Hornsea Project Four: Preliminary Environmental Information Report (PEIR)

Volume 4, Annex 4.5: Subsea Noise Technical Report

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Doc. no. A4.4.5
Version A

Table of Contents

List of Tables

List of Figures

Glossary

Term	Definition
Ambient noise	Normal background noise in the environment, which has no distinguishable sources.
Decibel	A customary scale most commonly used (in various ways) for reporting levels of sound. A difference of 10 dB corresponds to a factor of 10 in sound power. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be 10 $\log_{10}$(actual/reference), where (actual/reference) is a power ratio. Because sound power is usually proportional to sound pressure squared, the decibel value for sound pressure is 20$\log_{10}$(actual pressure/reference pressure). As noted above, the standard reference for underwater sound pressure is 1 micro-Pascal (μPa). The dB symbol is followed by a second symbol identifying the specific reference value (i.e., re 1 μPa).
High Voltage Alternating Current (HVAC)	High voltage alternating current is the bulk transmission of electricity by alternating current (AC), whereby the flow of electric charge periodically reverses direction.
Hornsea Four	The proposed Hornsea Project Four offshore wind farm project; the term covers all elements within the Development Consent Order (i.e. both the offshore and onshore components).
Most-likely modelling scenarios	The modelling scenarios undertaken that consider the most-likely modelling parameters for the majority of Hornsea Four.
Peak pressure	The highest pressure above or below ambient that is associated with a sound wave.
Peak-to-peak pressure	The sum of the highest positive and negative pressures that is associated with a sound wave.
Permanent Threshold Shift (PTS)	A total or partial permanent loss of hearing caused by some kind of acoustic or drug trauma. PTS results in irreversible damage to the sensory hair cells of the ear, and thus a permanent reduction of hearing acuity.
Sound Exposure Level (SEL)	The constant sound level acting for one second, which has the same amount of acoustic energy, as indicated by the square of the sound pressure, as the original sound. It is the time-integrated, sound-pressure-squared level. SEL is typically used to compare transient sound events having different time durations, pressure levels, and temporal characteristics.
Sound Pressure Level (SPL)	The sound pressure level or SPL is an expression of the sound pressure using the decibel (dB) scale and the standard reference pressures of 1 μPa for water and biological tissues, and 20 μPa for air and other gases
Temporary Threshold Shift (TTS)	Temporary loss of hearing as a result of exposure to sound over time. Exposure to high levels of sound over relatively short time periods will cause the same amount of TTS as exposure to lower levels of sound over longer time periods. The mechanisms underlying TTS are not well understood, but there may be some temporary damage to the sensory cells. The duration of TTS varies depending on the nature of the stimulus, but there is generally recovery of full hearing over time.
Threshold	The threshold generally represents the lowest signal level an animal will detect in some statistically predetermined percent of presentations of a signal.

Term	Definition
Unweighted sound level	Sound levels which are 'raw' or have not been adjusted in any way, for example to account for the hearing ability of a species.
Weighted sound level	A sound level which has been adjusted with respect to a 'weighting envelope' in the frequency domain, typically to make an unweighted level relevant to a particular species. Examples of this are the dB(A), where the overall sound level has been adjusted to account for the hearing ability of humans, or dBht(Species) for fish and marine mammals.
Maximum design modelling scenarios	The modelling scenarios undertaken that consider all the maximum design modelling parameters possible at Hornsea Four. However, by considering all parameters as maximum design it is possible that the resulting scenario is impossible to occur, which is why most-likely modelling scenarios have also been included.

Acronyms

Acronym	Definition
AfL	Agreement for Lease
DCO	Development Consent Order
EIA	Environmental Impact Assessment
GIS	Graphical Information System
HF	High-Frequency Cetaceans (Southall *et al.* (2019) marine mammal hearing group)
HVAC	High Voltage Alternative Current
INSPIRE	Impulse Noise Sound Propagation and Impact Range Estimator (Subacoustech Environmental's noise modelling software)
LF	Low-Frequency Cetaceans (Southall *et al.* (2019) marine mammal hearing group)
NMFS	National Marine Fisheries Service
NPL	National Physical Laboratory
PCW	Phocid Carnivores in Water (Southall *et al.* (2019) marine mammal hearing group)
PEIR	Preliminary Environmental Information Report
PTS	Permanent Threshold Shift
RMS	Root Mean Square
SE	Sound Exposure
SEL	Sound Exposure Level
SEL_{cum}	Cumulative Sound Exposure Level
SEL_{ss}	Single Strike Sound Exposure Level
SPL	Sound Pressure Level
SPL_{peak}	Peak Sound Pressure Level
$SPL_{peak\text{-}to\text{-}peak}$	Peak-to-peak Sound Pressure Level
TTS	Temporary Threshold Shift
VHF	Very High-Frequency Cetaceans (Southall *et al.* (2019) marine mammal hearing group)
WTG	Wind Turbine Generator

Units

Unit	Definition
dB	Decibel (sound pressure)
Hz	Hertz (frequency)
kHz	Kilohertz (frequency)
kJ	Kilojoule (energy)
km	Kilometres (distance)
km^2	Kilometres squared (area)
knot	Knot (speed, at sea)
m	Metres (distance)
ms^{-1}	Metres per second (speed)
μPa	Micropascal (pressure)

1 Introduction

1.1 Project background

1.1.1.1 Ørsted Hornsea Project Four Limited (the Applicant) is proposing to develop Hornsea Project Four Offshore Wind Farm (hereafter Hornsea Four). Hornsea Four will be located approximately 65 km offshore the East Riding of Yorkshire in the Southern North Sea and will be the fourth project to be developed in the former Hornsea Zone (please see **Volume 1, Chapter 1: Introduction** for further details on the Hornsea Zone). Hornsea Four will include both offshore and onshore infrastructure including an offshore generating station (wind farm), export cables to landfall, and connection to the electricity transmission network (please see **Volume 1, Chapter 4: Project Description** for full details on the Project Design). The location of Hornsea Four is illustrated in **Figure 1**. The Preliminary Environmental Information Report (PEIR) boundary combines the search areas for the onshore and offshore infrastructure.

1.1.1.2 The Hornsea Four Agreement for Lease (AfL) area was 848 km^2 at the Scoping phase of project development. In the spirit of keeping with Hornsea Four's approach to Proportionate Environmental Impact Assessment (EIA), the project is currently giving due consideration to the size and location (within the existing AfL area) of the final project that will be taken forward to consent application (DCO). This consideration is captured internally as the "Developable Area Process", which includes Physical, Biological and Human constraints in refining the developable area, balancing consenting and commercial considerations with technical feasibility for construction.

1.1.1.3 The combination of Hornsea Four's Proportionality in EIA and Developable Area process has resulted in a marked reduction in the AfL taken forward at the point of PEIR. (see **Figure 1**). The evolution of the AfL is detailed in **Volume 1; Chapter 3: Site Selection and Consideration of Alternatives** and **Volume 4, Annex 3.2: Selection and Refinement of the Offshore Infrastructure**. The final developable area taken forward to consent may differ from the PEIR boundary presented in **Figure 1** due to the results of the EIA, technical considerations and stakeholder feedback.

1.1.1.3 Subacoustech Environmental Ltd was commissioned by the Applicant to undertake a study of potential underwater noise related to the construction, operation, and eventual decommissioning of Hornsea Four, focussing on modelling results for impact piling and other noise sources relating to the construction and lifecycle of Hornsea Four.

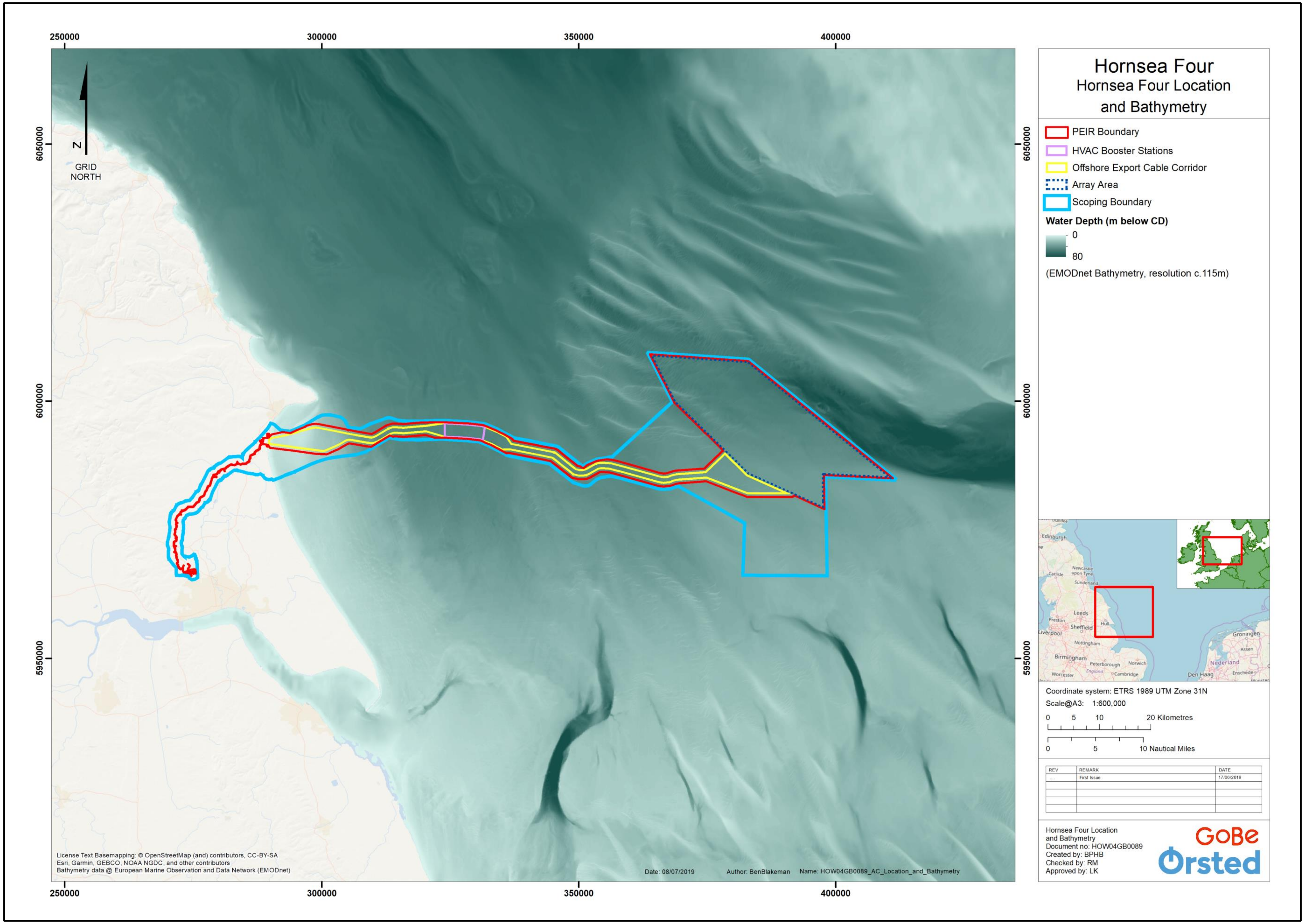

Figure 1: Map showing the boundaries of Hornsea Four, including the array area and the High Voltage Alternative Current (HVAC) booster station search area, and the surrounding bathymetry (not to scale).

1.2 Noise modelling

1.2.1 Introduction

1.2.1.1 This report focuses on pile driving activities during construction of Hornsea Four and also considers other noise sources that are likely to be present during the development lifecycle. Underwater noise modelling has been carried out in two parts. Impact piling has been considered using Subacoustech Environmental's INSPIRE subsea noise propagation and prediction software. Other noise sources have been considered using a high-level, simple modelling approach.

1.2.2 Impact piling

1.2.2.1 Impact piling has been proposed as a method for installing foundation piles into the seabed for wind turbine generators (WTGs), substations and accommodation platforms. Both monopile or pin pile (jacket) foundation options have been considered.

1.2.2.2 The impact piling technique involves a large weight, or "ram", being dropped or driven onto the top of the pile, forcing it into the seabed. Usually, double-acting hammers are used in which a downward force on the ram is applied, exerting a larger force than would be the case if it were only dropped under the action of gravity. Impact piling has been established as a source of high-level underwater noise (e.g. Würsig *et al.*, 2000; Caltrans, 2001; Nedwell *et al.* 2003b and 2007; Parvin *et al.*, 2006; and Thomsen *et al.* 2006).

1.2.2.3 Noise is created in air by the hammer as a direct result of the impact of the hammer on the pile and some of this airborne noise is transmitted into the water. Of more significance to the underwater noise is the direct radiation of noise from the pile following the impact of the hammer on the top. Structural pressure waves in the submerged section of the pile transmit sound efficiently into the surrounding water. These waterborne pressure waves will radiate outwards, usually providing the greatest contribution to the underwater noise.

1.2.3 Other sources of noise

1.2.3.1 Although impact piling is expected to be the greatest source of noise during construction (Bailey *et al.*, 2014; Bergström *et al.*, 2014), several other noise sources associated with the development of Hornsea Four may also be present. These include dredging (for seabed preparation for foundations and/or sandwave clearance for cable installation), drilling of foundation piles, cable laying, rock placement, trenching, vessel noise and noise from the operational WTGs. These noise sources have been considered using a simple modelling approach due to the relative levels of noise and available information from these activities. A high-level review of noise from decommissioning techniques has also been included.

1.3 Aims and objectives

1.3.1.1 This report presents detailed modelling study of the potential underwater noise from impact piling and other noise sources relating to the construction, operation, and decommissioning of Hornsea Four and covers the following:

- A review of information on the units for measuring and assessing underwater noise and a review of underwater noise metrics and criteria that have been used to aid assessment of possible environmental effects in marine receptors (**Section 2**);
- A brief description of baseline ambient noise (**Section 3**);
- Discussion of the approach, input parameters and assumptions for the impact piling noise modelling undertaken (**Section 4**);
- Presentation of detailed subsea noise modelling for impact piling using unweighted metrics (**Section 5.1**);
- Presentation of the subsea noise modelling results with regards to injury and behavioural effects in marine mammals and fish using various noise metrics and criteria (**Section 5.2**);
- Summary of the predicted noise levels from the simple modelling approach for dredging, drilling, cable laying, rock placement, trenching, vessel noise, noise from operational wind turbines, and a high-level review of decommissioning techniques (**Section 6**); and
- Summary of the results (**Section 7**).

2 Measurement of noise

2.1 Underwater Noise

2.1.1 Background

2.1.1.1 Sound travels much faster in water (approximately 1,500 ms^{-1}) than in air (340 ms^{-1}). Since water is a relatively incompressible, dense medium, the pressures associated with underwater sound tend to be much higher than in air. As an example, background noise levels in the sea of 130 dB re 1 μPa for UK coastal waters are not uncommon (Nedwell *et al.*, 2003a and 2007). It should be noted that stated underwater noise levels should not be confused with the noise levels in air, which use a different scale.

2.1.2 Units of measurement

2.1.2.1 Sound measurements underwater are usually expressed using the dB scale, which is a logarithmic measure of sound. A logarithmic scale is used because rather than equal increments of sound having an equal increase in effect, typically a constant ratio is required for this to be the case. That is, each doubling of sound level will cause a roughly equal increase in "loudness".

2.1.2.2 Any quantity expressed in this scale is termed a "level". If the unit is sound pressure, expressed on the dB scale, it will be termed a "sound pressure level". The fundamental definition of the dB scale is given by:

$$Level = 10 \times \log_{10}\left(\frac{Q}{Q_{ref}}\right)$$

Where Q is the quantity being expressed on the scale, and Q_{ref} is the reference quantity.

2.1.2.3 The dB scale represents a ratio and, for instance, 6 dB really means "twice as much as…" (although this description is simplistic). It is therefore used with a reference unit, which expresses the base from which the ratio is expressed. The reference quantity is conventionally smaller than the smallest value to be expressed on the scale, so that any level quoted is positive. For example, a reference quantity of 20 μPa is used for sound in air since this is the threshold of human hearing.

2.1.2.4 A refinement is that the scale, when used with sound pressure, is applied to the pressure squared rather than the pressure. If this were not the case, when the acoustic power level of a source rose by 10 dB the sound pressure level would rise by 20 dB. So that variations in the units agree, the sound pressure must be specified in units of RMS pressure squared. This is equivalent to expressing the sound as:

$$Sound\ pressure\ level = 20 \times \log_{10}\left(\frac{P_{RMS}}{P_{ref}}\right)$$

2.1.2.5 For underwater sound, typically a unit of 1 μPa is used as the reference unit; a Pascal is equal to the pressure exerted by one Newton over one square metre; one micropascal equals one millionth of this.

2.1.2.6 Unless otherwise defined, all noise levels in this report are referenced to 1 μPa.

2.1.3 Sound pressure level (SPL)

2.1.3.1 The sound pressure level (SPL) is normally used to characterise noise and vibration of a continuous nature such as drilling, boring, continuous wave sonar, or background sea and river noise levels. To calculate the SPL, the variation in sound pressure is measured over a specific period to determine the Root Mean Square (RMS) level of the time varying sound. The SPL can therefore be considered a measure of the average unweighted level of sound over the measurement period.

2.1.3.2 Where SPL is used to characterise transient pressure waves such as that from seismic airguns, underwater blasting or impact piling, it is critical that the period over which the RMS level is calculated is quoted. For instance, in the case of a pile strike lasting, say, a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean spread over one second. Often, transient sounds such as these are quantified using "peak" SPLs.

2.1.4 Peak sound pressure level (SPL_{peak})

2.1.4.1 Peak SPLs are often used to characterise sound transients from impulsive sources, such as percussive impact piling and seismic airgun sources. SPL_{peak} is calculated using the maximum variation of the pressure from positive to zero within the wave. This represents the maximum change in positive pressure (differential pressure from positive to zero) as the transient pressure wave propagates.

2.1.4.2 A further variation of this is the peak-to-peak SPL ($SPL_{peak\text{-}to\text{-}peak}$) where the maximum variation of the pressure from positive to negative within the wave is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak level will be twice the peak level, or 6 dB higher (see **Section 2.1.2**).

2.1.5 Sound exposure level (SEL)

2.1.5.1 When considering the noise from transient sources such as blast waves, impact piling or seismic airgun noise, the issue of the duration of the pressure wave is often addressed by measuring the total acoustic energy (energy flux density) of the wave. This form of analysis was used by Bebb and Wright (1953, 1954a, 1954b and 1955), and later by Rawlins (1987), to explain the apparent discrepancies in the biological effect of short and long-range blast waves on human divers. More recently, this form of analysis has been used to develop criteria for assessing the injury range from fish for various noise sources (Popper *et al.*, 2014).

2.1.5.2 The SEL sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound source and the duration the sound is present in the acoustic environment. Sound Exposure (SE) is defined by the equation:

$$SE = \int_0^T p^2(t)dt$$

Where p is the acoustic pressure in Pascals, T is the duration of the sound in seconds, and t is the time in seconds. The SE is a measure of acoustic energy and has units of Pascal squared seconds (Pa^2s).

2.1.5.3 To express the SE on a logarithmic scale by means of a dB, it is compared with a reference acoustic energy level (p^2_{ref}) and a reference time (T_{ref}). The SEL is then defined by:

$$SEL = 10 \times log_{10}\left(\frac{\int_0^T p^2(t)dt}{P^2{}_{ref}T_{ref}}\right)$$

2.1.5.4 By selecting a common reference pressure P_{ref} of 1 μPa for assessments of underwater noise, the SEL and SPL can be compared using the expression:

$$SEL = SPL + 10 \times \log_{10} T$$

Where the SPL is a measure of the average level of broadband noise, and the SEL sums the cumulative broadband noise energy.

2.1.5.5 This means that, for continuous sounds of less than one second, the SEL will be lower than the SPL. For periods greater than one second the SEL will be numerically greater than the SPL (i.e. for a continuous sound of ten seconds duration, the SEL will be 10 dB higher than the SPL, for a sound of 100 seconds duration the SEL will be 20 dB higher than the SPL, and so on).

2.1.5.6 Weighted metrics for marine mammals have been proposed by Southall *et al.*, (2019). These assign a frequency response to groups of marine mammals and are discussed in the following section.

2.2 Analysis of environmental effects

2.2.1 Background

2.2.1.1 Over the past 20 years it has become increasingly evident that noise from human activities in and around underwater environments can have an impact on the marine species in the area. The extent to which intense underwater sound might cause an adverse impact in a species is dependent upon the incident sound level, sound frequency, duration of exposure and/or repetition rate of an impulsive sound (see for example Hastings and Popper, 2005). As a result, scientific interest in the hearing abilities of aquatic species has increased. Studies are primarily based on evidence from high level sources of underwater noise such as blasting or impact piling, as these sources are likely to have the greatest immediate environmental impact and therefore the clearest observable effects, although interest in chronic noise exposure is increasing.

2.2.1.2 The impacts of underwater sound on marine species can be broadly summarised as follows:

- Physical traumatic injury and fatality;
- Auditory injury (either permanent or temporary); and
- Disturbance.

2.2.1.3 The following sections discuss the agreed criteria used in this study in respect of species of marine mammal and fish at Hornsea Four.

2.2.2 Criteria to be used

2.2.2.1 The main metrics and criteria that have been used in this study to aid assessment of environmental effect come from several key papers covering underwater noise and its effects:

- Southall *et al.*, (2019) marine mammal noise exposure criteria; and
- Sound exposure guidelines for fishes by Popper *et al.*, (2014).

2.2.2.2 At the time of writing, these include the most up to date and authoritative criteria for assessing environmental effects for use in impact assessments.

<u>Marine mammals</u>

2.2.2.3 The Southall *et al.*, (2019) paper is effectively an update of the previous Southall *et al.*, (2007) criteria, and gives identical thresholds to those from the NMFS (2018) guidance for marine mammals.

2.2.2.4 The Southall *et al.* (2019) guidance groups marine mammals into groups of similar species and applies filters to the unweighted noise to approximate the hearing sensitivity of the receptor. The hearing groups given in the Southall *et al.* (2019) are summarised in

2.2.2.5 **Table** 1 and **Figure 2**. Further groups for sirenians and other marine carnivores in water are also given in the guidance but this has not been used in this study as those species are not commonly found in the North Sea.

Table 1: Marine mammal hearing groups (from Southall *et al.*, 2019).

Hearing group	Generalised hearing range	Example species
Low-frequency cetaceans (LF)	7 Hz to 35 kHz	Baleen whales
High-frequency cetaceans (HF)	150 Hz to 160 kHz	Dolphins, toothed whales, beaked whales, bottlenose whales (including bottlenose dolphin)
Very high-frequency cetaceans (VHF)	275 Hz to 160 kHz	True porpoises (including harbour porpoises)
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	True seals (including harbour seal)

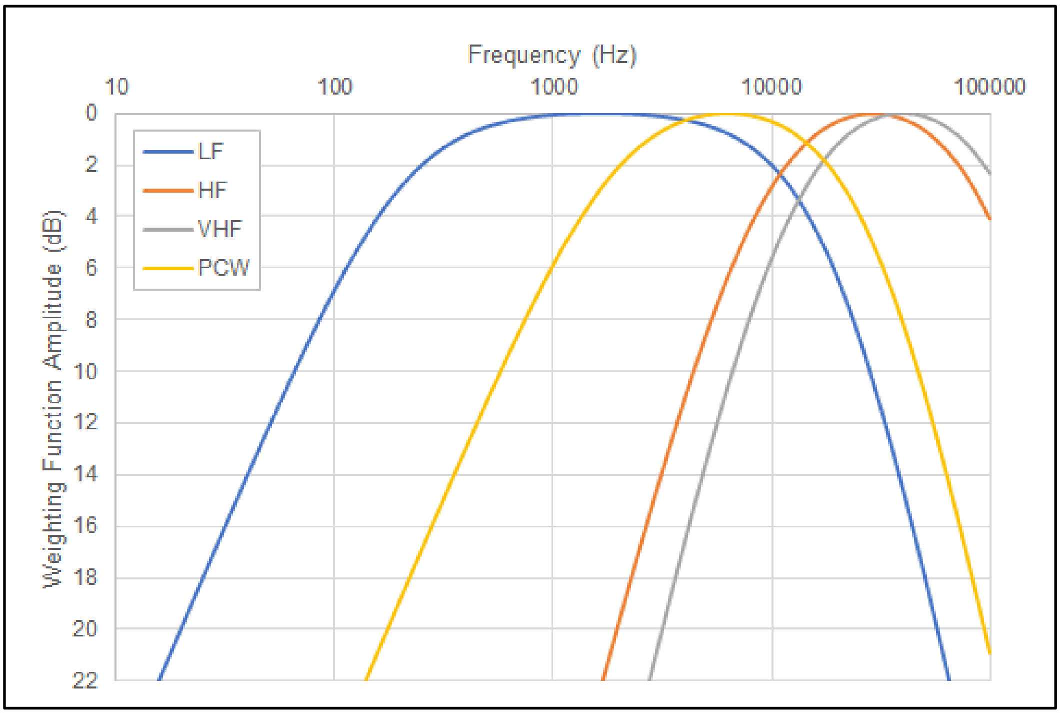

Figure 2: Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall *et al.*, 2019).

2.2.2.6 It should also be noted that the criteria in NMFS (2018), although numerically identical, apply different names to the marine mammal groupings and weightings. For example, what Southall *et al*. (2019) calls high-frequency cetaceans (HF), NMFS (2018) calls mid-frequency cetaceans (MF) and what Southall *et al*. (2019) calls very high-frequency cetaceans (VHF), NMFS (2018) refers to as high-frequency cetaceans. As such, great care should be taken when comparing results using the Southall *et al*. (2019) and NMFS (2018) criteria, especially as the HF groupings and criteria cover different species depending on which study is being used.

2.2.2.7 The Southall *et al.* (2019) criteria has been used for this study as it is a peer-reviewed and published paper in a reputable journal, whereas NMFS (2018) is a guidance document from a government agency and as such could be subject to changes at any point.

2.2.2.8 Southall *et al.* (2019) also gives individual criteria based on whether the noise source is considered impulsive or non-impulsive. Southall *et al.* (2019) categorises impulsive noises as having high peak sound pressure, short duration, fast rise-time and broad frequency content at source, and non-impulsive sources as steady-state noise. Explosives, impact piling and seismic airguns are considered impulsive noise sources, and sonars, vibropiling and other low-level continuous noises are considered non-impulsive. A non-impulsive sound does not necessarily have to have a long duration.

2.2.2.9 Southall *et al.* (2019) presents single strike, unweighted peak criteria (SPL_{peak}) and cumulative (i.e. more than a single sound impulse), weighted sound exposure criteria (SEL_{cum}) for both permanent threshold shift (PTS) where unrecoverable hearing damage may occur and temporary threshold shift (TTS) where a temporary reduction in hearing sensitivity may occur in individual receptors.

2.2.2.10 As sound pulses propagate through the environment and dissipate, they also lose their most injurious characteristics (e.g. rapid pulse rise time, high peak sound pressure) and become more like a "non-pulse" at greater distances. Southall *et al.* (2019) briefly discusses this. Active research is currently underway into the identification of the distance at which the pulse can be considered effectively non-impulsive, and Hastie *et al.* (2019) analysed a series of impulsive noise data to investigate this.

2.2.2.11 Although the situation is complex, the paper reported that most of the signals analysed crossed their threshold for rapid rise time and high peak pressure characteristics associated with impulsive noise dissipated at around 3.5 km from the source. At this stage we cannot definitively say that signals beyond 3.5 km should all be considered non-impulsive, but it is suggested that, beyond this point, signals will increasingly be better represented using the non-impulsive criteria.

2.2.2.12 **Table 2** and **Table 3** present the Southall *et al.* (2019) criteria for onset of risk of PTS and TTS for each of the key marine mammal hearing groups considering impulsive and non-impulsive noise sources.

Table 2: SPL_{peak} criteria for PTS and TTS in marine mammals (Southall *et al.*, 2019).

Southall et al. (2019)	Unweighted SPL_{peak} (dB re 1 μPa)	
	Impulsive	
	PTS	TTS
Low-frequency cetaceans (LF)	219	213
High-frequency cetaceans (HF)	230	224
Very high-frequency cetaceans (VHF)	202	196
Phocid carnivores in water (PCW)	218	212

Table 3: SEL_{cum} and SEL_{ss} criteria for PTS and TTS in marine mammals (Southall *et al.*, 2019).

Southall et al. (2019)	Weighted SEL_{cum} and SEL_{ss} (dB re 1 μPa²s)			
	Impulsive		Non-impulsive	
	PTS	TTS	PTS	TTS
Low-frequency cetaceans (LF)	183	168	199	179
High-frequency cetaceans (HF)	185	170	198	178
Very high-frequency cetaceans (VHF)	155	140	173	153
Phocid carnivores in water (PCW)	185	170	201	181

2.2.2.13 Where SEL_{cum} are required, a fleeing animal model has been used for marine mammals. This assumes that the receptor, when exposed to high noise levels, will swim away from the noise source. For this, a constant fleeing speed of 3.25 ms^{-1} has been assumed for the low-frequency cetaceans (LF) groups (Blix and Folkow, 1995), based on data for minke whale, and for other receptors a constant rate of 1.5 ms^{-1} has been assumed for fleeing, which is a cruising speed for a harbour porpoise (Otani *et al.*, 2000). These are considered worst-case as marine mammals are expected to be able to swim much faster under stress conditions. The modelling assumes that when a fleeing receptor reaches the coast it receives no more noise, as it is likely that the receptor will fleeing along the coast (rather than staying in a single location at the shore), and at this distance from Hornsea Four, the receptor will, in any case, be far enough from the piling that it will have received the majority of its expected noise exposure.

<u>Fish</u>

2.2.2.14 The large number of, and variation in, fish species leads to a greater challenge in the production of a generic noise criterion, or range of criteria, for the assessment of noise impacts. Whereas previous studies applied broad criteria based on limited studies of fish not present in UK waters (e.g. McCauley *et al.*, 2000), the publication of Popper *et al.* (2014) provides an authoritative summary of the latest research and guidelines for fish exposure to sound and uses categories for fish that are representative of the species present in UK waters.

2.2.2.15 The Popper *et al.* (2014) study groups species of fish into whether they possess a swim bladder, and whether it is involved in its hearing. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources; in this case, impact piling and continuous noise sources have been considered.

2.2.2.16 The criteria used for modelling are summarised in **Table 4** and **paragraph 2.2.2.18**.

2.2.2.17 In a similar fashion to marine mammals, a fleeing animal model has been used assuming a fish flees from the noise source at a constant rate of 1.5 ms^{-1}, based on data from Hirata (1999). This speed is the slowest of all species identified and as such is considered to be a worst-case assumption for flee speed. A stationary animal model has also been considered for fish, assuming that a fish remains still when exposed to the high noise levels. This is discussed further below.

Table 4: Criteria for mortality and potential mortal injury, recoverable injury and TTS in species of fish from impact piling noise (Popper *et al.*, 2014).

Impact piling	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS
Fish: no swim bladder	>219 dB SEL_{cum} or >213 dB SPL_{peak}	>216 dB SEL_{cum} or >213 dB SPL_{peak}	>>186 dB SEL_{cum}
Fish: swim bladder not involved in hearing	210 dB SEL_{cum} or >207 dB SPL_{peak}	203 dB SEL_{cum} or >207 dB SPL_{peak}	>186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} or >207 dB SPL_{peak}	203 dB SEL_{cum} or >207 dB SPL_{peak}	186 dB SEL_{cum}

2.2.2.18 Fish eggs and larvae are also included in the assessment and have the same criteria as "Fish: swim bladder not involved in hearing", for mortality and potential mortal injury.

Table 5: Criteria for recoverable injury and TTS in species of fish from continuous noise sources (Popper *et al.*, 2014).

Shipping and continuous sounds	Impairment	
	Recoverable injury	TTS
Fish: swim bladder involved in hearing	170 dB RMS for 48 hours	158 dB RMS for 12 hours

2.2.2.19 A further set of criteria also exists for turtles, which are not present at this site, and as such these have not been considered as part of this study.

2.2.2.20 Where insufficient data is available, Popper *et al.* (2014) also give qualitative criteria that summarise the effect of the noise as having either a high, moderate, or low effect on an individual in either the near-field (tens of metres), intermediate-field (hundreds of metres), or far-field (thousands of metres). These qualitative effects are reproduced in **Table 6** and **Table 7**.

Table 6: Summary of the qualitative effects on fish from impact piling from Popper *et al*. (2014) (N=Near-field, I=Intermediate-field, F=Far-field).

Impact piling	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	See Table 4	See Table 4	See Table 4	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	See Table 4	See Table 4	See Table 4	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing	See Table 4	See Table 4	See Table 4	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate

2.2.2.21 The thresholds for eggs and larvae in "Impairment" categories are all qualitative and have the values (N) Moderate, (I) Low and (F) Low.

Table 7: Summary of the qualitative effects on fish from continuous noise from Popper *et al*. (2014) (N=Near-field, I=Intermediate-field, F=Far-field).

Shipping and continuous sounds	Mortality and potential mortal injury	Impairment			Behaviour
		Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder not involved in hearing	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) High (I) High (F) Moderate	(N) Moderate (I) Moderate (F) Low
Fish: swim bladder involved in hearing	(N) Low (I) Low (F) Low	See paragraph 2.2.2.18 and Table 5	See paragraph 2.2.2.18 and Table 5	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low

2.2.2.22 Both a fleeing animal and stationary animal model have been modelled to cover the SEL_{cum} criteria for fish. It is recognised that there is limited evidence for fish fleeing from high noise sources in the wild and it would reasonably be expected that the reaction would differ between species. Most species are likely to move away from a sound that is loud enough to cause harm (Dahl *et al*., 2015; Popper *et al*., 2014), some may seek protection in the sediment and others may dive deeper in the water column. The flee speed chosen for this study of 1.5 ms^{-1} is relatively slow in relation to the data in Hirata (1999) and thus is considered somewhat conservative.

2.2.2.23 Although it is feasible that some species will not flee, those that are likely to remain are thought more likely be benthic species or species without a swim bladder; these are the least sensitive species. For example, from Popper *et al.* (2014): "There is evidence (e.g. Goertner *et al.*, 1994; Stephenson *et al.*, 2010; Halvorsen *et al.*, 2012) that little or no damage occurs to fishes without a swim bladder except at very short ranges from an in-water explosive event. Goertner (1978) showed that the range from an explosive event over which damage may occur to a non-swim bladder fish is in the order of 100 times less than that for swim bladder fish."

2.2.2.24 Stationary animal modelling has been included in this study, based on research from Hawkins *et al.* (2014). However, basing the modelling on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to fish species, especially when considering the precautionary nature of the parameters already built into the cumulative exposure model.

3 Baseline ambient noise

3.1.1.1 The baseline noise level in open water, in the absence of any anthropogenic noise source, is generally dependent on a mix of the movement of the water and sediment, weather conditions and shipping. There is a component of biological noise from marine mammals and fish vocalisation, as well as an element from invertebrates.

3.1.1.2 Outside of the naturally occurring ambient noise, man-made noise dominates the background. The North Sea is heavily shipped by fishing, cargo and passenger vessels, which contribute to the ambient noise in the water. The larger vessels are not only louder but the noise tends to have a lower frequency, which travels more readily, especially in the deeper open water. Other vessels such as dredgers and small fishing boats have a lower overall contribution. There are no dredging areas, active dredge zones, or dredging application option and prospecting areas within or in close proximity to the Hornsea Four project area.

3.1.1.3 Other sources of anthropogenic noise include oil and gas platforms and other drilling activity and military exercises. Drilling, including oil and gas drilling, may contribute some low frequency noise in the wind farm site, although due to its low-level nature (see **Section 6**), this is unlikely to contribute to the overall ambient noise. Little information is available on the scope and timing of military exercises, but they are not expected to last for an extended period and so would have little contribution to the long-term ambient noise in the area.

3.1.1.4 The Marine Strategy Framework Directive requires European Union members to ascertain baseline noise levels by 2020 and monitoring processes are being put into place for this around Europe. Good quality, long-term underwater noise data for the region is, however, not currently available.

3.1.1.5 Typical underwater noise levels show a frequency dependency in relation to different noise sources; the classic curves for this are given in Wenz (1962) and are reproduced in **Figure 3** below. **Figure 3** shows that any unweighted overall (i.e. single-figure, non-frequency-dependent) noise level is typically dependent on the very low frequency element of the noise. The introduction of a nearby anthropogenic noise source (such as piling or sources involving engines) will tend to increase the noise levels in the 100 to 1,000 Hz region, but to a lesser extent will also extend into higher and lower frequencies.

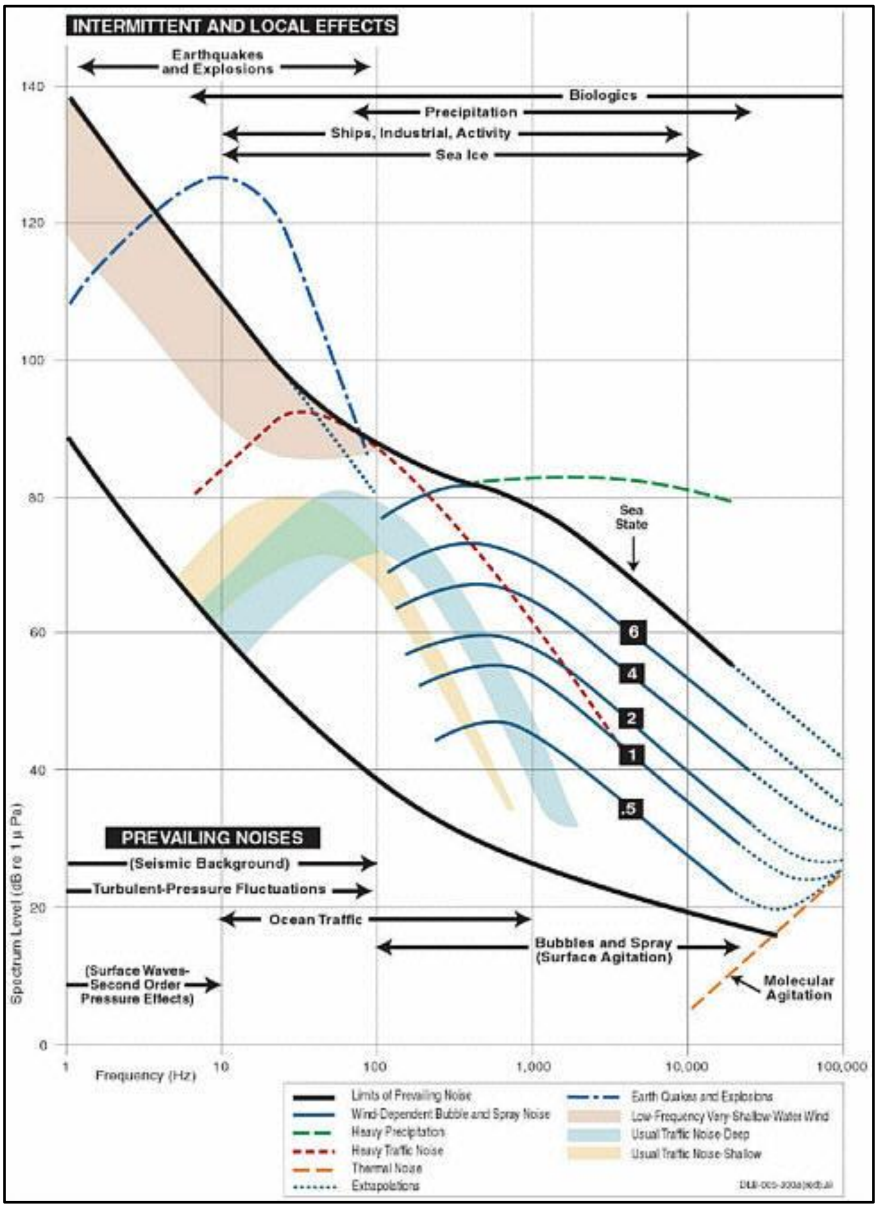

Figure 3: Ambient underwater noise, following Wenz (1962), showing frequency dependency from different noise sources.

3.1.1.6 In 2011, around the time of the met mast installation in the former Hornsea zone, snapshot baseline underwater noise levels were sampled as part of the met mast installation noise survey (Nedwell and Cheesman, 2011). Measurements were taken outside of the installation period and in the absence of any nearby vessel noise. The survey sampled noise levels of between 112 and 122 dB re 1 µPa (RMS) over two days, levels that were described as not unusual for the area. The higher figure was due to a higher sea state on that day. Unweighted overall noise levels of this type should be used with caution without access to more detail regarding the duration, frequency content and conditions under which the sound was recorded, although they do demonstrate an indication of the natural variation in background noise levels.

3.1.1.7 There is little additional, documented ambient noise data publicly available for the region. Merchant *et al*. (2014) measured underwater ambient noise in the Moray Firth, acquiring measurements of a similar order to the baseline snapshot levels noted above, although they showed significant variation (i.e. a 60 dB spread) in daily average noise levels. Although this is outside of the region and in a much more coastal and heavily shipped location, it demonstrates that the snapshot noted above gives only limited information as the average daily noise levels are so dependent on weather and local activity. However, the measurements taken do show noise levels that are of the same order as baseline noise levels sampled elsewhere in the North Sea (Nedwell *et al*., 2003a) and so are considered to be typical and realistic.

3.1.1.8 In principle, when noise introduced by anthropogenic sources propagates far enough it will reduce to the level of natural ambient noise, at which point it can be considered negligible. In practice, as the underwater noise thresholds defined in **Section 2.2.2** are all considerably above the level of background noise, any noise baseline would not feature in an assessment to these criteria.

4 Modelling methodology

4.1 Introduction

4.1.1.1 To estimate the underwater noise levels likely to arise during the construction and operation of Hornsea Four, predictive noise modelling has been undertaken. The methods described in this section, and utilised within this report, meet the requirements set by the NPL Good Practice Guide 133 for underwater noise measurement (Robinson *et al*., 2014).

4.1.1.2 The modelling of impact piling has been undertaken using the INSPIRE noise model. The INSPIRE model (currently version 4.0) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling and actual measured data. It is designed to calculate the propagation of noise in shallow, mixed water, typical of the conditions around the UK and very well suited to the region around Hornsea Four. The model has been tuned for accuracy using over 50 datasets of underwater noise propagation from monitoring around offshore piling activities.

4.1.1.3 The model provides estimates of unweighted SPL_{peak}, SEL_{ss}, and SEL_{cum} noise levels, as well as various other weighted noise metrics. Calculations are made along 180 equally spaced radial transects (one every two degrees). For each modelling run a criterion level can be specified allowing a contour to be drawn, within which a given effect may occur. These results can then be plotted over digital bathymetry data so that impact ranges can be clearly visualised as necessary. INSPIRE also produces these contours as GIS shapefiles.

4.1.1.4 INSPIRE considers a wide array of input parameters, including variations in bathymetry and source frequency content to ensure accurate results are produced specific to the location and nature of the piling operation. It should also be noted that the results presented in this study should be considered conservative as what are considered to be maximum design parameters have been selected in the model for:

- Piling hammer blow energies;
- Soft start, ramp up profile, and strike rate;
- Duration of piling; and
- Receptor swim speeds.

4.1.1.5 A simple modelling approach has been used for the other noise sources that may be present during the construction and lifecycle of Hornsea Four. These are discussed in **Section 6**.

4.1.1.6 The input parameters for the impact piling modelling using INSPIRE are detailed in the following sections.

4.2 Locations

4.2.1.1 Modelling has been undertaken at four representative locations at Hornsea Four, covering the extents of the wind farm and the HVAC area to encompass variations in bathymetry in and around Hornsea Four. These locations were agreed with stakeholders through the Evidence Plan process. The chosen locations are shown in **Figure 4** and summarised in **Table 8**.

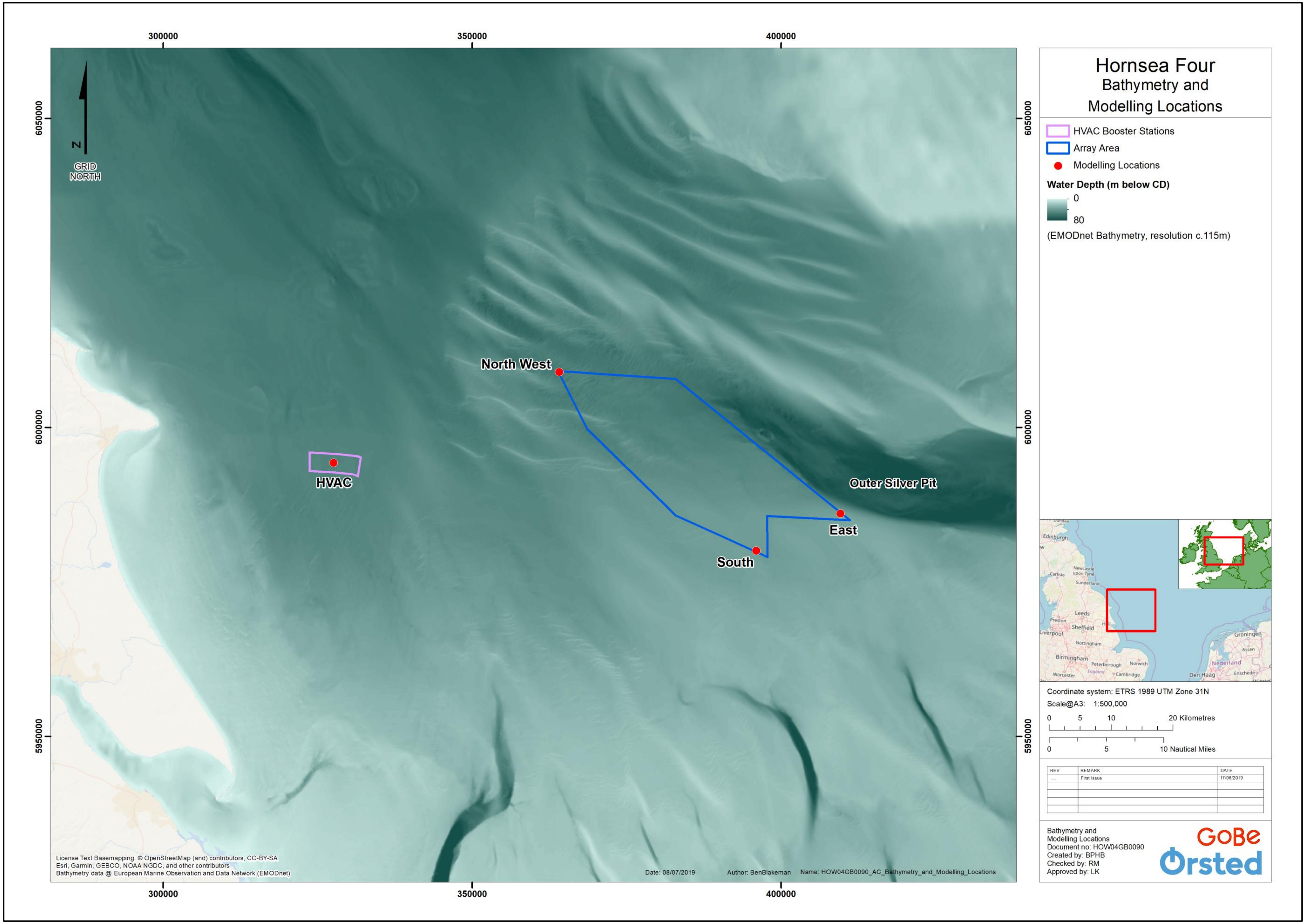

Figure 4: Map showing the underwater noise modelling locations at Hornsea Four (not to scale).

Table 8: Summary of the underwater noise modelling locations at Hornsea Four.

Modelling locations	North West (NW)	East (E)	South (S)	HVAC
Latitude	54° 12.6175′ N	54° 00.8544′ N	53° 57.4746′ N	54° 04.0376′ N
Longitude	00° 54.9763′ E	01° 37.2352′ E	01° 24.8516′ E	00° 21.8970′ E
Water depth (mean tide)	54.8 m	38.6 m	38.8 m	50.9 m

4.3 Input parameters

4.3.1 Introduction

4.3.1.1 The modelling takes full account of the environmental parameters within and around Hornsea Four and the characteristics of the noise source. The following parameters have been assumed for modelling.

4.3.2 Impact piling parameters

4.3.2.1 Four piling source scenarios have been modelled to include monopile and pin pile foundations for WTGs and HVAC substations at Hornsea Four covering both the maximum design and most-likely installation scenarios. The maximum design installation scenarios consider the maximum possible blow energies and piling durations, which may prove to be highly unlikely due to hammer capacity or pile fatigue; as a result the most-likely installation scenarios, whereby more conservative blow energies and durations have been chosen based on other wind farm installations. The modelled scenarios are:

- Maximum design scenario monopile – up to 15 m in diameter, installed using a maximum blow energy of 5,000 kJ;
- Most-likely scenario monopile – up to 15 m in diameter, installed using a maximum blow energy of 4,000 kJ;
- Maximum design scenario pin pile – up to 4.6 m in diameter, installed using a maximum blow energy of 2,500 kJ; and
- Most-likely scenario pin pile – up to 4.6 m in diameter, installed using a maximum blow energy of 1,750 kJ.

4.3.2.2 For cumulative SEL, the soft start and ramp up of blow energies along with total duration and strike rate have also been considered. These vary for the maximum design and most-likely scenarios. The soft start and ramp up scenarios for this modelling have been summarised in

4.3.2.3 **Table** 9 to **Table 10**. The primary difference between the two sets of scenarios is that the most-likely scenario utilises a soft start procedure whereby single blows of the piling hammer at 20 percent of maximum energy occur, interspersed with pauses of several minutes before ramping up to maximum energy.

4.3.2.4 The modelled scenarios contain a total of 6,675 strikes over 240 minutes (maximum design) or 2,553 strikes over 127.5 minutes (most-likely) inclusive of soft start and ramp up. Both monopile and pin pile scenarios assume the same number of strikes, total duration, and strike rates.

Table 9: Summary of the maximum design ramp up scenario used for calculating SEL_{cum} for monopiles and pin piles.

Percentage of maximum hammer energy	20%	40%	60%	80%	100%
Monopile blow energy	1,000 kJ	2,000 kJ	3,000 kJ	4,000 kJ	5,000 kJ
Pin pile blow energy	500 kJ	1,000 kJ	1,500 kJ	2,000 kJ	2,500 kJ
Number of strikes	75	75	112	113	6,300
Duration	7.5 minutes	7.5 minutes	7.5 minutes	7.5 minutes	210 minutes
Strike rate	10 strikes/min		15 strikes/min		30 strikes/min

Table 10: Summary of the most-likely soft start and ramp up scenario used for calculating SEL_{cum} for monopiles and pin piles.

Percentage of maximum hammer energy	20%	40%	60%	80%	100%
Monopile blow energy	800 kJ	1,600 kJ	2,400 kJ	3,200 kJ	4,000 kJ
Pin pile blow energy	350 kJ	700 kJ	1,050 kJ	1,400 kJ	1,750 kJ
Number of strikes	3	75	112	113	2,250
Duration	30 minutes	7.5 minutes	7.5 minutes	7.5 minutes	75 minutes
Strike rate	1 strike every 10 min	10 strikes/min	15 strikes/min		30 strikes/min

4.3.3 Source levels

4.3.3.1 Noise modelling requires knowledge of the source level, which is the theoretical noise level at one metre from the noise source.

4.3.3.2 The INSPIRE model assumes that the noise source, the hammer striking the pile, acts as a single point, as it will appear at distance. The source level is estimated based on the blow energy imparted on the pile by the hammer. This is then adjusted depending on the water depth at the modelling location to allow for the length of the pile in contact with the water, which can affect the amount of noise that is transmitted from the pile into its surroundings.

4.3.3.3 The unweighted single strike SPL_{peak} and SEL_{ss} source levels estimate for this study are provided in **Table 11** and **Table 12**.

Table 11: Summary of the unweighted SPL_{peak} source levels used for modelling at Hornsea Four.

SPL_{peak} source levels	Location	Monopile	Pin Pile
Maximum design *Monopile: 5,000 kJ* *Pin Pile: 2,500 kJ*	NW	244.8 dB re 1 μPa @ 1 m	242.0 dB re 1 μPa @ 1 m
	E	244.2 dB re 1 μPa @ 1 m	241.3 dB re 1 μPa @ 1 m
	S	244.3 dB re 1 μPa @ 1 m	241.4 dB re 1 μPa @ 1 m
	HVAC	244.8 dB re 1 μPa @ 1 m	242.0 dB re 1 μPa @ 1 m
Most-likely *Monopile: 4,000 kJ* *Pin Pile: 1,750 kJ*	NW	244.0 dB re 1 μPa @ 1 m	240.2 dB re 1 μPa @ 1 m
	E	243.4 dB re 1 μPa @ 1 m	239.5 dB re 1 μPa @ 1 m
	S	243.4 dB re 1 μPa @ 1 m	239.6 dB re 1 μPa @ 1 m
	HVAC	244.0 dB re 1 μPa @ 1 m	240.2 dB re 1 μPa @ 1 m

Table 12: Summary of the unweighted SEL_{ss} source levels used for modelling at Hornsea Four.

SEL_{ss} source levels	Location	Monopile	Pin Pile
Maximum design *Monopile: 5,000 kJ* *Pin Pile: 2,500 kJ*	NW	218.8 dB re 1 $μPa^2s$ @ 1 m	216.0 dB re 1 $μPa^2s$ @ 1 m
	E	218.2 dB re 1 $μPa^2s$ @ 1 m	215.3 dB re 1 $μPa^2s$ @ 1 m
	S	218.3 dB re 1 $μPa^2s$ @ 1 m	215.4 dB re 1 $μPa^2s$ @ 1 m
	HVAC	218.8 dB re 1 $μPa^2s$ @ 1 m	216.0 dB re 1 $μPa^2s$ @ 1 m
Most-likely *Monopile: 4,000 kJ* *Pin Pile: 1,750 kJ*	NW	218.0 dB re 1 $μPa^2s$ @ 1 m	214.2 dB re 1 $μPa^2s$ @ 1 m
	E	217.4 dB re 1 $μPa^2s$ @ 1 m	213.5 dB re 1 $μPa^2s$ @ 1 m
	S	217.4 dB re 1 $μPa^2s$ @ 1 m	213.6 dB re 1 $μPa^2s$ @ 1 m
	HVAC	218.0 dB re 1 $μPa^2s$ @ 1 m	214.2 dB re 1 $μPa^2s$ @ 1 m

4.3.4 Frequency content

4.3.4.1 The size of the pile being installed affects the frequency content of the noise it produces. For this modelling, frequency data has been sourced from Subacoustech Environmental's noise measurement database to obtain representative one-third octave band frequency spectrum levels (i.e. the frequency breakdown of a noise level) for installing monopiles and pin piles. The one-third octave band levels for maximum hammer energy used for modelling are illustrated in **Figure 5**; the shape of each spectrum is the same for all the other locations and blow energies, with the overall source levels adjusted depending on these parameters. This is particularly important when considering marine mammal species that are more sensitive to a particular frequency of sound than others.

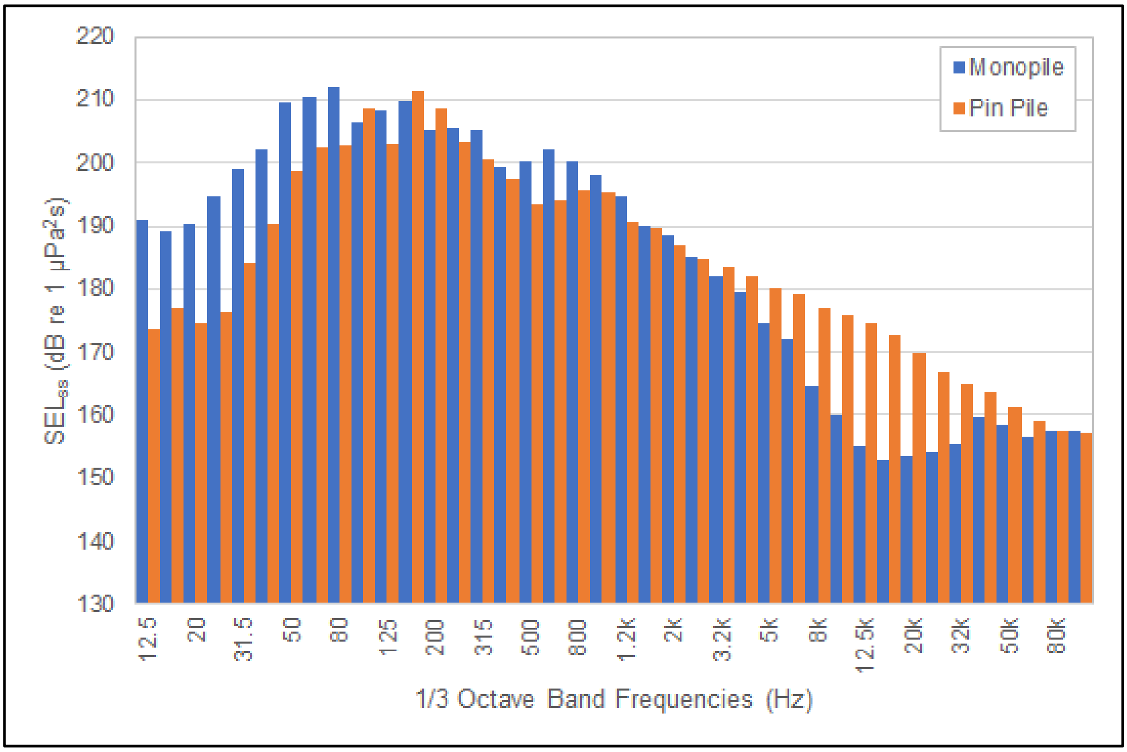

Figure 5: One-third octave source level frequency spectra for the maximum hammer blow energy at the NW modelling location (as unweighted SEL_{ss}).

4.3.4.2 Frequency spectra for piles of over seven metres in diameter, one of the largest with measured data available, have been used for the monopile modelling, and piles of approximately four metres in diameter (near the top end of the pin pile options being considered) have been used for pin pile modelling. It is worth noting that the monopile spectra contain more lower frequency content (approximately 25 to 160 Hz) and the pin piles contain more high frequency content due to the acoustics related to the dimensions of the pile. This trend would be expected to continue to larger piles under consideration for the monopiles at Hornsea Four. A larger diameter would be expected to move the dominant frequency of the sound produced (i.e. the frequency where the highest levels are present) lower, further below the frequencies of greatest hearing sensitivity of marine mammals. Thus, the sound would appear slightly quieter to a receptor more sensitive to higher frequencies such as dolphins and porpoises (HF and VHF cetaceans in Southall *et al.*, 2019) and the spectrum used is likely to be worst. Marine mammal hearing sensitivity is covered in **Section 2.2**.

4.3.5 Other environmental conditions

4.3.5.1 Accurate modelling of underwater noise propagation requires knowledge of the sea and seabed conditions. The semi-empirical nature of the INSPIRE model considers the seabed type and speed of sound in water for the mixed conditions around Hornsea Four as it is based on over 50 datasets taken of impact piling noise in coastal and offshore waters surrounding the UK.

4.3.5.2 Mean tidal depth has been used for the depth of water across the site as the tidal state will fluctuate throughout installation of the WTG foundations.

4.4 Modelling confidence

4.4.1.1 Modelling has been undertaken using the latest iteration (version 4.0) of the INSPIRE model.

4.4.1.2 As discussed in **Section 4.1**, INSPIRE is a semi-empirical model based around a combination of numerical modelling and actual measured data. The INSPIRE model has always endeavoured to give a conservative estimate of underwater noise levels from impact piling noise. There is always some variability with underwater noise measurements, even when considering measurements of pile strikes at the same blow energy taken at the same range. For example, there can be big variations in noise level, sometimes up to 5 or even 10 dB, as seen in Bailey *et al*. (2010) and the data shown in **Figure 6**. The INSPIRE model always assumes the highest of these measured noise levels at any range.

4.4.1.3 This latest version of INSPIRE is the product of re-analysing all the impact piling noise measurements in Subacoustech Environmental's measurement database and cross-referencing it with blow energy data from piling logs, giving a database of single strike noise levels referenced to a specific blow energy at a specific range. This re-analysis showed that the previous versions of INSPIRE overestimated the range of noise levels with blow energy, meaning that low blow energies were previously being underestimated. This led to underestimations in predicted levels, particularly for cumulative SELs.

4.4.1.4 As INSPIRE is semi-empirical, a validation process is inherently built into the development process. Whenever a new set of good, reliable impact piling measurement data is gathered through offshore surveys, it is compared against the outputted levels from INSPIRE and, if differences show that refinements need to be made to the model, it can go under further development to account for the new data. Currently over 50 separate impact piling noise datasets from all around the UK have been used as part of the development for the latest version of INSPIRE, and in each case, a conservative fit to the data is used. This is the same process that has been used for previous iterations of INSPIRE, however with each new version more measurement data is used.

4.4.1.5 **Figure 6** presents a small selection of measured impact piling noise data plotted against outputs from INSPIRE version 4.0. The plots show data points from measured data (in red) plotted alongside modelled data (in green) using INSPIRE version 4.0, matching the pile size, blow energy and range from the measured data. These show the conservative fit to data, with the INSPIRE modelled data points sitting at the higher end of the measured noise levels at each range.

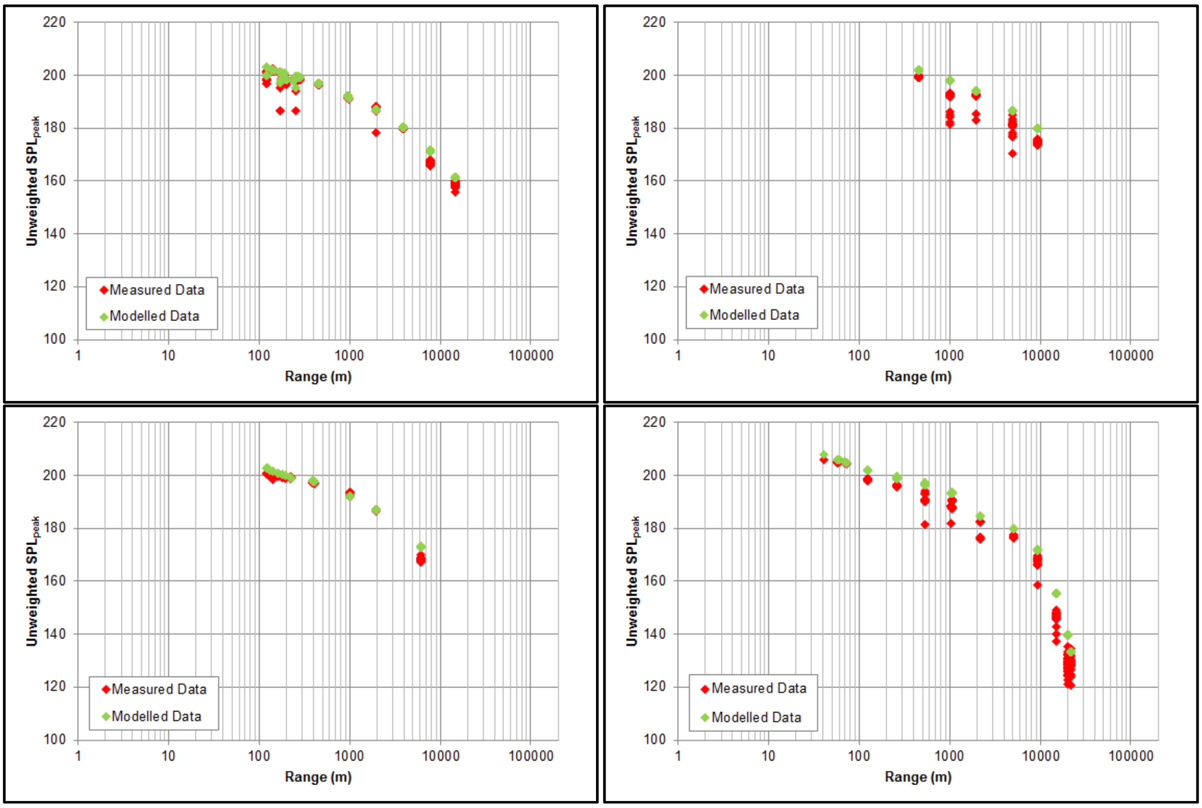

Figure 6: Comparison between example measured data (red points) and modelled data using INSPIRE version 4.0 (green points).

4.4.1.6 Due to the conservatism of the INSPIRE model, along with the upper-end parameters used for modelling, there is an inherent precaution built into the model. This includes the conservative fit to data shown in Figure 6, the assumed maximum blow energies and ramp-up scenarios considered for modelling in Section 4.3.2, the flee speeds considered for receptors and the modelling locations chosen. All of these factors are compounded when considering cumulative exposure calculations. When all these factors are considered separately, they can be reasonable and realistic, however when they are considered together, they can result in an overestimating in noise levels, and ultimately lead to a maximum design scenario (MDS) that is highly unlikely to occur in practice.

5 Impact piling noise modelling outputs

5.1 Unweighted subsea noise modelling

5.1.1.1 This section presents the unweighted noise level results (i.e. in the absence of any frequency weighting applied for hearing sensitivity) from the modelling undertaken for impact piling operations using the parameters detailed in Section 2.2.2.

5.1.1.2 The following figures present unweighted SPL_{peak} and SEL_{ss} noise levels from impact piling operations at the modelling locations at Hornsea Four illustrated in Figure 6. Figure 7 to Figure 14 show the unweighted SPL_{peak} and SEL_{ss} for monopiles and pin piles for the maximum design and most-likely installation scenarios discussed in Section 4.3.

5.1.1.3 Comparing these plots shows that, in general, the increased noise levels are expected to occur in deeper water, for example the Outer Silver Pit to the east of the Hornsea Four site (as shown in **Figure 4**). The effect of the differing water depths on noise transmission is also shown at greater distances to the north west of the site, where more "jagged" contours occur over the shallow areas and deeper channels.

5.1.1.4 Due to the transient nature of impact piling noise, the impulsive noise introduced to the water will return to background levels within seconds of the impulse passing. The SPL_{peak} and SEL_{ss} outputs shown on these plots should not be confused with background or ambient noise levels, which are typically described in terms of SPL_{RMS}. The different metrics are not directly comparable.

5.1.1.5 In addition, level against range plots are presented in **Figure 15** showing the noise levels from a deep water transect for both monopiles and pin piles giving the highest noise levels at range; these are 318° from the NW modelling location using the maximum design parameters.

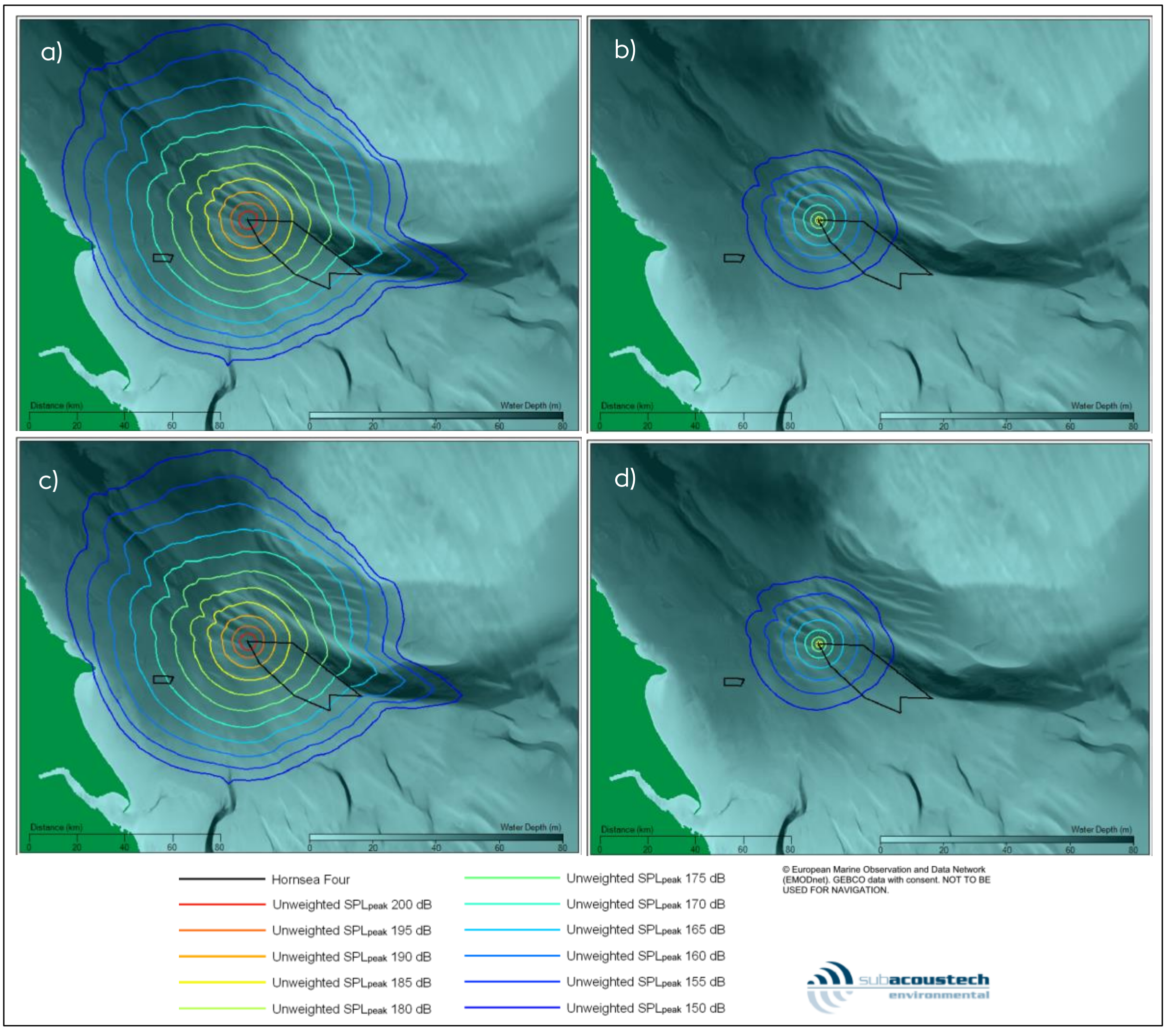

Figure 7: Contour plot showing the unweighted noise levels in 5 dB increments for the maximum design (a: SPL_{peak} & b: SEL_{ss}) and most-likely (c: SPL_{peak} & d SEL_{ss}) monopile parameters at the NW modelling location (not to scale).

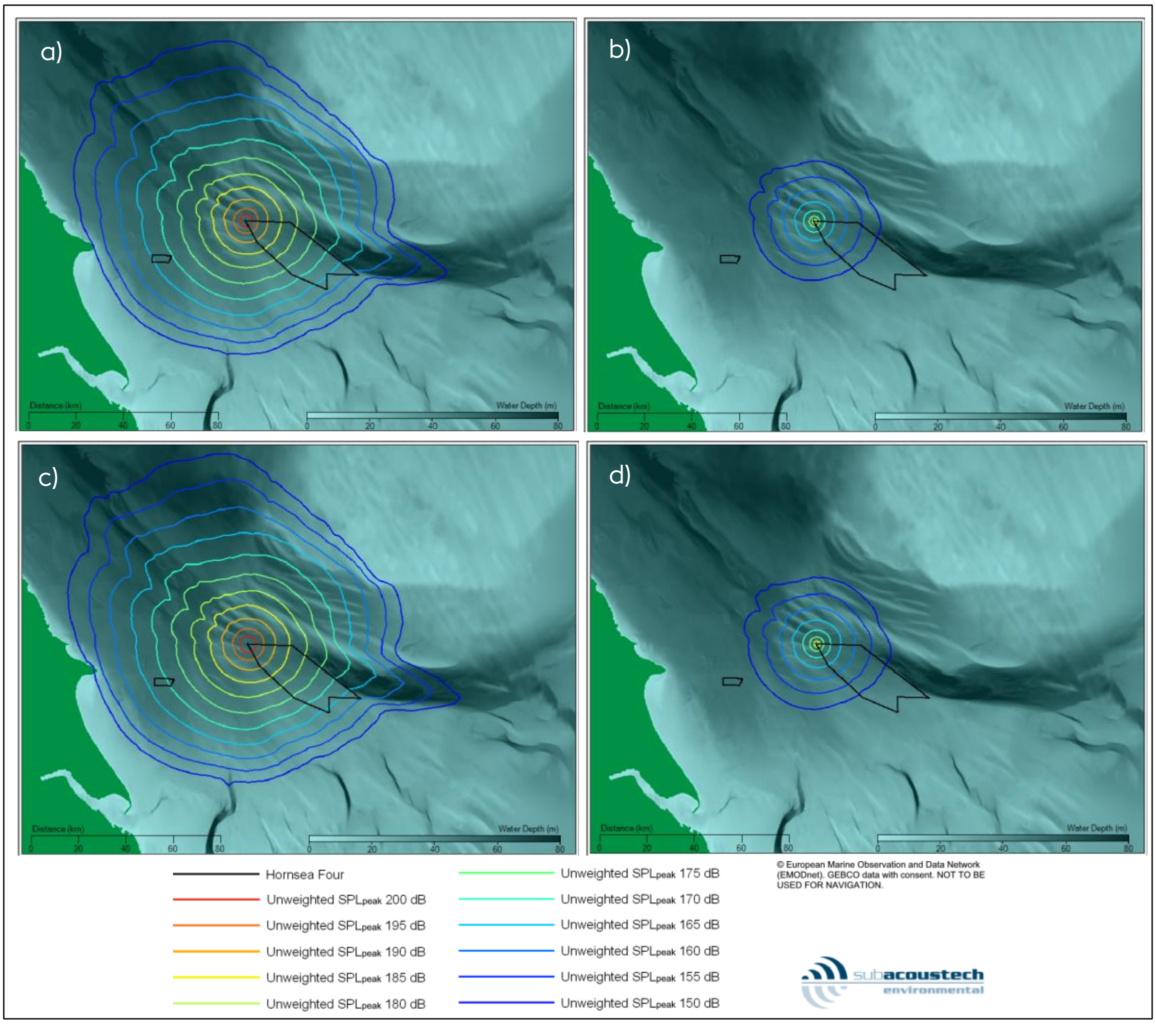

Figure 8: Contour plot showing the unweighted noise levels in 5 dB increments for the maximum design (a: SPL_{peak} & b: SEL_{ss}) and most-likely (c: SPL_{peak} & d SEL_{ss}) pin pile parameters at the NW modelling location (not to scale).

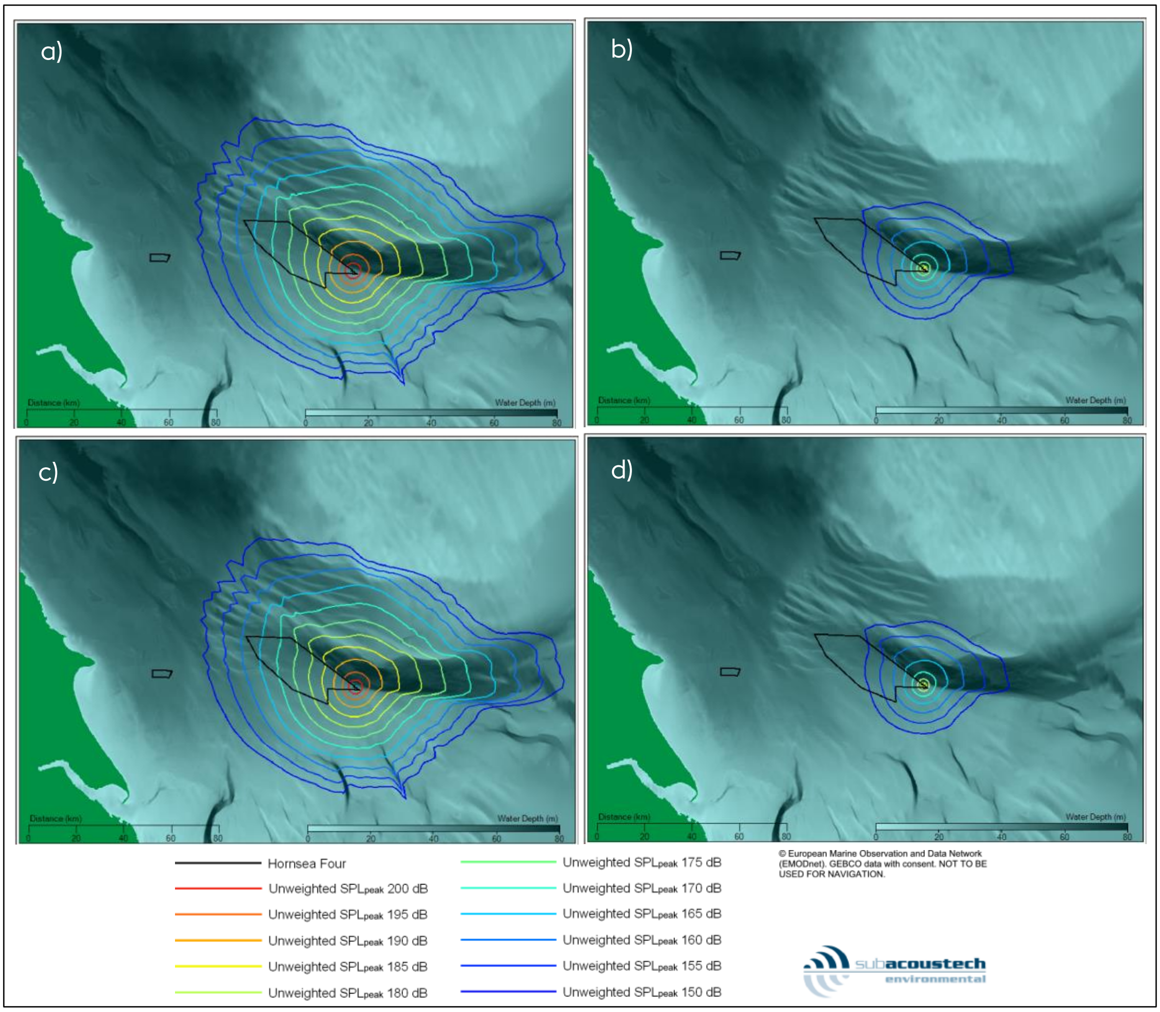

Figure 9: Contour plot showing the unweighted noise levels in 5 dB increments for the maximum design (a: SPL_{peak} & b: SEL_{ss}) and most-likely (c: SPL_{peak} & d SEL_{ss}) monopile parameters at the E modelling location (not to scale).

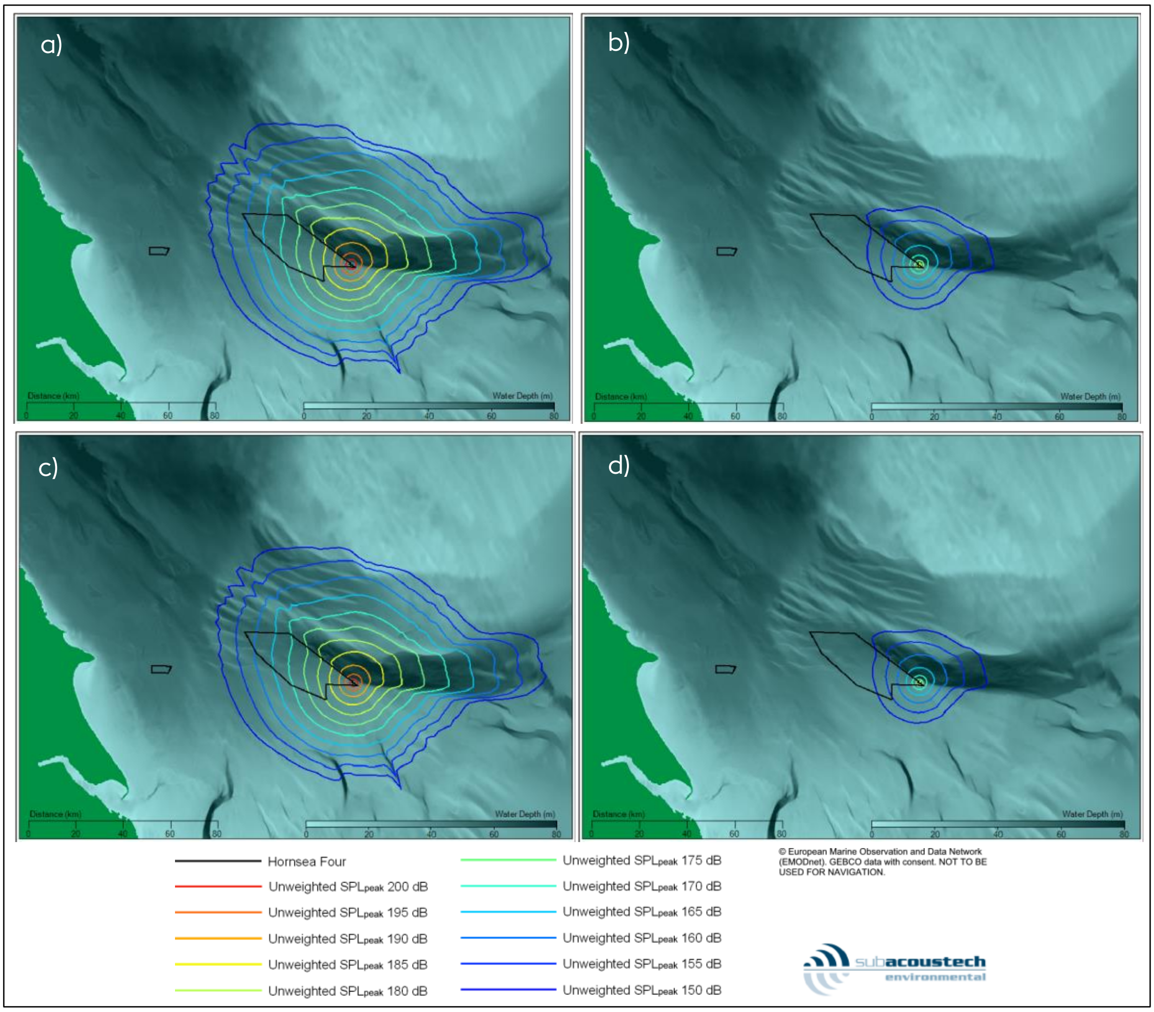

Figure 10: Contour plot showing the unweighted noise levels in 5 dB increments for the maximum design (a: SPL_{peak} & b: SEL_{ss}) and most-likely (c: SPL_{peak} & d SEL_{ss}) pin pile parameters at the E modelling location (not to scale).

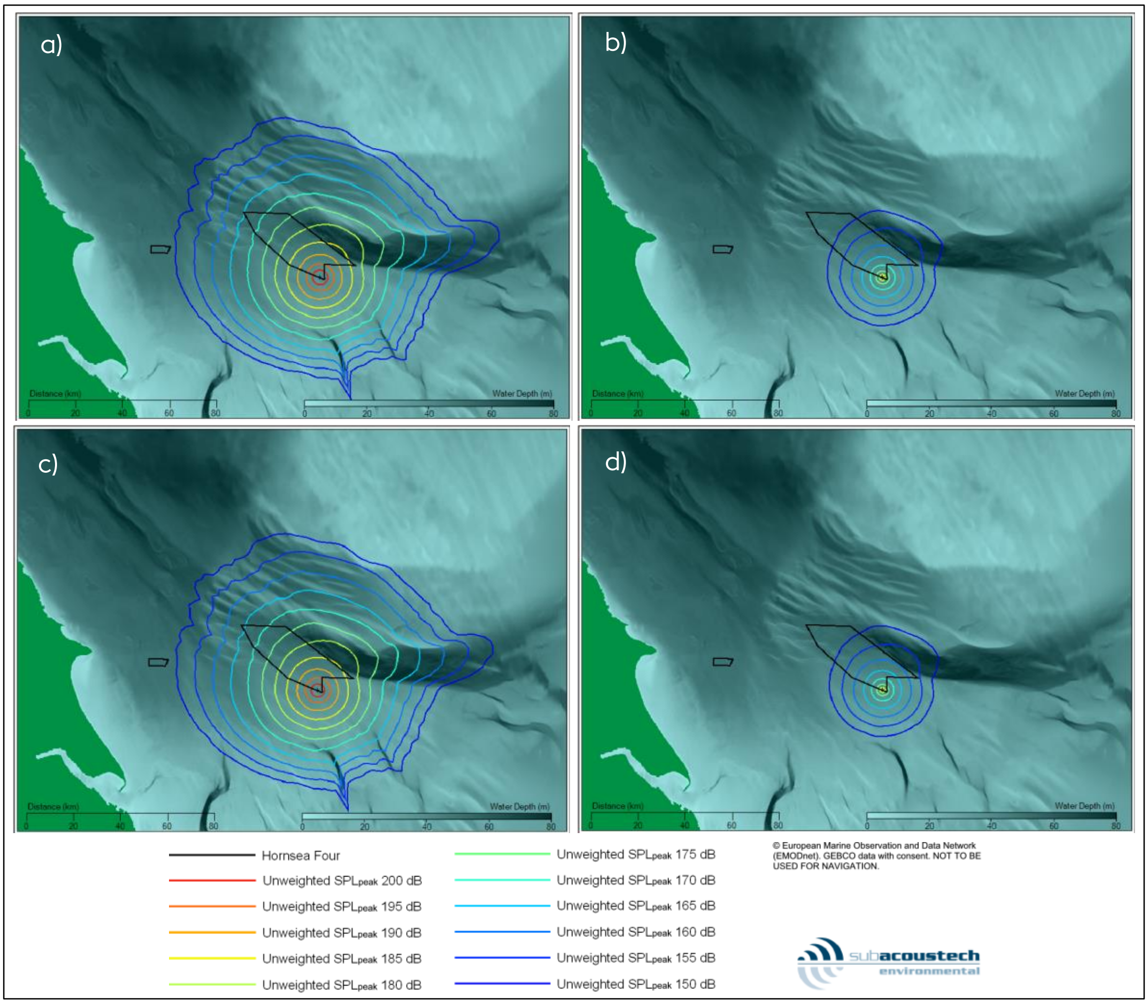

Figure 11: Contour plot showing the unweighted noise levels in 5 dB increments for the maximum design (a: SPL_{peak} & b: SEL_{ss}) and most-likely (c: SPL_{peak} & d SEL_{ss}) monopile parameters at the S modelling location (not to scale).

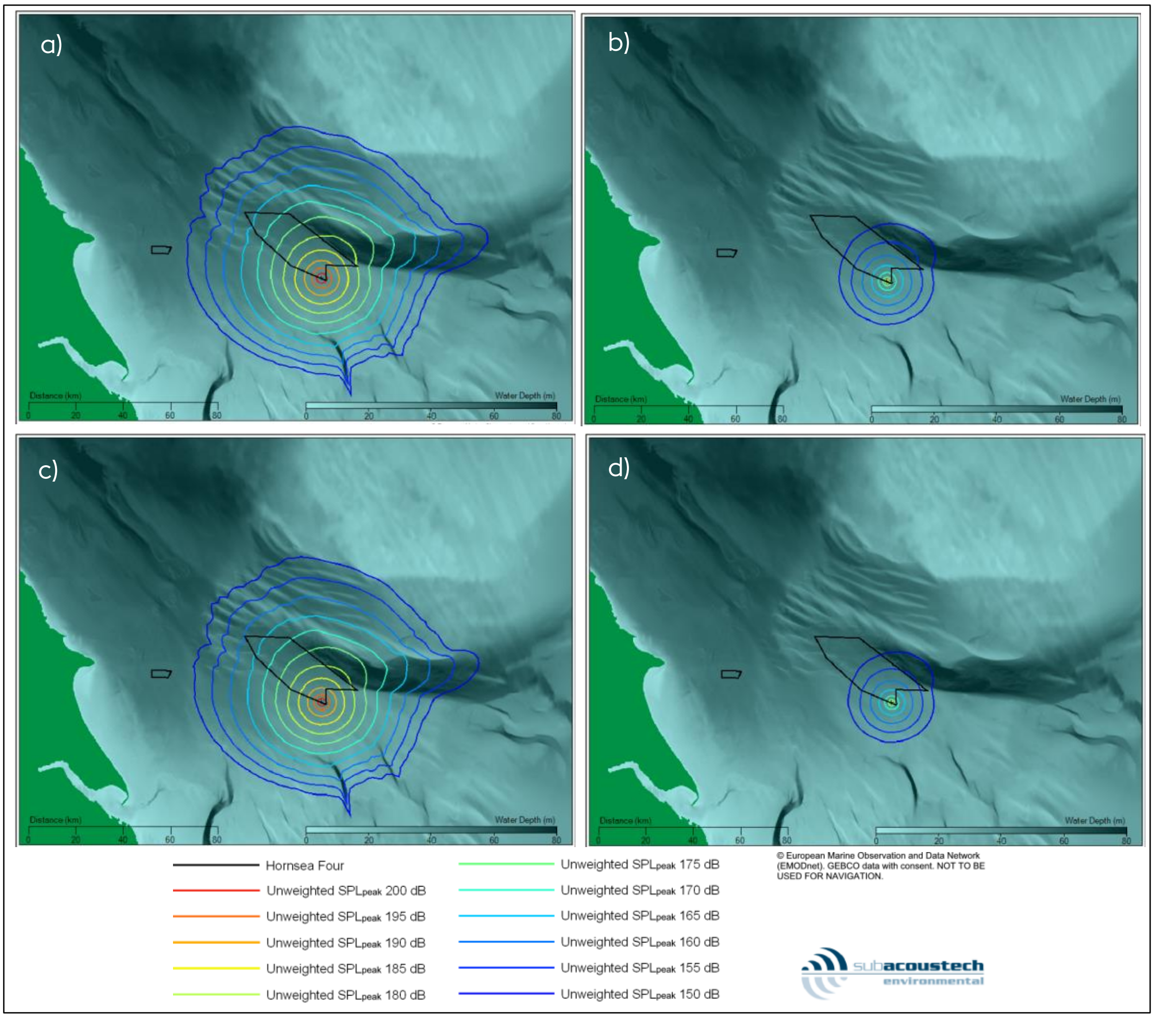

Figure 12: Contour plot showing the unweighted noise levels in 5 dB increments for the maximum design (a: SPL_{peak} & b: SEL_{ss}) and most-likely (c: SPL_{peak} & d SEL_{ss}) pin pile parameters at the S modelling location (not to scale).

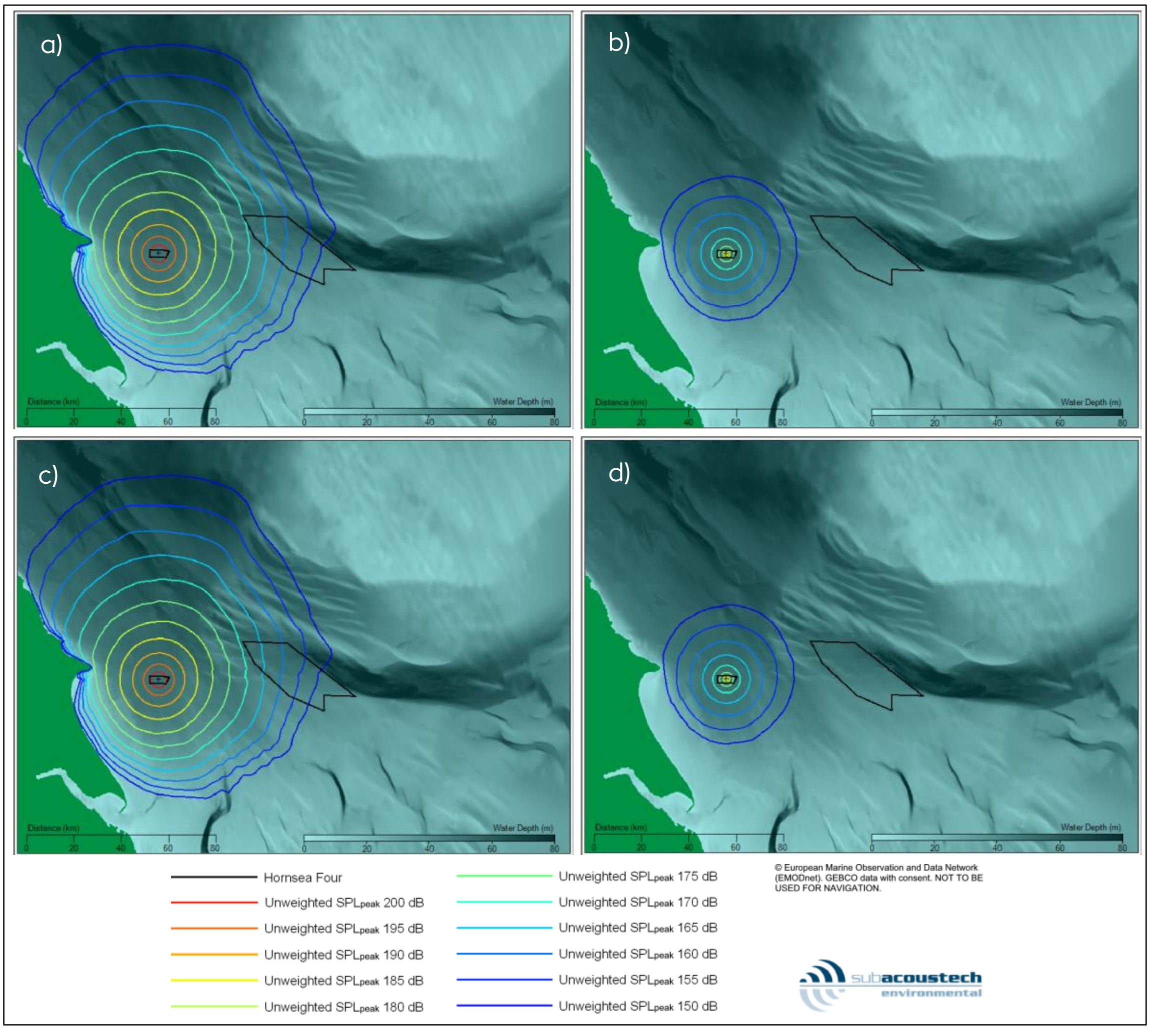

Figure 13: Contour plot showing the unweighted noise levels in 5 dB increments for the maximum design (a: SPL_{peak} & b: SEL_{ss}) and most-likely (c: SPL_{peak} & d SEL_{ss}) monopile parameters at the HVAC modelling location (not to scale).

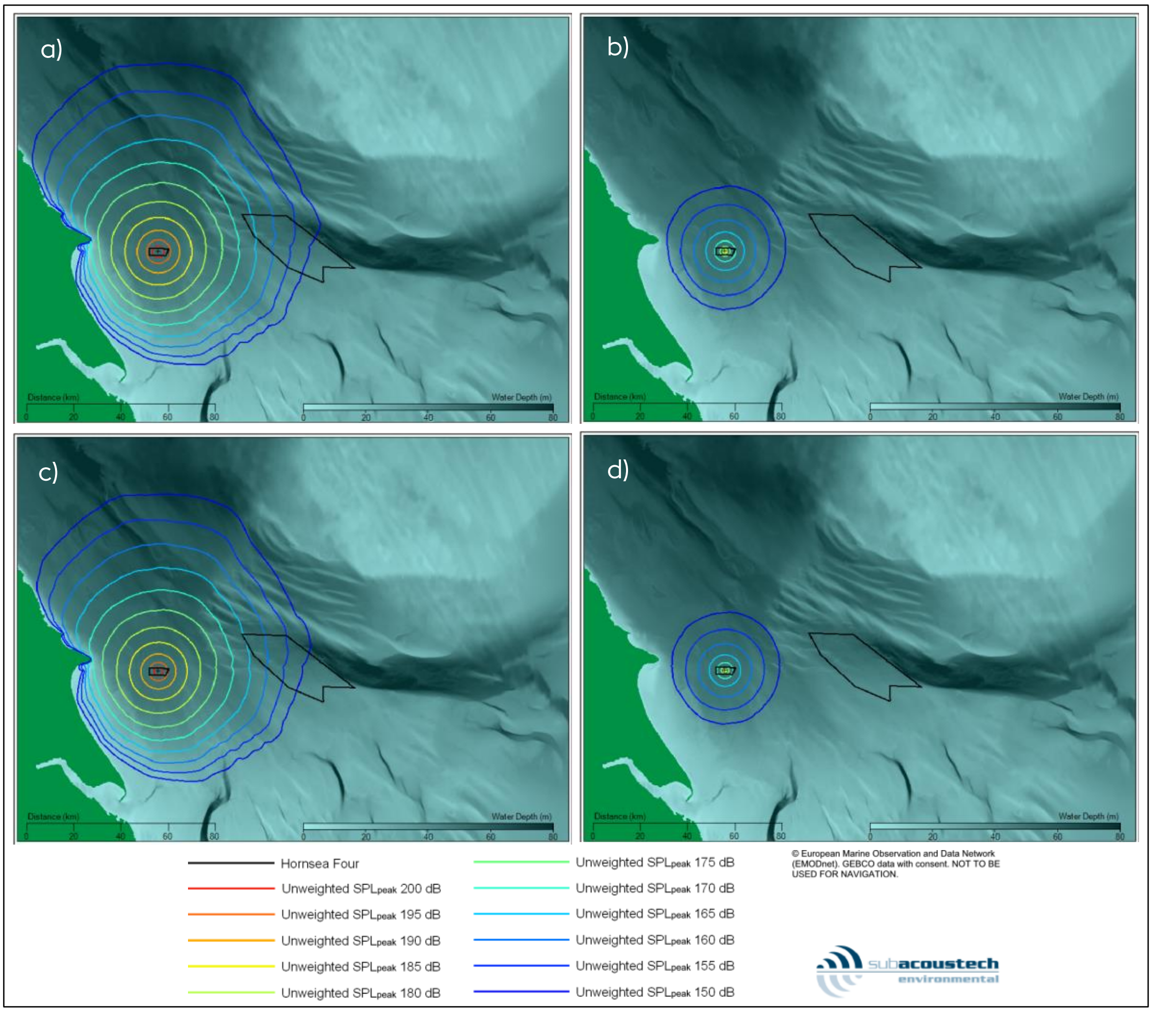

Figure 14: Contour plot showing the unweighted noise levels in 5 dB increments for the maximum design (a: SPL_{peak} & b: SEL_{ss}) and most-likely (c: SPL_{peak} & d SEL_{ss}) pin pile parameters at the HVAC modelling location (not to scale).

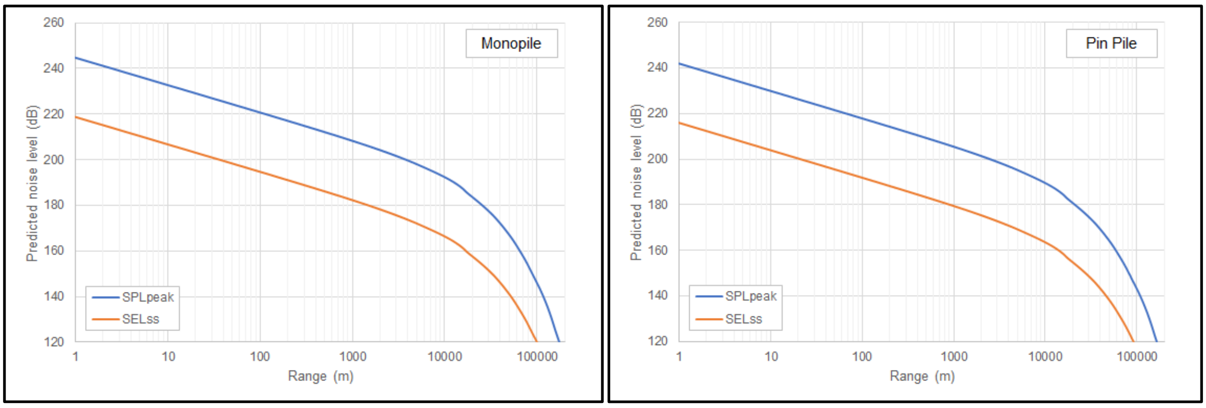

Figure 15: Level against range plots showing the unweighted SPL_{peak} and SEL_{ss} noise levels along one of the longest predicted transects; 318° from the NW modelling location using the maximum design parameters.

5.2 Noise modelling results in respect of marine mammal and fish impact criteria

5.2.1 Introduction

5.2.1.1 This section presents the modelling results in terms of noise metrics and criteria covered in **Section 2.2**. This discussion will guide the assessment of environmental impact from the predicted impact piling noise on marine species (see **Volume 2, Chapter 3: Fish and Shellfish Ecology** and **Volume 2, Chapter 4: Marine Mammals**). For all the results given in the following sections, ranges calculated to be less than 50 m for single strike criteria and 100 m for cumulative criteria have not been included due to the uncertainty in the accuracy of the results at such close range. In this case, the ranges are given as "< 50 m" or "< 100 m," indicating that the impact range will be closer to the pile than this distance.

5.2.2 Marine mammal criteria

5.2.2.1 This section presents the modelling results in biological terms for various species of marine mammals using the Southall *et al*. (2019) guidance. Interpretation of these modelling results are provided in **Volume 2, Chapter 4: Marine Mammals**. As discussed in **paragraph 2.2.2.13**, for the SEL_{cum} criteria, fleeing animal speeds of 3.25 ms^{-1} (Blix and Folkow, 1995) for LF cetaceans and 1.5 ms^{-1} (Otani *et al*., 2000) for other species of marine mammal have been used. It should be reiterated that the marine mammal categories used by Southall *et al.* (2019) are different to those used by NMFS (2018) and Southall *et al.* (2007), in that the former MF and HF categories are now effectively presented as HF and VHF, respectively.

5.2.2.2 **Table 13** to **Table 44** present the predicted PTS and TTS impact ranges for the different marine mammal hearing groups using the Southall *et al*. (2019) thresholds. The criteria are given as unweighted SPL_{peak} or weighted SEL_{cum} based on the hearing sensitivity of the receptor. Multiple pulse (SEL_{cum}) include the noise exposure to a fleeing animal receptor over the entire installation period. In addition, instantaneous SPL_{peak} values for the first strike of each scenario have been given.

5.2.2.3 In line with the unweighted results shown in section 5.1, the largest predicted ranges occur over the deeper water areas and transects with maximum SEL_{cum} PTS ranges of 13 km for LF cetaceans for monopiles and 10 km for VHF cetaceans for pin piles. The larger impact ranges for pin piles for HF and VHF cetaceans are also caused by the frequencies filtered by the Southall *et al*. (2019) species group weightings (**Table 2** and **Table 3**); this is discussed further in **paragraphs 5.2.2.4** to **5.2.2.7** after the results tables.

Impact ranges – maximum design monopile

Table 13: Summary of the SPL_{peak} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the maximum design monopile input parameters.

Southall *et al.* (2019) – PTS			Maximum design – Monopile (5,000 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	219 dB	0.06 km²	140 m	140 m	140 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	25 km²	2.9 km	2.8 km	2.8 km
	PCW	218 dB	0.09 km²	170 m	170 m	170 m
E	LF	219 dB	0.05 km²	120 m	120 m	120 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	19 km²	2.6 km	2.4 km	2.4 km
	PCW	218 dB	0.07 km²	150 m	150 m	150 m
S	LF	219 dB	0.05 km²	130 m	130 m	130 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	18 km²	2.4 km	2.4 km	2.4 km
	PCW	218 dB	0.07 km²	150 m	150 m	150 m
HVAC	LF	219 dB	0.06 km²	140 m	140 m	140 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	25 km²	2.8 km	2.8 km	2.8 km
	PCW	218 dB	0.09 km²	170 m	170 m	170 m

Table 14: Summary of the SPL_{peak} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the maximum design monopile input parameters.

Southall *et al.* (2019) – TTS *Unweighted SPL_{peak}*			Maximum design – Monopile (5,000 kJ) / Impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	213 dB	0.57 km²	430 m	430 m	430 m
	HF	224 dB	< 0.01 km²	60 m	50 m	60 m
	VHF	196 dB	130 km²	6.6 km	6.3 km	6.5 km
	PCW	212 dB	0.83 km²	520 m	510 m	520 m
E	LF	213 dB	0.44 km²	380 m	370 m	380 m
	HF	224 dB	< 0.01 km²	50 m	50 m	50 m
	VHF	196 dB	99 km²	6.4 km	5.0 km	5.6 km
	PCW	212 dB	0.63 km²	450 m	450 m	450 m
S	LF	213 dB	0.45 km²	380 m	380 m	380 m
	HF	224 dB	< 0.01 km²	50 m	50 m	50 m
	VHF	196 dB	87 km²	5.3 km	5.2 km	5.3 km
	PCW	212 dB	0.65 km²	460 m	460 m	460 m
HVAC	LF	213 dB	0.57 km²	430 m	430 m	430 m
	HF	224 dB	< 0.01 km²	60 m	50 m	60 m
	VHF	196 dB	130 km²	6.4 km	6.3 km	6.4 km
	PCW	212 dB	0.82 km²	510 m	510 m	510 m

Table 15: Summary of the impulsive SEL_{cum} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the maximum design monopile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – PTS *Weighted SEL_{cum}*			Maximum design – Monopile (5,000 kJ) / Impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	183 dB	260 km²	11 km	8.2 km	9.1 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	9.2 km²	1.9 km	1.6 km	1.7 km
	PCW	185 dB	1.6 km²	830 m	590 m	710 m
E	LF	183 dB	190 km²	13 km	4.0 km	7.4 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	4.1 km²	1.9 km	350 m	990 m
	PCW	185 dB	0.43 km²	670 m	< 100 m	260 m
S	LF	183 dB	97 km²	7.0 km	4.4 km	5.5 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	1 km²	650 m	500 m	570 m
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
HVAC	LF	183 dB	250 km²	10 km	8.0 km	9.0 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	8.5 km²	1.7 km	1.6 km	1.7 km
	PCW	185 dB	1.3 km²	700 m	630 m	660 m

Table 16: Summary of the impulsive SEL_{cum} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the maximum design monopile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – TTS *Weighted SEL_{cum}*			Maximum design – Monopile (5,000 kJ) / Impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	168 dB	3000 km^2	40 km	26 km	31 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	1100 km^2	22 km	17 km	19 km
	PCW	170 dB	890 km^2	20 km	15 km	17 km
E	LF	168 dB	2100 km^2	43 km	17 km	25 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	850 km^2	25 km	11 km	16 km
	PCW	170 dB	690 km^2	22 km	9.8 km	14 km
S	LF	168 dB	1700 km^2	30 km	17 km	23 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	610 km^2	17 km	11 km	14 km
	PCW	170 dB	480 km^2	15 km	10 km	12 km
HVAC	LF	168 dB	2600 km^2	37 km	20 km	28 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	1100 km^2	21 km	16 km	18 km
	PCW	170 dB	860 km^2	19 km	15 km	17 km

Table 17: Summary of the non-impulsive SEL_{cum} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the maximum design monopile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – PTS *Weighted SEL_{cum}*			Maximum design – Monopile (5,000 kJ) / Non-impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
E	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
S	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
HVAC	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m

Table 18: Summary of the non-impulsive SEL_{cum} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the maximum design monopile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – TTS			Maximum design – Monopile (5,000 kJ) / Non-impulsive criteria			
Weighted SEL_{cum}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	179 dB	650 km^2	18 km	13 km	14 km
	HF	178 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	153 dB	36 km^2	3.8 km	3.1 km	3.4 km
	PCW	181 dB	48 km^2	4.4 km	3.6 km	3.9 km
E	LF	179 dB	480 km^2	21 km	7.2 km	12 km
	HF	178 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	153 dB	22 km^2	3.9 km	1.4 km	2.4 km
	PCW	181 dB	31 km^2	4.6 km	1.7 km	2.9 km
S	LF	179 dB	300 km^2	13 km	7.6 km	9.7 km
	HF	178 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	153 dB	9.2 km^2	1.9 km	1.6 km	1.7 km
	PCW	181 dB	14 km^2	2.4 km	1.9 km	2.1 km
HVAC	LF	179 dB	620 km^2	16 km	12 km	14 km
	HF	178 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	153 dB	34 km^2	3.5 km	3.2 km	3.3 km
	PCW	181 dB	46 km^2	4.0 km	3.7 km	3.8 km

Table 19: Summary of the SPL_{peak} Southall *et al.* (2019) PTS impact ranges for the four modelling locations for the initial piling strike considering the maximum design monopile input parameters.

Southall *et al.* (2019) – PTS			Maximum design – Monopile, first strike (1,000 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	1.7 km^2	750 m	740 m	740 m
	PCW	218 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
E	LF	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	1.3 km^2	640 m	630 m	640 m
	PCW	218 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
S	LF	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	1.3 km^2	650 m	650 m	650 m
	PCW	218 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
HVAC	LF	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	1.7 km^2	740 m	740 m	740 m
	PCW	218 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table 20: Summary of the SPL_{peak} Southall *et al.* (2019) TTS impact ranges for the four modelling locations for the initial piling strike considering the maximum design monopile input parameters.

Southall *et al.* (2019) – TTS			Maximum design – Monopile, first strike (1,000 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	213 dB	0.03 km^2	100 m	100 m	100 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	14 km^2	2.1 km	2.1 km	2.1 km
	PCW	212 dB	0.01 km^2	120 m	120 m	120 m
E	LF	213 dB	0.02 km^2	80 m	80 m	80 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	9.6 km^2	1.8 km	1.7 km	1.8 km
	PCW	212 dB	0.03 km^2	100 m	100 m	100 m
S	LF	213 dB	0.02 km^2	90 m	90 m	90 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	9.7 km^2	1.8 km	1.8 km	1.8 km
	PCW	212 dB	0.03 km^2	100 m	100 m	100 m
HVAC	LF	213 dB	0.03 km^2	100 m	100 m	100 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	13 km^2	2.1 km	2.1 km	2.1 km
	PCW	212 dB	0.04 km^2	120 m	120 m	120 m

Impact ranges – maximum design pin pile

Table 21: Summary of the SPL_{peak} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the maximum design pin pile input parameters.

Southall *et al.* (2019) – PTS			Maximum design – Pin pile (2,500 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	219 dB	0.02 km^2	80 m	80 m	80 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	10 km^2	1.8 km	1.8 km	1.8 km
	PCW	218 dB	0.03 km^2	100 m	100 m	100 m
E	LF	219 dB	0.02 km^2	70 m	70 m	70 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	7.5 km^2	1.6 km	1.5 km	1.6 km
	PCW	218 dB	0.02 km^2	90 m	90 m	90 m
S	LF	219 dB	0.02 km^2	70 m	70 m	70 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	7.7 km^2	1.6 km	1.6 km	1.6 km
	PCW	218 dB	0.02 km^2	90 m	90 m	90 m
HVAC	LF	219 dB	0.02 km^2	80 m	80 m	80 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	10 km^2	1.8 km	1.8 km	1.8 km
	PCW	218 dB	0.03 km^2	100 m	100 m	100 m

Table 22: Summary of the SPL_{peak} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the maximum design pin pile input parameters.

Southall *et al.* (2019) – TTS			Maximum design – Pin pile (2,500 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	213 dB	0.2 km²	260 m	250 m	260 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	63 km²	4.6 km	4.4 km	4.5 km
	PCW	212 dB	0.29 km²	310 m	310 m	310 m
E	LF	213 dB	0.15 km²	220 m	220 m	220 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	46 km²	4.2 km	3.6 km	3.8 km
	PCW	212 dB	0.22 km²	270 m	270 m	270 m
S	LF	213 dB	0.16 km²	230 m	230 m	230 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	43 km²	3.8 km	3.7 km	3.7 km
	PCW	212 dB	0.23 km²	270 m	270 m	270 m
HVAC	LF	213 dB	0.2 km²	250 m	250 m	250 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	62 km²	4.5 km	4.4 km	4.4 km
	PCW	212 dB	0.29 km²	310 m	310 m	310 m

Table 23: Summary of the impulsive SEL_{cum} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the maximum design pin pile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – PTS			Maximum design – Pin pile (2,500 kJ) / Impulsive criteria			
Weighted SEL_{cum}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	183 dB	160 km²	8.9 km	6.5 km	7.1 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	220 km²	9.7 km	7.7 km	8.3 km
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
E	LF	183 dB	110 km²	9.7 km	2.7 km	5.5 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	160 km²	10 km	4.4 km	6.9 km
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
S	LF	183 dB	48 km²	4.9 km	3.1 km	3.9 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	91 km²	6.2 km	4.8 km	5.4 km
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
HVAC	LF	183 dB	160 km²	8.0 km	6.3 km	7.0 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	210 km²	8.9 km	7.9 km	8.3 km
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m

Table 24: Summary of the impulsive SEL_{cum} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the maximum design pin pile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – TTS			Maximum design – Pin pile (2,500 kJ) / Impulsive criteria			
Weighted SEL_{cum}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	168 dB	2600 km^2	36 km	24 km	28 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	2700 km^2	35 km	25 km	29 km
	PCW	170 dB	570 km^2	16 km	12 km	13 km
E	LF	168 dB	1800 km^2	40 km	15 km	23 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	1900 km^2	39 km	17 km	24 km
	PCW	170 dB	440 km^2	17 km	7.7 km	11 km
S	LF	168 dB	1400 km^2	28 km	15 km	21 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	1500 km^2	28 km	17 km	22 km
	PCW	170 dB	290 km^2	12 km	8.1 km	9.5 km
HVAC	LF	168 dB	2200 km^2	34 km	19 km	26 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	2400 km^2	33 km	21 km	27 km
	PCW	170 dB	560 km^2	15 km	12 km	13 km

Table 25: Summary of the non-impulsive SEL_{cum} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the maximum design pin pile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – PTS			Maximum design – Pin pile (2,500 kJ) / Non-impulsive criteria			
Weighted SEL_{cum}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
E	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
S	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
HVAC	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m

Table 26: Summary of the non-impulsive SEL_{cum} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the maximum design pin pile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – TTS			Maximum design – Monopile (2,500 kJ) / Non-impulsive criteria			
Weighted SEL_{cum}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	179 dB	460 km^2	15 km	11 km	12 km
	HF	178 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	153 dB	350 km^2	12 km	9.9 km	11 km
	PCW	181 dB	9.3 km^2	1.9 km	1.5 km	1.7 km
E	LF	179 dB	340 km^2	17 km	5.8 km	9.9 km
	HF	178 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	153 dB	270 km^2	13 km	5.9 km	9.0 km
	PCW	181 dB	3.9 km^2	1.8 km	270 m	930 m
S	LF	179 dB	200 km^2	10 km	6.2 km	7.9 km
	HF	178 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	153 dB	160 km^2	8.5 km	6.3 km	7.2 km
	PCW	181 dB	0.8 km^2	610 m	390 m	500 m
HVAC	LF	179 dB	450 km^2	14 km	10 km	12 km
	HF	178 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	153 dB	350 km^2	12 km	9.9 km	11 km
	PCW	181 dB	8.5 km^2	1.7 km	1.6 km	1.7 km

Table 27: Summary of the SPL_{peak} Southall *et al.* (2019) PTS impact ranges for the four modelling locations for the initial piling strike considering the maximum design pin pile input parameters.

Southall *et al.* (2019) – PTS			Maximum design – Pin pile, first strike (500 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.27 km^2	290 m	290 m	290 m
	PCW	218 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
E	LF	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.2 km^2	250 m	250 m	250 m
	PCW	218 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
S	LF	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.2 km^2	260 m	260 m	260 m
	PCW	218 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
HVAC	LF	219 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.26 km^2	290 m	290 m	290 m
	PCW	218 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Table 28: Summary of the SPL_{peak} Southall *et al.* (2019) TTS impact ranges for the four modelling locations for the initial piling strike considering the maximum design pin pile input parameters.

Southall *et al.* (2019) – TTS			Maximum design – Pin pile, first strike (500 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	2.4 km^2	880 m	870 m	870 m
	PCW	212 dB	< 0.01 km^2	50 m	< 50 m	50 m
E	LF	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	1.7 km^2	750 m	740 m	740 m
	PCW	212 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
S	LF	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	1.8 km^2	760 m	750 m	760 m
	PCW	212 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
HVAC	LF	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	2.4 km^2	870 m	870 m	870 m
	PCW	212 dB	< 0.01 km^2	50 m	< 50 m	50 m

Impact ranges – most likely monopile

Table 29: Summary of the SPL_{peak} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the most likely monopile input parameters.

Southall *et al.* (2019) – PTS			Most likely – Monopile (4,000 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	219 dB	0.04 km^2	120 m	120 m	120 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	20 km^2	2.5 km	2.5 km	2.5 km
	PCW	218 dB	0.07 km^2	150 m	140 m	150 m
E	LF	219 dB	0.03 km^2	110 m	110 m	110 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	14 km^2	2.2 km	2.1 km	2.1 km
	PCW	218 dB	0.05 km^2	130 m	130 m	130 m
S	LF	219 dB	0.04 km^2	110 m	110 m	110 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	14 km^2	2.1 km	2.1 km	2.1 km
	PCW	218 dB	0.05 km^2	130 m	130 m	130 m
HVAC	LF	219 dB	0.04 km^2	120 m	120 m	120 m
	HF	230 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	202 dB	19 km^2	2.5 km	2.5 km	2.5 km
	PCW	218 dB	0.07 km^2	150 m	140 m	150 m

Table 30: Summary of the SPL_{peak} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the most likely monopile input parameters.

Southall *et al.* (2019) – TTS			Most likely – Monopile (4,000 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	213 dB	0.42 km²	370 m	370 m	370 m
	HF	224 dB	< 0.01 km²	50 m	50 m	50 m
	VHF	196 dB	110 km²	5.9 km	5.7 km	5.8 km
	PCW	212 dB	0.61 km²	440 m	440 m	440 m
E	LF	213 dB	0.32 km²	320 m	320 m	320 m
	HF	224 dB	< 0.01 km²	50 m	50 m	50 m
	VHF	196 dB	80 km²	5.7 km	4.6 km	5.0 km
	PCW	212 dB	0.47 km²	390 m	390 m	390 m
S	LF	213 dB	0.34 km²	330 m	330 m	330 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	71 km²	4.8 km	4.7 km	4.8 km
	PCW	212 dB	0.48 km²	390 m	390 m	390 m
HVAC	LF	213 dB	0.42 km²	370 m	370 m	370 m
	HF	224 dB	< 0.01 km²	50 m	50 m	50 m
	VHF	196 dB	100 km²	5.8 km	5.7 km	5.7 km
	PCW	212 dB	0.61 km²	440 m	440 m	440 m

Table 31: Summary of the impulsive SEL_{cum} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the most likely monopile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – PTS			Most likely – Monopile (4,000 kJ) / Impulsive criteria			
Weighted SEL_{cum}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	183 dB	32 km²	4.8 km	2.5 km	3.2 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
E	LF	183 dB	27 km²	5.8 km	< 100 m	2.0 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
S	LF	183 dB	0.68 km²	1.1 km	< 100 m	300 m
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
HVAC	LF	183 dB	32 km²	3.9 km	2.6 km	3.2 km
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m

Table 32: Summary of the impulsive SEL_{cum} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the most likely monopile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – TTS *Weighted SEL_{cum}*			Most likely – Monopile (4,000 kJ) / Impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	168 dB	1900 km^2	31 km	20 km	24 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	580 km^2	16 km	12 km	14 km
	PCW	170 dB	430 km^2	14 km	11 km	12 km
E	LF	168 dB	1300 km^2	35 km	12 km	19 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	450 km^2	18 km	7.6 km	12 km
	PCW	170 dB	340 km^2	15 km	6.5 km	10 km
S	LF	168 dB	920 km^2	24 km	12 km	17 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	290 km^2	12 km	8.1 km	9.5 km
	PCW	170 dB	200 km^2	9.8 km	6.9 km	8.1 km
HVAC	LF	168 dB	1600 km^2	29 km	15 km	22 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	580 km^2	15 km	12 km	14 km
	PCW	170 dB	440 km^2	13 km	11 km	12 km

Table 33: Summary of the non-impulsive SEL_{cum} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the most likely monopile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – PTS *Weighted SEL_{cum}*			Most likely – Monopile (4,000 kJ) / Non-impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
E	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
S	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
HVAC	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m

Table 34: Summary of the non-impulsive SEL_{cum} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the most likely monopile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – TTS			Most likely – Monopile (4,000 kJ) / Non-impulsive criteria			
Weighted SEL_{cum}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	179 dB	210 km²	11 km	6.9 km	8.2 km
	HF	178 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	153 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	PCW	181 dB	0.34 km²	450 m	130 m	320 m
E	LF	179 dB	150 km²	13 km	2.0 km	6.0 km
	HF	178 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	153 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	PCW	181 dB	0.07 km²	330 m	< 100 m	< 100 m
S	LF	179 dB	56 km²	6.6 km	2.4 km	4.0 km
	HF	178 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	153 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	PCW	181 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
HVAC	LF	179 dB	210 km²	9.7 km	6.6 km	8.1 km
	HF	178 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	153 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	PCW	181 dB	0.16 km²	270 m	190 m	220 m

Table 35: Summary of the SPL_{peak} Southall *et al.* (2019) PTS impact ranges for the four modelling locations for the initial piling strike considering the most likely monopile input parameters.

Southall *et al.* (2019) – PTS			Most likely – Monopile, first strike (800 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	219 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	1 km²	570 m	560 m	570 m
	PCW	218 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
E	LF	219 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.73 km²	480 m	480 m	480 m
	PCW	218 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
S	LF	219 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.75 km²	490 m	490 m	490 m
	PCW	218 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
HVAC	LF	219 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.99 km²	560 m	560 m	560 m
	PCW	218 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table 36: Summary of the SPL_{peak} Southall *et al.* (2019) TTS impact ranges for the four modelling locations for the initial piling strike considering the most likely monopile input parameters.

Southall *et al.* (2019) – TTS			Most likely – Monopile, first strike (800 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	213 dB	0.02 km²	70 m	70 m	70 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	8.2 km²	1.6 km	1.6 km	1.6 km
	PCW	212 dB	0.02 km²	90 m	90 m	90 m
E	LF	213 dB	< 0.01 km²	60 m	60 m	60 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	5.8 km²	1.4 km	1.3 km	1.4 km
	PCW	212 dB	0.02 km²	80 m	80 m	80 m
S	LF	213 dB	< 0.01 km²	60 m	60 m	60 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	6 km²	1.4 km	1.4 km	1.4 km
	PCW	212 dB	0.02 km²	80 m	80 m	80 m
HVAC	LF	213 dB	0.02 km²	70 m	70 m	70 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	8.1 km²	1.6 km	1.6 km	1.6 km
	PCW	212 dB	0.02 km²	90 m	90 m	90 m

Impact ranges – most likely pin pile

Table 37: Summary of the SPL_{peak} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the most likely pin pile input parameters.

Southall *et al.* (2019) – PTS			Most Likely – Pin pile (1,750 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	219 dB	< 0.01 km²	60 m	60 m	60 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	5.6 km²	1.3 km	1.3 km	1.3 km
	PCW	218 dB	0.02 km²	70 m	70 m	70 m
E	LF	219 dB	< 0.01 km²	50 m	50 m	50 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	4.1 km²	1.2 km	1.1 km	1.1 km
	PCW	218 dB	< 0.01 km²	60 m	60 m	60 m
S	LF	219 dB	< 0.01 km²	50 m	50 m	50 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	4.2 km²	1.2 km	1.2 km	1.2 km
	PCW	218 dB	< 0.01 km²	60 m	60 m	60 m
HVAC	LF	219 dB	< 0.01 km²	60 m	60 m	60 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	5.6 km²	1.3 km	1.3 km	1.3 km
	PCW	218 dB	0.02 km²	70 m	70 m	70 m

Table 38: Summary of the SPL_{peak} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the most likely pin pile input parameters.

Southall *et al.* (2019) – TTS *Unweighted SPL_{peak}*			Most Likely – Pin pile (1,750 kJ) / Impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	213 dB	0.1 km²	180 m	180 m	180 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	38 km²	3.5 km	3.4 km	3.5 km
	PCW	212 dB	0.15 km²	220 m	220 m	220 m
E	LF	213 dB	0.08 km²	160 m	160 m	160 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	27 km²	3.2 km	2.8 km	3.0 km
	PCW	212 dB	0.11 km²	190 m	190 m	190 m
S	LF	213 dB	0.08 km²	160 m	160 m	160 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	26 km²	2.9 km	2.9 km	2.9 km
	PCW	212 dB	0.12 km²	190 m	190 m	190 m
HVAC	LF	213 dB	0.1 km²	180 m	180 m	180 m
	HF	224 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	196 dB	37km²	3.5 km	3.4 km	3.4 km
	PCW	212 dB	0.15 km²	220 m	220 m	220 m

Table 39: Summary of the impulsive SEL_{cum} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the most likely pin pile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – PTS *Weighted SEL_{cum}*			Most Likely – Pin pile (1,750 kJ) / Impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	183 dB	0.44 km²	1.2 km	< 100 m	250 m
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	31 km²	3.6 km	2.8 km	3.2 km
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
E	LF	183 dB	1.6 km²	1.7 km	< 100 m	440 m
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	18 km²	3.8 km	700 m	2.0 km
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
S	LF	183 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	4.4 km²	1.4 km	1.0 km	1.2 km
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
HVAC	LF	183 dB	0.21 km²	550 m	< 100 m	180 m
	HF	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	155 dB	30 km²	3.2 km	3.0 km	3.1 km
	PCW	185 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m

Table 40: Summary of the impulsive SEL_{cum} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the most likely pin pile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – TTS Weighted SEL_{cum}			Most Likely – Pin pile (1,750 kJ) / Impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	168 dB	1300 km^2	26 km	17 km	20 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	1500 km^2	26 km	20 km	22 km
	PCW	170 dB	180 km^2	8.9 km	6.9 km	7.6 km
E	LF	168 dB	870 km^2	30 km	9.2 km	16 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	1100 km^2	29 km	13 km	18 km
	PCW	170 dB	140 km^2	9.6 km	3.7 km	6.2 km
S	LF	168 dB	600 km^2	20 km	9.3 km	14 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	830 km^2	21 km	13 km	16 km
	PCW	170 dB	68 km^2	5.3 km	4.1 km	4.6 km
HVAC	LF	168 dB	1100 km^2	24 km	14 km	19 km
	HF	170 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	140 dB	1400 km^2	24 km	18 km	21 km
	PCW	170 dB	180 km^2	8.1 km	7.4 km	7.6 km

Table 41: Summary of the non-impulsive SEL_{cum} Southall *et al.* (2019) PTS impact ranges for the four modelling locations considering the most likely pin pile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – PTS Weighted SEL_{cum}			Most Likely – Pin pile (1,750 kJ) / Non-impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
E	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
S	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
HVAC	LF	199 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	HF	198 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	VHF	173 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	PCW	201 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m

Table 42: Summary of the non-impulsive SEL_{cum} Southall *et al.* (2019) TTS impact ranges for the four modelling locations considering the most likely pin pile input parameters assuming a fleeing receptor.

Southall *et al.* (2019) – TTS *Weighted SEL_{cum}*			Most Likely – Pin pile (1,750 kJ) / Non-impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	179 dB	74 km²	6.8 km	3.9 km	4.8 km
	HF	178 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	153 dB	83 km²	6.0 km	4.6 km	5.1 km
	PCW	181 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
E	LF	179 dB	54 km²	7.9 km	100 m	3.1 km
	HF	178 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	153 dB	57 km²	6.4 km	2.1 km	3.9 km
	PCW	181 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
S	LF	179 dB	6.9 km²	2.8 km	150 m	1.2 km
	HF	178 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	153 dB	23 km²	3.1 km	2.4 km	2.7 km
	PCW	181 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
HVAC	LF	179 dB	74 km²	5.9 km	4.0 km	4.9 km
	HF	178 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	VHF	153 dB	82 km²	5.4 km	5.0 km	5.1 km
	PCW	181 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m

Table 43: Summary of the SPL_{peak} Southall *et al.* (2019) PTS impact ranges for the four modelling locations for the initial piling strike considering the most likely pin pile input parameters.

Southall *et al.* (2019) – PTS *Unweighted SPL_{peak}*			Most Likely – Pin pile, first strike (350 kJ) / Impulsive criteria			
			Area	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	219 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.08 km²	170 m	160 m	170 m
	PCW	218 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
E	LF	219 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.06 km²	140 m	140 m	140 m
	PCW	218 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
S	LF	219 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.07 km²	150 m	150 m	150 m
	PCW	218 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
HVAC	LF	219 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	HF	230 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m
	VHF	202 dB	0.08 km²	170 m	160 m	170 m
	PCW	218 dB	< 0.01 km²	< 50 m	< 50 m	< 50 m

Table 44: Summary of the SPL_{peak} Southall *et al.* (2019) TTS impact ranges for the four modelling locations for the initial piling strike considering the most likely pin pile input parameters.

Southall *et al.* (2019) – TTS			Most Likely – Pin pile, first strike (350 kJ) / Impulsive criteria			
Unweighted SPL_{peak}			*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	LF	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	0.79 km^2	510 m	500 m	500 m
	PCW	212 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
E	LF	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	0.58 km^2	430 m	430 m	430 m
	PCW	212 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
S	LF	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	0.6 km^2	440 m	440 m	440 m
	PCW	212 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
HVAC	LF	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	HF	224 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	VHF	196 dB	0.79 km^2	500 m	500 m	500 m
	PCW	212 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m

Discussion of Marine Mammal Results

5.2.2.4 The ranges of impact using the Southall *et al.* (2019) criteria vary depending on the hearing (species) group and severity of impact. Looking at the monopile results for the maximum design parameters as an example (**Table 15** and **Table 16**), the SEL_{cum} results using the LF weighting lead to the greatest ranges as the HF, VHF and PCW weightings filter out much of the piling energy at lower frequencies. It is also worth noting that the greatest ranges are calculated for the transects travelling through the deepest water and the number of these ranges are somewhat limited; this is clearly shown in **Section 5.1**.

5.2.2.5 The SEL_{cum} results show that larger ranges are expected for pin piles than for monopiles for HF and VHF hearing groups, this is due to the differences between the marine mammal hearing group weightings and the sound frequencies produced by the different size piles.

5.2.2.6 The frequency spectra used as inputs to the model (**Figure 5**) show that the noise from pin piles contains more high frequency components than the noise from monopiles. The overall unweighted noise level is higher for the monopile due to the low frequency components of piling noise (i.e. most of the pile strike energy is in the lower frequencies). The HF and VHF cetacean filters (

5.2.2.7 **Table** 1) both remove much of the low frequency components of the noise, as the species in these groups are much less sensitive to noise at these frequencies. This leaves the higher frequency noise, which in the case of pin piles is higher than that for the monopiles.

5.2.2.8 To illustrate this, **Figure 16** and **Figure 17** show the sound frequency spectra for monopiles and pin piles, adjusted (weighted) to account for the sensitivities of the different cetacean hearing groups. These can be compared to the original unweighted frequency spectra in **Figure 5** (shown faintly in **Figure 16** and **Figure 17**). For the HF and VHF cetacean groups, higher levels are present in the weighted pin pile spectrum compared to the monopile.

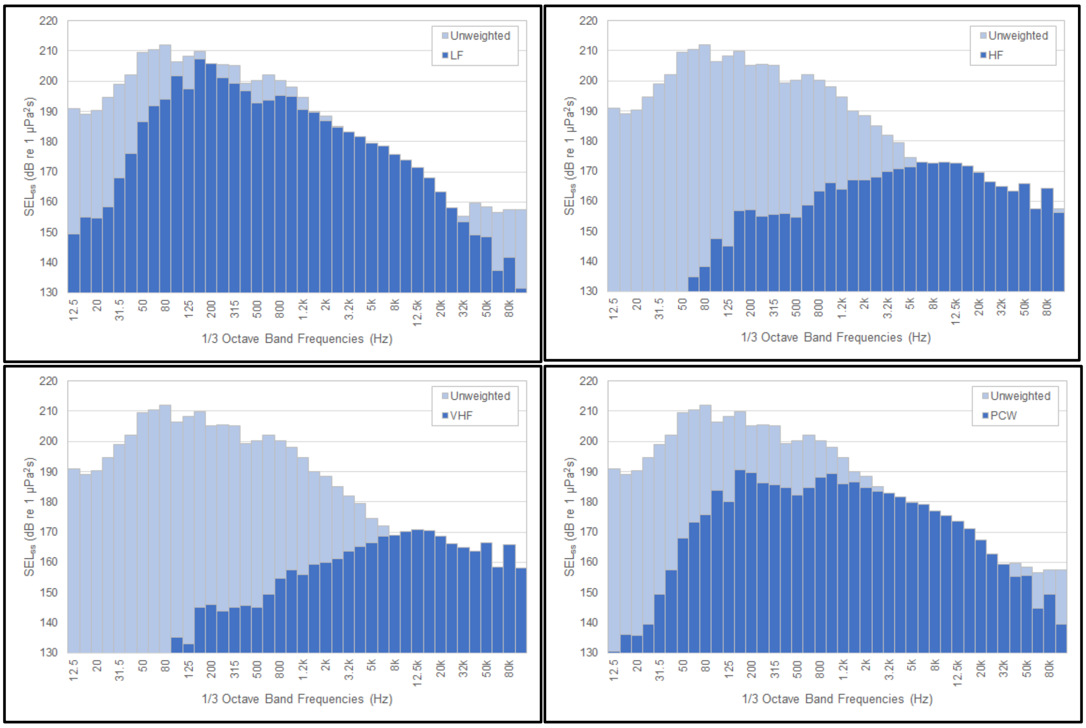

Figure 16: Filtered noise inputs for monopiles using the Southall *et al.* (2019) weightings. The lighter coloured bars show the unweighted one-third octave levels.

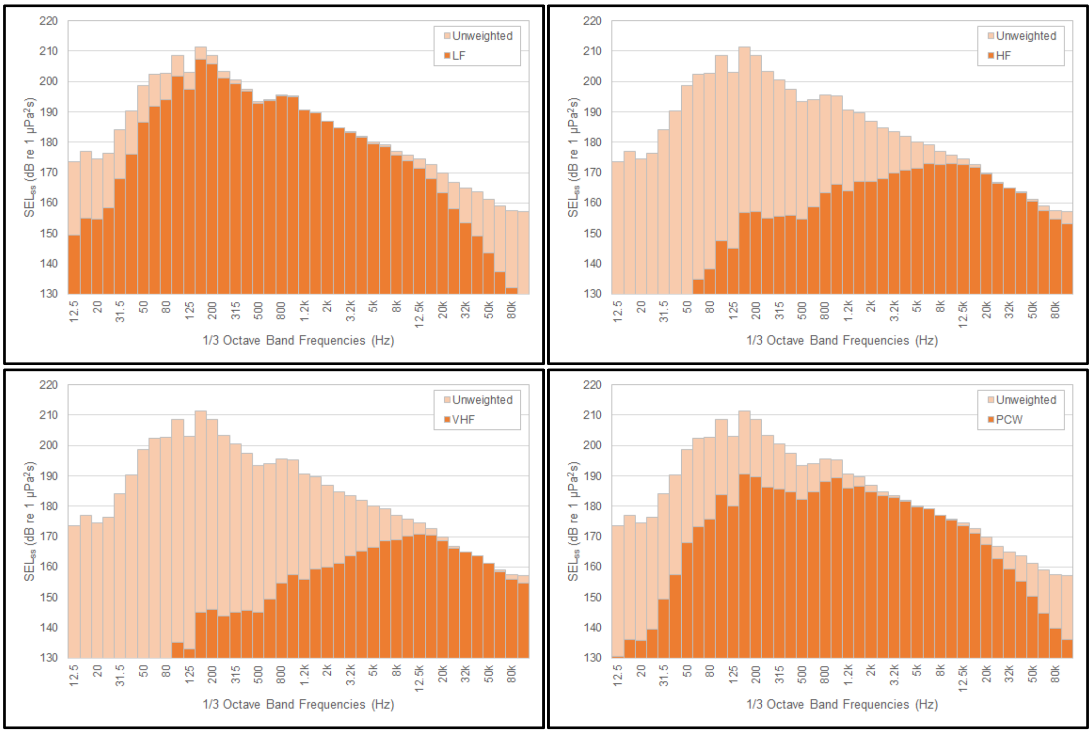

Figure 17: Filtered noise inputs for pin piles using the Southall *et al.* (2019) weightings. The lighter coloured bars show the unweighted one-third octave levels.

5.2.3 Fish criteria

5.2.3.1 Table 45 to Table 60 give detailed summaries of the impact ranges for species of fish based on the injury criteria found in the Popper *et al.* (2014) guidance. Interpretation of these modelling results are provided in **Volume 2, Chapter 3: Fish and Shellfish Ecology**. As discussed in Section 2.2.2, the Popper *et al.* (2014) criteria are given as unweighted SPL_{peak} and unweighted SEL_{cum}, grouping fish by physiology with regards to swim bladder. The Popper *et al.* (2014) criteria for impact piling are given in Table 4. In addition, instantaneous SPL_{peak} values for the first strike of each scenario have also been given.

5.2.3.2 As discussed in paragraphs 2.2.2.22 to 2.2.2.24 for SEL_{cum} criteria, both fleeing animal and stationary animal models have been used. For the fleeing animal model, a speed of 1.5 ms^{-1} has been assumed (Hirata, 1999).

5.2.3.3 It should be noted that some of the same noise levels are used as criteria for multiple effects. This is as per the Popper *et al.* (2014) guidelines (Table 4), which is based on a comprehensive literature review. The data available to create the criteria are very limited for fish and most criteria in Table 4 are "greater than", with a precise threshold not identified. All ranges associated with criteria defined with a ">" are therefore conservative and in practice the actual range at which an effect could occur will be somewhat lower.

5.2.3.4 The results show that the largest impact ranges occur in the deeper water areas, with maximum SPL_{peak} recoverable injury ranges of up to 1.3 km and maximum predicted SEL_{cum} TTS ranges of 26 km assuming a fleeing receptor and 36 km assuming a stationary receptor. Other injury criteria from Popper *et al.* (2014) result in much smaller ranges.

Impact ranges – maximum design monopile

Table 45: Summary of the unweighted SPL_{peak} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the maximum design monopile input parameters.

Popper *et al.* (2014)		**Maximum design – Monopile (5,000 kJ)**			
Unweighted SPL_{peak}		*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	213 dB	0.57 km^2	430 m	430 m	430 m
	207 dB	4.9 km^2	1.3 km	1.3 km	1.3 km
E	213 dB	0.44 km^2	380 m	370 m	380 m
	207 dB	3.7 km^2	1.1 km	1.1 km	1.1 km
S	213 dB	0.45 km^2	380 m	380 m	380 m
	207 dB	3.8 km^2	1.1 km	1.1 km	1.1 km
HVAC	213 dB	0.57 km^2	430 m	430 m	430 m
	207 dB	4.9 km^2	1.2 km	1.2 km	1.2 km

Table 46: Summary of the unweighted SEL_{cum} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the maximum design monopile input parameters assuming a fleeing receptor.

Popper *et al.* (2014)		Maximum design – Monopile (5,000 kJ) / Fleeing receptor			
Unweighted SEL_{cum}		*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	219 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	203 dB	0.66 km²	550 m	360 m	460 m
	186 dB	1.1 km²	23 km	17 km	19 km
E	219 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	203 dB	0.13 km²	380 m	< 100 m	140 m
	186 dB	870 km²	26 km	11 km	16 km
S	219 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	186 dB	630 km²	18 km	12 km	14 km
HVAC	219 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	203 dB	0.52 km²	440 m	390 m	410 m
	186 dB	1100 km²	21 km	16 km	19 km

Table 47: Summary of the unweighted SEL_{cum} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the maximum design monopile input parameters assuming a stationary receptor.

Popper *et al.* (2014)		**Maximum design – Monopile (5,000 kJ) / Stationary receptor**			
Unweighted SEL_{cum}		*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	219 dB	1.9 km^2	760 m	750 m	760 m
	216 dB	5.1 km^2	1.3 km	1.3 km	1.3 km
	210 dB	35 km^2	3.4 km	3.3 km	3.3 km
	207 dB	81 km^2	5.2 km	5.0 km	5.1 km
	203 dB	210 km^2	8.5 km	7.9 km	8.2 km
	186 dB	2600 km^2	33 km	27 km	29 km
E	219 dB	1.4 km^2	660 m	650 m	660 m
	216 dB	3.8 km^2	1.1 km	1.1 km	1.1 km
	210 dB	25 km^2	3.1 km	2.7 km	2.9 km
	207 dB	61 km^2	4.9 km	4.1 km	4.4 km
	203 dB	160 km^2	8.4 km	6.3 km	7.2 km
	186 dB	2000 km^2	36 km	20 km	25 km
S	219 dB	1.4 km^2	670 m	660 m	670 m
	216 dB	3.9 km^2	1.1 km	1.1 km	1.1 km
	210 dB	25 km^2	2.8 km	2.8 km	2.8 km
	207 dB	55 km^2	4.3 km	4.2 km	4.2 km
	203 dB	140 km^2	6.7 km	6.5 km	6.6 km
	186 dB	1700 km^2	28 km	20 km	23 km
HVAC	219 dB	1.8 km^2	760 m	750 m	760 m
	216 dB	5 km^2	1.3 km	1.3 km	1.3 km
	210 dB	34 km^2	3.3 km	3.3 km	3.3 km
	207 dB	79 km^2	5.1 km	5.0 km	5.0 km
	203 dB	200 km^2	8.2 km	8.0 km	8.1 km
	186 dB	2500 km^2	31 km	25 km	28 km

Table 48: Summary of the unweighted SPL_{peak} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) for the initial piling strike considering the maximum design monopile input parameters.

Popper *et al.* (2014)		Maximum design – Monopile, first strike (1,000 kJ)			
Unweighted SPL_{peak}		*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	213 dB	0.03 km^2	100 m	100 m	100 m
	207 dB	0.28 km^2	300 m	300 m	300 m
E	213 dB	0.02 km^2	80 m	80 m	80 m
	207 dB	0.2 km^2	260 m	260 m	260 m
S	213 dB	0.02 km^2	90 m	90 m	90 m
	207 dB	0.21 km^2	260 m	260 m	260 m
HVAC	213 dB	0.03 km^2	100 m	100 m	100 m
	207 dB	0.27 km^2	300 m	300 m	300 m

Impact ranges – maximum design pin pile

Table 49: Summary of the unweighted SPL_{peak} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the maximum design pin pile input parameters.

Popper *et al.* (2014)		Maximum design – Pin pile (2,500 kJ)			
Unweighted SPL_{peak}		*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	213 dB	0.2 km^2	260 m	250 m	260 m
	207 dB	1.8 km^2	770 m	760 m	770 m
E	213 dB	0.15 km^2	220 m	220 m	220 m
	207 dB	1.4 km^2	660 m	660 m	660 m
S	213 dB	0.16 km^2	230 m	220 m	230 m
	207 dB	1.4 km^2	670 m	670 m	670 m
HVAC	213 dB	0.2 km^2	250 m	250 m	250 m
	207 dB	1.8 km^2	760 m	760 m	760 m

Table 50: Summary of the unweighted SEL_{cum} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the maximum design pin pile input parameters assuming a fleeing receptor.

Popper *et al.* (2014) *Unweighted SEL_{cum}*		Maximum design – Pin pile (2,500 kJ) / Fleeing receptor			
		Area	*Maximum range*	*Minimum range*	*Mean range*
NW	219 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	186 dB	710 km^2	18 km	14 km	15 km
E	219 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	186 dB	550 km^2	20 km	8.7 km	13 km
S	219 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	186 dB	370 km^2	13 km	9.1 km	11 km
HVAC	219 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	186 dB	700 km^2	17 km	13 km	15 km

Table 51: Summary of the unweighted SEL_{cum} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the maximum design pin pile input parameters assuming a stationary receptor.

Popper *et al.* (2014) *Unweighted SEL_{cum}*		Maximum design – Pin pile (2,500 kJ) / Stationary receptor			
		Area	*Maximum range*	*Minimum range*	*Mean range*
NW	219 dB	0.65 km^2	460 m	450 m	460 m
	216 dB	1.9 km^2	790 m	770 m	780 m
	210 dB	15 km^2	2.2 km	2.2 km	2.2 km
	207 dB	37 km^2	3.5 km	3.5 km	3.5 km
	203 dB	110 km^2	6.0 km	5.8 km	5.9 km
	186 dB	1900 km^2	27 km	23 km	25 km
E	219 dB	0.49 km^2	400 m	390 m	400 m
	216 dB	1.4 km^2	680 m	670 m	670 m
	210 dB	11 km^2	1.9 km	1.8 km	1.8 km
	207 dB	27 km^2	3.2 km	2.9 km	3.0 km
	203 dB	81 km^2	5.7 km	4.7 km	5.1 km
	186 dB	1500 km^2	30 km	17 km	22 km
S	219 dB	0.51 km^2	410 m	400 m	410 m
	216 dB	1.5 km^2	690 m	680 m	690 m
	210 dB	11 km^2	1.9 km	1.8 km	1.8 km
	207 dB	26 km^2	3.0 km	2.9 km	2.9 km
	203 dB	73 km^2	4.9 km	4.8 km	4.8 km
	186 dB	1200 km^2	24 km	17 km	20 km
HVAC	219 dB	0.65 km^2	460 m	450 m	460 m
	216 dB	1.9 km^2	780 m	770 m	780 m
	210 dB	14 km^2	2.2 km	2.1 km	2.1 km
	207 dB	37 km^2	3.5 km	3.4 km	3.4 km
	203 dB	110 km^2	5.9 km	5.8 km	5.8 km
	186 dB	1900 km^2	26 km	22 km	24 km

Table 52: Summary of the unweighted SPL_{peak} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) for the initial piling strike considering the maximum design pin pile input parameters.

Popper *et al.* (2014) *Unweighted SPL_{peak}*		**Maximum design – Pin pile, first strike (500 kJ)**			
		Area	*Maximum range*	*Minimum range*	*Mean range*
NW	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	0.04 km^2	120 m	110 m	120 m
E	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	0.03 km^2	100 m	100 m	100 m
S	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	0.03 km^2	100 m	100 m	100 m
HVAC	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	0.04 km^2	120 m	110 m	120 m

Impact ranges – most likely monopile

Table 53: Summary of the unweighted SPL_{peak} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the most likely monopile input parameters.

Popper *et al.* (2014) *Unweighted SPL_{peak}*		**Most likely – Monopile (4,000 kJ)**			
		Area	*Maximum range*	*Minimum range*	*Mean range*
NW	213 dB	0.42 km^2	370 m	370 m	370 m
	207 dB	3.7 km^2	1.1 km	1.1 km	1.1 km
E	213 dB	0.32 km^2	320 m	320 m	320 m
	207 dB	2.8 km^2	950 m	930 m	940 m
S	213 dB	0.34 km^2	330 m	330 m	330 m
	207 dB	2.8 km^2	960 m	950 m	950 m
HVAC	213 dB	0.42 km^2	370 m	370 m	370 m
	207 dB	3.7 km^2	1.1 km	1.1 km	1.1 km

Table 54: Summary of the unweighted SEL_{cum} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the most likely monopile input parameters assuming a fleeing receptor.

Popper *et al.* (2014) *Unweighted SEL_{cum}*		**Most likely – Monopile (4,000 kJ) / Fleeing receptor**			
		Area	*Maximum range*	*Minimum range*	*Mean range*
NW	219 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	186 dB	590 km^2	16 km	12 km	14 km
E	219 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	186 dB	470 km^2	18 km	7.7 km	12 km
S	219 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	186 dB	300 km^2	12 km	8.2 km	9.7 km
HVAC	219 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km^2	< 100 m	< 100 m	< 100 m
	186 dB	600 km^2	15 km	13 km	14 km

Table 55: Summary of the unweighted SEL_{cum} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the most likely monopile input parameters assuming a stationary receptor.

Popper *et al.* (2014)		Most likely – Monopile (4,000 kJ) / Stationary receptor			
Unweighted SEL_{cum}		*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	219 dB	0.27 km^2	300 m	290 m	300 m
	216 dB	0.83 km^2	520 m	510 m	520 m
	210 dB	6.7 km^2	1.5 km	1.5 km	1.5 km
	207 dB	18 km^2	2.4 km	2.4 km	2.4 km
	203 dB	59 km^2	4.4 km	4.3 km	4.4 km
	186 dB	1400 km^2	24 km	20 km	21 km
E	219 dB	0.22 km^2	270 m	260 m	270 m
	216 dB	0.62 km^2	450 m	440 m	450 m
	210 dB	5 km^2	1.3 km	1.3 km	1.3 km
	207 dB	13 km^2	2.1 km	2.0 km	2.0 km
	203 dB	44 km^2	4.1 km	3.5 km	3.7 km
	186 dB	1200 km^2	25 km	15 km	19 km
S	219 dB	0.22 km^2	270 m	260 m	270 m
	216 dB	0.65 km^2	460 m	450 m	460 m
	210 dB	5.1 km^2	1.3 km	1.3 km	1.3 km
	207 dB	13 km^2	2.1 km	2.0 km	2.0 km
	203 dB	41 km^2	3.7 km	3.6 km	3.6 km
	186 dB	920 km^2	20 km	16 km	17 km
HVAC	219 dB	0.27 km^2	300 m	290 m	300 m
	216 dB	0.8 km^2	510 m	500 m	510 m
	210 dB	6.6 km^2	1.5 km	1.5 km	1.5 km
	207 dB	17 km^2	2.4 km	2.4 km	2.4 km
	203 dB	57 km^2	4.3 km	4.3 km	4.3 km
	186 dB	1400 km^2	23 km	20 km	21 km

Table 56: Summary of the unweighted SPL_{peak} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) for the initial piling strike considering the most likely monopile input parameters.

Popper *et al.* (2014) *Unweighted SPL_{peak}*		Most likely – Monopile, first strike (800 kJ)			
		Area	*Maximum range*	*Minimum range*	*Mean range*
NW	213 dB	0.02 km²	70 m	70 m	70 m
	207 dB	0.16 km²	220 m	220 m	220 m
E	213 dB	< 0.01 km²	60 m	60 m	60 m
	207 dB	0.12 km²	190 m	190 m	190 m
S	213 dB	< 0.01 km²	60 m	60 m	60 m
	207 dB	0.12 km²	200 m	200 m	200 m
HVAC	213 dB	0.02 km²	70 m	70 m	70 m
	207 dB	0.16 km²	220 m	220 m	220 m

Impact ranges – most likely pin pile

Table 57: Summary of the unweighted SPL_{peak} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the most likely pin pile input parameters.

Popper *et al.* (2014) *Unweighted SPL_{peak}*		Most likely – Pin Pile (1,750 kJ)			
		Area	*Maximum range*	*Minimum range*	*Mean range*
NW	213 dB	0.1 km²	180 m	180 m	180 m
	207 dB	0.95 km²	550 m	550 m	550 m
E	213 dB	0.08 km²	160 m	160 m	160 m
	207 dB	0.71 km²	480 m	470 m	480 m
S	213 dB	0.08 km²	160 m	160 m	160 m
	207 dB	0.73 km²	490 m	480 m	480 m
HVAC	213 dB	0.1 km²	180 m	180 m	180 m
	207 dB	0.95 km²	550 m	550 m	550 m

Table 58: Summary of the unweighted SEL_{cum} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the most likely pin pile input parameters assuming a fleeing receptor.

Popper *et al.* (2014)		Most likely – Pin Pile (1,750 kJ) / Fleeing receptor			
Unweighted SEL_{cum}		*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	219 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	186 dB	250 km²	11 km	8.2 km	9.0 km
E	219 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	186 dB	190 km²	11 km	4.6 km	7.5 km
S	219 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	186 dB	100 km²	6.6 km	5.1 km	5.7 km
HVAC	219 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	216 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	210 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	207 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	203 dB	< 0.01 km²	< 100 m	< 100 m	< 100 m
	186 dB	260 km²	9.6 km	8.7 km	9.1 km

Table 59: Summary of the unweighted SEL_{cum} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) considering the most likely pin pile input parameters assuming a stationary receptor.

Popper *et al.* (2014)		Most likely – Pin Pile (1,750 kJ) / Stationary receptor			
Unweighted SEL_{cum}		*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	219 dB	0.07 km²	150 m	140 m	150 m
	216 dB	0.2 km²	260 m	250 m	260 m
	210 dB	1.8 km²	760 m	750 m	760 m
	207 dB	5.1 km²	1.3 km	1.3 km	1.3 km
	203 dB	19 km²	2.6 km	2.5 km	2.5 km
	186 dB	850 km²	18 km	16 km	16 km
E	219 dB	0.06 km²	140 m	130 m	140 m
	216 dB	0.16 km²	230 m	220 m	230 m
	210 dB	1.3 km²	650 m	640 m	650 m
	207 dB	3.7 km²	1.1 km	1.1 km	1.1 km
	203 dB	14 km²	2.2 km	2.1 km	2.1 km
	186 dB	720 km²	19 km	12 km	15 km
S	219 dB	0.06 km²	140 m	130 m	140 m
	216 dB	0.16 km²	230 m	220 m	230 m
	210 dB	1.3 km²	660 m	650 m	660 m
	207 dB	3.8 km²	1.1 km	1.1 km	1.1 km
	203 dB	14 km²	2.2 km	2.1 km	2.1 km
	186 dB	540 km²	14 km	12 km	13 km
HVAC	219 dB	0.07 km²	150 m	140 m	150 m
	216 dB	0.2 km²	260 m	250 m	260 m
	210 dB	1.8 km²	760 m	750 m	760 m
	207 dB	5 km²	1.3 km	1.3 km	1.3 km
	203 dB	19 km²	2.5 km	2.5 km	2.5 km
	186 dB	860 km²	17 km	16 km	17 km

Table 60: Summary of the unweighted SPL_{peak} impact ranges for the various impact piling criteria for fish from Popper *et al.* (2014) for the initial piling strike considering the most likely pin pile input parameters.

Popper *et al.* (2014)		Most likely – Pin pile, first strike (350 kJ)			
Unweighted SPL_{peak}		*Area*	*Maximum range*	*Minimum range*	*Mean range*
NW	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	70 m	60 m	70 m
E	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	60 m	60 m	60 m
S	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	60 m	60 m	60 m
HVAC	213 dB	< 0.01 km^2	< 50 m	< 50 m	< 50 m
	207 dB	< 0.01 km^2	70 m	60 m	70 m

6 Other noise sources

6.1 Introduction

6.1.1.1 Although impact piling is expected to be the primary noise source during offshore wind farm construction and development (Bailey *et al.*, 2014), several other anthropogenic noise sources may be present. Each of these has been considered, and relevant biological noise criteria presented, in this section.

6.1.1.2 **Table 61** provides a summary of the various noise producing sources, aside from impact piling, that are expected to be present during the construction and operation of Hornsea Four.

Table 61: Summary of the possible noise making activities at Hornsea Four other than impact piling.

Activity	Description
Dredging	Trailer suction hopper dredger may be required on site for the export cable, array cable and interconnector cable installation, as well as seabed preparation works for certain foundation options.
Drilling	Necessary in case of impact piling refusal.
Cable laying	Noise from the cable laying vessel and any other associated noise during the offshore cable installation.
Rock placement	Potentially required on site for installation of offshore cables (Cable crossings and cable protection) and scour protection around foundation structures.
Trenching	Plough trenching may be required during offshore cable installation.
Vessel noise	Jack-up barges for piling substructure and WTG installation. Other large and medium sized vessels on site to carry out other construction tasks, and anchor handling. Other small vessels for crew transport and maintenance on site.
Operational WTG	Noise transmitted through the water from operational WTG. The project design envelope gives turbines with rotor diameters of up to 305 m.

6.1.1.3 In addition, a high-level review of potential noise from decommissioning activities is given in Section 6.4.

6.1.1.4 The NPL Good Practice Guide 133 for underwater noise measurements (Robinson *et al.*, 2014) indicates that under certain circumstances, a simple modelling approach may be considered acceptable. Such an approach has been used for these noise sources, which are variously either quiet compared to impact piling (e.g. drilling and cable laying) or where detailed modelling would imply an unwarranted accuracy (e.g. where data is limited such as with large operational WTG noise). The high-level overview of modelling that has been presented is here considered sufficient and it is considered that there would be little benefit in using a more detailed model at this stage. The limitations of this approach are noted, including the lack of frequency or bathymetry dependence.

6.2 Noise making activities

6.2.1.1 For the purposes of identifying the greatest noise levels, approximate subsea noise levels have been predicted using a simple modelling approach based on measured data from Subacoustech Environmental's own underwater noise measurement database, scaled to relevant parameters for the site and specific noise source. Predicted source levels for the construction activities are presented in Table 62 along with a summary of the number of datasets used in each case. As previously, all SEL_{cum} criteria use the same assumptions as presented in Section 2.2.2, and ranges smaller than 50 m (single strike) and 100 m (cumulative) have not been presented. It should be noted that this modelling approach does not take bathymetry or other environmental conditions into account, and as such can be applied to any location in the Hornsea Four project area. Noise from operational WTGs has been reviewed separately in Section 6.3 and decommissioning noise is reviewed in Section 6.4.

Table 62: Summary of the estimated unweighted source levels for the different construction noise sources considered.

Source	Estimated unweighted source level	Comments
Dredging	186 dB re 1 µPa @ 1 m (RMS)	Based on five datasets from suction and cutter suction dredgers.
Drilling	179 dB re 1 µPa @ 1 m (RMS)	Based on seven datasets of offshore drilling using a variety of drill sizes and powers.
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	Based on 11 datasets from a pipe laying vessel measuring 300 m in length; this is considered a maximum design noise source for cable laying operations.
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	Based on four datasets from rock placement vessel 'Rollingstone.'
Trenching	172 dB re 1 µPa @ 1 m (RMS)	Based on three datasets of measurements from trenching vessels more than 100 m in length.
Vessel noise (large)	171 dB re 1 µPa @ 1 m (RMS)	Based on five datasets of large vessels including container ships, FPSOs and other vessels more than 100 m in length. Vessel speed assumed as 12 knots.
Vessel noise (medium)	164 dB re 1 µPa @ 1 m (RMS)	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 12 knots.

6.2.1.2 **Table 63** and **Table 64** summarise the predicted impact ranges for these noise sources. It is worth noting that the Southall *et al.* (2019) and Popper *et al.* (2014) criteria give different criteria for non-impulsive or continuous noise sources compared to impulsive noise (see **Section 2.2.2**); all sources in this section are considered non-pulse or continuous-type.

6.2.1.3 Given the modelled impact ranges, any marine mammal would have to remain in close proximity (in most cases less than 50 m) from the source continuously for 24 hours to be exposed to levels sufficient to induce PTS as per Southall *et al.* (2019). In most hearing groups, the noise levels are low enough that there is negligible risk. For fish, there is a low to negligible risk of any injury or TTS, in line with guidance for continuous noise sources in Popper *et al.* (2014) and presented in **paragraph 2.2.2.18** and **Table 5**. All sources presented here are much quieter than those presented for impact piling in **Section 5**.

Table 63 Summary of the impact ranges for the different construction noise sources using the non-impulsive criteria from Southall *et al.* (2019) for marine mammals at Hornsea Four.

Southall et al. (2019)		Dredging	Drilling	Cable laying	Rock placement	Trenching	Vessels (large)	Vessels (medium)
PTS	199 dB (LF SEL_{cum})	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
PTS	198 dB (HF SEL_{cum})	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
PTS	173 dB (VHF SEL_{cum})	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
PTS	201 dB (PCW SEL_{cum})	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
TTS	179 dB (LF SEL_{cum})	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
TTS	178 dB (HF SEL_{cum})	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
TTS	153 dB (VHF SEL_{cum})	230 m	< 100 m	< 100 m	990 m	< 100 m	< 100 m	< 100 m
TTS	181 dB (PCW SEL_{cum})	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 64: Summary of the impact ranges from Popper *et al*. (2014) for shipping and continuous noise, covering the different construction noise sources for species of fish (swim bladder involved in hearing for Hornsea Four.

Popper et al. (2014)	Dredging	Drilling	Cable laying	Rock placement	Trenching	Vessels (large)	Vessels (medium)
Recoverable injury *170 dB (48 hours)* *Unweighted SPL_{RMS}*	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
TTS *158 dB (12 hours)* *Unweighted SPL_{RMS}*	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m

6.3 Operational WTG noise

6.3.1.1 It is believed that the main source of underwater noise from operational WTGs will be mechanically generated vibration from the rotating machinery in the turbines, which is transmitted into the sea through the structure of the turbine tower, pile and foundations (Nedwell *et al*., 2003a). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

6.3.1.2 The project design envelope for Hornsea Four gives the maximum potential WTG rotor diameter as 305 m. A summary of operational WTG where measurements have been collected is given in **Table 65**.

Table 65: Characteristics of measured operational wind farms used as a basis for modelling.

Wind farm	Lynn	Inner Dowsing	Gunfleet Sands 1 & 2	Gunfleet Sands 3
Type of turbine used	Siemens SWT-3.6-107	Siemens SWT-3.6-107	Siemens SWT-3.6-107	Siemens SWT-6.0-120
Number of turbines	27	27	48	2
Rotor diameter	107 m	107 m	107 m	120 m
Water depths	6 to 8 m	6 to 14 m	0 to 15 m	5 to 12 m
Representative sediment type	Sandy gravel / muddy sandy gravel	Sandy gravel / muddy sandy gravel	Sand / muddy sand / muddy sandy gravel	Sand / muddy sand / muddy sandy gravel
Turbine separation (representative)	500 m	500 m	890 m	435 m

6.3.1.3 The estimation of the effects of operational noise in these situations has two features that make it harder to predict compared with noise sources such as impact piling. Primarily, the problem is one of level; noise measurements made at many wind farms have demonstrated that the operational noise produced was at such a low level that it was difficult to measure relative to background noise (Cheesman, 2016) at distances of a few hundred metres. Also, the multiple turbines of an offshore wind farm could be considered as an extended, distributed noise source, as opposed to a "point source" as would be appropriate for pile driving at a single location, for example. The measurement techniques used at the sites above have dealt with these issues by considering the operational noise spectra in terms of levels within and on the edge of the wind farm (but relatively close to the turbines, so that some noise above background could be detected).

6.3.1.4 The considered turbine size for modelling Hornsea Four is larger than those for which data is available. Hornsea Four is also situated in greater water depths, and as such, estimations of a scaling factor must be conservative to minimise the risk of underestimating the noise. However, it is recognised that the available data on which to base the scaling factor is limited and the extrapolation that must be made is significant.

6.3.1.5 The operational source levels (as SPL_{RMS}) for the measured sites are given in **Table 66** (Cheesman, 2016), with an estimated source level for Hornsea Four in the bottom row. To predict operational WTG noise levels at Hornsea Four, the level sampled at each of the sites has been taken and then a linear correction factor has been included to scale up the source levels (**Figure 18**). A linear fit was applied to the data as this was the most conservative extrapolation, leading to the highest, and thus maximum design, estimation of source level noise from the larger 305 m diameter rotor WTGs. This resulted in an estimated source level of 165.4 dB SPL_{RMS} @ 1 m, 19.4 dB higher than the 120 m diameter rotor WTG; the largest for which noise data is currently available.

Table 66: Measured operational WTG noise taken at operational wind farms, and the predicted source level for the maximum turbine size considered at Hornsea Four.

Site	Unweighted source level
Lynn (107 m)	141 dB re 1 μPa (RMS) @ 1 m
Inner Dowsing (107 m)	142 dB re 1 μPa (RMS) @ 1 m
Gunfleet Sands 1 & 2 (107 m)	145 dB re 1 μPa (RMS) @ 1 m
Gunfleet Sands 3 (120 m)	146 dB re 1 μPa (RMS) @ 1 m
Hornsea Four (305 m)	165.4 dB re 1 μPa (RMS) @ 1 m

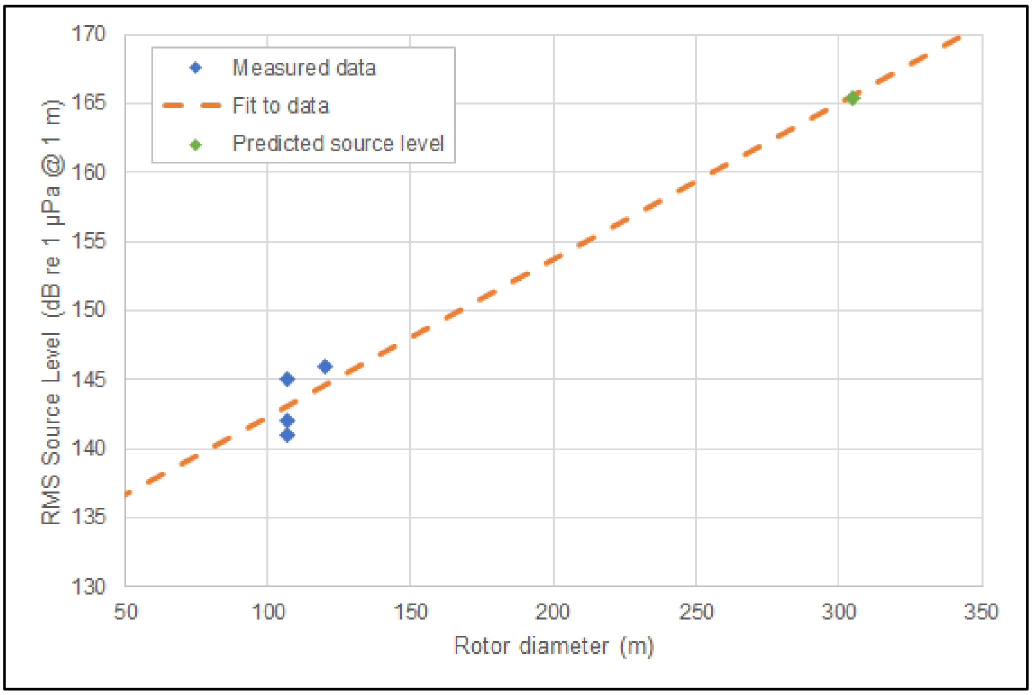

Figure 18: Extrapolated source levels from operational WTGs plotted with a linear fit to estimate the source level for a WTG with a rotor diameter of 305 m.

6.3.1.6 A summary of the predicted impact ranges is given in **Table 67** and **Table 68**. All SEL_{cum} criteria use the same assumptions as presented in **Section 2.2.2**, and ranges smaller than

50 m (single strike) and 100 m (cumulative) have not been presented. The operational WTG source is considered a non-impulsive sound by Southall *et al.* (2019) and a continuous source by Popper *et al.* (2014).

Table 67: Summary of the impact ranges for operational WTGs using the non-impulsive noise criteria from Southall *et al.* (2019) for marine mammals at Hornsea Four.

Southall et al. (2019)		Operational WTG (305 m)
PTS	199 dB (LF SEL_{cum})	< 100 m
	198 dB (HF SEL_{cum})	< 100 m
	173 dB (VHF SEL_{cum})	< 100 m
	201 dB (PCW SEL_{cum})	< 100 m
TTS	179 dB (LF SEL_{cum})	< 100 m
	178 dB (HF SEL_{cum})	< 100 m
	153 dB (VHF SEL_{cum})	< 100 m
	181 dB (PCW SEL_{cum})	< 100 m

Table 68: Summary of the impact ranges for shopping and continuous noise from Popper *et al.* (2014) for operational WTGs for species of fish (swim bladder involved in hearing) at Hornsea Four.

Popper et al. (2014)	Operational WTG (305 m)
Recoverable injury *170 dB (48 hours) Unweighted SPL_{RMS}*	< 50 m
TTS *158 dB (12 hours) Unweighted SPL_{RMS}*	< 50 m

6.3.1.7 These results show that, for operational WTGs, any injury risk is minimal. Taking both sets of results into account (operational WTG noise and other noise sources related to construction, see **Section 6.2**), and comparing them to the impact piling results in the **Section 5** (specifically **Section 5.2**), it is clear that noise from impact piling results in much greater levels and impact ranges, and hence should be considered the activity which has the potential to have the greatest effect during the construction and lifecycle of Hornsea Four.

6.4 Decommissioning noise

6.4.1.1 Decommissioning noise also needs to be considered even in the light of the expected 35 years of operational life. With present technologies, the following decommissioning techniques have been considered:

- High-powered water jetting/cutting apparatus; and
- Grinding or drilling techniques.

6.4.1.2 It is also worth noting that by the time Hornsea Four is decommissioned, there are likely to be many more options available for decommissioning.

6.4.1.3 Water jetting and grinding techniques would produce noise at a much lower and less intrusive level than impact piling. Decommissioning is anticipated to take approximately five years, about the same duration as expected for construction. Thus, the overall impact is expected to be lower than during the construction phase.

6.4.1.4 Only closer to the time of decommissioning, when local marine life is known and understood, can a realistic and useful assessment of the effects of the noise, and the appropriate mitigation, be carried out. Subsequently, it seems clear that a separate and new impact assessment will be required closer to the time of decommissioning and no further discussion will be made here.

7 Discussion

7.1.1.1 This report presents a study presenting the potential levels of underwater noise during the development of Hornsea Four; primarily focussing on impact piling noise as this has been recognised as the activity known to have the greatest potential underwater noise levels.

7.1.1.2 The level of underwater noise from the installation of monopiles and pin piles during construction has been estimated using the INSPIRE subsea noise modelling software, which considers a wide variety of input parameters including bathymetry, hammer blow energy and the frequency content of the noise.

7.1.1.3 Four representative locations were chosen at Hornsea Four array area and the nearby HVAC location to give spatial variation as well as changes in water depth. At each location four scenarios were considered, covering maximum design and most-likely parameters for installing monopiles and pin piles at each location. The maximum design maximum blow energies used for modelling were 5,000 kJ for monopiles and 2,500 kJ for pin piles. Lower blow energies of 4,000 kJ and 1,750 kJ were used for the most-likely scenarios. The results showed that greater levels of noise are predicted along transects travelling through deeper water.

7.1.1.4 The modelling results were analysed in terms of relevant noise metrics and criteria to aid assessments of the impacts from the impact piling noise on marine mammals and fish. Southall *et al.* (2019) was used for various species of marine mammal using unweighted SPL_{peakj} and weighted SEL_{cum} metrics. The largest impact ranges for these criteria are summarised in **Table 69**. For all cases in the table below, the maximum design modelling parameters at the East location provided the largest impact ranges.

Table 69: Summary of the maximum predicted impact ranges for marine mammal criteria (E location, maximum design parameters).

Southall et al. (2019) (weighted SEL_{cum})		Maximum design monopile (5,000 kJ)	Maximum design pin pile (2,500 kJ)
PTS	Low-frequency cetacean (LF)	13 km	9.7 km
	High-frequency cetacean (HF)	< 100 m	< 100 m
	Very high-frequency cetacean (VHF)	1.9 km	10 km
	Phocid Carnivore in Water (PCW)	670 m	< 100 m
TTS	Low-frequency cetacean (LF)	43 km	40 km
	High-frequency cetacean (HF)	< 100 m	< 100 m
	Very high-frequency cetacean (VHF)	25 km	39 km
	Phocid Carnivore in Water (PCW)	22 km	17 km

7.1.1.5 Impact range criteria from Popper *et al.* (2014) was used for various groups of fish, with ranges of up to 1.3 km for recoverable injury (SPL_{peak}) and out to 26 km (fleeing) and 33 km (stationary) for TTS (SEL_{cum}) at the maximum blow energies when considering the maximum design parameters for monopiles at the East modelling location.

7.1.1.6 Noise sources other than piling have been considered using a high-level, simple modelling approach, including dredging, drilling, cable laying, rock placement, trenching, vessel noise and operational WTG noise. The predicted noise levels for the other construction noise sources and during WTG operation are well below those predicted for impact piling noise. The risk of any potential injurious effects to fish or marine mammals from these sources are expected to be negligible as the noise emissions from these are very close to, or below, the appropriate injury criteria at the source of the noise. Noise during decommissioning techniques has the potential for considerable effect, however a separate and new impact assessment will be required once the techniques are understood.

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