The number of animals predicted to experience PTS or a behavioural response during one day of pile-driving for each operation needed to be determined. Another parameter to decide on was the number of days an animal will be disturbed if it exhibits a behavioural response. Within the iPCoD framework this is referred to as the number of days of residual disturbance. Finally, estimates of the life history parameters that describe the underlying demographic characteristics of the population under consideration are required.

3.6.1 Piling schedule

Currently there are few data available to document the detailed sequence of the piling of each single foundation (piling event) that occurs during the construction of a wind farm (operation). Therefore, a hypothetical piling schedule was constructed using the actual or proposed start and end dates of construction and considering any proposed 'down times' (i.e. breaks in construction). Two different types of foundations that require piling activities were considered: monopiles and jacket foundations. Any foundation explicitly planned (at the time of data compilation) as a low noise foundation (e.g.: gravity base) was not considered. The following assumptions were made, unless otherwise stated in the ESs:

- A maximum of one piling event will occur per day within one operation,
- Concurrent piling events can occur on one day if they occur at different operations (but only one per operation, as above),

- There is no restriction on the number of available piling vessels,
- Monopile foundations require one day of piling,
- Monopile foundations within the same operation can be erected on consecutive days, with no down time between foundations,
- Jacket foundations require one day of piling,
- Jacket foundations within the same operation cannot be erected on consecutive days. One day of down time is required between the construction of consecutive foundations to allow the pile installation frame to be moved.

No restriction of the number of available piling vessels was assumed as a wide variety of foundation pile diameters are planned to be installed (Table 1), which may allow the use of different types of vessels for installation. This means that a variety of vessels can be used simultaneously at two or more wind farms constructed at the same time. We furthermore assumed that the supply of vessels will increase with the increasing demand associated with the construction of the wind farms as they are currently planned (Figure 4). These assumptions are based on the best publicly available information at the current time.

The implementation of one day of down-time after the installation of a jacket foundation was based on the description of jacket foundation construction in the Beatrice windfarm (Beatrice Offshore Windfarm Ltd. 2015). However, the ES for Neart na Gaoithe outlined a different installation technique compared to that described for Beatrice, and estimated that five piling days would be required for the installation of one jacket foundation. This figure was therefore used to construct the piling schedule for Neart na Gaoithe specifically while the other jacket operations followed the schedule outlined for Beatrice.

Piling days were distributed randomly throughout the foundation construction period for each operation. This assumes that piling construction is equally likely to occur in all months of the year. We have chosen to not use a seasonally restricted piling schedule despite the fact that winter months are often considered as a time period where construction is less likely to occur due to limiting weather conditions. We did not restrict the schedule because the foundations for Gunfleet Sands were installed during the winter months (between October and April), indicating that winter construction is possible.

The above calculations and assumptions resulted in a piling schedule with a total of 2,773 piling days, characterised by a mean number of 9.9 piling days per month (range 0 to 30) and a mean number of 1.5 simultaneous piling events on days when piling occurred. The piling schedule resulted in only one single piling event occurring on 67.3% of the piling days, two simultaneous piling events occurring on 23.6% of the piling days, and three simultaneous piling events occurring on 7.4% of the piling days. Only 0.3% (9 piling days) of the piling days were scheduled as having five simultaneous piling events, and 0.04% (1 piling day) with six simultaneous piling events. The number of piling days per month and the average number of piling sites per day (summarised by month) in the hypothetical piling schedule are shown in Figure 3. The whole period of construction started in June 2000 and ended in May 2024 (Figure 4). There was a marked increase in the calculated number of piling days per month and the daily number of simultaneous piling sites after 2016 (Figure 3).

The iPCoD framework can be used to provide forecasts of the population size for many years in the future after construction of the developments has ended. However, these forecasts become increasingly unreliable as the period of simulation is extended, because they assume that the vital rates do not change over the course of the simulations. Therefore, simulated populations do not recover once the effects of disturbance and PTS have ceased. Some increase in vital rates is to be expected in practice, provided that there are no other threats to the population (Harwood *et al*. 2014). As a rule of thumb, Harwood *et al*. (2014) recommended that forecasts of more than 12 years after the end of piling construction should be treated with caution.

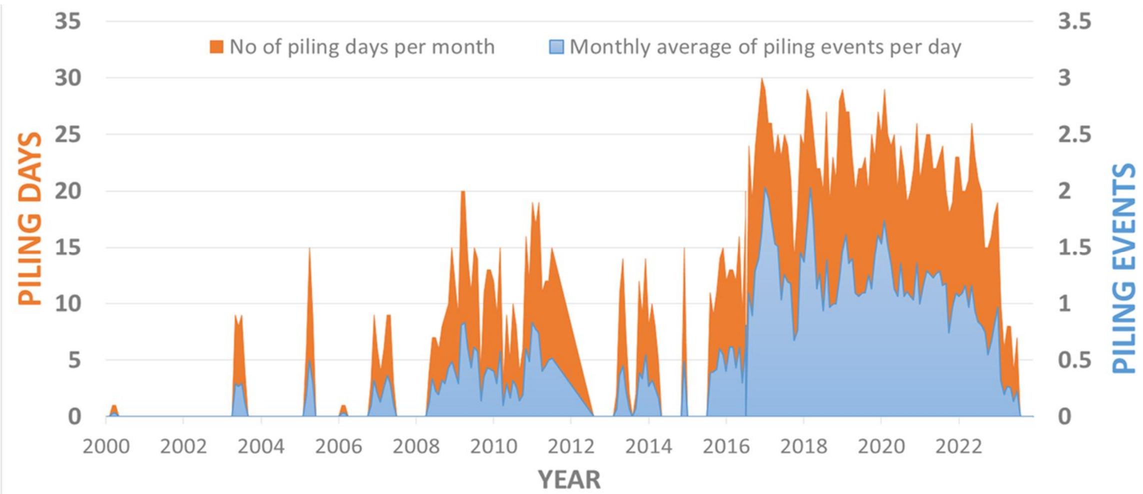

Figure 3. Number of piling days per month (orange) and simultaneous piling events per day as a monthly average (blue) over the construction period between June 2000 and May 2024 as assigned in the hypothetical piling schedule built for the current project.

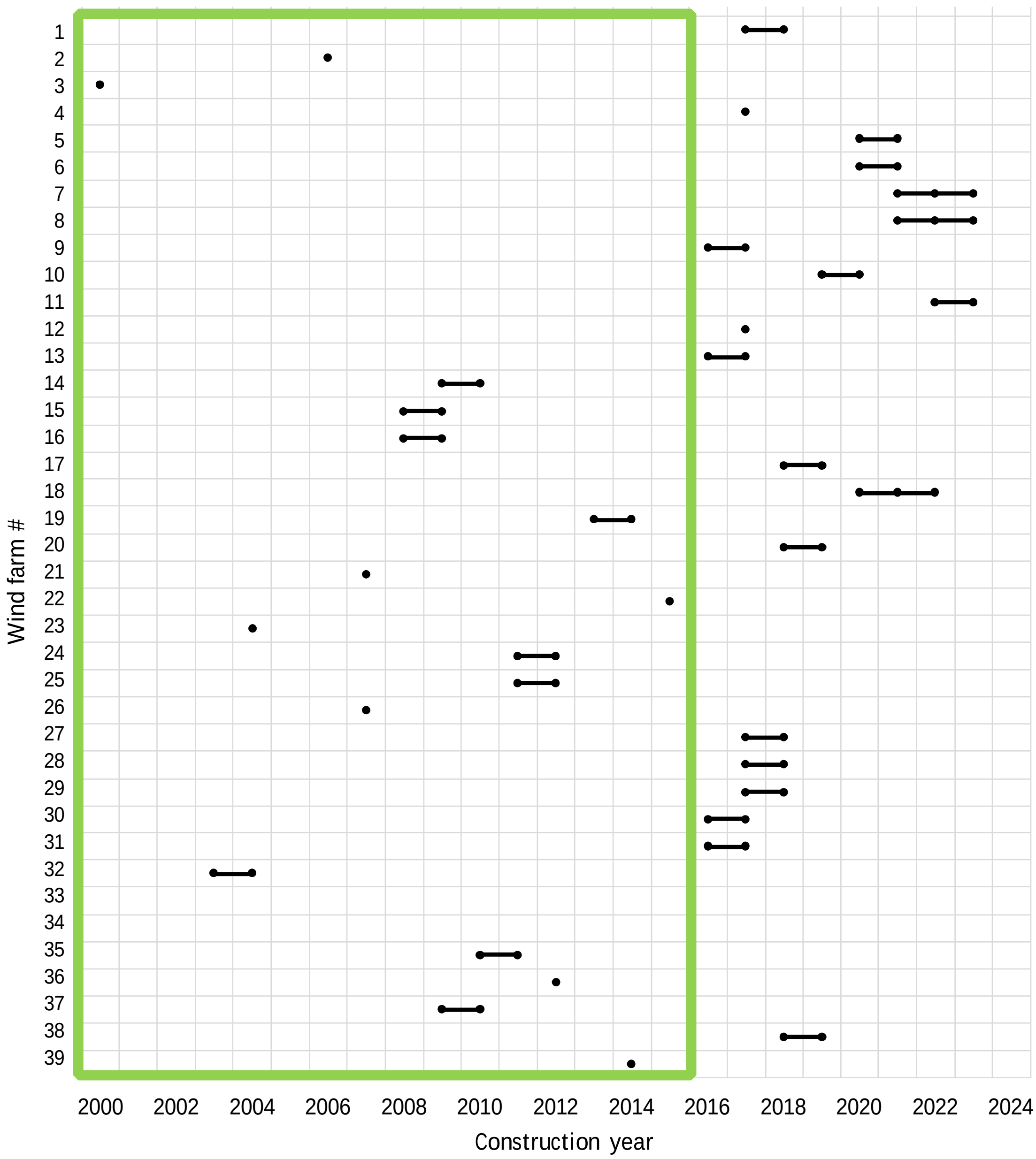

Figure 4. Year(s) in which the wind farms listed in Table 1 were, or are planned to be, constructed. Green box contains those wind farms which have already been constructed. Numbers on the y-axis serve as identifiers for the specific wind farm projects as listed in Table 1.

3.6.2 Number of animals in an impact area

In Environmental Statements or their accompanying documents (ESs), the potential impacts on marine mammals is usually estimated by modelling one or more worst-case impact scenarios based on information available at the time that the environmental impact was assessed (i.e. before the consent process). They often assess the impact of the piling of a single foundation as well as the piling of two foundations concurrently, where the impact areas of two piling events would overlap with each other. They also model the impact of different foundation types (e.g. monopile as well as jacket foundation), different pile diameters and/or hammer energies that are used to drive the foundation into the seabed. Some ESs determined the impact range for PTS or behavioural responses with two or more threshold values.

For this project, the estimates of the mean number of porpoises within the impact areas for PTS and behavioural disturbance were obtained from the impact assessment given in the corresponding ES. Where more than one impact scenario was calculated in an ES, the most likely scenario with regards to foundation type and pile diameter was selected to take forward. Only single piling impact scenarios were considered where feasible to obtain the impact area of one piling event. When different thresholds were used for determining impact ranges, we chose that threshold forecasting the highest impact. This step was taken to ensure we could identify the effect caused by noise reduction (i.e. if the baseline risk is low, it is hard to quantify any reduction in risk).

The mean number of animals calculated as at risk for PTS and behavioural disturbance was used where available. In some cases, however, only the size of the impact area was provided. In these cases, the number porpoises in the impact area was estimated by multiplying the density of animals in the vicinity of the wind farm by the size of the impact area. Where available, site-specific estimates of porpoise density from the ES were used. When no site-specific porpoise density data was provided in the relevant ES chapter, the density was obtained from the porpoise density surface map produced from the 2005 SCANS II surveys (Hammond et al. 2006).

If the impact area was not given in the ES, this was calculated from the mean impact range by calculating the area of a circle with the same radius as the impact range. The mean impact range was used because the impact area is usually not a circle; the extent of the range in each direction depends on local features of the seascape, and the minimum and maximum range give the limits of the range based on these features rather than the uncertainties around range estimates. Therefore, the mean impact range is the most appropriate measure while the minimum and maximum values would lead to an under- or overestimation of the impact area.

The calculated impact area will however, be larger than the true impact area in cases where the wind farm location is sufficiently close to the coast that part of the calculated impact area overlaps with land. In these instances, the mean of four radii at right angles to each other, one of which was orthogonal to the coast, was used.

Where neither the numbers of animals, impact range nor impact area were given, an assumed impact range was used, which was obtained from an impact assessment with a similar pile diameter and foundation type, preferably from a wind farm close to the wind farm considered. The decision tree shown in Figure 5 summarises this process.

The ESs considered here used a number of different threshold values to calculate impact ranges and impact areas and so the resulting estimates are not directly comparable. The thresholds used for this project are given in Table 3. The 75 dB_{ht} threshold was the most frequent dB_{ht} value used in this study to estimate the number of animals in the impact area of behavioural response. However, three ESs presented the impact range for "strong" behavioural response only, using a threshold value of 90 dB_{ht}. To adjust the 90 dB_{ht} values to a value that is closer to the 75 dB_{ht} value, a correction factor was used. This correction factor was calculated by taking the mean of the ratio between the 90 dB_{ht} and the 75 dB_{ht} impact ranges from four ESs that stated both values.

3.6.3 Number of disturbance days per piling event

The default setting for iPCOD is that any individual that exhibits a behavioural response as a result of a piling event experiences one day of disturbance (the day of piling). However, the user can define a number of residual days of disturbance, which is the period during which the disturbance persists after the piling day ceased. We define the total number of days an animal is disturbed by a particular event as the sum of one piling day and the number of residual days of disturbance.

The user can also define that a portion of the animals within an impact area will be disturbed for longer than the remaining portion, so that animals closer to a piling site at the time of disturbance can be disturbed for longer than individuals further away from the site but still within the impact area at the time of disturbance.

For this project we assumed that 16% of the animals within the impact area (irrespective of which threshold was used to calculate the size of the impact area) were disturbed for a total of two days with the remaining 84% experiencing a total of one day of disturbance. This assumption was based on Brandt *et al.*'s (2011) study of changes in the distribution of harbour porpoise during the construction of the Horns Rev II, Denmark, wind farm using 3.9 m diameter monopiles. They installed an array of passive acoustic monitoring (PAM) devices between 2.5 km and 21.2 km away from a piling site, and logged the presence of porpoise using their vocalisations. As harbour porpoise vocalise frequently (Akamatsu *et al*. 2005; Verfuss *et al*. 2005), PAM is an appropriate method for monitoring the presence of this species (e.g. Verfuss *et al*. 2007). Brandt *et al*. (2011) found that, at the closest distance studied (2.5 km) there was a significant decline in the detection rate of porpoise that lasted for 24 to 72 hours after end of piling. At PAM positions 3.2 km and 4.8 km from the piling site, this effect lasted no longer than 42 hours, and at 10.1 and 17.8 km no longer than 23 hours. No reduction in detection rate was observed at 21.2 km. We modelled this by assuming that animals within the first 40% of the impact range of the piling site, which corresponds to 16% of the total impact area, experience 48 hours (two days) of disturbance. Following Brandt *et al.* (2011) this would translate into 48 hours of disturbance for animals within an 8 km range to the piling site with an impact range of 20 km, and 24 hours of disturbance for animals between 8 and 20 km range to the piling site.

To investigate the effect of the duration of residual disturbance days on the risk of a potential population decline, we re-ran the simulations assuming 72 hours of total disturbance of animals within 16% of the total impact area (i.e. the duration of residual disturbance increased by one day).

Table 3. Number and percentage of wind farms, of which the corresponding ES used the same threshold for assessing the impact of piling resulting in auditory injury or behavioural responses. Given is the threshold value where feasible or the method as stated in the ES as well as the source the threshold is derived from, where mentioned.

Information	Threshold or method	Source	No of wind farms	%
Auditory injury	130 dB_{ht}	Nedwell *et al*. 2007	4	10%
	179 dB re 1 μPa^2s	Lucke *et al*. 2009	8	21%
	195 dB re 1 μPa^2s	NMFS NOAA, 2006	1	3%
	198 dB re 1 μPa^2s	Southall *et al*. 2007	5	13%
	Auditory injury	Not stated	1	3%
	PTS within 8 hours	Not stated	2	5%
	SAFESIMM	Sparling *et al*. 2012	1	3%
Behavioural response	145 dB re 1 μPa^2s	Lucke *et al*. 2009	8	21%
	75 dB_{ht} (weak response)	Nedwell *et al*. 2007	7	18%
	90 dB_{ht} (strong response)	Nedwell *et al*. 2007	3	8%
	Behavioural displacement: High	Not stated	2	5%
	Potential adverse behavioural response	Not stated	1	3%
	SAFESIMM	Sparling *et al*. 2012	1	3%

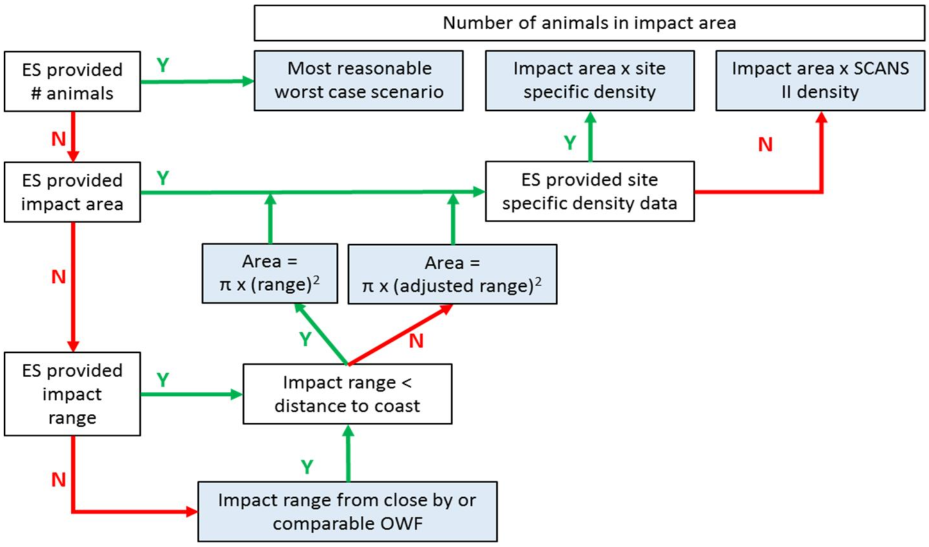

Figure 5. Decision tree for the retrieval of the number of animals estimated to be present in the impact area. A full description of the decision making is outlined in the above section. Y: information available, N: information not available.

3.6.4 Population Parameters

The iPCoD framework uses a stochastic population dynamic model which incorporates population parameters for survival at each life stage (calf, juvenile and adult) and fecundity. The population parameters for the North Sea harbour porpoise MU were obtained from IAMMWG (2015) and Harwood and King (2014) and are listed in Table 4.

Table 4. Harbour porpoise population parameters input into the interim PCoD model.

iPCoD Parameter	Value
Population size (North Sea MU)	227,298
Calf survival	0.6
Juvenile survival	0.85
Adult survival	0.85
Fecundity value	0.96
Age at which a calf becomes independent	1
Age at which an average female gives birth to her first calf	5

3.7 Model outputs

For each piling scenario, iPCoD forecast trajectories for 1000 identical pairs of populations (i.e. in 1000 simulation runs) over a 36-year period. One member of each pair was subject to the effects of disturbance and the other was not. For each pair of simulation runs, iPCoD selects from the distribution of opinions on the effect of PTS/disturbance on vital rates and a set of values for the effects of environmental stochasticity from the underlying statistical distributions. These are used along with the user-specified estimates of the number of animals likely to be disturbed by 1 day of piling for each site and the piling schedule in order to forecast the trajectory for each pair (see Harwood et al. 2013 and King et al. 2015 for detailed explanations of iPCoD).

Most of the indicators of favourable conservation status described in Evans and Arvela (2010), which need to be reported on in a 6-year cycle, cannot be assessed using the outputs of iPCoD. However, Annex C (European Commission, 2005b) advises that a population decline of more than 1% per year would represent unfavourable conservation status for that population under the Habitats Directive (see section 2), therefore we have chosen to assess the risk of annual 1% and 2% declines as indicators of population status for exploring the potential benefits of noise reduction measures. However, many of the trajectories forecast by iPCoD for an undisturbed population are likely to show a decline of more than 1% in some years as a result of environmental stochasticity. Therefore, for each scenario, we calculated the additional risk due to wind farm construction of a 1% and a 2% population decline per year as the difference between the forecasted probability of decline of the disturbed and undisturbed simulated populations. The resulting forecasts of the additional annual risk of a population decline were averaged over 6-year periods to reflect the 6-year reporting cycle to the EU as required by the habitats directive. Averages are therefore given for the time periods 2002-07, 2008-13, 2014-19, 2026-31, and 2032-37.

For those time periods where the additional risk in the baseline scenario exceeded 1%, the ratio in risk between the noise reduction scenarios and baseline were calculated, expressed as "% of baseline risk". This ratio reflects the effectiveness of the noise reduction measures by quantifying the resulting reduction of the risk of a population decline.

4 Results

Figure 6 shows how the predictions from the iPCoD framework of the additional risk of a 1% or 2% annual decline in the size of the North Sea harbour porpoise population are affected by the different construction scenarios and disturbance days as described in section 3. The risk under all scenarios increases sharply in 2019 after the predicted increase in large-scale construction activity (as outlined in Figure 3 and reflected in the grey inset of Figure 6), and generally decreases once construction work ceases in 2024. Assuming an extra day of residual disturbance for 16% of the animals within the impact area (Figure 6, $DD_{(16\%)}$=3) generally leads to an increase of the additional risk in population decline. Reducing the impact area associated with construction activity at wind farm sites within or overlapping with the southern North Sea pSAC by 60% or 80% decreases the risk of a 1% or 2% decline to approximately half to a quarter of the risk under the baseline scenario (no noise reduction at any site). Further reductions in risks are predicted if noise reduction methods are used at all wind farm sites.

A closer look at the averaged additional risk values and the reduction in risk achieved by noise measures as a ratio to the baseline risk (Table 5, Table 6) reveal that:

- Where the additional risk is above 1%, any of noise reduction measures investigated clearly decrease the risk of a population decline due to wind farm construction in all of the 6-year periods;
- The more effective the noise reduction the more effective is the reduction of the additional risk of a population decline due to wind farm construction, with the reduction in risk ranging from 34% to 96% for a 1% decline and 61% to 99% for a 2% decline;
- The effectiveness of each noise reduction scenario is roughly the same magnitude for a 1% population decline regardless of the duration of residual disturbance.

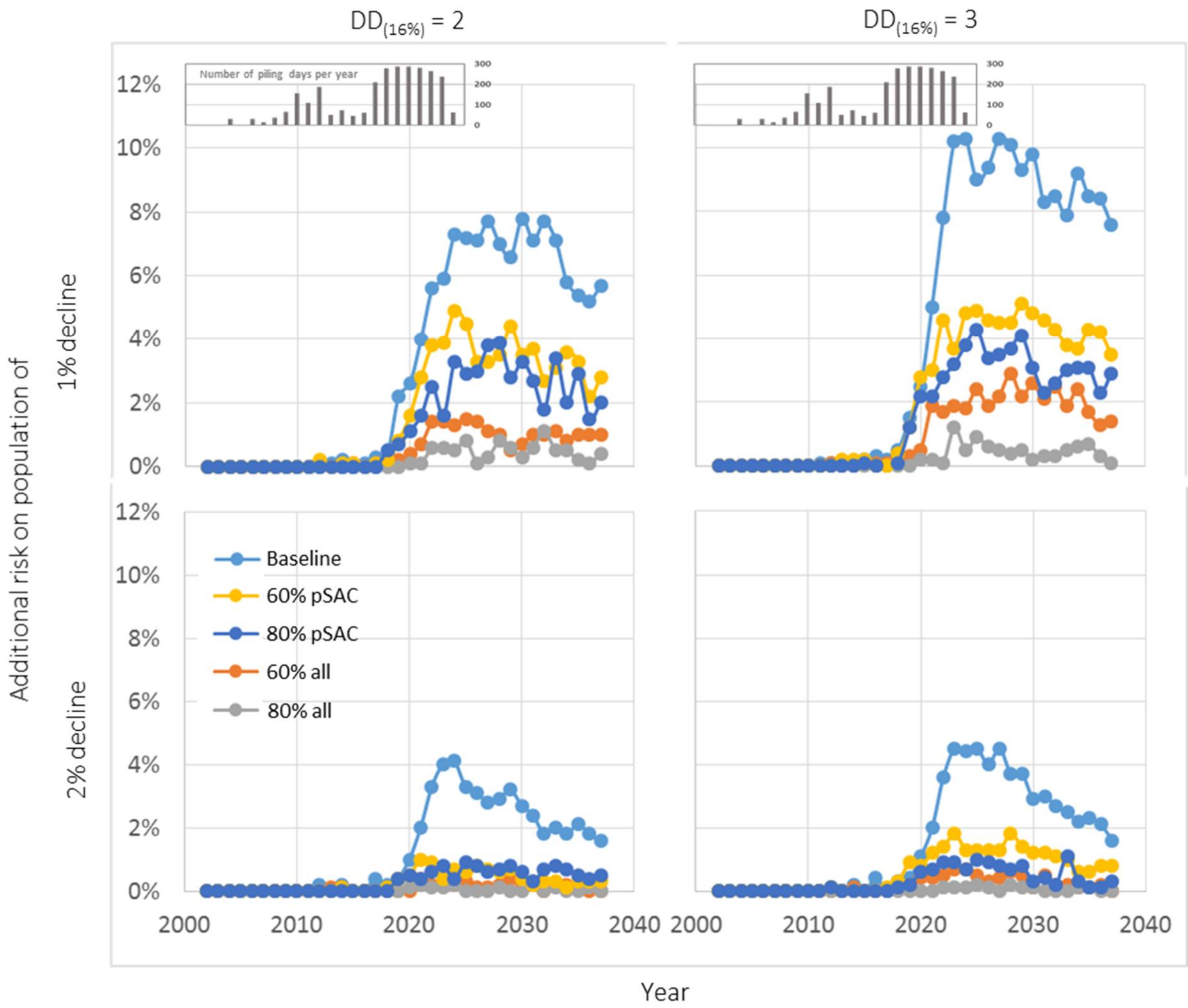

Figure 6. Forecasted additional risk of a 1% and 2% population decline per year of the North Sea harbour porpoise population over a 36-year period, caused by a hypothetical 24-year period of wind farm construction (grey inset: bar chart of the number of piling days per year) as outlined in the Methods section. Given is the forecasted additional risk when piling with a 500 m mitigation zone as required by JNCC (2010) (Baseline) and the risk when using noise reduction systems reducing the impact area by 60% or 80%, for wind farm construction either within an SAC only (60% / 80% pSAC) or for all wind farms (60% / 80% all) for two cases: 1) 16% of the animals within an impact area will be disturbed for 2 days ($DD_{(16\%)}$ = 2), and 2) 16% of the animals will be disturbed for 3 days ($DD_{(16\%)}$ = 3). In both cases, the remaining 86% of the animals within an impact area will be disturbed for 1 day.

Table 5. Forecasted additional risks of an annual 1% and 2% population decline of the North Sea harbour porpoise population as shown in Figure 6, averaged over six 6-year-periods. Given is the forecasted additional risk for the baseline scenario (see text for details) and the risk when using noise reduction systems reducing the impact area by 60% or 80%, for wind farm construction either within an SAC only or for all wind farms for two cases: 1) 16% of the animals within an impact area will be disturbed for 2 days ($DD_{(16\%)} = 2$), and, 2) 16% of the animals will be disturbed for 3 days ($DD_{(16\%)} = 3$). In both cases, the remaining 86% of the animals within an impact area will be disturbed for 1 day.

		$DD_{(16\%)} = 2$						$DD_{(16\%)} = 3$					
		2002-07	2008-13	2014-19	2020-25	2026-31	2032-37	2002-07	2008-13	2014-19	2020-25	2026-31	2032-37
Additional risk on population of 1% decline	Baseline	0.0 %	0.0 %	0.5 %	5.4 %	7.2 %	6.2 %	0.0 %	0.1 %	0.5 %	7.5 %	9.5 %	8.4 %
	60% pSAC	0.0 %	0.0 %	0.2 %	3.6 %	3.6 %	3.0 %	0.0 %	0.0 %	0.3 %	4.0 %	4.7 %	4.0 %
	80% pSAC	0.0 %	0.0 %	0.2 %	2.2 %	3.3 %	2.3 %	0.0 %	0.0 %	0.2 %	3.1 %	3.4 %	2.8 %
	60% all	0.0 %	0.0 %	0.1 %	1.1 %	1.0 %	1.0 %	0.0 %	0.0 %	0.2 %	1.7 %	2.3 %	1.9 %
	80% all	0.0 %	0.0 %	0.0 %	0.5 %	0.5 %	0.5 %	0.0 %	0.0 %	0.0 %	0.5 %	0.4 %	0.4 %
Additional risk on population of 2% decline	Baseline	0.0 %	0.0 %	0.2 %	3.0 %	2.9 %	1.9 %	0.0 %	0.0 %	0.2 %	3.4 %	3.6 %	2.2 %
	60% pSAC	0.0 %	0.0 %	0.1 %	0.7 %	0.6 %	0.3 %	0.0 %	0.0 %	0.2 %	1.3 %	1.4 %	0.8 %
	80% pSAC	0.0 %	0.0 %	0.1 %	0.6 %	0.6 %	0.6 %	0.0 %	0.0 %	0.1 %	0.8 %	0.7 %	0.4 %
	60% all	0.0 %	0.0 %	0.0 %	0.2 %	0.2 %	0.1 %	0.0 %	0.0 %	0.1 %	0.5 %	0.4 %	0.1 %
	80% all	0.0 %	0.0 %	0.0 %	0.1 %	0.1 %	0.0 %	0.0 %	0.0 %	0.0 %	0.1 %	0.1 %	0.0 %

Table 6. Effectiveness of noise reduction measures to reduce the risk of an annual 1% and 2% population decline due to wind farm construction. For the 6-year periods given in Table 5, the ratio between the averaged additional risks obtained for each noise reduction scenario and the corresponding baseline is given, expressed as "% of baseline risk". Compared to the corresponding baseline values are the risk values when using noise reduction systems reducing the impact area by 60% or 80%, for wind farm construction either within an SAC only or for all wind farms, for two cases: 1) 16% of the animals within an impact area will be disturbed for 2 days ($DD_{(16\%)} = 2$), and, 2) 16% of the animals will be disturbed for 3 days ($DD_{(16\%)} = 3$). In both cases, the remaining 86% of the animals within an impact area will be disturbed for 1 day. Only baseline values from the 6-year period 2020-25 on were used for this evaluation.

		$DD_{(16\%)} = 2$						$DD_{(16\%)} = 3$					
		2002-07	2008-13	2014-19	2020-25	2026-31	2032-37	2002-07	2008-13	2014-19	2020-25	2026-31	2032-37
% of baseline risk 1% decline	Baseline												
	60% pSAC				66 %	50 %	48 %				53 %	49 %	48 %
	80% pSAC				40 %	45 %	37 %				41 %	35 %	34 %
	60% all				21 %	13 %	16 %				23 %	24 %	22 %
	80% all				8 %	6 %	8 %				7 %	4 %	5 %
% of baseline risk 2% decline	Baseline												
	60% pSAC				23 %	20 %	14 %				39 %	38 %	37 %
	80% pSAC				20 %	22 %	32 %				24 %	18 %	16 %
	60% all				8 %	7 %	5 %				16 %	11 %	6 %
	80% all				4 %	2 %	2 %				2 %	2 %	1 %

5 Discussion

5.1 General considerations

The use of noise reduction measures can clearly help to reduce the risk of a population decline due to cumulative impacts of wind farm construction. The effectiveness of the measures investigated in this study ranged from reducing the risk to 66% of baseline risk for a 60% reduction of the impact area in the pSAC to 4% of baseline risk for an 80% reduction of the impact area in all wind farms. The efficiency is effectively determined by the reduction in the total impact area associated with all of the piling operations that are modelled in the baseline scenario. Similar reductions in risk can be achieved by large scale reductions in the impact area at a limited number of construction sites, for example those within a pSAC, or a smaller reduction in the impact area at a large number of sites. This is consistent with other analyses of the potential effects of wind farm construction made using the iPCoD framework. For example, Heinis *et al*. (2015) showed that, to a first approximation, the predicted effects of all proposed wind farm construction on the North Sea harbour porpoise population were effectively determined by the total number of animals disturbed per day multiplied by the number of days they are disturbed (called number of porpoise-disturbance days) associated with construction work. Using noise reduction measures in areas with high porpoise densities, as assumed for a pSAC area, will therefore be a more efficient measure to reduce the risk of a population decline than applying noise reduction methods with the same effectiveness in areas of lower porpoise densities. The effectiveness of noise reduction measures was relatively insensitive to the duration of residual disturbance.

The appropriate amount of noise reduction will depend on the level of risk of causing unfavourable conservation status that is considered acceptable by regulators. As mentioned previously, a population decline of more than 1% per year would represent unfavourable conservation status for that population under the Habitats Directive (European Commission, 2005). What can be achieved may, however, depend on the practical and financial viability of achieving that level of reduction given the individual characteristics of each site and project, including the required construction timelines.

An insight into the process of implementing noise reduction measures in response to the Habitats Directive elsewhere in Europe can be gained from a concept for sound mitigation, the “Schallschutzkonzept” (BMU 2013). The “Schallschutzkonzept” was developed by the German government to protect the harbour porpoise population in the EEZ of the German North Sea from the effects of offshore wind farm construction. In addition to a requirement to keep piling noise below a certain noise threshold (generally accomplished by using noise reduction systems), no more than 10% of the German North Sea EEZ is to be impacted by piling noise from all wind farm projects at a time. For calculating the total cumulative area impacted, the impact areas for all projects currently undergoing foundation construction have to be combined. The 10% spatial threshold was based on the assumption that the behavioural disturbance caused by pile driving is temporary, and that porpoises will eventually re-enter the area from which they were displaced. However, a 1% spatial threshold is applied to areas with a high porpoise density and to the breeding and mating season from May to August, when disturbance may have a greater impact on harbour porpoise vital rates. For SACs, these spatial thresholds are measured against the size of the protection area rather than the whole EEZ (i.e. no more than 10% of an SAC can be impacted by piling noise, while from May to August, not more than 1% can be impacted).

We cannot say how adoption of the “Schallschutzkonzept” affects the risk of a 1% population decline without further investigations. However, we can conclude that adoption of a noise threshold, such as the 160 dB SEL threshold used in Germany (introduced to prevent auditory injury to harbour porpoises; BMU, 2013), will also reduce the behavioural impact of construction activity and therefore reduce any potential risk of a negative effect on favourable population status. The consequences of restricting the total impact area associated with wind farm construction to 10% of an SAC over a given time period could be investigated with scenarios based on the current study. Varying the piling schedule, a spatio-temporal limitation of piling, the use of noise reduction methods during piling or the use of low-noise foundations as suggested by JNCC and Natural England (2016) can ensure that the total impact area is less than 10% of an SAC. It should also be considered that there is potential that only a subset of the planned offshore wind farms will be built, which further reduces the actual risk of decline. It is challenging to predict at this stage what level of pile driving will occur. Many of these measures involve additional costs and have a number of practical considerations, none of which have been addressed here. Conducting a cost/benefit analysis, including consideration of the social and environmental costs of not reducing noise, as well as the financial costs of reducing noise, would help to understand which of the measures would be the most suitable for implementing the habitats directive.

We would like to highlight that the absolute values of the predicted risks of a 1% or 2% decline in the harbour porpoise population shown in Figure 6 should be interpreted with some caution because they are based on estimates of the number of animals predicted to experience PTS or exhibit a behavioural response drawn from developer ESs. We will discuss the uncertainties associated with these estimates in detail in section 5.2. While the wish to estimate of the absolute risk of a decline would result in the need to reduce the uncertainties mentioned below, we believe that the predictions of the relative reductions in the risk of an annual 1% decline in population size that result from different noise mitigation measures are robust.

5.2 Uncertainties in input data

This study is based on a – at the time of generation –publicly available up-to-date UK context, both in terms of offshore windfarm location and timetables as well as density and distribution of harbour porpoise. However, as mentioned in section 5.1, the predicted additional risks of a population decline as a result of offshore wind farm construction should be interpreted with caution, as they are based on estimates which are associated with uncertainties. It was not the aim of this study to forecast the absolute value of this risk, but rather to investigate how the use of noise reduction measures will influence the forecasted risk of a decline.

In the following, we discuss the main sources of uncertainty connected to the predicted risk of decline.

5.2.1 Estimates of the number of animals that experience PTS or exhibit a behavioural response

The estimation of the number of animals within an impact area, as conducted in this project, is connected to uncertainties that arise firstly from the density estimates used to calculate the number of animals within an impact area, and secondly from the impact assessment methods, and in particular the thresholds used in the ESs to determine the size of the impact area and the proportion of animals in the impact area which are affected. It should also be noted that developers are encouraged to use worst-case scenarios in these calculations and, as a result, may therefore obtain larger impact areas than those that would be obtained with the final set-up of the construction.

Density estimates

The 2005 SCANS II data from Hammond *et al*. (2006) that were used to calculate the number of animals within an impact area in cases where no site-specific estimates were available in ESs, were from surveys conducted to determine the absolute abundance of small cetacean populations over large areas. Therefore, they might not accurately reflect a site specific density. They were obtained from extensive flight and vessel surveys from a single temporal snapshot, in July 2005 and thus may not be representative of the density at different times of the year or in other years. Even where site specific surveys were carried out by developers, there may be a substantial lag between the surveys and the date of construction (for example, the site-specific boat-based surveys outlined in the Dogger Bank Creyke Beck ES were conducted between January 2010 and January 2012 while construction is planned to start in 2020). The construction of the wind farms in our hypothetical piling schedule are conducted over 24 years. As the density of harbour porpoise at a site varies seasonally (Evans and Teilmann, 2009) and can also change between years (Hammond *et al*. 2013), the density used to calculate the number of animals within an impact area may be different from the density of porpoise in the area when construction takes place. A recent and site specific survey would be needed to provide more realistic data.

The iPCoD software captures uncertainty in the density estimates that are associated with the number of animals associated with PTS and behavioural response (Harwood *et al*. 2014; King *et al*. 2015). In each different simulation, these numbers are multiplied by a randomly chosen scalar with mean of 1 and 95% confidence limits of 0.5 and 1.5 (i.e. the actual values of the number of animals used in the simulation may be up to 50% smaller or larger than the input values). This is an attempt to capture the uncertainty in local density estimates for harbour porpoises in the North Sea, as reported in Paxton *et al*. (2016).

Thresholds

As indicated in Table 2, the calculations used in ESs to estimate the number of animals within an impact area involved a range of different threshold values for both behavioural response and PTS. Some thresholds, such as those based on dB_{ht}, take account of a species hearing sensitivity at a particular frequency, whereas others, based on SEL values, do not. Some methods (e.g. SAFESIMM) use a dose-response relationship to calculate these numbers, whereas others assume that all animals that are exposed to sound above a specified threshold will be affected.

The impact assessment methods used in the bulk of ESs for the wind farms considered in these investigations are unlikely to be comparable, and this leads to substantial uncertainty in the input data used in this study. Given the objective of this study was to assess the potential effects of the use of noise reduction methods during construction, and not to assess the cumulative impact of such activities on the harbour porpoise population – it is useful to discuss these briefly here. It is unclear how the changes in these uncertainties might (if at all) affect the efficacy of noise reduction methods. These uncertainties might be explored by calculating revised impact areas for each development using one consistent methodology for all wind farms (as was conducted by Heinis *et al*. 2015), which would involve a re-assessment of the impact of the piling events with noise modelling for each site.

5.2.2 Wind farms considered

The predicted piling schedule used in this study was based on current published plans for wind farm construction. However, changes in government policy and the financial climate are likely to affect the number of wind farms that are eventually built in UK waters. The number of foundations that are actually installed may also be lower than we have assumed because of improvements in turbine efficiency. In addition, foundation type and diameter may change as construction technology improves – potentially reducing the number of foundations to be piled (e.g. using gravity base or suction bucket foundations). As a result, the scenarios used here are likely to overestimate the potential effects of planned wind farm construction in UK waters on the North Sea harbour porpoise MU. However, other European countries have already constructed, and are planning to construct, further wind farms within the range of this MU, and these may add an additional burden on the porpoise population that is not considered in the investigations presented here.

6 Conclusion

The use of noise reduction as a mitigation measure has the potential to significantly reduce the predicted cumulative effect of wind farm construction on a harbour porpoise population. The effect of noise reduction measures on the risk of a population decline is effectively determined by the reduction in the total impact area and the associated reduction in numbers of animals affected. In general, the greater the reduction in the number of animals affected, the greater the reduction in cumulative impact.

This study is the first attempt of its kind (that we know of) in a UK context to identify the scale of relative effect of using noise reduction technologies during piling, in terms of a reduced additional risk of population decline on harbour porpoises. It is also the first attempt in a UK context to explore this with respect to protected areas such as the possible SAC for harbour porpoise. It is further based, as far as practicable, on a realistic picture of UK offshore windfarm construction (though a number of uncertainties are identified above).

While the predictions of the relative reduction in risk, as a result of implementing different noise reduction measures, are considered to be robust, the absolute values of the predicted baseline risks presented in this report should be interpreted with some caution because of the uncertainties associated with the underlying estimates. How the use of alternative mitigation measures such as varying the piling schedule, or a spatio-temporal limitation of piling (as well as improved information on animal density, behavioural response and PTS thresholds) are likely to influence the predicted cumulative effect of wind farm construction on a harbour porpoise population could be subject to further investigations.

7 References

7.1 Literature cited

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8 Glossary of Terms, Acronyms and Abbreviations

Term	Description
BBC	Big Bubble Curtain
CI	Confidence Interval
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EPS	European Protected Species
ES	Environmental Statement
iPCoD	interim Population Consequences of Disturbance
MU	Management Unit
PAM	Passive Acoustic Monitoring
pSAC	possible Special Area of Conservation

Term	Description
PTS	Permanent Threshold Shift
SAC	Special Area of Conservation
TTS	Temporary Threshold Shift