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Volume 7B Proposed Development (Offshore) Appendices

Appendix 7-2 Marine Mammals Underwater Noise Assessment Methodology

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Acronyms and Abbreviations

CIEEM	Chartered Institute of Ecology and Environmental Management
EDR	Effective Deterrence Range
EIAR	Environment Impact Assessment Report
iPCoD	Interim Population Consequences of Disturbance Model
JNCC	Joint Nature Conservation Committee
MNR	Marine Noise Registry
NMFS	National Marine Fisheries Service
OECC	Offshore Export Cable Corridor
OWF	Offshore Wind Farm
PTS	Permanent Threshold Shift
SEL	Sound Exposure Level
SPL	Sound Pressure Level
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
WTG	Wind Turbine Generator
MBES	Multi-beam Echosounder
SSS	Side-scan Sonar
SBP	Sub-bottom profiler
USBL	Ultra-short Baseline
UHRS	Ultra High Resolution Seismic

1 Marine Mammals Underwater Noise Assessment Methodology

1.1 Introduction

1.1.1.1 This appendix provides detail on the methodology used for the assessment of auditory injury (Permanent Threshold Shift; PTS) and disturbance to marine mammals from various sources of underwater noise (Section 1.2). In line with Chartered Institute of Ecology and Environmental Management (CIEEM, 2018[1]) guidelines, limitations of methods are discussed in section 7.3. This appendix is referred to as a source of information about methodology and limitations of the assessment throughout Volumes 2, 3 and 4, Chapter 7: Marine Mammals of the Environmental Impact Assessment Report (EIAR).

1.2 Methodology

1.2.1 Overview

1.2.1.1 This section provides information on the methods used to assess auditory injury (PTS) and disturbance to marine mammals from different impact pathways.

1.2.2 Assessment of PTS

PTS Thresholds

1.2.2.1 Exposure to loud sounds can lead to a reduction in hearing sensitivity (a shift in hearing threshold). This threshold shift results from physical injury to the auditory system and may be temporary (Temporary Threshold Shift; TTS) or permanent (PTS). The point at which threshold shifts occur in marine mammals is species specific (i.e., functional hearing group dependent, see Table 1-1).

1.2.2.2 The auditory injury (PTS) thresholds used in the assessment for marine mammals are those presented in Southall *et al.* (2019[2]). These include two different thresholds covering ‘instantaneous’ PTS (SPL_{peak}, sound pressure from a single noise pulse), and ‘cumulative’ PTS (SEL_{cum}, accumulated sound energy over 24 hours), with the latter thresholds being frequency-weighted to marine mammal functional hearing groups. The method used to calculate PTS-onset impact ranges are detailed in Volume 7, Appendix 6: Underwater Noise Assessment.

1.2.2.3 The number of animals impacted by PTS was calculated by combining the PTS-impact range with the density estimate for each species (presented in Volume 7B, Appendix 7-1: Marine Mammals Baseline Characterisation).

Table 1-1: PTS-onset thresholds for impulsive noise (Southall *et al.*, 2019[2]).

Hearing Group	Species	Cumulative PTS (SEL_{cum} dB re 1µPa²s Weighted)	Instantaneous PTS (SPL_{peak} dB re 1µPa Unweighted)
Very High Frequency (VHF) Cetacean	Harbour porpoise	155	202
High Frequency (HF) Cetacean	Bottlenose dolphin White-beaked dolphin Common dolphin Risso's dolphin	185	230
Low Frequency (LF) Cetacean	Minke whale Humpback whale	183	219
Phocid Carnivores in Water (PCW)	Harbour seal Grey seal	185	218

Swimming Speed

1.2.2.4 The cumulative PTS onset impact ranges represent the minimum safe starting distances from the piling location for fleeing animals to avoid a dose higher than the threshold. This assessment used the marine mammal swimming speeds recommended by Scottish Natural Heritage (2016[3]):

- Harbour porpoise: 1.4m/s based on an average descent and ascent speed from tagged porpoise (Westgate *et al.*, 1995[4]).
- Minke whale: 2.1m/s based on Williams (2009[5]) where routine speeds for mysticete whales is 2.1-2.6m/s.
- Seals: 1.8m/s based on Thompson (2015[6]) which estimated typical grey seal swimming speeds in the range of 1.8-2.0m/s.
- Dolphins: 1.52m/s based on the mean swimming speed during foraging presented in Bailey and Thompson (2006[7]). Due to lack of data for other high frequency cetaceans, this swimming speed has been applied to all species within this hearing group (white-beaked dolphin, common dolphin, Risso's dolphin).

1.2.2.5 In all cases, a "typical" or "routine" swimming speed has been used, which is expected to under-estimate potential fleeing speeds.

PTS from UXO Clearance

1.2.2.6 In line with the advice received in the Scoping Opinion (Volume 7, Appendix 3), Caledonia Offshore Wind Farm Ltd (the Applicant) has considered alternatives to high order detonations alongside the effectiveness of these techniques. The Unexploded Ordnance (UXO) items found within the Moray West Offshore Wind Farm (OWF) site were cleared using a low order deflagration technique, with 100% success rate (Ocean Winds, 2024[8]). Low order deflagration neutralises the munition by “burning out” the explosive contents, reducing underwater noise produced during UXO clearance. As such, given that low order deflagration is a viable and effective method to be applied during UXO clearance at the Caledonia OWF and Caledonia Offshore Export Cable Corridor (OECC), the potential effects of high order detonation were not assessed.

1.2.2.7 Full details of the underwater noise modelling and the resulting PTS-onset impact areas and ranges are detailed in Volume 7, Appendix 6: Underwater Noise Assessment. A low-order clearance scenario has been modelled, assuming a donor charge of 0.25kg.

PTS from Piling

1.2.2.8 To inform this impact assessment, sound modelling has considered both instantaneous PTS and cumulative PTS over a piling event. However, it should be noted that NatureScot confirmed that injury ranges based on the SEL_{cum} metric are over-precautionary due to considerable conservatism in assessments, leading to over-estimation of impact zones, and therefore it would be disproportionate to expect these to be fully mitigated (see consultation table in Volumes 2, 3 and 4, Chapter 7: Marine Mammals).

PTS from other Construction Activities

1.2.2.9 While impact piling will be the loudest noise source during the construction phase, there will also be several other construction activities that will produce underwater noise. A simple assessment of the noise impacts from other construction activities is presented in Volume 7, Appendix 6: Underwater Noise Assessment using the Southall *et al.* (2019[2]) non-impulsive (weighted SEL_{cum}) thresholds. The following activities were assessed:

- Cable laying;
- Dredging (backhoe and suction);
- Drilling;
- Vibro-piling;
- Rock placement;
- Trenching; and

- Vessel noise.

PTS from Geophysical Surveys

1.2.2.10 Underwater noise generated from geophysical survey sources has the potential to cause injury (e.g., hearing damage) to marine mammals. The following geophysical survey sources are assessed:

- Multi-beam echosounder (MBES; 210–240 dB re 1μPa (SPL_{peak}) for multiple beams and 197dB re 1μPa (SPL_{peak}) for a single beam; 200–400kHz)
- Side-scan Sonar (SSS; 210 dB re 1μPa (SPL_{peak}); 300 & 900kHz)
- Sub-bottom profiler (SBP; 210–220 dB re 1μPa (SPL_{peak}); 2–15kHz with a peak frequency of 3.5kHz)
- Ultra-short baseline (USBL; 187 – 206 dB re 1 μPa; 19–34kHz)
- Ultra high resolution seismic (UHRS; 200 – 226 dB re 1 μPa; 100Hz to 5kHz).

1.2.3 Assessment of Disturbance

Disturbance from UXO Clearance

1.2.3.1 Our understanding of the effect of disturbance from UXO clearance is very limited, and as such the assessment can only provide an indication of the number of animals potentially at risk of disturbance given the limited evidence available. The assessment considered potential effects of low order deflagration only (see paragraph 1.2.2.6), however, there are no empirical data upon which to set a threshold for disturbance from low-order UXO clearance.

1.2.3.2 There is no dose-response function available that appropriately reflects the behavioural disturbance from UXO clearance, therefore other behavioural disturbance thresholds have been considered instead. These alternatives are summarised in the sections below.

5km EDR

1.2.3.3 Data has shown that low-order deflagration produces underwater noise that is over 20 dB lower than high-order detonation (Robinson *et al.*, 2020[9]; Lepper *et al.*, 2024[10]). The recorded sound levels during UXO clearance at Moray West OWF showed that underwater noise produced during deflagration of the largest LMB mine (700kg) was 22 dB lower than the predicted sound level for a high-order detonation (Ocean Winds, 2024[8]). Both studies highlight that the Effective Deterrence Range (EDR) for low-order UXO clearance should be significantly lower than that 26km EDR used for high-order clearance methods. The Joint Nature Conservation Committee (JNCC) Marine Noise Registry (MNR) disturbance tool (JNCC, 2023[11]) provides default and worst-case EDRs for various noise sources, and lists the default low-order UXO clearance EDR as 5km. In the absence of any further data, and in line with the methodology presented in the Scoping Report, this 5km EDR for low-order UXO clearance was assumed here.

TTS as a Proxy for Disturbance

1.2.3.4 Recent assessments of UXO clearance activities in Scottish waters have used the Temporary Threshold Shift (TTS) onset threshold to indicate the level at which a 'fleeing' response may be expected to occur in marine mammals (e.g., Seagreen, Neart na Goithe and Moray West OWFs). This is a result of discussion in Southall *et al.* (2007[12]) which states that in the absence of empirical data on responses, the use of the TTS-onset threshold may be appropriate for single pulses (like UXO clearance):

"… upon exposure to a single pulse, the onset of significant behavioral disturbance is proposed to occur at the lowest level of noise exposure that has a measurable transient effect on hearing (i.e., TTS-onset). We recognize that this is not a behavioral effect per se, but we use this auditory effect as a de facto behavioral threshold until better measures are identified.

This approach is expected to be precautionary because TTS at onset levels is unlikely to last a full diel cycle or to have serious biological consequences during the time TTS persists" (Southall *et al.*, 2007[12]).

1.2.3.5 Therefore, an estimation of the extent of behavioural disturbance can be based on the sound levels at which the onset of TTS is predicted to occur from single pulse, impulsive sounds. TTS-onset thresholds are taken as those proposed for different functional hearing groups by Southall *et al.* (2019[2]). In line with caveats highlighted by Southall *et al.* (2019[2]), TTS-onset thresholds are likely to over-estimate the true behavioural response of any number of individuals predicted to be impacted.

Disturbance from Piling

1.2.3.6 The assessment of disturbance from pile-driven foundations was based on the current best practice methodology, making use of the best available scientific evidence. This incorporates the application of a species-specific dose-response approach rather than a fixed behavioural threshold approach, which is in line with approach applied in the marine mammal assessments across Scottish OWF EIARs.

1.2.3.7 The latest guidance provided in Southall *et al.* (2019[2]) is that:

"Apparent patterns in response as a function of received noise level (sound pressure level) highlighted a number of potential errors in using all-or-nothing "thresholds" to predict whether animals will respond. Tyack and Thomas (2019[13]) subsequently and substantially expanded upon these

observations. The clearly evident variability in response is likely attributable to a host of contextual factors, which emphasizes the importance of estimating not only a dose-response function but also characterizing response variability at any dosage".

1.2.3.8 The number of animals potentially disturbed was calculated by modelling 5dB noise contours, overlaying them on the species specific density surfaces to obtain the number of animals within the contour, then scaling the number of animals present by the predicted dose-response level (see below) to provide an estimate of the number of animals that may respond within each contour.

Harbour Porpoise Dose-response Function

1.2.3.9 To estimate the number of porpoise predicted to experience behavioural disturbance as a result of piling, this impact assessment uses the porpoise dose-response function presented in Graham *et al.* (2017[14]) developed using data on harbour porpoise collected during the first six weeks of piling during Phase 1 of the Beatrice OWF monitoring program (Figure 1-1).

1.2.3.10 Since the initial development of the dose-response function in 2017, additional data from the remaining pile driving events at Beatrice OWF have been processed and are presented in (Graham *et al.*, 2019[15]). The passive acoustic monitoring showed a 50% probability of porpoise response within 7.4km at the first location piled, with decreasing response levels over the construction period (excluding pre-construction surveys) to a 50% probability of response within 1.3km by the final piling location (Graham *et al.*, 2019[2]). Using the dose-response function derived from the initial piling events in the impact assessment is precautionary, as evidence shows that porpoise response is likely to diminish over the construction period (excluding pre-construction surveys).

Seal Dose-response Function

1.2.3.11 For seals, the dose-response function adopted was based on the data presented in Whyte *et al.* (2020[32]) (Figure 1-2). The study used telemetry data from harbour seals tagged in the Wash to assess how seal usage changed in relation to the pile driving activities at the Lincs OWF in 2011-2012. Given the large confidence intervals on the data, the assessment presents the mean number of seals predicted to be disturbed using both the mean dose-response and the 95% confidence intervals (CI) (as advised by the authors).

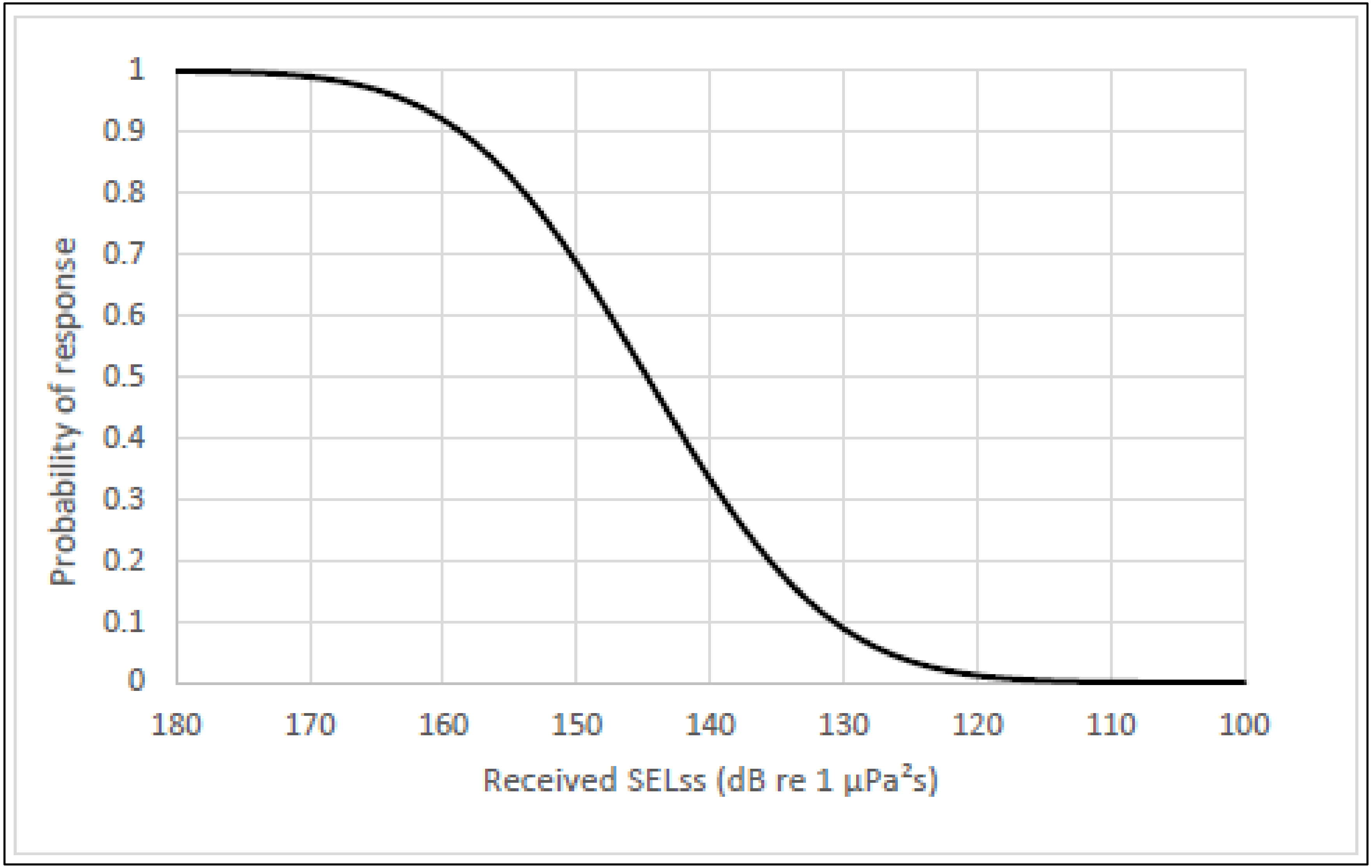

Figure 1-1: Relationship between the proportion of porpoise responding and the received single strike SEL (SEL_{ss}) (not weighted to porpoise hearing), based on passive acoustic monitoring results obtained during Phase 1 of the Beatrice OWF monitoring program (Graham *et al.*, 2017[14]).

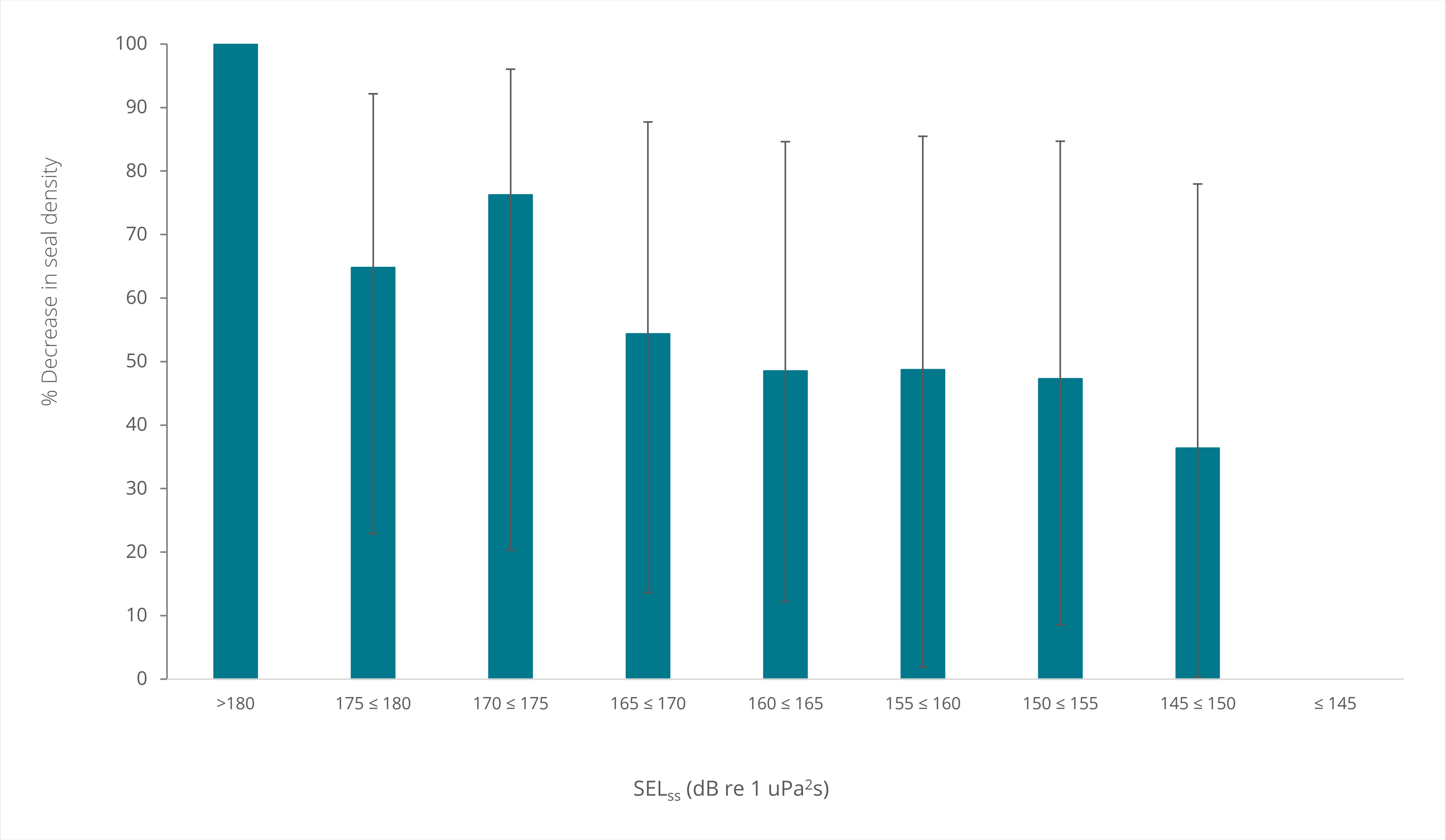

Figure 1-2: Predicted decrease in seal density as a function of estimated sound exposure level, error bars show 95% CI (Whyte *et al.*, 2020[32]). Note, it has been assumed that all seals are displaced at sound exposure levels above 180 dB re 1 μPa^{2}s - this is a conservative assumption since there were no data presented in the study for harbour seal responses at this level.

1.2.3.12 There are no corresponding data for grey seals and, as such, the harbour seal dose-response function is applied to the grey seal disturbance assessment. This is considered to be an appropriate proxy for grey seals, since both species are categorised within the same functional hearing group. However, it is likely that this over estimates the grey seal response, since grey seals are considered to be less sensitive to behavioural disturbance than harbour seals (Booth *et al.*, 2019[16]). Recent studies of tagged grey seals have shown that there is vast individual variation in responses to pile driving, with some animals not showing any evidence of a behavioural response (Aarts *et al.*, 2018[17]). Likewise, if the impacted area is considered to be a high quality foraging patch, it is likely that some grey seals may show no behavioural response at all, given their motivation to remain in the area for foraging (Hastie *et al.*, 2021[18]). Therefore, the adoption of the harbour seal dose-response function for grey seals is considered to be precautionary as it will likely over-estimate the potential for impact on grey seals.

Disturbance from Other Construction Activities and Geophysical Surveys

1.2.3.13 There is currently no guidance on the thresholds to be used to assess disturbance of marine mammals from other construction activities as well as geophysical surveys. Therefore, the impact assessment provides a qualitative assessment for these impacts. The assessment is based on the evidence that is available in the existing literature for that impact pathway and species combination, where available.

1.2.3.14 The majority of available evidence on the impact of disturbance of marine mammals from other construction activities focuses on the impact of vessel activity and dredging. Both these activities are of relevance during the construction of the Proposed Development (Offshore).

1.2.3.15 In terms of geophysical surveys, the assessment considers the overlap between hearing sensitivity and operating frequencies of the equipment. Where information is provided in the literature, this has been considered in relation to potential impact ranges.

1.3 Assessment Limitations

1.3.1 Overview

1.3.1.1 In line with the CIEEM (2018[1]) guidance, detail is provided on the assumptions and limitations of the assessment methods. The key uncertainties relating to the underwater noise modelling and impact assessment relate to predicting exposure of animals to underwater noise, predicting the response of animals to underwater noise and predicting potential population consequences of disturbance from underwater noise. Further detail of such uncertainty is set out below.

1.3.2 PTS-onset Assumptions

1.3.2.1 There are no empirical data on the threshold for auditory injury in the form of PTS-onset for marine mammals, as to test this would be inhumane. Therefore, PTS-onset thresholds are estimated based on extrapolating from TTS-onset thresholds. For pulsed noise, such as piling, National Marine Fisheries Service (NMFS) have set the onset of TTS at the lowest level that exceeds natural recorded variation in hearing sensitivity (6 dB), and assumes that PTS occurs from exposures resulting in 40 dB or more of TTS measured approximately four minutes after exposure (NMFS, 2018[19]). This assumption is used in the Southall *et al.* (2019[2]) thresholds for PTS which are used in this assessment.

Instantaneous PTS

1.3.2.2 The predictions for instantaneous PTS-onset assume that all animals within the PTS-onset range are impacted, which is likely to overestimate the true number of impacted animals.

Cumulative PTS

1.3.2.3 There is much more uncertainty associated with the prediction of the cumulative PTS impact ranges than with those for the instantaneous PTS. One reason is that the sound levels an animal receives, and which are cumulated over a whole piling sequence are difficult to predict over such long periods of time as a result of uncertainties about the animal's (responsive) movement in terms of its changing distance to the sound source and the related speed, and its position in the water column.

1.3.2.4 Another reason is that the prediction of the onset of PTS is determined with the assumptions that:

- The amount of sound energy an animal is exposed to within 24 hours will have the same effect on its auditory system, regardless of whether it is received all at once (i.e., with a single bout of sound) or in several smaller doses spread over a longer period (called the equal-energy hypothesis); and
- The sound keeps its impulsive character, regardless of the distance to the sound source.

1.3.2.5 However, in practice:

- There is a recovery of a threshold shift caused by the sound energy if the dose is applied in several smaller doses (e.g., between pulses during pile driving or in piling breaks) leading to an onset of PTS at a higher energy level than assumed with the given SEL_{cum} threshold; and

- Pulsed sound loses its impulsive characteristics while propagating away from the sound source, resulting in a slower shift of an animal's hearing threshold than would be predicted for an impulsive sound.

1.3.2.6 Both assumptions, therefore, lead to a conservative determination of the impact ranges and are discussed in further detail in the sections below.

Equal Energy Hypothesis

1.3.2.7 The equal-energy hypothesis assumes that exposures of equal energy are assumed to produce equal amounts of noise-induced threshold shift, regardless of how the energy is distributed over time however, a continuous and an intermittent noise exposure of the same SEL will produce different levels of TTS (Ward, 1997[20]). However, Finneran (2015[21]) showed that several marine mammal studies have demonstrated that the temporal pattern of the exposure does in fact affect the resulting threshold shift (e.g., Kastak *et al.*, 2005[22]; Mooney *et al.*, 2009[23]; Finneran *et al.*, 2010[24]; Kastelein *et al.*, 2013[25]). Intermittent noise allows for some recovery of the threshold shift in between exposures, and therefore recovery can occur in the gaps between individual pile strikes and in the breaks in piling activity, resulting in a lower overall threshold shift, compared to continuous exposure at the same SEL. Therefore, the equal energy hypothesis assumption behind the $\mathrm{SEL}_{\mathrm{cum}}$ threshold is not valid, and as such, models will overestimate the level of threshold shift experienced from intermittent noise exposures. The degree to which the threshold shift is over-estimated is explored in detail below.

1.3.2.8 Kastelein *et al.* (2014[26]) showed that a porpoise experienced a 6-8 dB lower TTS when exposed to sound with a duty cycle of 25% compared to a continuous sound. Kastelein *et al.* (2015[27]) also showed for a 100% duty cycle (continuous noise), PTS-onset is predicted to be reached at a $\mathrm{SEL}_{\mathrm{cum}}$ of 196 dB re 1 $\mu\mathrm{Pa}^2\mathrm{s}$, but for a 10% duty cycle, the 40 dB hearing threshold shift is predicted to be reached at a $\mathrm{SEL}_{\mathrm{cum}}$ of 206 dB re 1 $\mu\mathrm{Pa}^2\mathrm{s}$ (thus resulting in a 10 dB re 1 $\mu\mathrm{Pa}^2\mathrm{s}$ difference in the threshold).

1.3.2.9 For piling at the Proposed Development (Offshore), the initial soft-start has been modelled to start at 6 blows per minute for the first minute, increasing to 30 blows per minute after that for the remainder of the ramp-up for the worst-case scenario (the same ramp-up is used for monopiles, pin piles for jackets and anchors). Assuming a signal duration of around 0.5 seconds for a pile strike, the initial soft-start will be a 5% duty cycle (0.5 second pulse followed by 9.5 seconds of silence) and the ramp-up will be a 25% duty cycle (0.5 second pulse followed by 1.5 seconds of silence). In the study of Kastelein *et al.* (2014[26]), the reduction in TTS at a duty cycle of 25% is 5.5-8.3 dB. This means, if the same SEL elicits a ≥5.5 dB lower TTS at 25% duty cycle compared to 100% duty cycle, to elicit the same TTS as a sound of 100% duty cycle, a ≥2.4 dB[i] higher SEL is needed. The threshold at which PTS-onset is likely is therefore, expected to be a minimum of 2.4 dB higher than the PTS-onset threshold proposed by Southall *et al.* (2019[2]) and used in the current assessment.

1.3.2.10 Table 1-2 summarises the difference in the predicted PTS impact ranges using the current and adjusted thresholds. If the threshold accounts for recovery in hearing between pulses, then PTS impact ranges decrease from 15.1km for harbour porpoise to 8.8km (range reduction of 42%). For minke whale, if the threshold accounts for recovery in hearing between pulses, then PTS impact ranges decrease from 35.7km to 22.7km (range reduction of 36%). Therefore, accounting for recovery in hearing between pulses by increasing the PTS-onset threshold by 2 or 3 dB significantly decreases the predicted PTS-onset impact ranges.

1.3.2.11 The approach to modelling cumulative PTS is in development. Therefore, this impact assessment will present the cumulative PTS impact ranges using the current Southall *et al*. (2019[2]) PTS-onset impact threshold without accounting for recovery between pulses.

Table 1-2: Difference in predicted cumulative PTS impact ranges for harbour porpoise and minke whales if recovery between pulses is accounted for and the PTS-onset threshold is increased by 2 or 3 dB.

Threshold		Maximum Impact Range (km)	Reduction in Impact Range (km)
Harbour porpoise			
PTS	155 SEL_{cum}	15.1	-
PTS + 2 dB	157 SEL_{cum}	10.7	4.4
PTS + 3 dB	158 SEL_{cum}	8.8	6.3
Minke whale			
PTS	183 SEL_{cum}	35.7	-
PTS + 2 dB	185 SEL_{cum}	26.8	8.9
PTS + 3 dB	186 SEL_{cum}	22.7	13.0

Impulsive Characteristics

1.3.2.12 Southall *et al.* (2019[2]) assumed that an animal's hearing threshold will shift by 2.3 dB per dB SEL received from an impulsive sound, but only 1.6 dB per dB SEL when the sound received is non impulsive. The PTS onset

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[i] Calculated as: 5.5 dB divided by 2.3, based on the assumption that an animal's hearing threshold will shift by 2.3 dB per dB SEL received from an impulsive sound, as per Southall *et al.* (2019[2]).

threshold for non-impulsive sound is, therefore, higher than for impulsive sound, as more energy is needed to cause PTS. Consequently, an animal subject to both types of sound will be at risk of PTS at an SEL_{cum} that lies somewhere between the PTS onset thresholds of impulsive and non-impulsive sound.

1.3.2.13 Southall *et al.* (2019[2]) acknowledges that as a result of propagation effects, the sound signal of certain sound sources (e.g., impact piling) loses its impulsive characteristics and could potentially be characterised as non-impulsive beyond a certain distance. The changes in noise characteristics with distance generally result in exposures becoming less physiologically damaging (Southall *et al.*, 2007[12]).

1.3.2.14 Hastie *et al.* (2019[28]) estimated the transition from impulsive to non-impulsive characteristics of impact piling noise during the installation of OWF turbine foundations at the Wash and in the Moray Firth. They showed that the noise signal experienced a high degree of change in its impulsive characteristics with increasing distance. Based on this data it is expected that the probability of a signal being defined as "impulsive" (using the criteria of rise time being less than 25ms) reduces to only 20% between ~2 and 5km from the source.

1.3.2.15 Martin *et al.* (2020[29]) investigated the sound emission of different sound sources (including piling) to test techniques for distinguishing between the sound being impulsive or non-impulsive. They suggested the use of kurtosis (a measure of the asymmetry of a probability distribution of a real-valued variable) to further investigate the impulsiveness of sound. Martin *et al.* (2020[29]) argued that:

- Kurtosis of 0-3 = continuous sinusoidal signal (non-impulsive);
- Kurtosis of 3-40 = transition from non-impulsive to impulsive sound; and
- Kurtosis of 40 = fully impulsive (based on data from Hamernik *et al.,* 2007).

1.3.2.16 The results from Martin *et al.* (2020[29]) shows (for unweighted and LF-C weighted sound) that piling sound loses its impulsiveness with increasing distance from the piling site - the kurtosis value decreases with increasing distance and therefore the sound loses its harmful impulsive characteristics.

1.3.2.17 Southall (2021[30]) points out that:

1.3.2.18 "*At present there are no properly designed, comparative studies evaluating TTS for any marine mammal species with various noise types, using a range of impulsive metrics to determine either the best metric or to define an explicit threshold with which to delineate impulsiveness*".

1.3.2.20 Southall (2021[30]) also notes that:

> "*It should be recognized that the use of impulsive exposure criteria for receivers at greater ranges (tens of kilometers) is almost certainly an overly precautionary interpretation of existing criteria*".

1.3.2.21 Most recently, as a part of the range dependent nature of impulsive noise (RaDIN) project, Matei *et al.* (2024[31]) modelled four metrics of impulsiveness and found that impulsiveness of pile driving noise decreased as it travelled further away from the source. Although a decrease in impulsiveness was noted within the first five kilometres from the piling location for all metrics, the authors caveat that this is not equivalent to a range at which these sounds are no longer impulsive (Matei *et al.*, 2024[31]).

Animal Depth

1.3.2.22 Empirical data on SEL_{ss} levels recorded during piling construction at the Lincs OWF have been compared to estimates obtained using the Aquarius pile driving model (Whyte *et al.*, 2020[32]; for more information on the Aquarius model see de Jong *et al*., 2019[33]). This has demonstrated that measured recordings of SEL_{ss} levels made at 1m depth were all lower than the model predicted single-strike sound exposure levels for the shallowest depth bin (2.5m). In contrast, measurements made at 9m depth were much closer to the model predicted single-strike sound exposure levels. This highlights the limitations of modelling exposure using depth averaged sound levels, as the acoustic model can overpredict exposure at the surface. This is important to note since animals may conduct shorter and shallower dives when fleeing (e.g., van Beest *et al.*, 2018[34]).

Cumulative PTS Summary

1.3.2.23 Considering that an increasing proportion of the sound emitted during a piling sequence will become less impulsive (and thereby less harmful) while propagating away from the sound source, and this effect starts at ranges below 5km in all above mentioned examples, the cumulative PTS-onset threshold for animals starting to flee at 5km should be higher than the Southall (2021[30]) threshold adopted for this assessment (i.e., the risk of experiencing PTS becomes lower), and any impact range estimated beyond this distance should be considered as an unrealistic over-estimate, especially when they result in very large distances.

1.3.2.24 For the purpose of presenting a precautionary assessment, this quantitative impact assessment is based on fully impulsive thresholds, but the potential for overestimation should be noted.

1.3.2.25 Given the above, the Project considers that the calculated SEL_{cum} PTS onset impact ranges are highly precautionary and that the true extent of effects (impact ranges and numbers of animals experiencing PTS) will likely be considerably less than that assessed here.

1.3.2.26 NatureScot agreed with this conclusion, stating that "some of the assumptions made in the SEL modelling are over-precautionary, and there is considerable conservatism in assessments. This can lead to over-estimation of impact zones, and therefore it would be disproportionate to expect these to be fully mitigated". Therefore, NatureScot requires only instantaneous PTS (using the SPL_{peak} metric) to be mitigated.

1.3.2.27 The cumulative PTS impact ranges (using the SEL_{cum} metric) are presented in this assessment for information only.

1.3.3 Density Assumptions

1.3.3.1 There are uncertainties relating to the ability to predict the responses of animals to underwater noise and the number of animals potentially exposed to levels of noise that may cause an impact is uncertain. Given the high spatial and temporal variation in marine mammal abundance and distribution in any particular area of the sea, it is difficult to predict how many animals may be present within the range of noise impacts. All methods for determining at sea abundance and distribution suffer from a range of biases and uncertainties. The density estimates selected for the quantitative impact assessment the Proposed Development are the most recent and most robust density estimates available for each species, as detailed in Volume 7B, Appendix 7-1: Marine Mammals Baseline Characterisation.

1.3.4 Disturbance Assumptions

Dose-response Function

1.3.4.1 In the absence of species-specific data on dolphin species or minke whales, the Graham *et al*. (2017[14]) dose-response function has been adopted for all cetaceans. However, it should be noted that various studies have shown that other cetacean species show comparatively less of a disturbance response from underwater noise compared with harbour porpoise, meaning this approach is highly precautionary. Porpoise are considered to be particularly responsive to anthropogenic disturbance, with playback experiments showing avoidance reactions to very low levels of sound (Tyack, 2009[35]), and multiple studies showing that porpoise respond (avoidance and reduced vocalisation) to a variety of anthropogenic noise sources to distances of multiple kilometers (e.g., Brandt *et al.*, 2013[36]; 2018[37]; Thompson *et al.*, 2013[38]; 2020[39]; Tougaard *et al.*, 2013[40]; Sarnocinska *et al.*, 2019[41]; Benhemma-Le Gall *et al.*, 2021[42]).

1.3.4.2 Evidence suggests that dolphin species are less sensitive to disturbance compared to harbour porpoise. A literature review of recent (post-Southall *et al.,* 2007[12]) behavioural responses by harbour porpoises and bottlenose dolphins to noise was conducted by Moray Offshore Renewables Limited

(2012[43]). Several studies have reported a moderate to high level of behavioural response at a wide range of received SPLs (100 and 180 dB re 1µPa) (Lucke *et al.*, 2009[44]; Tougaard *et al.*, 2009[45]; Brandt *et al.*, 2011[46]). Conversely, a study by Niu *et al.* (2012[47]) reported moderate level responses to non-pulsed noise by bottlenose dolphins at received SPLs of 140 dB re 1µPa. Another high frequency cetacean, Risso's dolphin, reported no behavioural response at received SPLs of 135 dB re 1µPa (Southall *et al.*, 2010[48]). Whilst both species showed a high degree of variability in responses and a general positive trend with higher responses at higher received levels, moderate level responses were observed above 80 dB re 1µPa in harbour porpoise and above 140 dB re 1µPa in bottlenose dolphins (Natural Power and SMRU Ltd, 2012[49]), indicating that moderate level responses by bottlenose dolphins will be exhibited at a higher received SPL and, therefore, they are likely to show a lesser response to disturbance. Likewise, other high-frequency cetacean species, such as striped and common dolphins, have been shown to display less of a response to underwater noise signals and construction-related activities compared with harbour porpoise (e.g., Kastelein *et al.*, 2006[50]; Culloch *et al.*, 2016[51]).

Exposure to Noise

1.3.4.3 There are uncertainties relating to the ability to predict the exposure of animals to underwater noise, as well as in predicting the response to that exposure. These uncertainties relate to a number of factors: the ability to predict the level of noise that animals are exposed to, particularly over long periods of time; the ability to predict the numbers of animals affected, and the ability to predict the individual and ultimately population consequences of exposure to noise. These are explored in further detail in the paragraphs below.

1.3.4.4 The propagation of underwater noise is relatively well understood and modelled using standard methods. However, there are uncertainties regarding the amount of noise actually produced by each pulse at source and how the pulse characteristics change with range from the source. There are also uncertainties regarding the position of receptors in relation to received levels of noise, particularly over time, and understanding how position in the water column may affect received levels. Noise monitoring is not always carried out at distances relevant to the ranges predicted for effects on marine mammals, so effects at greater distances remain un-validated in terms of actual received levels. The extent to which ambient noise and other anthropogenic sources of noise may mask signals from the Project construction are not specifically addressed. The dose-response functions for porpoise include behavioural responses at noise levels down to 120 dB SEL_{ss} (sound exposure level single strike) which may be indistinguishable from ambient noise at the ranges these levels are predicted.

Predicted Response

1.3.4.5 The current methods for prediction of behavioural responses are based on received sound levels, but it is likely that factors other than noise levels alone will also influence the probability of response and the strength of response (e.g., previous experience, behavioural and physiological context, proximity to activities, characteristics of the sound other than level, such as duty cycle and pulse characteristics). However, at present, it is impossible to adequately take these factors into account in a predictive sense. This assessment makes use of the monitoring work that has been carried out during the construction of the Beatrice OWF and, therefore, uses the most recent and site-specific information on disturbance to harbour porpoise in relation to received levels of pile driving noise. However, it should be noted that more recent data from Moray West resulted in similar responses despite the use of much greater hammer energies. Ongoing work through the PrePARED project will reduce these uncertainties through analyses that integrate data from Beatrice, Moray East and Moray West OWFs and will report on how received noise levels and proximity to activities interact to influence disturbance responses to piling. However, this is not yet available to include in this EIAR (expected in 2025).

1.3.4.6 There is also a lack of information on how observed effects (e.g., short-term displacement around impact piling activities) manifest themselves in terms of effects on individual fitness, and ultimately population dynamics to attempt to quantify the amount of disturbance required before vital rates are impacted.

Duration of Impact

1.3.4.7 The duration of disturbance is another uncertainty. Studies at Horns Rev 2 demonstrated that porpoises returned to the area between one and three days (Brandt *et al.*, 2011[46]) and monitoring at the Dan Tysk Wind Farm found return times of around 12 hours (van Beest *et al.*, 2015[52]). Two studies at Alpha Ventus demonstrated that the return of porpoises was about 18 hours after piling (Dähne *et al.*, 2013[53]) and a study of porpoise at the Gemini wind farm found that local population densities recovered between two and six hours after piling (Nabe-Nielsen *et al.*, 2018[54]). An analysis of data collected at the first seven OWF in Germany has shown that harbour porpoise detections were reduced between one and two days after piling (Brandt *et al.*, 2018[37]).

1.3.4.8 Population modelling using the Interim Population Consequences of Disturbance (iPCoD) Model (see Volume 7B, Appendix 7-4) assumes that disturbance from piling equates to six hours of non-foraging time for harbour porpoise. Emerging data from monitoring at Moray West were presented at the 2024 PrePARED Knowledge Exchange Meeting and indicate that this assumption may be conservative (Thompson *et al*., 2024[55]). These site-specific data will be further explored during 2025 to validate this assumption and reported to MFRAG but are not available to include in this EIA.

1.3.4.9 Analysis of data from monitoring of marine mammal activity during piling of jacket pile foundations at Beatrice OWF (Graham *et al.*, 2017[14]; 2019[15]) provides evidence that harbour porpoise were displaced during pile driving but return after cessation of piling, with a reduced extent of disturbance over the duration of the construction period. This suggests that the assumptions adopted in the current assessment are precautionary as animals are predicted to remain disturbed at the same level for the entire duration of piling during construction.

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