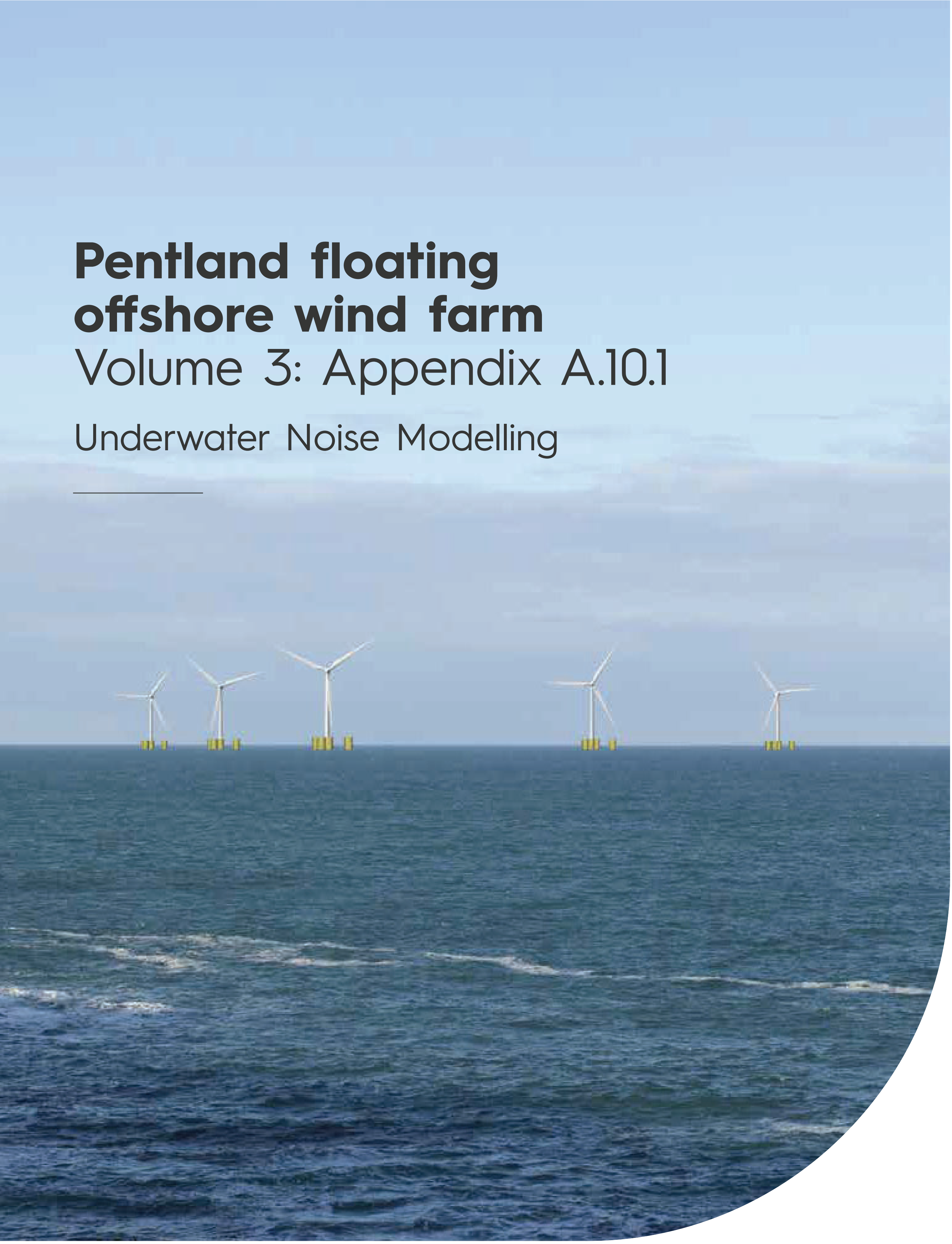
Pentland floating offshore wind farm

Volume 3: Appendix A.10.1

Underwater Noise Modelling



PENTLAND
FLOATING
OFFSHORE
WIND FARM

OFFSHORE EIAR (VOLUME 3): TECHNICAL APPENDICES

APPENDIX 10.1: UNDERWATER NOISE MODELLING

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Pentland Floating Offshore Wind Farm (PFOWF): Underwater noise modelling

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Glossary

Term	Definition
Decibel (dB)	A customary scale 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 $20\log_{10}(actual\ pressure/reference\ pressure)$. The standard reference for underwater sound is 1 micropascal (μPa). The dB symbol is followed by a second symbol identifying the specific reference value (e.g., re 1 μPa).
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 are associated with a sound wave.
Permanent Threshold Shift (PTS)	A permanent total or partial loss of hearing caused by acoustic 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 is an expression of sound pressure using the decibel (dB) scale; the standard frequency pressures of which are 1 μPa for water and 20 μPa for air.
Temporary Threshold Shift (TTS)	Temporary reduction of hearing acuity because of exposure to sound over time. Exposure to high levels of sound over relatively short time periods could cause the same level 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.
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 in air, or the filters used by Southall *et al*. (2019) for marine mammals.

1 Introduction

The Pentland Floating Offshore Wind Farm (PFOWF) is a proposed wind farm located off the northern coast of mainland Scotland. Subacoustech Environmental Ltd. have undertaken detailed underwater noise modelling and analysis in relation to potential impact from piling noise at the site as a part of the construction of a floating wind array.

A map showing the site of PFOWF is shown in Figure 1-1. The figure includes the location used for underwater noise modelling.

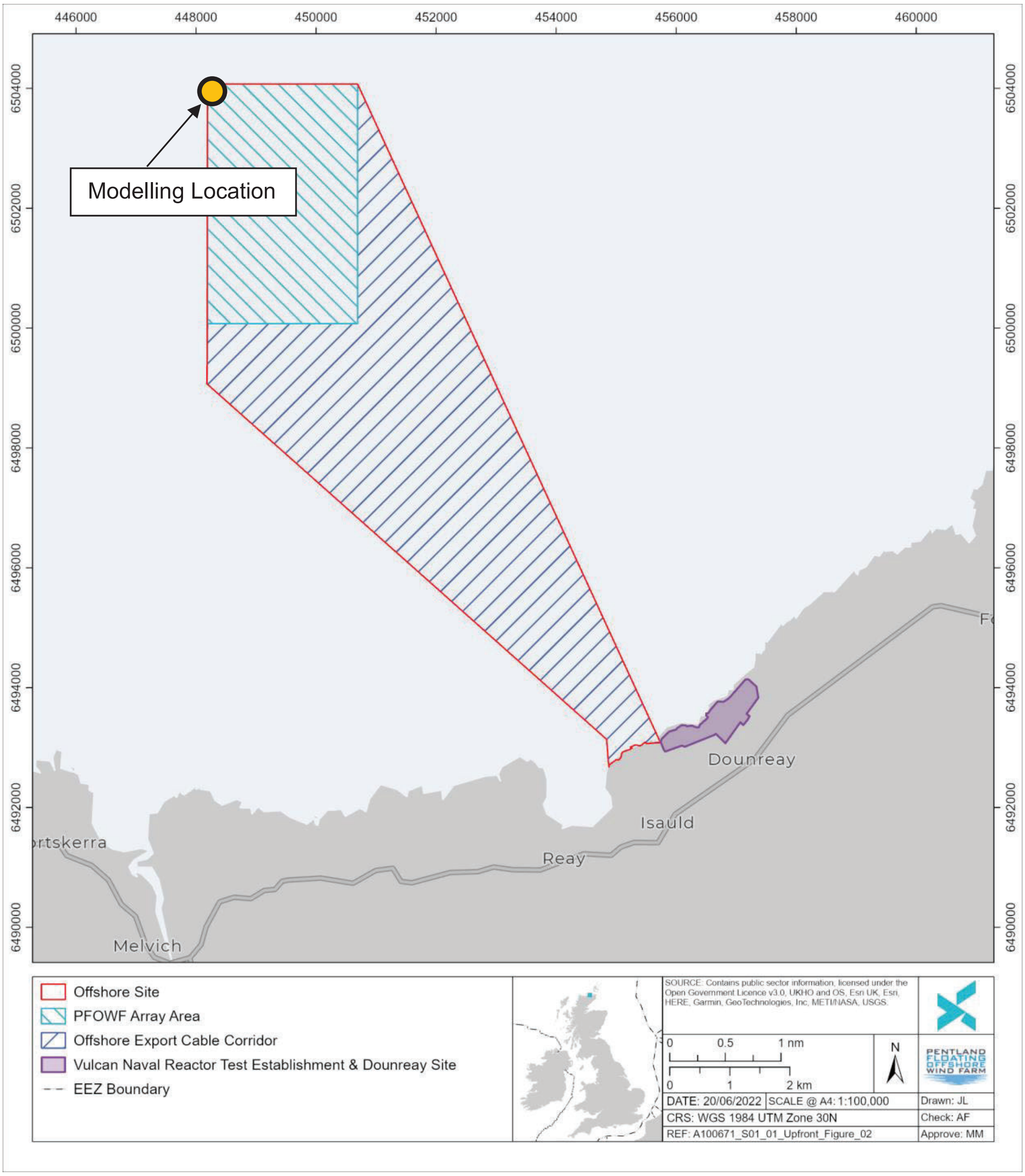

Figure 1-1 Overview map showing the Pentland Floating Offshore Wind Farm boundary and the approximate location used for the modelling.

This report presents a detailed assessment of the potential underwater noise during the construction and operation of Pentland Floating Offshore Wind Farm and its effects, and covers the following:

- A review of background information on the units for measuring and assessing underwater noise (Section 2.1);
- A review of underwater noise metrics and criteria used to assess the possible environmental effect in marine receptors (Section 2.2);
- Discussion of the approach, input parameters and assumptions for the detailed noise modelling undertaken (Section 3);
- Presentation and interpretation of the detailed subsea noise modelling for impact piling with regards to the effect on marine mammals and fish using various metrics and criteria (Section 4);
- Noise modelling of the other noise sources expected around the construction and operation of PFOWF including cable laying, rock placement, dredging, trenching, vessel activity, operational WTG noise, and Unexploded Ordnance (UXO) clearance (Section 5); and
- Summary and conclusions (Section 6).

2 Background to underwater noise metrics

2.1 Underwater noise

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 pressure associated with underwater sound tends 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*. 2003; Nedwell *et al.* 2007).

It should be noted that underwater noise levels such as those stated in this report should not be confused with noise levels in air, which use a different scale.

2.1.1 Units of measurement

Sound measurements underwater are usually expressed using the decibel (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 each doubling of sound level will cause a roughly equal increase of “loudness.”

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.

The dB scale represents a ratio. 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 that is the lower threshold of human hearing.

When used with sound pressure, the pressure is squared. So that variations in the units agree, the sound pressure must be specified as units of Root Mean Square (RMS) pressure squared. This is equivalent to expressing the sound as:

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

For underwater sound, a unit of 1 µPa is typically used as the reference unit (P_{ref}); 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 Sound Pressure Level (SPL)

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 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.

Where SPL is used to characterise transient pressure waves, such as that from impact piling, seismic airgun or underwater blasting, 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 a tenth of a second, the mean taken over a tenth of a second will be ten times higher than the mean averaged over one second. Often, transient sounds such as these are quantified using “peak” SPLs or Sound Exposure Levels (SELs).

Unless otherwise defined, all SPL noise levels in this report are referenced to 1 μPa. It is recognised that ISO 18405 (2017) defines SPL in reference to the unit 1 μPa². As the key publications used in this assessment use the unit 1 μPa, this terminology will also be used in this report. This does not affect any results or values.

2.1.3 Peak Sound Pressure Level (SPL_{peak})

Peak SPLs are often used to characterise transient sound from impulsive sources, such as percussive impact piling. 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.

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 is considered. Where the wave is symmetrically distributed in positive and negative pressure, the peak-to-peak pressure will be twice the peak level, or 6 dB higher (see section 2.1.1).

2.1.4 Sound Exposure Level (SEL)

When considering the noise from transient sources, 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, 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 injury ranges for fish and marine mammals from various noise sources (Popper *et al.*, 2014 and Southall *et al.*, 2019).

The SEL sums the acoustic energy over a measurement period, and effectively takes account of both the SPL of the sound and the duration it 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 total duration of the sound in seconds, and t is the time in seconds. The SE is a measurement of acoustic energy and has units of Pascal squared seconds (Pa^2s).

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

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

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.

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 10 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).

Where a single impulse noise such as the soundwave from a pile strike is considered in isolation, this can be represented by a “single strike" SEL or SEL_{ss}.

2.2 Analysis of environmental effects

Over the last 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 adverse impacts in species is dependent upon the incident sound level, source frequency, duration of exposure, and/or repetition rate of an impulsive sound (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.

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.

The following sections discuss the underwater noise criteria used in this study with respect to species of marine mammals and fish that may be present in the study area.

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

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

At the time of writing these are used as the most up to date and authoritative criteria for assessing environmental effects for use in impact assessments.

2.2.1 Marine mammals

The Southall *et al*. (2019) paper is effectively an update of the previous Southall *et al.* (2007) paper and provides identical thresholds to those from the National Marine Fisheries Service (NMFS) (2018) guidance for marine mammals.

The Southall *et al*. (2019) guidance groups marine mammals into categories of similar species and applies filters to the unweighted noise to approximate the hearing sensitivities of the receptor. The hearing groups given in Southall *et al*. (2019) are summarised in Table 2-1 and Figure 2-1. Further groups for sirenians and other marine carnivores in water are also given, but these have not been used for this study as those species are not commonly found in the region.

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 porpoise)
Phocid carnivores in water (PCW)	50 Hz to 86 kHz	True seals (including harbour seal)

Table 2-1 Marine mammal hearing groups (from Southall et al., 2019)

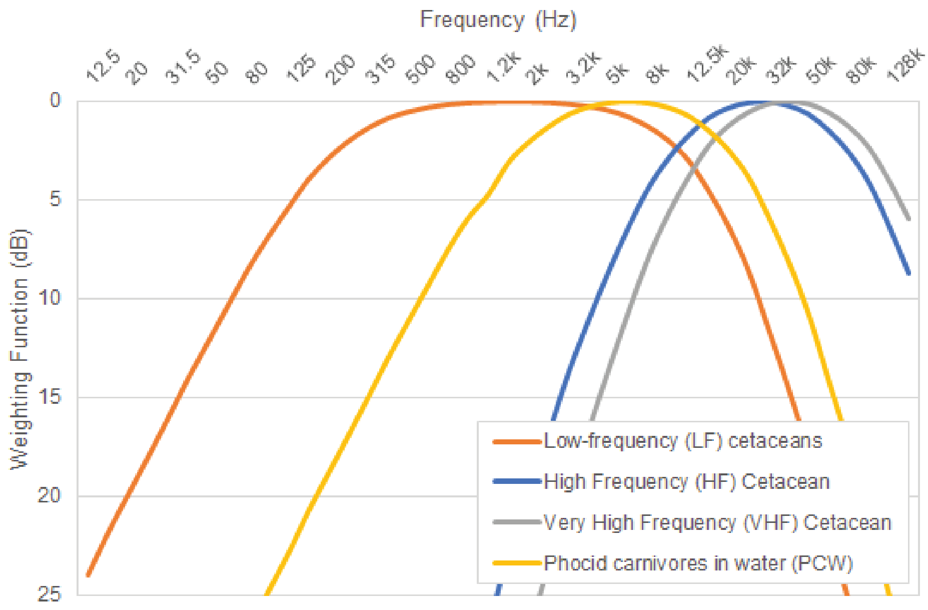

Figure 2-1 Auditory weighting functions for low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), and phocid carnivores in water (PCW) (from Southall et al., 2019)

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, vibro-piling, drilling and other low-level continuous noises are considered non-impulsive. A non-impulsive noise does not necessarily have to have a long duration.

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.

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

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 2-2 Single strike SPL_{peak} criteria for PTS and TTS in marine mammals (Southall et al., 2019)

Southall *et al.* (2019)	Weighted SEL_{cum} (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

Table 2-3 Impulsive SEL_{cum} criteria for PTS and TTS in marine mammals (Southall et al., 2019)

Where SEL_{cum} are required for marine mammals, a fleeing animal model has been used. This assumes that a receptor, when exposed to high noise levels, will swim away from the noise source. For this, the following flee speeds have been used for each marine mammal group:

- 2.1 ms^{-1} for low-frequency cetaceans (LF) (SNH, 2016);
- 1.52 ms^{-1} for high-frequency cetaceans (HF) (Bailey and Thompson, 2006);
- 1.4 ms^{-1} for very high-frequency cetaceans (VHF) (SNH, 2016); and
- 1.8 ms^{-1} for phocid carnivores in water (PCW) (SNH, 2016).

These are considered worst case assumptions as marine mammals are expected to swim much faster under stress conditions.

2.2.2 Fish

The large number of, and variation in, fish species leads to a greater challenge in 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 that are not present in UK waters (e.g., McCauley *et al.*, 2000) or measurement data not intended to be used as criteria (Hawkins *et al.*, 2014), 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.

The Popper *et al.* (2014) study groups species of fish by whether they possess a swim bladder, and whether it is involved in its hearing; a group for fish eggs and larvae is also included. The guidance also gives specific criteria (as both unweighted SPL_{peak} and unweighted SEL_{cum} values) for a variety of noise sources.

For this study, criteria for impact piling, continuous noise sources, and explosions have been considered, this is summarised in Table 2-4 to Table 2-6.

Type of animal	Mortality and potential mortal injury	Impairment	
		Recoverable injury	TTS
Fish: no swim bladder	> 219 dB SEL_{cum} > 213 dB peak	> 216 dB SEL_{cum} > 213 dB peak	>> 186 dB SEL_{cum}
Fish: swim bladder is not involved in hearing	210 dB SEL_{cum} > 207 dB peak	203 dB SEL_{cum} > 207 dB peak	> 186 dB SEL_{cum}
Fish: swim bladder involved in hearing	207 dB SEL_{cum} > 207 dB peak	203 dB SEL_{cum} > 207 dB peak	186 dB SEL_{cum}
Sea turtles	> 210 dB SEL_{cum} > 207 dB peak	See Table 2-7	See Table 2-7
Eggs and larvae	> 210 dB SEL_{cum} > 207 dB peak	See Table 2-7	See Table 2-7

Table 2-4 Criteria for mortality and potential mortal injury, recoverable injury and TTS in species of fish from impact piling noise (Popper et al., 2014)

Type of animal	Impairment	
	Recoverable injury	TTS
Fish: swim bladder involved in hearing	170 dB RMS for 48 hrs	158 dB RMS for 12 hrs

Table 2-5 Criteria for recoverable injury and TTS in species of fish from continuous noise sources (Popper et al., 2014)

Type of animal	Mortality and potential mortal injury
Fish: no swim bladder	229 – 234 dB peak
Fish: swim bladder is not involved in hearing	229 – 234 dB peak
Fish: swim bladder involved in hearing	229 – 234 dB peak
Sea turtles	229 – 234 dB peak
Eggs and larvae	> 13 mm/s peak velocity

Table 2-6 Criteria for potential mortal injury in species of fish from explosions (Popper et al., 2014)

Where insufficient data are available, Popper *et al*. (2014) also gives 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 2-7 to Table 2-9.

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder	See Table 2-4	See Table 2-4	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	See Table 2-4	See Table 2-4	(N) Moderate (I) Low (F) Low	(N) High (I) Moderate (F) Low
Fish: swim bladder involved in hearing	See Table 2-4	See Table 2-4	(N) High (I) High (F) Moderate	(N) High (I) High (F) Moderate
Sea turtles	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) High (I) Moderate (F) Low
Eggs and larvae	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low	(N) Moderate (I) Low (F) Low

Table 2-7 Summary of the qualitative effects on species of fish from impact piling noise (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	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 is 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 Table 2-5	See Table 2-5	(N) High (I) High (F) High	(N) High (I) Moderate (F) Low
Sea turtles	(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) High (I) Moderate (F) Low
Eggs and larvae	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) Low (I) Low (F) Low	(N) High (I) Moderate (F) Low	(N) Moderate (I) Moderate (F) Low

Table 2-8 Summary of the qualitative effects on fish from continuous noise from Popper et al. (2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Type of animal	Impairment			Behaviour
	Recoverable injury	TTS	Masking	
Fish: no swim bladder	(N) High (I) Low (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) Moderate (F) Low
Fish: swim bladder is not involved in hearing	(N) High (I) High (F) Low	(N) High (I) Moderate (F) Low	N/A	(N) High (I) High (F) Low
Fish: swim bladder involved in hearing	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
Sea turtles	(N) High (I) High (F) Low	(N) High (I) High (F) Low	N/A	(N) High (I) High (F) Low
Eggs and larvae	(N) High (I) Low (F) Low	(N) High (I) Low (F) Low	N/A	(N) High (I) Low (F) Low

Table 2-9 Summary of the qualitative effects on species of fish from explosions (Popper et al., 2014) (N = Near-field; I = Intermediate-field; F = Far-field)

Both fleeing animal and stationary animal models have been used to assess the SEL_{cum} criteria for fish. It is recognised that there is limited evidence for fish fleeing from high level 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. For those species that flee, the speed chosen for this study of 1.5 ms^{-1} is relatively slow in relation to data from Hirata (1999) and thus is considered somewhat conservative.

Although it is feasible that some species will not flee, those that are likely to remain are thought more likely to 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."

Stationary animal modelling has been included in this study, based on research from Hawkins *et al*. (2014) and other modelling for similar EIA projects. However, basing the modelling on a stationary (zero flee speed) receptor is likely to greatly overestimate the potential risk to fish species, assuming that an individual would remain in the high noise level region of the water column, especially when considering the precautionary nature of the parameters already built into the cumulative exposure calculations.

2.2.2.1 Particle motion

The criteria defined in the above section all define the noise impacts on fishes in terms of sound pressure or sound pressure-associated functions (i.e., SEL). It has been identified by researchers (e.g., Popper and Hawkins, 2019; Nedelec *et al*., 2016; Radford *et al.*, 2012) that species of fish, as well as invertebrates, are more sensitive to particle motion than pressure. Particle motion describes the back-and-forth movement of a tiny theoretical 'element' of water, substrate or other media as a sound wave passes, rather than the pressure caused by the action of the force created by this movement. Particle motion is usually defined in reference to the velocity of the particle (often a peak particle velocity, PPV), but sometimes the related acceleration or displacement of the particle is used. Note that species in the "Fish: swim bladder involved in hearing" category in Popper *et al*. (2014), the most sensitive species category, are sensitive to sound pressure.

Popper and Hawkins (2018) state that in derivation of the sound pressure-based criteria in Popper *et al.* (2014) it may be the unmeasured particle motion detected by the fish, to which the fish were responding: there is a correlation between particle motion and sound pressure in a medium. This correlation is very difficult to define where the sound field is complex, especially when close to the noise source or where there are multiple reflections of the sound wave in shallow water. Even these terms "shallow" and "close" do not have simple definitions.

The primary reason for the continuing use of sound pressure for the criteria, despite particle motion appearing to be the physical measure to which many of the fish react or sense, is a lack of data (Popper and Hawkins, 2018) both in respect of predictions of the particle motion level as a consequence of a noise source such as piling, and a lack of knowledge of the sensitivity of a fish, or a wider category of fishes, to a particle motion value. There continue to be calls for additional research on the levels of and effects with respect to levels of particle motion. Until sufficient data are available to enable revised thresholds based on the particle motion metric, Popper *et al.* (2014) continues to be the best source of criteria in respect to fish impacts (Andersson *et al.,* 2016, Popper and Hawkins*,* 2019).

3 Modelling methodology

3.1 Modelling introduction

To estimate the underwater noise levels likely to arise during the construction and operation of the proposed PFOWF, 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).

The noise source most important to consider is impact piling due to the noise level and duration it will be present (Bailey *et al*., 2014). As such, the noise related to impact piling activities is the primary focus of this study.

The modelling of impact piling has been undertaken using the INSPIRE underwater noise model. INSPIRE (currently version 5.1) is a semi-empirical underwater noise propagation model based around a combination of numerical modelling, (a combined geometric and energy flow/hysteresis loss method), 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 as such is very well suited to the region around Pentland Firth. The model has been tuned for accuracy using over 80 datasets of underwater noise propagation from monitoring around offshore piling activities.

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.

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

- Impact piling hammer blow energies;
- Soft start, ramp up profile, and strike rate;
- Total duration of impact piling; and
- Receptor swim speeds.

A simple modelling approach has been used for noise sources other than piling that may be present during construction and operation of PFOWF, and these are discussed in section 5.

3.2 Modelling confidence

The INSPIRE model is semi-empirical and thus a validation process is inherently built into the development. 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 necessary, the model can be adjusted accordingly. Currently over 80 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, an average fit is used.

In addition, INSPIRE is also validated by comparing the noise levels outputted from the model with measurements and modelling undertaken by third parties, as well as in Thompson *et al.* (2013).

The current version of INSPIRE (version 5.1) 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. This gave a database of single strike noise levels referenced to a specific blow energy at a specific range. This analysis showed that, based on the most up to date measurement data for large piles at high blow energies, the previous versions of INSPIRE tended to overestimate the predicted noise levels at these blow energies.

Previous iterations of the INSPIRE model have endeavoured to give a worst-case estimate of underwater noise levels produced by impact piling. There is always some natural variability with underwater noise measurements, even when considering measurements of pile strikes under the same conditions (i.e., at the same blow energy, taken at the same range). For example, there can be variations in noise level of up to five or even 10 dB, as seen in Bailey *et al*. (2010) and the data shown in Figure 3-1. When modelling using the upper bounds of this range, in combination with other worst case parameter selections, conservatism can be compounded and create excessively overcautious predictions, especially when calculating SEL_{cum}. With this in mind, the current version of the INSPIRE model attempts to calculate closer to the average fit of the measured noise levels at all ranges.

Figure 3-1 presents a small selection of measured impact piling noise data plotted against outputs from INSPIRE. The plots show data points from measured data (in blue) plotted alongside modelled data (in orange) using INSPIRE version 5.1, matching the pile size, blow energy and range from the measured data. These show the fit to the data, with the INSPIRE model data points sitting, more or less, in the middle of the measured noise levels at each range. When combined with the worst-case assumptions in parameter selection, modelled results will remain precautionary.

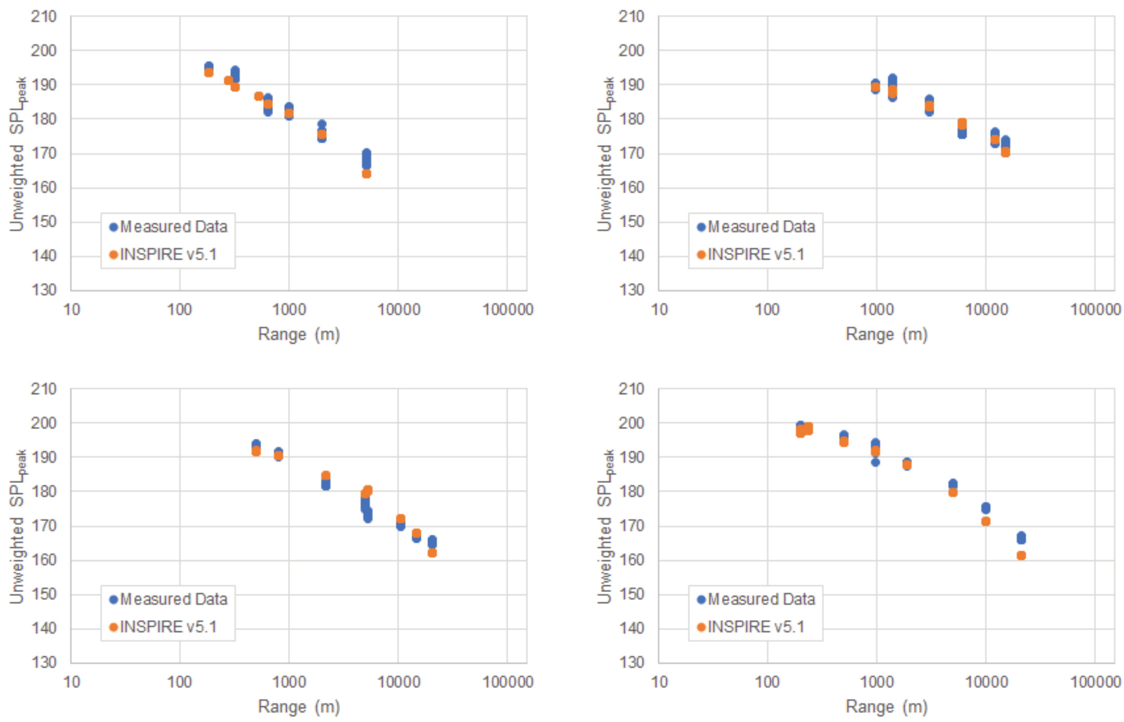

Figure 3-1 Comparison between example measured impact piling data (blue points) and modelled data using INSPIRE version 5.1 (orange points)

Top Left: 1.8 m pile, Irish Sea, 2010; Top Right: 9.5 m pile, North Sea, 2020; Bottom Left: 6.1 m pile, Southern North Sea, 2009; Bottom Right: 6 m pile, Southern North Sea, 2009.

3.3 Modelling parameters

3.3.1 Modelling locations

The PFOWF site covers an area of approximately 20 km^2. Water depth within the site ranges from less than 70 m up to a maximum of 104 m. A location at the Northwest extremity of the site has been selected to model noise propagation. This location was chosen as the deepest part of the site and the greatest distance from the mainland. These factors are likely to result in a worst case assessment for the impact of sound propagation as the deep water allows for the greatest area to be considered throughout the modelling process. Details of the location are summarised in Table 3-1 and illustrated in Figure 1-1.

Latitude	Longitude	Water depth (mean tide)
58.6737°N	-003.8932°W	104 m

Table 3-1 Summary of the underwater noise modelling location at Pentland Firth

3.3.2 Impact piling parameters

The impact piling scenario that has been considered in this report considers a worst case (i.e. largest) pile diameter, total piling time duration, and hammer energy ramp up used in construction. All piling will take place below the surface of the water. The changing surface area of the pile in the water as it is driven affects its sound radiation, and this is included in the model. Details of the modelled scenario are as follows:

- 5 m diameter tubular pile, 20 m max length in the water for sound radiation.
- Installed using a hammer with maximum blow energy of 2500 kJ,
- 14912 blows over a total period of 8 hours with
- Three piles installed in a 24-hour period (resulting in 44736 blows over 24 hours).

This scenario represents the cautious worst-case scenario for impact piling as it considers the maximum possible pile size, piling durations, and blow energies. The scenario may be considered highly precautionary due to hammer capacity, pile fatigue, the likelihood of three piles all being installed within 24 hours with the worst-case parameters, or other on-site practicalities. However, this has been provided to demonstrate this worst case.

Worst case scenario	5%	10%	20%	40%	100%
Blow energy	125 kJ	250 kJ	500 kJ	1000 kJ	2500 kJ
Number of blows	80	80	80	80	14592
Duration	5 min	5 mins	5 mins	5 mins	456 mins
Blow rate	16 bl/min	16 bl/min	16 bl/min	16 bl/min	32 bl/min

Table 3-2 Summary of the piling scenario soft start and ramp up parameters for calculating SEL_{cum} for impact piling using a 2500 kJ hammer. Modelling assumes 3 piles installed per day.

3.3.3 Source levels

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

It is worth noting that the 'source level' technically does not exist in the context of many shallow water noise sources (Heaney *et al.*, 2020). In practice, in underwater noise modelling such as this, it is effectively an 'apparent source level' and simply a value that can be used to produce correct noise levels at range (for a specific model), as required in impact assessments.

The unweighted, single strike SPL_{peak} and SEL_{ss} source levels estimated for this study are provided in Table 3-3. These figures are presented in accordance with typical requests by regulatory authorities, although as indicated above they are not necessarily compatible or comparable with any other model or predicted source levels.

	SPL_{peak} source levels	**SEL_{ss} source levels**
Worst case scenario 5 m diameter / 20 m length / 2500 kJ max	241.1 dB re 1 μPa @ 1 m	221.8 dB re 1 μPa^{2}s @ 1 m

Table 3-3 Summary of the unweighted source levels used for modelling

3.3.4 Environmental conditions

With the inclusion of measured noise propagation data for similar offshore piling operations in UK waters, the INSPIRE model intrinsically accounts for various environmental conditions. This includes the differences that can occur with the temperature and salinity of the water, as well as the sediment type surrounding the site. Data from the Marine Themes Digital Elevation Model show that the seabed surrounding the Pentland Firth site is generally made up of various combinations of sand and gravelly sand.

Digital bathymetry, from the European Marine Observation and Data Network (EMODnet), has been used for this modelling. Mean tidal depth has been used throughout.

4 Modelling results

The following sections present the modelled impact ranges for impact piling noise following the parameters detailed in section 3.3, split into the marine mammal criteria from Southall *et al*. (2019) (section 4.1), and the fish criteria from Popper *et al*. (2014) (section 4.2).

For the results presented throughout this section, any predicted ranges smaller than 50 m and areas less than 0.01 km^2 for single strike criteria, and ranges smaller than 100 m and areas less than 0.1 km^2 for cumulative criteria, have not been presented. At ranges this close to the noise source, the modelling processes are unable to model to a sufficient level of accuracy due to acoustic effects near the pile. Ranges are given as "less than" this limit.

The largest ranges are predicted for LF cetaceans using the Southall *et al*. (2019) criteria.

4.1 Marine mammal criteria

Table 4-1 and Table 4-2 present the modelling results in terms of the Southall *et al*. (2019) marine mammal criteria, covering impact piling parameters described in section 3.3.2. All SEL_{cum} ranges assume the animal flee speeds in section 2.2.1.

The largest predicted PTS impact ranges are for LF cetaceans, with maximum predicted impact ranges of up to 27 km when considering tubular piles installed using the worst case piling parameters. Large ranges are also predicted for VHF cetaceans using the same parameters, with maximum PTS ranges of up to 8.7 km.

4.1.1 *Worst case scenario - 5 m diameter pile, max energy 2500 kJ*

Southall *et al*. (2019) **Unweighted SPL_{peak}**		**Piling Scenario– Worst case**			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**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)	0.98 km^2	560 m	560 m	560 m
	PCW (218 dB)	<0.01 km^2	<50 m	<50 m	<50 m
TTS	**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)	6.4 km^2	1.4 km	1.4 km	1.4 km
	PCW (212 dB)	0.04 km^2	100 m	100 m	100 m

Table 4-1 Summary of the modelled impact ranges for the worst case scenario using the impulsive Southall et al. (2019) unweighted SPL_{peak} criteria for marine mammals

Southall *et al*. (2019) **Weighted SEL_{cum}**		**Piling Scenario – Worst Case**			
		Area	**Max range**	**Min range**	**Mean range**
PTS	**LF** (183 dB)	1000 km^2	27 km	7.3 km	17 km
	HF (185 dB)	<0.1 km^2	<100 m	<100 m	<100 m
	VHF (155 dB)	150 km^2	8.7 km	4.6 km	6.9 km
	PCW (185 dB)	<0.1 km^2	<100 m	<100 m	<100 m
TTS	**LF** (168 dB)	5400 km^2	86 km	9.1 km	36 km
	HF (170 dB)	<0.1 km^2	<100 m	<100 m	<100 m
	VHF (140 dB)	2600 km^2	49 km	9 km	26 km
	PCW (170 dB)	540 km^2	18 km	6.4 km	12 km

Table 4-2 Summary of the modelled impact ranges for the worst case scenario using the impulsive Southall et al. (2019) weighted SEL_{cum} criteria for marine mammals assuming a fleeing animal

4.2 Fish criteria

Table 4-3 and Table 4-4 present the impact ranges for fish using the Popper *et al*. (2019) criteria for impact piling, covering the soft start and ramp up scenario described in section 3.3.2.

The largest recoverable injury ranges in species of fish are predicted for the worst case scenario. When considering a fleeing receptor, ranges of up to 400 m (207 dB SPL_{peak} threshold) are predicted. When a stationary animal model is used the predicted ranges increase up to 16 km (203 dB SELcum threshold). Maximum TTS impact ranges (186 dB SEL_{cum} threshold) are predicted out to 30 km for a fleeing animal, up to 62 km for a stationary receptor.

4.2.1 Worst case scenario - 5 m diameter pile, max energy 2500 kJ

Popper *et al*. (2014) **Unweighted SPL_{peak}**	**Piling Scenario – Worst Case**			
	Area	**Max range**	**Min range**	**Mean range**
213 dB	0.03 km²	100 m	100 m	100 m
207 dB	0.20 km²	250 m	250 m	250 m

Table 4-3 Summary of the modelled impact ranges for the worst case scenario using the Popper et al. (2014) unweighted SPL_{peak} impact piling criteria for fish

Popper *et al*. (2014) **Unweighted SEL_{cum}**		**Piling Scenario – Worst Case**			
		Area	**Max range**	**Min range**	**Mean range**
Fleeing (1.5 m/s)	219 dB	<0.1 km²	<100 m	<100 m	<100 m
	216 dB	<0.1 km²	<100 m	<100 m	<100 m
	210 dB	<0.1 km²	<100 m	<100 m	<100 m
	207 dB	<0.1 km²	<100 m	<100 m	<100 m
	203 dB	<0.1 km²	<100 m	<100 m	<100 m
	186 dB	1.3 km²	30 km	8.2 km	19 km
Stationary	219 dB	10 km²	1.8 km	1.8 km	1.8 km
	216 dB	25 km²	2.9 km	2.8 km	2.8 km
	210 dB	140 km²	6.7 km	6.4 km	6.6 km
	207 dB	280 km²	10 km	8.9 km	9.5 km
	203 dB	630 km²	16 km	11 km	14 km
	186 dB	4500 km²	62 km	11 km	34 km

Table 4-4 Summary of the modelled impact ranges for the worst case scenario using the Popper et al. (2014) unweighted SEL_{cum} impact piling criteria for fish assuming both fleeing and stationary animal models

5 Other noise sources

5.1 Introduction

Although impact piling is expected to be the greatest noise source during offshore 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.

Table 5-1 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 PFOWF.

Activity	Description
Cable laying	Noise from the cable laying vessel and any other associated noise during the offshore cable installation.
Dredging	Dredging may be required on site for seabed preparation work for certain anchor options, as well as for the export cable and array cable installation. Suction dredging has been assumed as a worst-case.
Trenching	Plough trenching may be required during offshore cable installation.
Rock placement	Included as an example of protection for offshore cables (cable crossings and cable protection) and scour protection around anchors.
Vessel noise	Jack-up barges for piling substructure and WTG installation. Other large and medium sized vessels 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 provides for up to 7 WTGs with a maximum power output of 20 MW.
UXO clearance	There is a possibility that Unexploded Ordnance (UXO) may exist within the boundaries of PFOWF, which would need to be cleared before construction can begin. If this is required, this will be dealt with under a separate application and consent.

Table 5-1 Summary of the possible noise making activities at PFOWF other than impact piling

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 either quiet compared to impact piling (e.g., cable laying and dredging), or where detailed modelling would imply unjustified accuracy (e.g., where data is limited such as with large operational WTG noise or UXO detonation). The high-level overview of modelling that has been presented here is considered sufficient and 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 bathymetric dependence.

Most of these activities are considered in Section 5.2, with operational WTG noise and UXO clearance assessed in Sections 5.3 and 5.4 respectively.

5.2 Noise making activities

For the purposes of identifying the greatest noise levels, approximate subsea noise levels have been predicted using a simple modelling approach based on measurement data from Subacoustech Environmental's own underwater noise measurement database, scaled to relevant parameters for the site and to the specific noise sources to be used. The calculation of underwater noise transmission loss for the non-impulsive sources is based on an empirical analysis of the noise measurements taken along transects around these sources by Subacoustech Environmental. The predictions use the following principle fitted to the measured data, where R is the range from the source, N is the transmission loss, and α is the absorption loss.

$$Recieved\ level = Source\ level\ (SL) - N\log_{10}R - \alpha R$$

Predicted source levels and propagation calculations for the construction activities are presented in Table 5-2 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, 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 any other environmental conditions into account, and as such can be applied to any location in and around the PFOWF site.

Source	Estimated unweighted source level	Approximate transmission loss	Comments
Cable laying	171 dB re 1 µPa @ 1 m (RMS)	$13\log_{10} R$ (no absorption)	Based on 11 datasets from a cable laying vessel measuring 300 m in length; this is considered a worst-case noise source for cable laying operations
Suction dredging	186 dB re 1 µPa @ 1 m (RMS)	$19\log_{10} R - 0.0009R$	Based on five datasets from suction and cutter suction dredgers
Trenching	172 dB re 1 µPa @ 1 m (RMS)	$13\log_{10} R - 0.0004R$	Based on three datasets of measurements from trenching vessels more than 100 m in length
Rock placement	172 dB re 1 µPa @ 1 m (RMS)	$12\log_{10} R - 0.0005R$	Based on four datasets from rock placement vessel '*Rollingstone*'
Vessel noise (large)	168 dB re 1 µPa @ 1 m (RMS)	$12\log_{10} R - 0.0021R$	Based on five datasets of large vessels including container ships, FPSOs and other vessels more than 100 m in length. Vessel speed assumed as 10 knots.
Vessel noise (medium)	161 dB re 1 µPa @ 1 m (RMS)	$12\log_{10} R - 0.0021R$	Based on three datasets of moderate sized vessels less than 100 m in length. Vessel speed assumed as 10 knots

Table 5-2 Summary of the estimated unweighted source levels and transmission losses for the different construction noise sources considered

For SEL_{cum} calculations, the duration the noise is present also needs to be considered, with all sources operating for a worst-case 24-hour period.

To account for the weightings required for modelling using the Southall *et al*. (2019) criteria (Section 2.2.1), reductions in source level have been applied to the various noise sources. Figure 5-1 shows the representative noise measurements used, which have been adjusted for the source levels given in Table 5-2. Table 5-3 presents details of the reductions in source levels for each of the weightings used for modelling.

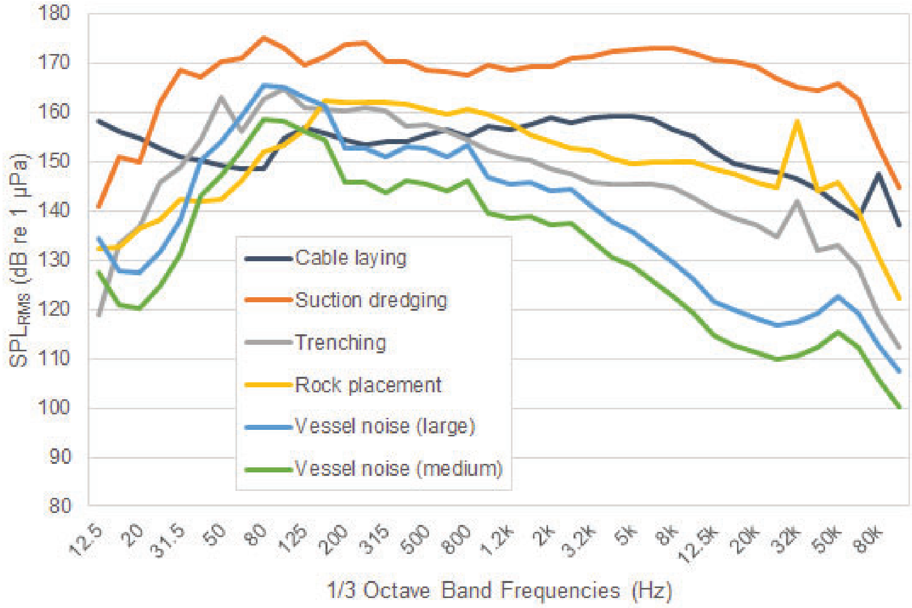

Figure 5-1 Summary of the 1/3rd octave frequency bands used as a basis for the Southall et al. (2019) weightings used in the simple modelling

Source	**Reduction in source level from the unweighted level (Southall *et al.* 2019)**			
	LF	**HF**	**VHF**	**PCW**
Cable laying	3.6 dB	22.9 dB	23.9 dB	13.2 dB
Suction Dredging	2.5 dB	7.9 dB	9.6 dB	4.2 dB
Trenching	4.1 dB	23.0 dB	25.0 dB	13.7 dB
Rock placement	1.6 dB	11.9 dB	12.5 dB	8.2 dB
Vessel noise	5.5 dB	34.4 dB	38.6 dB	17.4 dB

Table 5-3 Reductions in source level for the different construction noise sources considered when the Southall et al. (2019) weightings are applied

Table 5-4 and Table 5-5 summarise the predicted impact range for these noise sources. All the sources in this section are considered non-impulsive or continuous.

Given the modelled impact ranges, any marine mammal would have to be closer than 100 m from the continuous noise source at the start of the activity in most cases, to acquire the necessary exposure to induce PTS as per Southall *et al*. (2019). The exposure calculation assumes the same receptor swim speed as the impact piling modelling in section 4. Some of the increased ranges for TTS are considered to be highly unlikely as marine mammals will be mobile and not remain close enough to the sources for long enough to acquire the necessary exposure.

For fish, there is a low to negligible risk of any injury or TTS with reference to the SPL_{RMS} guidance for continuous noise sources in Popper *et al*. (2014).

All sources presented here result in much quieter levels than those presented for impact piling in section 4.

Southall *et al*. (2019) Weighted SEL_{cum}		Cable laying	Suction dredging	Trenching	Rock placement	Vessels (large)	Vessels (medium)
PTS	199 dB (LF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	198 dB (HF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	173 dB (VHF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	201 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
TTS	179 dB (LF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	178 dB (HF)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m
	153 dB (VHF)	< 100 m	200 m	< 100 m	1.0 km	200 m	< 100 m
	181 dB (PCW)	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m	< 100 m

Table 5-4 Summary of the impact ranges for the different construction noise sources using the non-impulsive criteria from Southall et al. (2019) for marine mammals

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

Table 5-5 Summary of the impact ranges for fish from Popper et al. (2014) for shipping and continuous noise, covering the different construction noise sources

5.3 Operational WTG noise

The main source of underwater noise from operational WTGs will be mechanically generated vibration from the rotating machinery in the WTGs, which is transmitted into the sea through the structure of the WTG tower and foundations (Nedwell *et al*., 2003, Tougaard *et al*, 2020). Noise levels generated above the water surface are low enough that no significant airborne sound will pass from the air to the water.

Tougaard *et al*. (2020) published a study investigating underwater noise data from 17 operational WTGs in Europe and the United Sates, from 0.2 MW to 6.15 MW nominal power output. The paper identified the nominal power output and wind speed as the two primary driving factors for underwater noise generation. Although the datasets were acquired under different conditions, the authors devised a formula based on the published data for the operational wind farms, allowing a broadband noise level to be estimated based on the application of wind speed, turbine size (by nominal power output) and distance from the turbine:

$$L_{eq} = C + \alpha \log_{10}\left(\frac{distance}{100\ m}\right) + \beta \log_{10}\left(\frac{wind\ speed}{10\ ms^{-1}}\right) + \gamma \log_{10}\left(\frac{turbine\ size}{1\ MW}\right)$$

Where C is a fixed constant and the coefficients α, β, and γ are derived from the empirical data for the 17 datasets.

As the WTGs at PFOWF do not have directly connected fixed foundations, the surface area from which this noise can radiate will be lower compared to typical monopile or jacket pile foundations. As much of the noise from designs considered by Tougaard *et al.* (2020) will be radiated from the foundation piles, floating designs by nature are expected to have a lower noise output than the calculations above would indicate. Due to lack of available study data from floating turbine designs, the noise output from solid-foundation WTGs have been used for this assessment and will represent a worst case.

The maximum turbine size considered at PFOWF is much larger than those used for the estimation above, with a maximum power output of 20 MW, so caution must be used when considering the results presented in this section. Figure 5-2 presents a level against range plot for 10 and 20 MW turbines using the Tougaard *et al*. (2020) calculation, assuming an average 9.8 ms^{-1} wind speed.

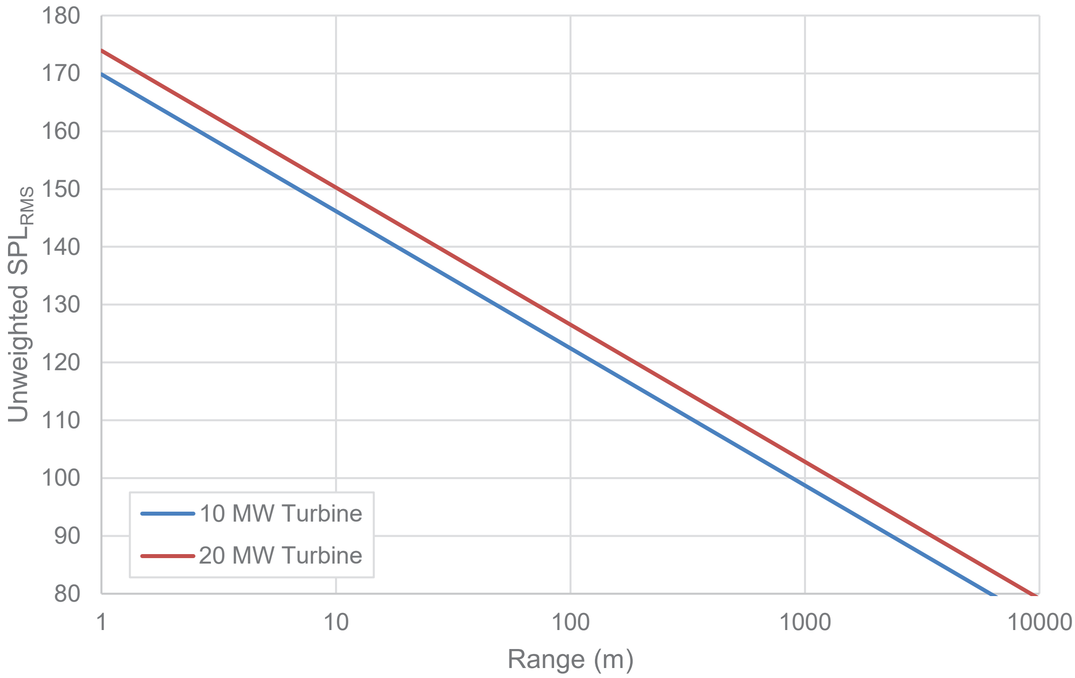

Figure 5-2 Predicted unweighted SPL_{RMS} from 10 and 20 MW operational WTGs using the calculation from Tougaard et al. (2020)

Using this data, a summary of the predicted impact ranges has been produced, shown in Table 5-6 and Table 5-7. All SEL_{cum} criteria use the same assumptions as presented in Section 4, and ranges smaller than 100 m have not been presented. The operational WTG source is considered a non-impulsive or continuous source. For SEL_{cum} calculations it has been assumed that the operational WTG noise is present 24 hours a day.

Southall *et al.* (2019) Weighted SEL_{cum}		**Operational WTG (10 MW)**	**Operational WTG (20 MW)**
PTS (non-impulsive)	199 dB (LF SEL_{cum})	< 100 m	< 100 m
	198 dB (HF SEL_{cum})	< 100 m	< 100 m
	173 dB (VHF SEL_{cum})	< 100 m	< 100 m
	201 dB (PCW SEL_{cum})	< 100 m	< 100 m
TTS (non-impulsive)	179 dB (LF SEL_{cum})	< 100 m	< 100 m
	178 dB (HF SEL_{cum})	< 100 m	< 100 m
	153 dB (VHF SEL_{cum})	< 100 m	< 100 m
	181 dB (PCW SEL_{cum})	< 100 m	< 100 m

Table 5-6 Summary of the operational WTG noise impact ranges using the non-impulsive noise criteria from Southall et al. (2019) for marine mammals

Popper *et al.* (2014) Unweighted SPL_{RMS}	**Operational WTG (10 MW)**	**Operational WTG (20 MW)**
Recoverable injury 170 dB (48 hours) Unweighted SPL_{RMS}	< 50 m	< 50 m
TTS 158 dB (12 hours) Unweighted SPL_{RMS}	< 50 m	< 50 m

Table 5-7 Summary of the operational WTG noise impact ranges using the continuous noise criteria from Popper et al. (2014) for fish (swim bladder involved in hearing)

These results show that, for operational WTGs, injury risk from these continuous-type noise sources to marine mammals and fish is minimal.

5.4 UXO clearance

Based on a desk-based risk assessment of the area, UXO clearance is not anticipated to be required for the PFOWF. Following specific UXO surveys of the site, should it be determined that UXO clearance will be required, a separate application will be made. This section considers a general overview of UXO clearance and its potential impact.

It is possible that UXO devices with a range of charge weights (or quantity of contained explosive) are present within the boundaries of PFOWF. These would need to be cleared before any construction can begin. When modelling potential noise from UXO clearance, a variety of explosive types need to be considered, with the potential that many have been subject to degradation and burying over time. Two otherwise identical explosive devices are likely to produce different blasts in the case where one has spent an extended period on the seabed. A selection of explosive sizes has been considered based on what might be present and, in each case, it has been assumed that the maximum explosive charge in each device is present and detonates with the clearance.

5.4.1 *Estimation of underwater noise levels*

The noise produced by the detonation of explosives is affected by several different elements, only one of which can easily be factored into a calculation: the charge weight. In this case the charge weight is based on the equivalent weight of TNT. Many other elements relating to its situation (e.g., its design, composition, age, position, orientation, whether it is covered by sediment) and exactly how they will affect the sound produced by detonation are usually unknown and cannot be directly considered in this type of assessment. This leads to a high degree of uncertainty in the estimation of the source noise level. A worst-case estimation has therefore been used for calculations, assuming the UXO to be detonated is not buried, degraded or subject to any other significant attenuation from its "as new" condition.

The consequence of this is that the noise levels produced, particularly by the larger explosives under consideration, are likely to be over-estimated as some degree of degradation would be expected.

The range of equivalent charge weights for the potential UXO devices that could be present within the PFOWF site boundary have been estimated as 25, 55, 120, 240 and 525 kg, plus the donor weight of 0.5 kg in each case used to initiate detonation. In addition, low-order deflagration has been assessed, which assumes that the donor or shaped charge (charge weight of 0.5 kg) detonates fully but without the follow-up detonation of the UXO. No mitigation has been considered for this modelling.

Estimation of the source noise level for each charge weight has been carried out in accordance with the methodology of Soloway and Dahl (2014), which follows Arons (1954) and MTD (1996).

5.4.2 *Estimation of underwater noise propagation*

For this assessment, the attenuation of the noise from UXO detonation has been accounted for in calculations using geometric spreading and a sound absorption coefficient, primarily using the methodologies cited in Soloway and Dahl (2014), which establishes a trend based on measured data in open water. These are, for SPL_{peak}:

$$SPL_{peak} = 52.4 \times 10^{6} \left(\frac{R}{W^{1/3}}\right)^{-1.13}$$

and for SEL_{ss}

$$SEL = 6.14 \times \log_{10}\left(W^{1/3}\left(\frac{R}{W^{1/3}}\right)^{-2.12}\right) + 219$$

where W is the equivalent charge weight for TNT in kilograms and R is the range from the source.

These equations give a relatively simple calculation which can be used to give an indication of the range of effect. The equation does not consider variable bathymetry or seabed type, and thus calculation results will be the same regardless of where it is used. An attenuation correction can be added to the Soloway and Dahl (2014) equations for the absorption over long ranges (i.e., of the order of thousands of metres), based on measurements of high intensity noise propagation taken in the North and Irish Seas.

Despite this attenuation correction, the resulting noise levels still need to be considered carefully. For example, SPL_{peak} noise levels over larger distances are difficult to predict accurately (von Benda-Beckmann *et al*., 2015). Soloway and Dahl (2014) only verify results from the equation above for small charges at ranges of less than 1 km, although the results do agree with the measurements presented by von Benda-Beckmann *et al*. (2015). At longer ranges, greater confidence is expected with the SEL (rather than SPL_{peak}) calculations.

An impulsive wave tends to be smoothed (i.e., the pulse becomes longer) over distance (Cudahy and Parvin, 2001), meaning the injurious potential of a wave at greater range can be even lower than that indicated by a reduction in the absolute noise level. An assessment in respect of SEL is considered preferential at long range as it considers the overall energy, and the smoothing of the peak is less critical.

The selection of assessment criteria must also be considered in light of this. The smoothing of the pulse at range means that a pulse may be considered non-impulsive at greater ranges, suggesting that, at greater ranges, it may be more appropriate to use the non-impulsive criteria. Results based on both sets of criteria are presented.

A summary of the unweighted UXO source levels calculated using the equations above are given in Table 5-8.

Charge weight	0.5 kg	25 kg + donor	55 kg + donor	120 kg + donor	240 kg + donor	525 kg + donor
SPL_{peak} source level (dB re 1 µPa @ 1 m)	272.1	284.9	287.5	290.0	292.3	294.8
SEL_{ss} source level (dB re 1 µPa^{2}s @ 1 m)	217.1	228.0	230.1	232.3	234.2	236.4

Table 5-8 Summary of the unweighted SPL_{peak} and SEL_{ss} source levels used for UXO modelling

5.4.3 Impact ranges

Table 5-9 to Table 5-12 present the impact ranges for UXO detonation, considering various charge weights and impact criteria. It should be noted that Popper *et al*. (2014) gives specific impact criteria for explosions (Table 2-6). A UXO detonation source is defined as a single pulse, and as such the SEL_{cum} criteria from Southall *et al*. (2019) have been given as SEL_{ss} in the tables below, thus, fleeing animal assumptions do not apply.

Although the impact ranges presented in Table 5-9 to Table 5-12 are large, the duration the noise is present must also be considered. For the detonation of a UXO, each explosion is a single noise event, compared to the multiple pulse nature and longer durations of impact piling.

Southall *et al.* (2019) Unweighted SPL_{peak}		**0.5 kg**	**25 kg + donor**	**55 kg + donor**	**120 kg + donor**	**240 kg + donor**	**525 kg + donor**
PTS	219 dB (LF)	220 m	820 m	1.0 km	1.3 km	1.7 km	2.2 km
	230 dB (HF)	70 m	260 m	340 m	450 m	560 m	730 m
	202 dB (VHF)	1.2 km	4.6 km	6.0 km	7.8 km	9.8 km	13 km
	218 dB (PCW)	240 m	910 m	1.1 km	1.5 km	1.9 km	2.5 km
TTS	213 dB (LF)	410 m	1.5 km	1.9 km	2.5 km	3.2 km	4.1 km
	224 dB (HF)	130 m	490 m	640 m	830 m	1.0 km	1.3 km
	196 dB (VHF)	2.3 km	8.5 km	11 km	14 km	18 km	23 km
	212 dB (PCW)	450 m	1.6 km	2.1 km	2.8 km	3.5 km	4.6 km

Table 5-9 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, unweighted SPL_{peak} noise criteria from Southall et al. (2019) for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		**0.5 kg**	**25 kg + donor**	**55 kg + donor**	**120 kg + donor**	**240 kg + donor**	**525 kg + donor**
PTS (Impulsive)	183 dB (LF)	320 m	2.2 km	3.2 km	4.7 km	6.5 km	9.5 km
	185 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	50 m
	155 dB (VHF)	110 m	570 m	740 m	950 m	1.1 km	1.4 km
	185 dB (PCW)	60 m	390 m	570 m	830 m	1.1 km	1.6 km
TTS (Impulsive)	168 dB (LF)	4.5 km	29 km	41 km	57 km	76 km	103 km
	170 dB (HF)	< 50 m	150 m	210 m	300 m	390 m	530 m
	140 dB (VHF)	930 m	2.4 km	2.8 km	3.2 km	3.5 km	4.0 km
	170 dB (PCW)	800 m	5.2 km	7.5 km	11 km	14 km	20 km

Table 5-10 Summary of the PTS and TTS impact ranges for UXO detonation using the impulsive, weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals

Southall *et al.* (2019) Weighted SEL_{ss}		**0.5 kg**	**25 kg + donor**	**55 kg + donor**	**120 kg + donor**	**240 kg + donor**	**525 kg + donor**
PTS (Non-impulsive)	199 dB (LF)	< 50 m	130 m	190 m	280 m	390 m	570 m
	198 dB (HF)	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m	< 50 m
	173 dB (VHF)	< 50 m	< 50 m	< 50 m	70 m	100 m	130 m
	201 dB (PCW)	< 50 m	< 50 m	< 50 m	< 50 m	70 m	100 m
TTS (Non-impulsive)	179 dB (LF)	650 m	4.4 km	6.4 km	9.4 km	13 km	19 km
	178 dB (HF)	< 50 m	< 50 m	60 m	80 m	110 m	160 m
	153 dB (VHF)	150 m	730 m	940 m	1.1 km	1.4 km	1.7 km
	181 dB (PCW)	110 m	790 m	1.1 km	1.6 km	2.3 km	3.3 km

Table 5-11 Summary of the PTS and TTS impact ranges for UXO detonation using the non-impulsive, weighted SEL_{ss} noise criteria from Southall et al. (2019) for marine mammals

Popper *et al.* (2014) Unweighted SPL_{peak}	**0.5 kg**	**25 kg + donor**	**55 kg + donor**	**120 kg + donor**	**240 kg + donor**	**525 kg + donor**
234 dB (Mortality and potential mortal injury)	< 50 m	170 m	230 m	300 m	370 m	490 m
229 dB (Mortality and potential mortal injury)	80 m	290 m	380 m	490 m	620 m	810 m

Table 5-12 Summary of the impact ranges for UXO detonation using the unweighted SPL_{peak} explosion noise criteria from Popper et al. (2014) for species of fish

5.4.4 Summary

The maximum PTS range calculated for UXO is 13 km for the VHF cetacean category, based on the unweighted SPL_{peak} criteria. For SEL_{ss} criteria, the largest PTS range is calculated for LF cetaceans with a predicted impact of 9.5 km using the impulsive SEL_{ss} criteria. As explained earlier, this assumes no degradation of the UXO and no smoothing of the pulse over that distance, which is very precautionary. Although an assumption of non-pulse could under-estimate the potential impact (Martin *et al.* 2020) (the equivalent range based on LF cetacean non-pulse criteria is 570 m), it is likely that the long-range smoothing of the pulse peak would reduce its potential harm and the maximum ‘impulsive’ range for all species is very precautionary.

6 Summary and conclusions

Subacoustech Environmental have undertaken a study on behalf of Highland Wind Limited to assess the potential underwater noise, and its effects, during the installation of piles at the proposed Pentland Firth Floating Offshore Wind Farm.

The level of underwater noise from the installation of tubular piles during construction has been estimated using the INSPIRE semi-empirical underwater noise model. The modelling considers a wide variety of input parameters including bathymetry, hammer blow energy, blow rate, and receptor fleeing speed.

A single modelling location was chosen as it would provide the most conservative estimates for sound propagation and impact. A worst case scenario has been considered at the selected location:

- 5 m diameter tubular pile, 20 m length.
- Installed using a hammer with maximum blow energy of 2500 kJ.
- 14912 blows over a total period of 8 hours.
- Three piles installed in a 24-hour period (resulting in 44736 blows over 24 hours).

The loudest levels of noise, and greatest impact ranges, have been predicted based on a layering of worst-case parameters which is highly precautionary and not expected to occur in practice.

The modelling results were analysed in terms of relevant noise metrics and criteria to assess the effect of the impact piling noise on marine mammals (Southall *et al*., 2019) and fish (Popper *et al*., 2014), which have been used to aid biological assessments.

For marine mammals, maximum PTS and TTS ranges were predicted for LF cetaceans, with PTS and TTS ranges from the pile of up to 27 km and 86 km respectively. For fish, the largest recoverable injury ranges were predicted to be less than 100 m from the pile, assuming a fleeing animal, increasing to 16 km for a stationary receptor. TTS ranges for fish were predicted to be 30 km assuming a fleeing receptor and 62 km when assuming a stationary receptor.

Noise sources other than piling were considered using a high-level, simple modelling approach, including cable laying, trenching, rock placement, drilling, dredging, 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 potentially injurious effects to fish or marine mammals from these sources are expected to be negligible as the noise emissions from these are close to, or below, the appropriate injury criteria when very close to the source of the noise.

Based on a desk-based risk assessment of the area, UXO clearance is not anticipated to be required for PFOWF. Following specific UXO surveys of the site, should it be determined that UXO clearance will be required, a separate application will be made. Nonetheless, for the purpose of providing a comprehensive assessment of potential worst-case impacts associated with PFOWF, an initial assessment of noise-related impacts from UXO clearance has been undertaken at this stage. For the expected UXO detonation noise, there is a risk of PTS up to 13 km for the largest UXO considered, a 525 kg device using the unweighted SPL_{peak} Southall *et al*. (2019) criteria for VHF cetaceans. However, this is likely to be very precautionary as the impact range is based on worst case criteria that do not account for any smoothing of the pulse over long ranges. This reduces the pulse peak and other characteristics of the sound that cause injury.

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