GREEN VOLT

Technical Appendix 9.1

Underwater Noise Technical Report

Offshore EIA Report: Volume 2

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Seiche Ltd
Bradworthy Industrial Estate
Langdon Road, Bradworthy
Holsworthy, Devon EX22 7SF
United Kingdom

Tel: +44 (0) 1409 404050
Email: info@seiche.com
Web: www.seiche.com

Green Volt Offshore Wind Farm

Underwater Noise Technical Report

Document Control

Report Number	P1638-REPT-01-R0
Client	Floatation Energy
Client Reference	-
Revision/Date	17/06/2022
Author(s)	Charlotte Birch
Reviewed by	Simon Stephenson
Authorised for release	

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Glossary

Term	Meaning
Decibel	A customary scale most commonly used (in various ways) for reporting levels of sound. The actual sound measurement is compared to a fixed reference level and the "decibel" value is defined to be 10 log10(actual/reference), where (actual/reference) is a power ratio. The standard reference for underwater sound pressure is 1 micro-Pascal (μPa), and 20 micro-Pascals is the standard for airborne sound. The dB symbol is followed by a second symbol identifying the specific reference value (i.e. re 1 μPa).
Grazing angle	A glancing angle of incidence (the angle between a ray incident on a surface and the line perpendicular to the surface).
Peak pressure	The highest pressure above or below ambient 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 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 representation of a noise event if all the energy were compressed into a 1 second period. This provides a uniform way to make comparisons between noise events of different durations.
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.

Acronyms

Term	Meaning
ADD	Acoustic Deterrent Device
DP	Dynamic Positioning
HF	High Frequency
EIA	Environmental Impact Assessment
GEBCO	General Bathymetric Chart of the Oceans
HESS	High Energy Seismic Survey
JNCC	Joint Nature Conservation Committee
LAT	Lowest Astronomical Tide
LF	Low Frequency
MBES	Multi-Beam Echo-Sounder
MF	Mid Frequency
ncMPA	Nature Conservation Marine Protected Area
NEQ	Net Explosive Quantity
NMFS	National Marine Fisheries Service
OCA	Other Marine Carnivores in Air
OCW	Other Marine Carnivores in Water
OSP	Offshore Substation Platform
OW	Otariid Pinnipeds
PTS	Permanent Threshold Shift
PCW	Phocid Carnivores in Water
RL	Received Level
RMS	Root Mean Square
SAC	Special Area of Conservation
SBP	Sub-Bottom Profiler
SEL	Sound Exposure Level
SL	Source Level
SPL	Sound Pressure Level
SSS	Sidescan Sonar
TL	Transmission Loss
TTS	Temporary Threshold Shift
UXO	Unexploded Ordnance
VHF	Very High Frequency
λ	Wavelength

Units

Unit	Description
μPa	Micro Pascal
dB	Decibel (Sound)
dB/m	Acoustic attenuation (dB/λ)
dB/rad	Attenuation per grazing angle
dB/λ	Attenuation per wavelength
Hrs	Hours
Hz	Hertz (Frequency)
kHz	Kilohertz (Frequency)
kJ	Kilojoule (Energy)
km	Kilometres (distance)
km	Kilometre (Distance)
km^2	Kilometre squared (Area)
m	*Metre (distance)*
ms	Millisecond (10^{-3} seconds) (Time)
ms^{-1} or m/s	Metres per second (Velocity)
MW	Mega Watt
Pa	Pascal (Pressure)
s	Second
T90	T90 pulse duration (i.e. the period that contains 90% of the total cumulative sound energy)

1 Introduction

This Subsea Noise Technical Report presents the results of a desktop study undertaken by Seiche Ltd considering the potential effects of underwater noise on the marine environment from construction of the Green Volt Offshore Wind Farm (hereafter referred to as the ‘Proposed Development’).

The location of the Proposed Development is in the North Sea, adjacent to the Buzzard oil field. The planned activities at this site fall into both pre-construction and construction phases. Within each of these four working categories different underwater noise sources are identified. These noise sources are both continuous and intermittent in characteristics.

Sound is readily transmitted into the underwater environment and there is potential for the sound emissions from the survey to adversely affect marine mammals and fish. At close ranges from the noise source with high noise levels permanent or temporary hearing damage may occur to marine species, while at a very close range gross physical trauma is possible. At long ranges the introduction of any additional noise could potentially cause short-term behavioural changes, for example to the ability of species to communicate and to determine the presence of predators, food, underwater features, and obstructions. This report provides an overview of the potential effects due to underwater noise from the proposed survey on the surrounding marine environment.

The primary purpose of this underwater noise study is to predict the likely range for the onset of potential injury (i.e. permanent threshold shifts (PTS) in hearing) and behavioural effects on different marine fauna when exposed to the different anthropogenic noises that occur during different phases of the Proposed Development. The results from this underwater noise appraisal have been used to inform the following chapters of the Environmental Impact Assessment (EIA) Report in order to determine the potential impact of underwater noise on marine life:

- Benthic Subtidal and Intertidal Ecology;
- Fish and Shellfish Ecology; and
- Marine Mammals.

Consequently, the sensitivity of species, magnitude of impact and significance of effect from underwater noise associated with the development are addressed within the relevant chapters.

2 Acoustic Concepts and Terminology

Sound travels through the water as vibrations of the fluid particles in a series of pressure waves. The waves comprise a series of alternating compressions (positive pressure) and rarefactions (negative pressure). Because sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The decibel (dB) scale is used to conveniently communicate the large range of acoustic pressures encountered, with a known pressure amplitude chosen as a reference value (i.e., 0 dB). In the case of underwater sound, the reference value (P_{ref}) is taken as 1 μPa, whereas the airborne sound is usually referenced to a pressure of 20 μPa. To convert from a sound pressure level referenced to 20 μPa to one referenced to 1 μPa, a factor of 20 log (20/1) i.e., 26 dB has to be added to the former quantity. Thus 60 dB re 20 μPa is the same as 86 dB re 1 μPa, although differences in sound speeds and different densities mean that the decibel level difference in sound intensity is much more than the 26 dB when converting pressure from air to water. All underwater sound pressure levels in this report are quantified in dB re 1 μPa.

There are several descriptors used to characterise a sound wave. The difference between the lowest pressure variation (rarefaction) and the highest-pressure variation (compression) is called the peak to peak (or pk-pk) sound pressure level. The difference between the highest variation (either positive or negative) and the mean pressure is called the peak pressure level. Lastly, the root mean square (rms) sound pressure level is used as a description of the average amplitude of the variations in pressure over a specific time window. Decibel values reported should always be quoted along with the P_{ref} value employed during calculations. For example, the measured SPL_{rms} value of a pulse may be reported as 100 dB re 1 μPa. These descriptions are shown graphically in Figure 2.1.

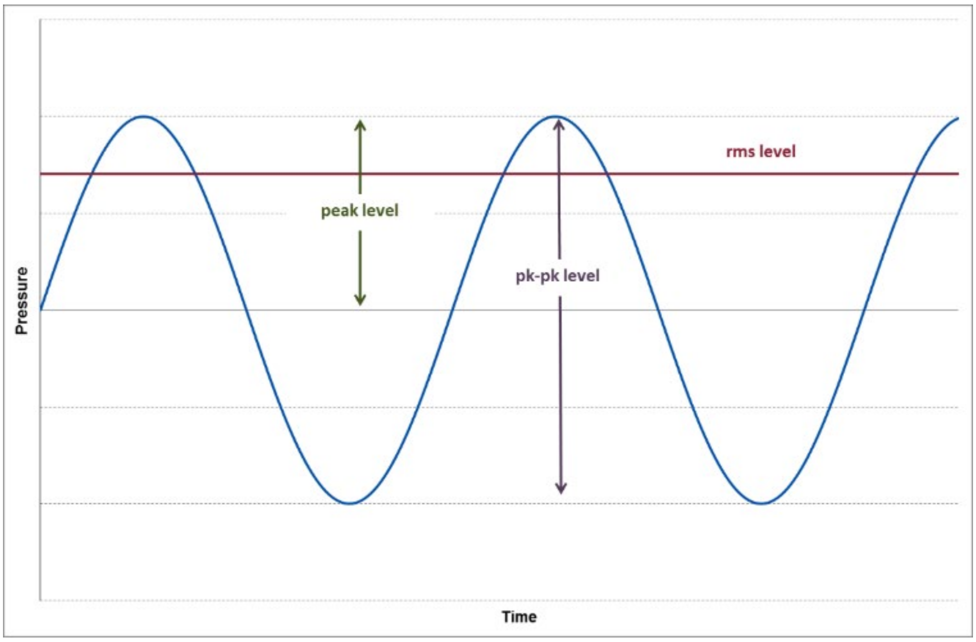

Figure 2.1: Graphical representation of acoustic wave descriptors

The rms sound pressure level (SPL) is defined as follows:

$$SPL_{rms} = 10log_{10}\left(\frac{1}{T}\int_{0}^{T}\left(\frac{p^2}{p_{ref}^2}\right)dt\right) \quad (1)$$

The magnitude of the rms sound pressure level for an impulsive sound (such as that from a seismic source array) will depend upon the integration time, T, used for the calculation (Madsen 2005). It has become customary to utilise the T90 time period for calculating and reporting rms sound pressure levels. This is the interval over which the cumulative energy curve rises from 5% to 95% of the total energy and therefore contains 90% of the sound energy.

Another useful measure of sound used in underwater acoustics is the Sound Exposure Level, or SEL. This descriptor is used as a measure of the total sound energy of an event or a number of events (e.g., over the course of a day) and is normalised to one second. This allows the total acoustic energy contained in events lasting a different amount of time to be compared on a like for like basis[1]. The SEL is defined as follows:

$$SEL = 10log_{10}\left(\int_0^T \left(\frac{p^2(t)}{p_{ref}^2 t_{ref}}\right) dt\right) \quad (2)$$

The frequency, or pitch, of the sound is the rate at which the acoustic oscillations occur in the medium (air/water) and is measured in cycles per second, or Hertz (Hz). When sound is measured in a way which approximates to how a human would perceive it using an A-weighting filter on a sound level meter, the resulting level is described in values of dBA. However, the hearing faculty of marine mammals is not the same as humans, with marine mammals hearing over a wider range of frequencies and with a different sensitivity. It is therefore important to understand how an animal's hearing varies over its entire frequency range to assess the effects of anthropogenic sound on marine mammals. Consequently, use can be made of frequency weighting scales (m-weighting) to determine the level of the sound in comparison with the auditory response of the animal concerned. A comparison between the typical hearing response curves for fish, humans and marine mammals is shown in Figure 2.2. (It is worth noting that hearing thresholds are sometimes shown as audiograms with sound level on the y axis rather than sensitivity, resulting in the graph shape being the inverse of the graph shown.)

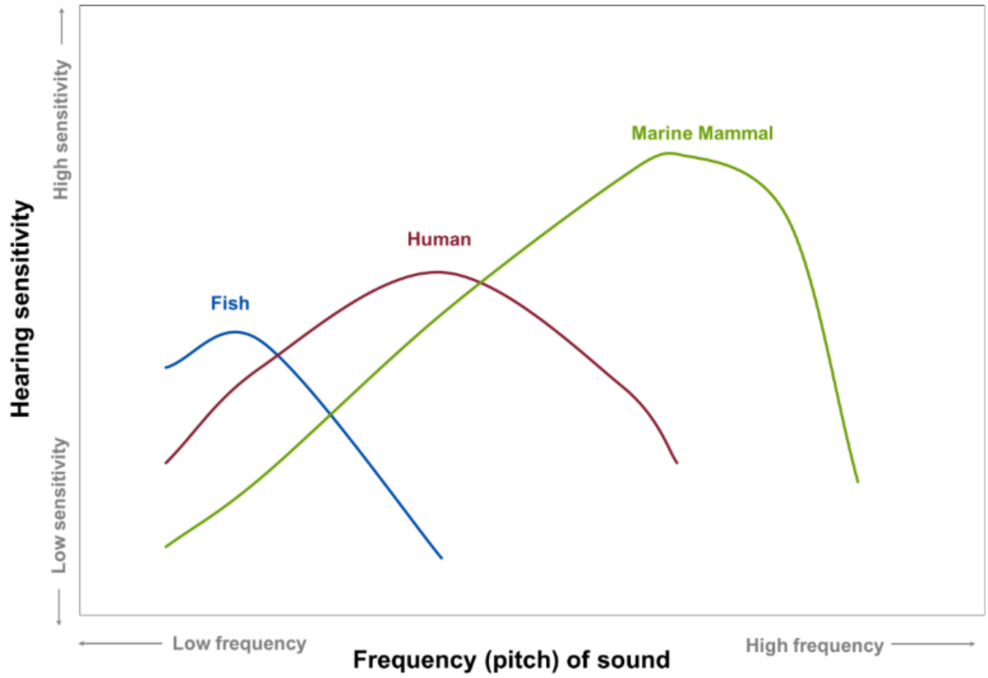

Figure 2.2: Comparison between hearing thresholds of different animals

Other relevant acoustic terminology and their definitions used in the report are detailed below.

1/3rd octave bands

The broadband acoustic power (i.e., containing all the possible frequencies) emitted by a sound source, measured/modelled at a location within the survey region is generally split into and reported in a series of frequency bands. In marine acoustics, the spectrum is generally reported in standard 1/3rd octave band frequencies, where an octave represents a doubling in sound frequency.

[1] *Historically, use was primarily made of rms and peak sound pressure level metrics for assessing the potential effects of sound on marine life. However, the SEL is increasingly being used as it allows exposure duration and the effect of exposure to multiple events to be considered.*

Source level (SL)

The source level is the sound pressure level of an equivalent and infinitesimally small version of the source (known as *point source*) at a hypothetical distance of 1 m from it. The source level may be combined with the transmission loss (TL) associated with the environment to obtain the received level (RL) in the *far field* of the source. The far field distance is chosen so that the behaviour of the distributed source can be approximated to that of a point source. Source levels do not indicate the real sound pressure level at 1 m.

Transmission loss (TL)

TL at a frequency of interest is defined as the loss of acoustic energy as the signal propagates from a hypothetical (point) source location to the chosen receiver location. The TL is dependent on water depth, source depth, receiver depth, frequency, geology, and environmental conditions. The TL values are generally evaluated using an acoustic propagation model (various numerical methods exist) accounting for the above dependencies.

Received level (RL)

The RL is the sound level of the acoustic signal recorded (or modelled) at a given location, that corresponds to the acoustic pressure/energy generated by a known active sound source. This considers the acoustic output of a source and is modified by propagation effects. This RL value is strongly dependant on the source, environmental properties, geological properties and measurement location/depth. The RL is reported in dB either in rms or peak-to-peak SPL, and SEL metrics, within the relevant third-octave band frequencies. The RL is related to the SL as

$$RL = SL - TL \tag{3}$$

where TL is the transmission loss of the acoustic energy within the survey region.

The directional dependence of the source signature and the variation of TL with azimuthal direction α (which is strongly dependent on bathymetry) are generally combined and interpolated to report a 2-D plot of the RL around the chosen source point up to a chosen distance.

3 Acoustic Assessment Criteria

3.1 Introduction

Underwater noise has the potential to affect marine life in different ways depending on its noise level and characteristics. Richardson et al. (1995) defined four zones of noise influence which vary with distance from the source and level. These are:

- **The zone of audibility:** this is the area within which the animal can detect the sound. Audibility itself does not implicitly mean that the sound will have an effect on the marine mammal.
- **The zone of masking:** this is defined as the area within which noise can interfere with detection of other sounds such as communication or echolocation clicks. This zone is very hard to estimate due to a paucity of data relating to how marine mammals detect sound in relation to masking levels (for example, humans can hear tones well below the numeric value of the overall noise level).
- **The zone of responsiveness:** this is defined as the area within which the animal responds either behaviourally or physiologically. The zone of responsiveness is usually smaller than the zone of audibility because, as stated previously, audibility does not necessarily evoke a reaction.
- **The zone of injury / hearing loss:** this is the area where the sound level is high enough to cause tissue damage in the ear. This can be classified as either temporary threshold shift (TTS) or permanent threshold shift (PTS). At even closer ranges, and for very high intensity sound sources (e.g., underwater explosions), physical trauma or even death are possible.

For this study, it is the zones of injury and disturbance (i.e., responsiveness) that are of concern. To determine the potential spatial range of injury and disturbance, a review has been undertaken of available evidence, including international guidance and scientific literature. The following sections summarise the relevant thresholds for onset of effects and describe the evidence base used to derive them.

3.2 Injury to Marine Mammals

Sound propagation models can be constructed to allow the received noise level at different distances from the source to be calculated. To determine the consequence of these received levels on any marine mammals which might experience such noise emissions, it is necessary to relate the levels to known or estimated impact thresholds. The injury criteria proposed by Southall et al (2019) are based on a combination of linear (i.e., un-weighted) peak pressure levels and mammal hearing weighted sound exposure levels (SEL). The hearing weighting function is designed to represent the bandwidth for each group within which acoustic exposures can have auditory effects. The categories include:

- **Low Frequency (LF) cetaceans:** i.e. marine mammal species such as baleen whales;
- **High Frequency (HF) cetaceans:** i.e. marine mammal species such as dolphins, toothed whales, beaked whales and bottlenose whales;
- **Very High Frequency (VHF) cetaceans:** i.e. marine mammal species such as true porpoises, river dolphins and pygmy/dwarf sperm whales and some oceanic dolphins, generally with auditory centre frequencies above 100 kHz);
- **Phocid Carnivores in Water (PCW):** i.e. true seals; hearing in air is considered separately in the group PCA; and
- **Other Marine Carnivores in Water (OCW):** including otariid pinnipeds (e.g. sea lions and fur seals), sea otters and polar bears; air hearing considered separately in the group Other Marine Carnivores in Air (OCA).

These weightings have therefore been used in this study and are shown in Figure 3.1.

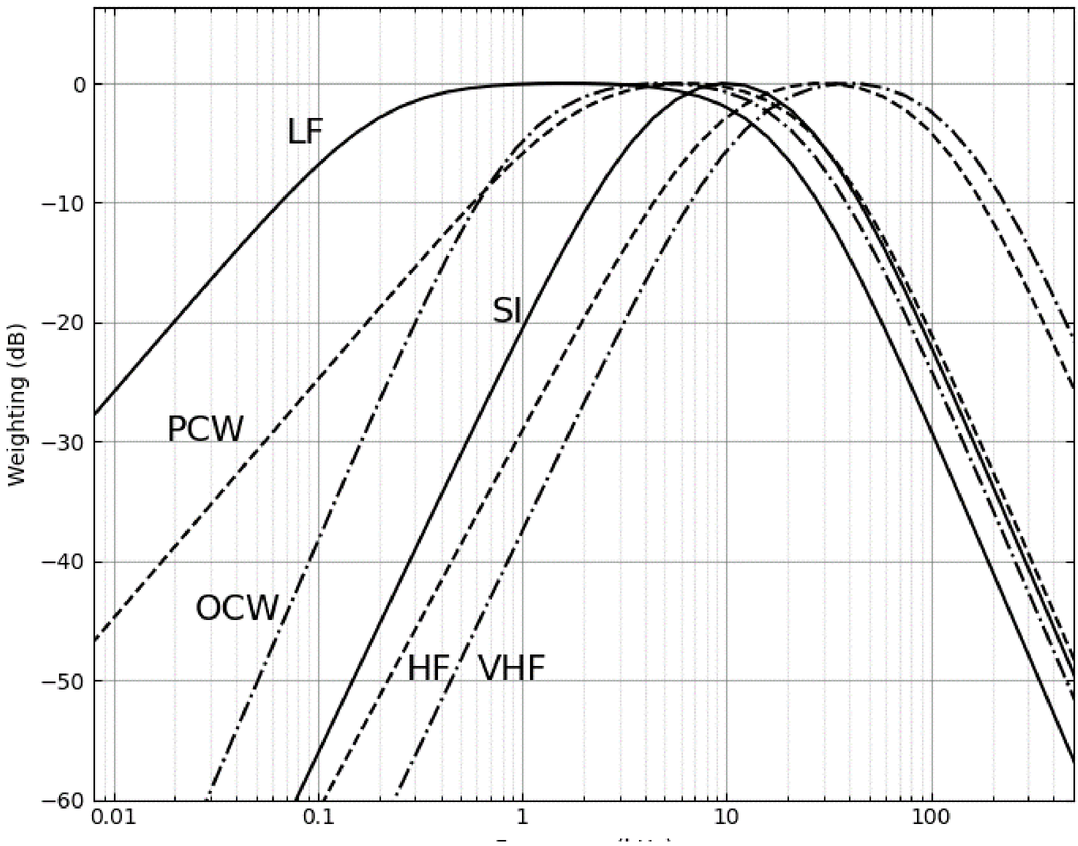

Figure 3.1: Hearing weighting functions for marine mammals (Southall et al. 2019)

Injury criteria are proposed in Southall et al (2019) are for two different types of sound as follows:

- **Impulsive sounds** which are typically transient, brief (less than 1 second), broadband, and consist of high peak sound pressure with rapid rise time and rapid decay (ANSI 1986; NIOSH 1998; ANSI 2005). This category includes sound sources such as seismic surveys, impact piling and underwater explosions; and
- **Non-impulsive sounds** which can be broadband, narrowband or tonal, brief or prolonged, continuous or intermittent and typically do not have a high peak sound pressure with rapid rise/decay time that impulsive sounds do (ANSI 1995; NIOSH 1998). This category includes sound sources such as continuous running machinery, drilling, sonar and vessels.

The criteria for impulsive and non-impulsive sound have been adopted for this study given the nature of the sound source used during construction activities. The relevant criteria proposed by Southall et al. (2019) are as summarised in Table 3.1 and Table 3.2.

Table 3.1: Summary of PTS Onset Acoustic Thresholds (Southall et al., 2019; Tables 6 and 7)

Hearing Group	Parameter	Impulsive	Non-impulsive
Low-frequency (LF) cetaceans	Peak, unweighted	219	-
	SEL, LF weighted	183	199
High-frequency (HF) cetaceans	Peak, unweighted	230	-
	SEL, HF weighted	185	198
Very High-frequency (VHF) cetaceans	Peak, unweighted	202	-
	SEL, VHF weighted	155	173
Phocid Carnivores in Water (PCW)	Peak, unweighted	218	-
	SEL, PCW weighted	185	201
Other Marine Carnivores in Water (OCW)	Peak, unweighted	232	-
	SEL, OCW weighted	203	219

Table 3.2: Summary of TTS Onset Acoustic Thresholds (Southall et al., 2019; Tables 6 and 7)

Hearing Group	Parameter	Impulsive	Non-impulsive
Low-frequency (LF) cetaceans	Peak, unweighted	213	-
	SEL, LF weighted	168	179
High-frequency (HF) cetaceans	Peak, unweighted	224	-
	SEL, HF weighted	170	178
Very High-frequency (VHF) cetaceans	Peak, unweighted	196	-
	SEL, VHF weighted	140	153
Phocid Carnivores in Water (PCW)	Peak, unweighted	212	-
	SEL, PCW weighted	170	181
Other Marine Carnivores in Water (OCW)	Peak, unweighted	226	-
	SEL, OCW weighted	188	199

These updated marine mammal injury criteria were published in March 2019 (Southall et al. 2019). The paper utilised the same hearing weighting curves and thresholds as presented in the preceding regulations document (NMFS 2018) with the main difference being the naming of the hearing groups and introduction of additional thresholds for animals not covered by NMFS (2018). A comparison between the two naming conventions is shown in Table 3.3.

For avoidance of doubt, the naming convention used in this report is based upon those set out in Southall et al. (2019). Consequently, this assessment utilises criteria which are applicable to both NMFS (2018) and Southall et al. (2019).

Table 3.3: Comparison of hearing group names between NMFS 2018 and Southall 2019

NMFS (2018) hearing group name	Southall et al. (2019) hearing group name
Low frequency cetaceans (LF)	Low-frequency cetaceans (LF)
Mid frequency cetaceans (MF)	High-frequency cetaceans (HF)
High frequency cetaceans (HF)	Very high-frequency cetaceans (VHF)

NMFS (2018) hearing group name	Southall et al. (2019) hearing group name
Phocid pinnipeds in water (PW)	Phocid carnivores in water (PCW)

3.3 Disturbance to Marine Mammals

Beyond the area in which injury may occur, the effect on marine mammal behaviour is the most important measure of impact. Significant (i.e. non-trivial) disturbance may occur when there is a risk of animals incurring sustained or chronic disruption of behaviour or when animals are displaced from an area, with subsequent redistribution being significantly different from that occurring due to natural variation.

To consider the possibility of significant disturbance resulting from the Proposed Development, it is therefore necessary to consider the likelihood that the sound could cause non-trivial disturbance, the likelihood that the sensitive receptors will be exposed to that sound and whether the number of animals exposed are likely to be significant at the population level. Assessing this is however a very difficult task due to the complex and variable nature of sound propagation, the variability of documented animal responses to similar levels of sound, and the availability of population estimates, and regional density estimates for all marine mammal species.

Southall *et al.* (2007) recommended that the only currently feasible way to assess whether a specific sound could cause disturbance is to compare the circumstances of the situation with empirical studies. Joint Nature Conservation Committee (JNCC) guidance in the UK (JNCC, 2010) indicates that a score of five or more on the Southall *et al.* (2007) behavioural response severity scale could be significant. The more severe the response on the scale, the lower the amount of time that the animals will tolerate it before there could be significant negative effects on life functions, which would constitute a disturbance.

Southall *et al.* (2007) present a summary of observed behavioural responses for various mammal groups exposed to different types of noise: continuous (non-pulsed) or impulsive (single or multiple pulsed).

3.3.1 Continuous (Non-Pulsed, Non-Impulsive) Sound

For non-pulsed sound (e.g. drilled piles, vessels etc.), the lowest sound pressure level at which a score of five or more occurs for low frequency cetaceans is 90 dB to 100 dB re 1 µPa (rms). However, this relates to a study involving migrating grey whales. A study for minke whales showed a response score of three at a received level of 100 dB to 110 dB re 1 µPa (rms), with no higher severity score encountered for this species. For mid frequency cetaceans, a response score of eight was encountered at a received level of 90 dB to 100 dB re 1 µPa (rms), but this was for one mammal (a sperm whale *Physeter macrocephalus*) and might not be applicable for the species likely to be encountered in the vicinity of the Proposed Development. For Atlantic white-beaked dolphin *Lagenorhynchus albirostris*, a response score of three was encountered for received levels of 110 to 120 dB re 1 µPa (rms), with no higher severity score encountered. For high frequency cetaceans such as bottlenose dolphins *Tursiops truncatus*, a number of individual responses with a response score of six are noted ranging from 80 dB re 1 µPa (rms) and upwards. There is a significant increase in the number of mammals responding at a response score of six once the received sound pressure level is greater than 140 dB re 1 µPa (rms).

The NMFS (2005) guidance sets the marine mammal level B harassment threshold for continuous noise at 120 dB re 1 µPa (rms). This value sits approximately mid-way between the range of values identified in Southall et al. (2007) for continuous sound but is lower than the value at which the majority of mammals responded at a response score of six (i.e. once the received rms sound pressure level is greater than 140 dB re 1 µPa). Considering the paucity and high level variation of data relating to onset of behavioural effects due to continuous sound, it is recommended that any ranges predicted using this number are viewed as probabilistic and potentially over precautionary.

3.3.2 Impulsive (Pulsed) Sound

Southall *et al*. (2007) presents a summary of observed behavioural responses due to multiple pulsed sound, although the data are primarily based on responses to seismic exploration activities (rather than for piling). Although these datasets contain much relevant data for LF cetaceans, there are no strong data for MF or HF cetaceans. Low frequency cetaceans, other than bow-head whales, were typically observed to respond significantly at a received level of 140 dB to 160 dB re 1 μPa (rms). Behavioural changes at these levels during multiple pulses may have included visible startle response, extended cessation or modification of vocal behaviour, brief cessation of reproductive behaviour or brief/minor separation of females and dependent offspring. The data available for MF cetaceans indicate that some significant response was observed at a SPL of 120 dB to 130 dB re 1μPa (rms), although the majority of cetaceans in this category did not display behaviours of this severity until exposed to a level of 170 dB to 180 dB re 1μPa (rms). Furthermore, other MF cetaceans within the same study were observed to have no behavioural response even when exposed to a level of 170 dB to 180 dB re 1μPa (rms).

A more recent study is described in Graham *et al.* (2017). Empirical evidence from piling at the Beatrice Offshore Wind Farm (Moray Firth, Scotland) was used to derive a dose-response curve for harbour porpoise. The unweighted single pulse SEL contours were plotted in 5 dB increments and applied the dose-response curve to estimate the number of animals that would be disturbed by piling within each stepped contour. The study shows a 100% probability of disturbance at an (un-weighted) SEL of 180 dB re 1 μPa^{2}s, 50% at 155 dB re 1 μPa^{2}s and dropping to approximately 0% at an SEL of 120 dB re 1 μPa^{2}s. This is an accepted approach to understanding the behavioural effects from piling, and has been applied at other UK offshore windfarms (for example Seagreen and Hornsea Three).

According to Southall *et al.* (2007) there is a general paucity of data relating to the effects of sound on pinnipeds in particular. One study using ringed *Pusa hispida*, bearded *Erignathus barbatus* and spotted seals *Phoca largha* (Harris *et al.,* 2001) found onset of a significant response at a received sound pressure level of 160 dB to 170 dB re 1 μPa (rms), although larger numbers of animals showed no response at noise levels of up to 180 dB re 1 μPa (rms). It is only at much higher sound pressure levels in the range of 190 dB to 200 dB re 1 μPa (rms) that significant numbers of seals were found to exhibit a significant response. For non-pulsed sound, one study elicited a significant response on a single harbour seal at a received level of 100 dB to 110 dB re 1 μPa (rms), although other studies found no response or non-significant reactions occurred at much higher received levels of up to 140 dB re 1 μPa (rms). No data are available for higher noise levels and the low number of animals observed in the various studies means that it is difficult to make any firm conclusions from these studies.

Southall *et al.* (2007) also notes that, due to the uncertainty over whether HF cetaceans may perceive certain sounds and due to paucity of data, it was not possible to present any data on responses of HF cetaceans. However, Lucke *et al.* (2009) showed a single harbour porpoise consistently showed aversive behavioural reactions to pulsed sound at received SPL above 174 dB re 1 μPa (peak-to-peak) or a SEL of 145 dB re 1 μPa^{2}s, equivalent to an estimated[2] rms sound pressure level of 166 dB re 1 μPa.

Clearly, there is much intra-category and perhaps intra-species variability in behavioural response. As such, a conservative approach should be taken to ensure that the most sensitive marine mammals remain protected.

The High Energy Seismic Survey (HESS) workshop on the effects of seismic (i.e. pulsed) sound on marine mammals (HESS, 1997) concluded that mild behavioural disturbance would most likely occur at rms sound levels greater than 140 dB re 1 μPa (rms). This workshop drew on studies by Richardson (1995) but recognised that there was some degree of variability in reactions between different studies and mammal groups. Consequently, for the purposes of this study, a precautionary level of 140 dB re 1 μPa (rms) is used to indicate the onset of low-level marine mammal disturbance effects for all mammal groups for impulsive sound.

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[2] *Based on an analysis of the time history graph in Lucke et al. (2007), the T90 period is estimated to be approximately 8 ms, resulting in a correction of 21 dB applied to the SEL to derive the rms_{T90} sound pressure level. However, the T90 was not directly reported in the paper.*

This assessment adopts a conservative approach and uses the NMFS (2005) Level B harassment threshold of 160 dB re 1 µPa (rms) for impulsive sound. Level B Harassment is defined by NMFS (2005) as having the potential to disturb a marine mammal or marine mammal stock in the wild by causing disruption of behavioural patterns, including, but not limited to, migration, breathing, nursing, breeding, feeding, or sheltering but which does not have the potential to injure a marine mammal or marine mammal stock in the wild. This is similar to the JNCC (2010) description of non-trivial disturbance and has therefore been used as the basis for onset of behavioural change in this assessment.

It is important to understand that exposure to sound levels in excess of the behavioural change threshold stated above does not necessarily imply that the sound will result in significant disturbance. As noted previously, it is also necessary to assess the likelihood that the sensitive receptors will be exposed to that sound and whether the numbers exposed are likely to be significant at the population level.

Table 3.4: Disturbance Criteria for Marine Mammals Used in this Study

Effect	Non-Impulsive Threshold	Impulsive Threshold (Other than Piling)	Impulsive Threshold (Piling)
Mild disturbance (all marine mammals)	-	140 dB re 1µ Pa (rms)	Based on SEL 5 dB contours
Strong disturbance (all marine mammals)	120 dB re 1µ Pa (rms)	160 dB re 1µ Pa (rms)	Based on SEL 5 dB contours
Disturbance (harbour porpoise)		Based on SEL 5 dB contours	Based on SEL 5 dB contours

3.4 Fish and Sea Turtles

Adult fish not in the immediate vicinity of the noise generating activity are generally able to vacate the area and avoid physical injury. However, larvae and eggs are not highly mobile and are therefore more likely to incur injuries from the sound energy in the immediate vicinity of the sound source, including damage to their hearing, kidneys, hearts and swim bladders. Such effects are unlikely to happen outside of the immediate vicinity of even the highest energy sound sources.

For fish, the most relevant criteria for injury are considered to be those contained in the recent Sound Exposure Guidelines for Fishes and Sea Turtles (Popper et al. 2014). These guidelines do not group by species but instead broadly group fish into the following categories based on their anatomy and the available information on hearing of other fish species with comparable anatomies:

- **Group 1 fish:** fishes with no swim bladder or other gas chamber (e.g. elasmobranchs, flatfishes and lampreys). These species are less susceptible to barotrauma and are only sensitive to particle motion, not sound pressure. Basking shark, which does not have a swim bladder, falls into this hearing group.
- **Group 2 fish:** fishes with swim bladders but the swim bladder does not play a role in hearing (e.g. salmonids). These species are susceptible to barotrauma, although hearing only involves particle motion, not sound pressure.
- **Group 3:** Fishes with swim bladders that are close, but not connected, to the ear (e.g. gadoids and eels). These fishes are sensitive to both particle motion and sound pressure and show a more extended frequency range than groups 1 and 2, extending to about 500 Hz.
- **Group 4:** Fishes that have special structures mechanically linking the swim bladder to the ear (e.g. clupeids such as herring, sprat and shads). These fishes are sensitive primarily to sound pressure, although they also detect particle motion. These species have a wider frequency range, extending to several kHz and generally show higher sensitivity to sound pressure than fishes in Groups 1, 2 and 3.
- **Sea Turtles:** There is limited information on auditory criteria for sea turtles and the effect of impulsive noise is therefore inferred from documented effects to other vertebrates. Bone conducted hearing is the most likely mechanism for auditory reception in sea turtles and, since high frequencies are

attenuated by bone, the range of hearing are limited to low frequencies only (Tonndorf, 1972). For leatherback turtle *Dermochelys coracea* the hearing range has been recorded as between 50 and 1,200 Hz with maximum sensitivity between 100 and 400 Hz (Piniak, 2012); and

- **Fish eggs and larvae**: separated due to greater vulnerability and reduced mobility. Very few peer-reviewed studies report on the response of eggs and larvae to anthropogenic sound.

The guidelines set out criteria for injury due to different sources of noise. Those relevant to the Proposed Development are considered to be those for injury due to impulsive piling sources only, as non-impulsive sources were not considered to be a key impact and therefore were screened out of the guidance[3]. The criteria include a range of indices including SEL, rms and peak SPLs. Where insufficient data exist to determine a quantitative guideline value, the risk is categorised in relative terms as “high”, “moderate” or “low” at three distances from the source: “near” (i.e. in the tens of metres), “intermediate” (i.e. in the hundreds of metres) or “far” (i.e. in the thousands of metres). It should be noted that these qualitative criteria cannot differentiate between exposures to different noise levels and therefore all sources of noise, no matter how noisy, would theoretically elicit the same assessment result. However, because the qualitative risks are generally qualified as “low”, with the exception of a moderate risk at “near” range (i.e. within tens of metres) for some types of animal and impairment effects, this is not considered to be a significant issue with respect to determining the potential effect of noise on fish.

The injury criteria used in this noise assessment for impulsive piling are given in Table 3.5. In the table, both peak and SEL criteria are unweighted. Physiological effects relating to injury criteria are described below (Popper et al., 2014; Popper and Hawkins, 2016):

- **Mortality and potential mortal injury**: either immediate mortality or tissue and/or physiological damage that is sufficiently severe (e.g. a barotrauma) that death occurs sometime later due to decreased fitness. Mortality has a direct effect upon animal populations, especially if it affects individuals close to maturity.
- **Recoverable injury**: Tissue and other physical damage or physiological effects, that are recoverable but which may place animals at lower levels of fitness, may render them more open to predation, impaired feeding and growth, or lack of breeding success, until recovery takes place.
- **TTS**: Short term changes in hearing sensitivity may, or may not, reduce fitness and survival. Impairment of hearing may affect the ability of animals to capture prey and avoid predators, and also cause deterioration in communication between individuals; affecting growth, survival, and reproductive success. After termination of a sound that causes TTS, normal hearing ability returns over a period that is variable, depending on many factors, including the intensity and duration of sound exposure.

Table 3.5: Criteria for Onset of Injury to Fish and Sea Turtles due to Impulsive Piling (Popper et al., 2014)

Type of Animal	Parameter	Mortality and Potential Mortal Injury	Recoverable Injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	SEL, dB re 1 μPa^{2}s	>219	>216	>>186
	Peak, dB re 1 μPa	>213	>213	-
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	SEL, dB re 1 μPa^{2}s	210	203	>186
	Peak, dB re 1 μPa	>207	>207	-

[3] *Guideline exposure criteria for seismic surveys, continuous sound and naval sonar are also presented though are not applicable to the Proposed Development.*

Type of Animal	Parameter	Mortality and Potential Mortal Injury	Recoverable Injury	TTS
Groups 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	SEL, dB re 1 $\mu Pa^2 s$	207	203	186
	Peak, dB re 1 µPa	>207	>207	-
Sea turtles	SEL, dB re 1 $\mu Pa^2 s$	210	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Low (Far) Low
	Peak, dB re 1 µPa	>207		
Eggs and larvae	SEL, dB re 1 $\mu Pa^2 s$	>210	(Near) Moderate (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
	Peak, dB re 1 µPa	>207		

The criteria used in this noise assessment for non-impulsive piling and other continuous noise sources, such as vessels, are given in Table 3.6. The only numerical criteria for these sources are for recoverable injury and TTS for Groups 3 and 4 Fish.

Table 3.6: Criteria for onset of injury to fish and sea turtles due to non-impulsive sound (Popper et al., 2014).

Type of animal	Mortality and potential mortal injury	Recoverable injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	(Near) Low (Intermediate) Low (Far) Lo w	(Near) Low (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
Groups 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	(Near) Low (Intermediate) Low (Far) Low	170 dB re 1 µPa (rms) for 48 hours	158 dB re 1 µPa (rms) for 12 hours
Sea turtles	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Low (Far) Low
Eggs and larvae	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low	(Near) Low (Intermediate) Low (Far) Low

The criteria used in this noise assessment for non-impulsive piling and other continuous noise sources, such as vessels, are given in Table 3.7.

Table 3.7: Criteria for Injury to Fish due to Explosives (Popper et al., 2014)

Type of Animal	Parameter	Mortality and Potential Mortal Injury	Recoverable Injury	TTS
Group 1 Fish: no swim bladder (particle motion detection)	Peak, dB re 1 μPa	229 - 234	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	Peak, dB re 1 μPa	229 - 234	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	Peak, dB re 1 μPa	229 - 234	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) High (Far) Low

It should be noted that there are no thresholds in Popper *et al.* (2014) in relation to noise from high frequency sonar (>10 kHz). This is because the hearing range of fish species falls well below the frequency range of high frequency sonar systems. Consequently, the effects of noise from high frequency sonar surveys on fish has not been conducted as part of this study, due to the frequency of the source being beyond the range of hearing and also due to the lack of any suitable thresholds.

Behavioural reaction of fish to sound has been found to vary between species based on their hearing sensitivity. Typically, fish sense sound via particle motion in the inner ear which is detected from sound-induced motions in the fish's body. The detection of sound pressure is restricted to those fish which have air filled swim bladders; however, particle motion (induced by sound) can be detected by fish without swim bladders[4].

Highly sensitive species such as herring have elaborate specialisations of their auditory apparatus, known as an otic bulla – a gas filled sphere, connected to the swim bladder, which enhances hearing ability. The gas filled swim bladder in species such as cod and salmon may be involved in their hearing capabilities, so although there is no direct link to the inner ear, these species are able to detect lower sound frequencies and as such are considered to be of medium sensitivity to noise. Flat fish and elasmobranchs have no swim bladders and as such are considered to be relatively less sensitive to sound pressure.

The most recent criteria for disturbance are considered to be those contained in Popper *et al.* (2014) which set out criteria for disturbance due to different sources of noise. The risk of behavioural effects is categorised in relative terms as "high", "moderate" or "low" at three distances from the source: "near" (i.e. in the tens of metres), "intermediate" (i.e. in the hundreds of metres) or "far" (i.e. in the thousands of metres), as shown in Table 3.8.

It is important to note that the Popper *et al.* (2014) criteria for disturbance due to sound are qualitative rather than quantitative. Consequently, a source of noise of a particular type (e.g. piling) would result in the same predicted impact, no matter the level of noise produced or the propagation characteristics.

[4] *It should be noted that the presence of a swim bladder does not necessarily mean that the fish can detect pressure. Some fish have swim bladders that are not involved in the hearing mechanism and can only detect particle motion.*

Table 3.8: Criteria for Onset of Behavioural Effects in Fish and Sea Turtles for Impulsive and Non-Impulsive Sound (Popper et al., 2014)

Type of Animal	Relative Risk of Behavioural Effects		
	Impulsive Piling	**Explosives**	**Non-Impulsive Sound**
Group 1 Fish: no swim bladder (particle motion detection)	(Near) High (Intermediate) Moderate (Far) Low	(Near) High (Intermediate) Moderate (Far) Low	(Near) Moderate (Intermediate) Moderate (Far) Low
Group 2 Fish: where swim bladder is not involved in hearing (particle motion detection)	(Near) High (Intermediate) Moderate (Far) Low	(Near) High (Intermediate) High (Far) Low	(Near) Moderate (Intermediate) Moderate (Far) Low
Groups 3 and 4 Fish: where swim bladder is involved in hearing (primarily pressure detection)	(Near) High (Intermediate) High (Far) Moderate	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Sea turtles	(Near) High (Intermediate) Moderate (Far) Low	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Eggs and larvae	(Near) Moderate (Intermediate) Low (Far) Low	(Near) High (Intermediate) Low (Far) Low	(Near) Moderate (Intermediate) Moderate (Far) Low

Therefore, the criteria presented in the Washington State Department of Transport Biological Assessment Preparation for Transport Projects Advanced Training Manual (WSDOT, 2011) are also used in this assessment for predicting the extent of behavioural effects due to impulsive piling. The manual suggests an un-weighted sound pressure level of 150 dB re 1 μPa (rms) as the criterion for onset of behavioural effects, based on work by (Hastings, 2002). Sound pressure levels in excess of 150 dB re 1 μPa (rms) are expected to cause temporary behavioural changes, such as elicitation of a startle response, disruption of feeding, or avoidance of an area. The document notes that levels exceeding this threshold are not expected to cause direct permanent injury but may indirectly affect the individual fish (such as by impairing predator detection). It is important to note that this threshold is for onset of potential effects, and not necessarily an ‘adverse effect’ threshold.

4 Source Noise Levels

4.1 Overview of Modelling Scenarios

The following modelling scenarios have been determined based on the project description and an identification of potential sources of noise:

Pre-construction and Survey Works

- Tugs / Barges
- Support vessels / other vessels
- Geophysical site investigation: Sub-Bottom Profiler (SBP), Multi-Beam Echo-Sounder (MBES) and Sidescan Sonar (SSS).

Piling Works

- Impact pile driving of substation jacket foundations
- Jack-up rig
- Misc. small vessels (e.g. tugs, support vessels and RIBs)
- Additional construction phase works: cable trenching and laying

Operational Phase

- Qualitative review provided

4.2 Source Levels

Underwater noise sources are usually quantified in dB re 1 μPa, as if measured at a hypothetical distance of 1 m from the source (the Source Level). In practice, it is not usually possible to measure at 1 m from a source, but this metric allows comparison and reporting of different source levels on a like-for-like basis. In reality, for a large sound source this imagined point at 1 m from the acoustic centre does not exist. Furthermore, the energy is distributed across the source and does not all emanate from this imagined acoustic centre point. Therefore, the stated sound pressure level at 1 m does not actually occur for large sources. In the acoustic near-field (i.e. close to the source), the sound pressure level will be significantly lower than the value predicted by the SL.

A wealth of experimental data and literature-based information is available for quantifying the noise emission from different construction operations. This information, which allows us to predict with a good degree of accuracy the sound generated by a noise source at discrete frequencies in one-third octave bands, will be employed to characterise their acoustic emission in the underwater environment.

4.2.1 Geophysical Surveys

It is understood that several sonar based survey types will potentially be used for the geophysical surveys. Sound source data for the types of equipment likely to be used has been provided by the Applicant.

During the survey a transmitter emits an acoustic signal directly toward the seabed (or alongside, at an angle to the seabed, in the case of side scan techniques). The equipment likely to be used can typically work at a range of signal frequencies, depending on the distance to the bottom and the required resolution. The signal is highly directional and acts as a beam, with the energy narrowly concentrated within a few degrees of the direction in which it is aimed. The signal is emitted in pulses, the length of which can be varied as per the survey requirements. The assumed pulse rate, pulse width and beam width used in the assessment are based on a review of typical units used in other similar surveys. It should be noted that sonar based survey sources are classed as non-impulsive sound because they generally compromise a single (or multiple discrete) frequency (e.g. a sine wave or swept sine wave) as opposed to a broadband signal with high kurtosis, high peak pressures and rapid rise times.

The characteristics assumed for each device modelled in this assessment are summarised in Table 4.1. For the purpose of impacts, these sources are considered to be continuous (non-impulsive).

Table 4.1: Sonar Based Survey Equipment Parameters used in Assessment

Survey Type	Unit	Frequency (kHz)	Source Level, (dB re 1 µPa re 1 m) (rms)	Pulse Rate, s^{-1}	Pulse Width, ms	Beam Width
MBES	Kongsberg 2040	200 - 400	245 Dual Head: 248	40	3	1°
MBES	Reson 7125	200 - 400	220 Dual Head: 224	40	20	2°
SSS	Edgetech 4200	100 - 900	196	30	0.5	1°
Parametric SBP	Innomar SES 2000 Standard	100	247	40	1.5	2°

The assumed pulse rate has been used to calculate the SEL, which is normalised to one second, from the rms sound pressure level. Directivity corrections were calculated based on the transducer dimensions and ping frequency and taken from manufacturer's datasheets. It is important to note that directivity will vary significantly with frequency, but that these directivity values have been used in line with the modelling assumptions stated above.

4.2.2 UXO Clearance

The precise details and locations of potential UXOs is unknown at this time. For the purposes of this assessment, it has been assumed that the maximum, worst case, UXO size will be 1,000 kg with a realistic worst case of 300 kg.

The Applicant has indicated the potential for the use of deflagration (subsonic combustion) as the methodology for clearance of UXO. The technique uses a single charge of 30 g to 80 g Net Explosive Quantity (NEQ) which is placed in close proximity to the UXO to target a specific entry point. When detonated, a shaped charge penetrates the casing of the UXO to introduce a small, clinical plasma jet into the main explosive filling. The intention is to excite the explosive molecules within the main filling to generate enough pressure to burst the UXO casing, producing a deflagration of the main filling and neutralising the UXO.

Recent controlled experiments showed low order deflagration to result in a substantial reduction in acoustic output over traditional high order methods, with SPL_{pk} and SEL being typically significantly lower for the deflagration of the same size munition, and with the acoustic output being proportional to the size of the shaped charge, rather than the size of the UXO itself (Robinson *et al.,* 2020). Using this low order deflagration method, the probability of a low order outcome is high; however, there is a small inherent risk with these clearance methods that the UXO will detonate or deflagrate violently.

It is possible that there will be residual explosive material remaining on the seabed following deflagration. In this case, recovery will be performed, including the potential need of a small (500 g) 'clearing shot'.

The noise modelling has been undertaken for a range of donor charge configurations as set out in Table 4.2. In addition, the noise modelling investigated the potential range of effects for an accidental high order detonation based on a realistic maximum scenario UXO size and a maximum (but unlikely) UXO size.

Table 4.2: Details of UXO and their Relevant Deflagration Charge Sizes Employed for Modelling

Charge Size (kg TNT Equivalent)	Notes/Assumptions
Deflagration (Low Order Disposal)	
0.08 kg	Maximum size of donor charge used for deflagration
0.5 kg	Maximum size of clearing shot to neutralise any residual explosive material
Detonation (High Order Disposal)	
300 kg	Realistic worst case UXO size
1,000 kg	Maximum worst-case UXO size

4.2.3 Impact Piling

The sound generated and radiated by a pile as it is driven into the ground is complex, due to the many components which make up the generation and radiation mechanisms. However, a wealth of experimental data is available which allow us to predict with a good degree of accuracy the sound generated by a pile at discrete frequencies. Third octave band noise spectra have been presented in literature for various piling activities (e.g. Matuschek and Betke, 2009; De Jong and Ainslie, 2008; Wyatt, 2008; Nedwell *et al.*, 2003; Nedwell and Edwards, 2004; Nedwell *et al.,* 2007; CDoT, 2001; Nehls *et al.,* 2007; Thomsen *et al.,* 2006; Robinson *et al.*, 2020; Lepper *et al.*, 2009).

For the Proposed Development, the assessments have been carried out for the wind turbine installation of up to 3 m diameter piles with an average maximum hammer energy typically at 2,300 kJ.

Using the equation below (De Jong and Ainslie, 2008), a broadband source level value is evaluated for the noise emitted during impact pile driving operation in each operation window.

$$\text{SEL} = 120 + 10\, log_{10}\left(\frac{\beta E C_0 \rho}{4\pi}\right).$$

In this equation, β is the energy transmitted from the pile into the water column, E is the hammer energy employed in joules, C_0 is the speed of sound in the water column, and ρ is the density of the water. From the SEL result calculated using the equation above, source level spectra can also be calculated for different third octave frequency bands.

The assumption used for the modelling is that the amount of sound radiated into the water column depends on both the hammer energy and the length of pile exposed above the seabed in the water column.

A variable conversion factor (β) has been used ranging from β = 4% at the start of piling to β = 0.5% at the end of piling when the pile is almost fully embedded in the seabed. These values were chosen based on the following reasoning:

- measurements on piles using above water impact hammers show approximately linear SEL to hammer energy relationship (e.g. Bailey *et al.*, 2010; Robinson *et al.,* 2007; Robinson *et al.*, 2009; Lepper *et al.*, 2012; Robinson *et al.*, 2013).
- peer reviewed literature which considers theoretical concepts, concluded that a representative energy conversion factor is likely to be:
    - in the range β ≈ 0.3% to 1.5% (Zampolli *et al.,* 2013),
    - Dahl *et al.* (2015) concluded that β ≈ 0.5% based on a review of both theoretical considerations and measurement data by others.
- the theoretical upper limit of the energy conversion factor is therefore approximately 1.5%, although this is only likely to apply when the hammer is operating at the lower end of its power rating, with lower conversion factors being more likely throughout the remainder of the piling period (that are subject to higher hammer energies). An average hammer energy conversion factor of β ≈ 1% is therefore

concluded to be representative and precautionary across the range of hammer energies used during a pile installation using an above water hammer;

- peer reviewed studies based on measurements on above water piling hammers determined real world energy conversion factors of β = 0.8% (De Jong and Ainslie, 2008) and β ≈ 1% (Dahl and Reinhall, 2013). However, use of a submersible hammer can result in the conversion factor varying depending on pile penetration depth.
- both measurement data and detailed source modelling presented for a partially submersible hammer in Lippert *et al*. (2017) supports a varying conversion factor of between β ≈ 2% and 0.5% depending on penetration depth and the length of pile above water.
- Thompson *et al*. (2020), whilst ostensibly indicating conversion factors ranging between β ≈ 10% and 1% for a fully submersible hammer, is considered to be a considerable overestimate of the true energy radiated into the water column caused by discrepancies between the noise modelling and real world propagation. True conversion factors are thought likely to be in the order of half these values, or less;
- of the above two studies, the Lippert *et al*. (2017) study is considered scientifically robust because of the very strong correlation between the detailed finite element modelling and measured data;
- it is recognised that for the Lippert *et al*. (2017) study a significant proportion of the pile was above water at the start of the piling sequence which could have reduced the apparent conversion factor compared to a situation where the pile starts just above the water line. Assuming that the energy radiated into the water is approximately proportional to the length of pile which is exposed to the water then the conversion factor at the start of piling in the Lippert *et al* study can be estimated to be approximately 4%;
- for the Proposed Development, although no detailed piling methodology is available at the point of Application, it is considered likely that in the deepest waters, piling will commence below the water line and will finalise with pile penetration just above the seafloor, in water depths of up to 100 m. Consequently, a conversion factor of β ≈ 4% has been used for the Proposed Development at the start of the piling sequence. This 4% conversion factor is higher than that derived in the Lippert *et al*. (2017) study and is therefore considered conservative;
- in the Lippert *et al* study, the piles remained approximately 17 m above the seabed floor at the end of the piling sequence which means that the β ≈ 1% conversion factor at the end of the piling sequence is likely to be an overestimate compared to the Proposed Development case where a greater proportion of the pile will penetrate the seabed. Since the final pile position in the Lippert *et al* study was a little below mid-water depth (and since, when the pile is subsea, the fall-off in acoustic energy cited by Lippert *et al* is ~2.5 dB per halving of exposed pile above the seabed) this infers a final conversion factor of 0.5% or less at the end of piling; and
- consequently, based on this review, the assumption that piling is likely to use a submersible hammer, best available scientific evidence, and professional judgement it is proposed to utilise a varying energy conversion factor of β = 4% at the start of piling to 0.5% at the end of piling for subsea noise modelling at the Proposed Development.

The impact piling scenario that has been modelled for the Proposed Development is shown in Table 4.3.

Table 4.3: Impact piling schedule used in the assessment

Activity / stage	Duration, minutes	Hammer Energy, kJ	Strike Rate (strikes per minute)	Number of strikes	Notes / description
Pile self-weight penetration	N/A	N/A	N/A	N/A	Pile self-weight penetration where the pile will sink into the seabed under its own weight.
Initiation	1	300	6	6	Slow start to allow for alignment etc.

Activity / stage	Duration, minutes	Hammer Energy, kJ	Strike Rate (strikes per minute)	Number of strikes	Notes / description
					and to allow marine mammals to leave area
Soft start	20	500	40	800	Soft start at low hammer energy for 20 minutes
Ramp Up	40	500 - 1200	40	1600	Minimise hammer energies at levels sufficient for pile installation, resulting in energy ramp-up throughout the piling operation
	80	1200 - 2000	40	3200	
	120	2000 - 2300	40	4800	

The peak sound pressure level can be calculated from SEL values via the empirical fitting between pile driving SEL and peak SPL data, given in Lippert *et al*. (2015), as:

$$SPL_{pk} = 1.43 \times SEL - 44.0\ .$$

Root mean square (rms) sound pressure levels were calculated assuming a typical T90 pulse duration (i.e. the period that contains 90% of the total cumulative sound energy) of 100 ms. It should be noted that in reality the rms T90 period will increase significantly with distance which means that any ranges based on rms sound pressure levels at ranges of more than a few kilometres are likely to be significant overestimates and should therefore be treated as highly conservative.

The piling of foundations described in Table 4.3 was also modelled with the inclusion of an acoustic deterrent device (ADD) before commencement of piling. Use of an ADD was modelled for a duration of 15 minutes prior to commencement of piling, all other stages of piling remained the same, and the ADD itself was assumed to not contribute towards any animal injury.

4.2.4 Additional Construction Phase Sources

The other noise source potentially active during the construction phase are related to cable installation (i.e. trenching and cable laying activities), and their related operations such as the jack-up rigs. The SEL based source levels are presented in Table 4.4.

Table 4.4: SEL Based Source Levels for Other Noise Sources

Sources	Data Source	RMS (dB re 1 μPa)	Frequency (Hz)											
			16	31.5	63	125	250	500	1k	2k	4k	8k	16k	31.5k
Cable laying	Wyatt (2008)	188	176	174	174	173	170	165	161	162	146	139	133	169
Cable trenching / cutting	Nedwell et al. (2003)	178	135	135	148	161	167	169	167	162	157	148	142	141
Jack up rig	Evans (1996)	127	99	104	111	115	120	120	116	113	117	120	115	109

4.2.5 Vessels (All Phases)

The noise emissions from the types of vessels that may be used for the Proposed Development are quantified in Table 4.4, based on a review of publicly available data. Sound from the vessels themselves (e.g. propeller, thrusters and sonar (if used)) primarily dominates the emission level.

In Table 4.5, a correction of +3 dB has been applied to the rms sound pressure level to estimate the likely peak sound pressure level. SELs have been estimated for each source based on 24 hours continuous operation, although it is important to note that it is highly unlikely that any marine mammal or fish would stay at a stationary location or within a fixed radius of a vessel (or any other noise source) for 24 hours. Consequently, the acoustic modelling has been undertaken based on an animal swimming away from the source (or the source moving away from an animal). Source noise levels for vessels depend on the vessel size and speed as well as propeller design and other factors. There can be considerable variation in noise magnitude and character between vessels even within the same class. Therefore, source data for the Proposed Development has been based on worst-case assumptions (i.e. using noise data toward the higher end of the scale for the relevant class of ship as a proxy).

Table 4.5: Source Noise Data for Construction and Installation Vessels

Item	Description/ Assumptions	Data Source	Source SPL at 1 m	
			RMS (dB re 1 µPa)	SEL(24h) (dB re 1 µPa^{2}s)
Main Installation Vessels (Jack-up Barge/DP vessel)	‘Gerardus Mercator’ trailer hopper suction dredger using DP as proxy	Wyatt (2008)	180	229
Tug/Anchor Handlers	Tug used as proxy	Richardson (1995)	172	221
Guard Vessels	Tug used as proxy	Richardson (1995)	172	221
Survey Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	228
Crew Transfer Vessels	Offshore support vessel used as proxy	McCauley (1998)	179	228

5 Propagation Model

5.1 Propagation of Sound Underwater

As distance from the sound source increases the level of sound recorded reduces, primarily due to the spreading of the sound energy with distance, in combination with attenuation due to absorption of sound energy by molecules in the water. This latter mechanism is more important for higher frequency sound than for lower frequencies.

The way that the sound spreads (geometrical divergence) will depend upon several factors such as water column depth, pressure, temperature gradients, salinity as well as water surface and bottom (i.e. seabed) conditions. Thus, even for a given locality, there are temporal variations to the way that sound will propagate. However, in simple terms, the sound energy may spread out in a spherical pattern (close to the source) or a cylindrical pattern (much further from the source), although other factors mean that decay in sound energy may be somewhere between these two simplistic cases.

In acoustically shallow waters[5] in particular, the propagation mechanism is coloured by multiple interactions with the seabed and the water surface (Lurton 2002; Etter 2013; Urick 1983; Brekhovskikh and Lysanov 2014; Kinsler *et al.*, 1999). Whereas in deeper waters, the sound will propagate further without encountering the surface or bottom of the sea, in shallower waters the sound may be reflected from either or both boundaries (potentially more than once).

At the sea surface, the majority of sound is reflected back into the water due to the difference in acoustic impedance (i.e. sound speed and density) between air and water. However, scattering of sound at the surface of the sea can be an important factor with respect to the propagation of sound. In an ideal case (i.e. for a perfectly smooth sea surface), the majority of sound energy will be reflected back into the sea. However, for rough seas, much of the sound energy is scattered (e.g. Eckart 1953; Fortuin 1970; Marsh, Schulkin, and Kneale 1961; Urick and Hoover 1956). Scattering can also occur due to bubbles near the surface such as those generated by wind or fish or due to suspended solids in the water such as particulates and marine life. Scattering is more pronounced for higher frequencies than for low frequencies and is dependent on the sea state (i.e. wave height). However, the various factors affecting this mechanism are complex.

Because surface scattering results in differences in reflected sound, its effect will be more important at longer ranges from the sound source and in acoustically shallow water (i.e. where there are multiple reflections between the source and receiver). The degree of scattering will depend upon the sea state/wind speed, water depth, frequency of the sound, temperature gradient, grazing angle and range from source. It should be noted that variations in propagation due to scattering will vary temporally within an area primarily due to different sea-states / wind speeds at different times. However, over shorter ranges (e.g. several hundred meters or less) the sound will experience fewer reflections and so the effect of scattering should not be significant.

When sound waves encounter the bottom, the amount of sound reflected will depend on the geo-acoustic properties of the bottom (e.g. grain size, porosity, density, sound speed, absorption coefficient and roughness) as well as the grazing angle and frequency of the sound (Cole 1965; Hamilton 1970; Mackenzie 1960; McKinney and Anderson 1964; Etter 2013; Lurton 2002; Urick 1983). Thus, bottoms comprising primarily mud or other acoustically soft sediment will reflect less sound than acoustically harder bottoms such as rock or sand. This will also depend on the profile of the bottom (e.g. the depth of the sediment layer and how the geo-acoustic properties vary with depth below the sea floor). The effect is less pronounced at low frequencies (a few kHz and below). A scattering effect (similar to that which occurs at

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[5] *Acoustically, shallow water conditions exist whenever the propagation is characterised by multiple reflections with both the sea surface and bottom (Etter 2013). Consequently, the depth at which water can be classified as acoustically deep or shallow depends upon numerous factors including the sound speed gradient, water depth, frequency of the sound and distance between the source and receiver.*

the surface) also occurs at the bottom (Essen 1994; Greaves and Stephen 2003; McKinney and Anderson 1964; Kuo 1992), particularly on rough substrates (e.g. pebbles).

Waveguide effect should also be considered, which defines the shallow water columns do not allow the propagation of low frequency sound (Urick 1983; Etter 2013). The cut-off frequency of the lowest mode in a channel can be calculated based on the water depth and knowledge of the sediment geo-acoustic properties. Any sound below this frequency will not propagate far due to energy losses through multiple reflections.

Changes in the water temperature and the hydrostatic pressure with depth mean that the speed of sound varies throughout the water column. This can lead to significant variations in sound propagation and can also lead to sound channels, particularly for high-frequency sound. Sound can propagate in a duct-like manner within these channels, effectively focussing the sound, and conversely, they can also lead to shadow zones. The frequency at which this occurs depends on the characteristics of the sound channel but, for example, a 25 m thick layer would not act as a duct for frequencies below 1.5 kHz. The temperature gradient can vary throughout the year and thus there will be potential variation in sound propagation depending on the season.

Sound energy is also absorbed due to interactions at the molecular level converting the acoustic energy into heat. This is another frequency dependent effect with higher frequencies experiencing much higher losses than lower frequencies.

5.1.1 Modelling approach

There are several methods available for modelling the propagation of sound between a source and receiver ranging from very simple models which simply assume spreading according to a 10 log (R) or 20 log (R) relationship (as discussed above, and where R is the range from source to receiver) to full acoustic models (e.g. ray tracing, normal mode, parabolic equation, wavenumber integration and energy flux models). In addition, semi-empirical models are available, whose complexity and accuracy are somewhere in between these two extremes.

In choosing the correct propagation model to employ, it is important to ensure that it is fit for purpose and produces results with a suitable degree of accuracy for the application in question, taking into account the context (as detailed in Monitoring Guidance for Underwater Noise in European Seas Part III, NPL Guidance Wang et al 2014, and Farcas et al., 2016). Thus, in some situations (e.g. low risk due to underwater noise, range dependent bathymetry is not an issue, non-impulsive sound) a simple (N log R) model will be sufficient, particularly where other uncertainties outweigh the uncertainties due to modelling. On the other hand, some situations (e.g. very high source levels, impulsive sound, complex source and propagation path characteristics, highly sensitive receivers and low uncertainties in assessment criteria) warrant a more complex modelling methodology.

The first step in choosing a propagation model is therefore to examine these various factors, such as set out below:

- Balancing of errors / uncertainties;
- Range dependant bathymetry;
- Frequency dependence;
- Source characteristics.

Modelling was caried out at the proposed location of the substation, however the bathymetry across the development area is relatively flat, and therefore the injury range results are unlikely to vary significantly if the substation were to be installed in an alternative location within the project boundary.

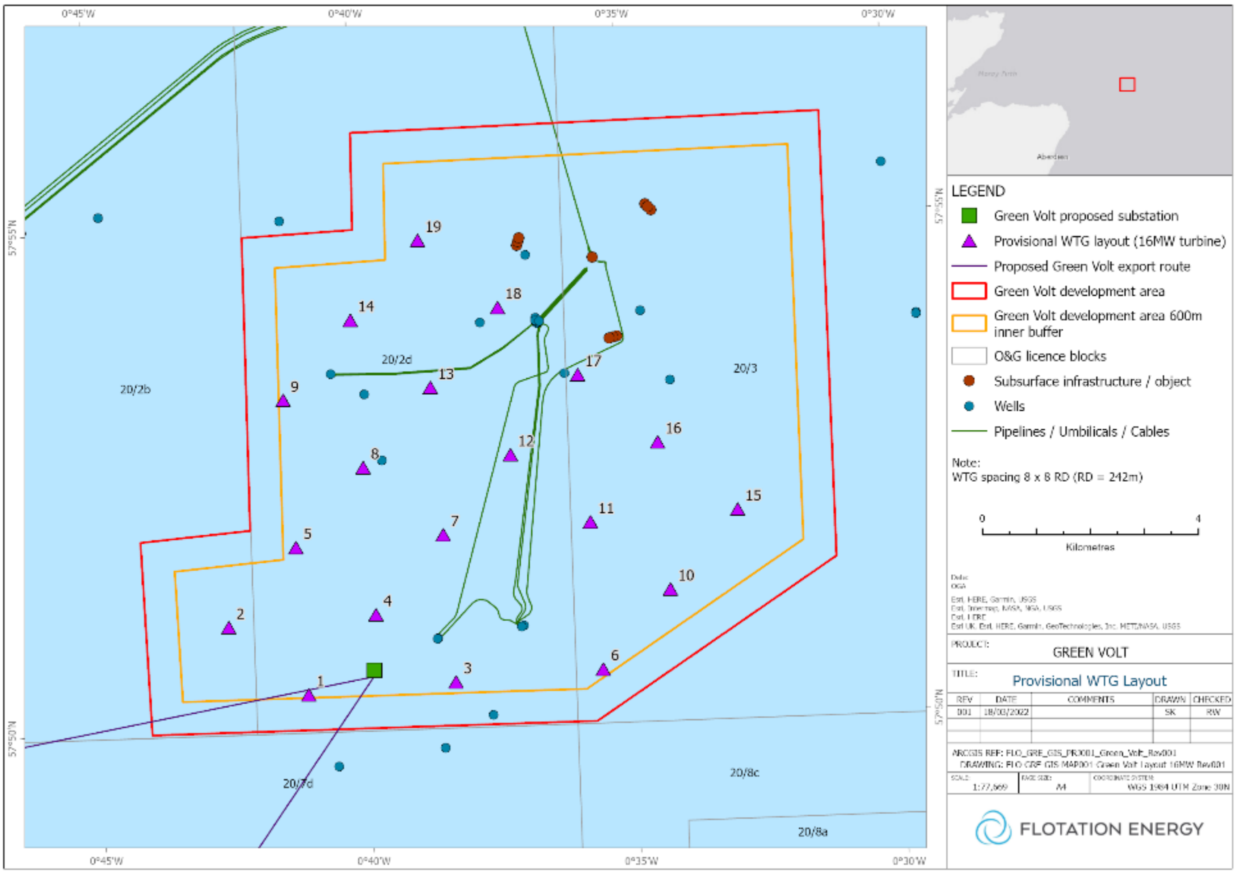

Figure 5.1: Map showing the location of the substation within the development boundary

For the sound field model, relevant survey parameters were chosen based on a combination of data provided by the Applicant combined with the information gathered from the publicly available literature. These parameters were fed into an appropriate propagation model routine, in this case the Weston Energy Flux model (Weston, 1971; 1980a; 1980b), suited to the region and the frequencies of interest. The frequency-dependent loss of acoustic energy with distance (TL) values were then evaluated along different transects around the chosen source points. The frequencies of interest in the present study are from 20 Hz to 80 kHz, with different noise sources operating in different frequency bands. These frequencies overlap with the hearing sensitivities (as per Figure 3.1) of some of the marine mammals that are likely to be present in the survey area.

Table 5.1: Regions of Transmission Loss Derived by Weston (1971)

Region	Transmission Loss	Range of validity
Spherical	$TL = 10\log_{10}[R^2]$	$R < \frac{H_a}{2\theta_c}$
Channelling	$TL = 10\log_{10}\left[\frac{RH_aH_b}{2H_c\theta_c}\right]$	$\frac{H_a}{2\theta_c} < R < \frac{6.8H_a}{\alpha{\theta_c}^2}$
Mode stripping	$TL = 10\log_{10}\left[\frac{RH_aH_b}{5.22}\left(\alpha\int_0^R \frac{dR}{H^3}\right)^{1/2}\right]$	$\frac{6.8H_a}{\alpha{\theta_c}^2} < R < \frac{27k^2{H_a}^3}{(2\pi)^2\alpha}$
Single mode	$TL = 10\log_{10}\left[\frac{RH_aH_b}{\lambda}\right] + \frac{\lambda^2\alpha}{8}\int_0^R \frac{dR}{H^3}$	$R > \frac{27k^2{H_a}^3}{(2\pi)^2\alpha}$

The propagation loss is calculated using one for the four formulae detailed in the table above, depending on the distance of the receiver location from the source, and related to the frequency and the seafloor conditions such as depth and its composition.

In Table 5.1, H_a is the depth at the source, H_b is the depth at the receiver, H_c is the minimum depth along the bathymetry profile (between the source and the receiver), θ_c is the critical grazing angle (related to the speed of sound in both seawater and the seafloor material), λ and k are the wavelength and wavenumber as usual, and α is the seabed reflection loss gradient, empirically derived to be 12.4 dB/rad in Weston (1971).

The spherical spreading region exists in the immediate vicinity of the source, which is followed by a region where the propagation follows a cylindrical spread out until the grazing angle is equal to the critical grazing angle θ_c. Above the critical grazing angle in the mode stripping region an additional loss factor is introduced which is due to seafloor reflection loss, where higher modes are attenuated faster due to their larger grazing angles. In the final region, the single-mode region, all modes but the lowest have been fully attenuated.

For estimation of propagation loss of acoustic energy at different distances away from the noise source location (in different directions), the following steps were considered:

- The bathymetry information around this chosen source point was extracted from the GEBCO database up to 80 km.
- A calibrated Weston Energy model was employed to estimate the TL matrices for different frequencies of interest (from 20 Hz to 80 kHz).
- The source level values calculated were combined with the TL results to achieve a frequency and range dependant RL of acoustic energy around the chosen source position.
- The recommended marine mammal weightings (m-weightings) were employed for injury and the TTS and PTS impact ranges for different marine mammal groups were calculated using relevant metrics (from Southall *et al.*, 2019) and by employing a fleeing marine mammal model where necessary.

It should be borne in mind that noise levels (and associated range of effects) will vary depending on actual conditions at the time (day-to-day and season-to-season) and that the model predicts a typical worst-case scenario. Considering factors such as animal behaviour and habituation, any injury and disturbance ranges should be viewed as indicative and probabilistic ranges to assist in understanding potential impacts on marine life rather than lines either side of which an impact will or will not occur[6].

5.2 Exposure Calculations

As well as calculating the un-weighted rms sound pressure levels at various distances from the source, it is also necessary to calculate the acoustic signal in the SEL metric for a mammal using the relevant hearing weightings to which it is exposed. For operation of the different sources, the SEL sound data was numerically equal to the SPL rms value integrated over 1-second window as the sources are continuous and non-impulsive. These SEL values are employed for calculation of cSEL (cumulative SEL) metric for different marine mammal groups to assess impact ranges.

Simplified exposure modelling could assume that the mammal either being static and at a fixed distance away from the noise source, or that the mammal is swimming at a constant speed in a perpendicular direction away from a noise source. For fixed receiver calculations, it has generally been assumed (in literature) that an animal will stay at a known distance from the noise source for a period of 24 hours. As the animal does not move, the noise will be constant over the integration period of 24 hours (assuming the source does not change its operational characteristics over this time). This, however, would give an unrealistic level of exposure, as the animals are highly unlikely to remain stationary when exposed to loud noise, and is therefore expected to swim away from the source. The approximation used in these

[6] This is a similar approach to that adopted for airborne noise where a typical worst case is taken, though it is known that day to day levels may vary to those calculated by 5 to 10 dB depending on wind direction etc.

calculations, therefore, is that the animals flee directly away from the source. It should be noted that the sound exposure calculations are based on the simplistic assumption that the noise source is active continuously over a 24-hour period. The real-world situation is more complex. The SEL calculations presented in this study do not take any breaks in activity into account.

It should be noted that the sound exposure calculations are based on the simplistic assumption that the noise source is active continuously (or intermittently based on shot-timings) over a 24 hour period. The real world situation is more complex. The SEL calculations presented in this study do not take any breaks in activity into account, such as repositioning of the piling vessel.

Furthermore, the sound criteria described in the Southall et al. (2019) guidelines assume that the animal does not recover hearing between periods of activity. It is likely that both the intervals between operations could allow some recovery from temporary hearing threshold shifts for animals exposed to the sound and, therefore, the assessment of sound exposure level is conservative.

In order to carry out the swimming mammal calculation, it has been assumed that a mammal will swim away from the noise source at the onset of activities. For impulsive sounds of piledriving the calculation considers each pulse to be established separately resulting in a series of discrete SEL values of decreasing magnitude (see Figure 5.2).

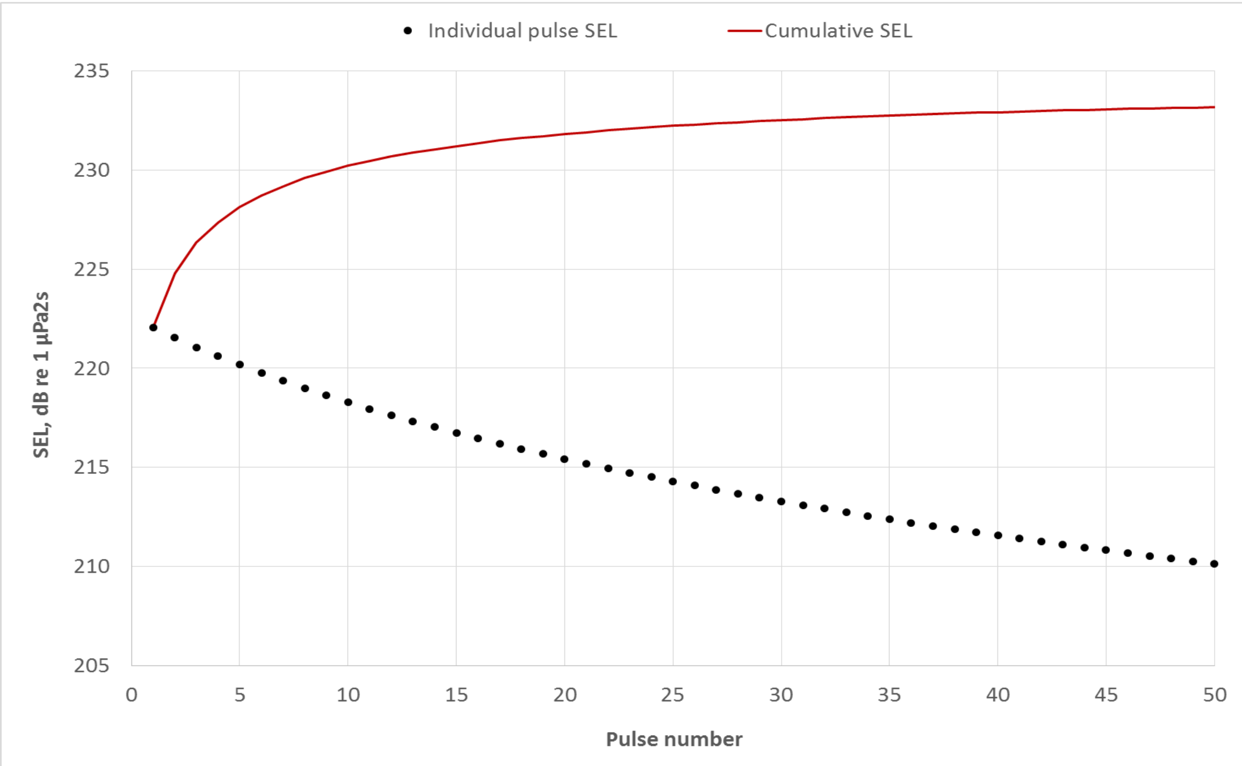

Figure 5.2: A Comparison of Discrete "Pulse" Based SEL and a Cumulative of SEL Values

As a marine mammal swims away from the sound source, the noise it experiences will become progressively more attenuated; the cumulative SEL is derived by logarithmically adding the SEL to which the mammal is exposed as it travels away from the source. This calculation was used to estimate the approximate minimum start distance for a marine mammal in order for it to be exposed to sufficient sound energy to result in the onset of potential injury. It should be noted that the sound exposure calculations are based on the simplistic assumption that the animal will continue to swim away at a fairly constant relative speed. The real-world situation is more complex, and the animal is likely to move in a more complex manner.

The swim speeds of marine mammals used in this assessment are summarised in Table 5.2 along with the source papers for the assumptions.

Table 5.2: Swim Speeds Assumed for Exposure Modelling

Species	Hearing Group	Swim Speed (m/s)	Source Reference
Harbour porpoise	VHF	1.5	Otani *et al.*, 2000
Harbour seal	PCW	1.8	Thompson, 2015
Grey seal	PCW	1.8	Thompson, 2015
Minke whale	LF	2.3	Boisseau *et al.*, 2021
Bottlenose dolphin	HF	1.52	Bailey and Thompson, 2010
White-beaked dolphin	HF	1.52	Bailey and Thompson, 2010
Basking shark	Group 1 fish	1.0	Sims, 2000

To perform this calculation, the first step is to parameterise the m-weighted sound exposure levels for single strikes of a given energy via a line of best fit. This function is then used to predict the exposure level for each strike in the planned hammer schedule (periods of slow start, ramp up and full power).

5.3 UXO Noise Modelling

5.3.1 Detonation

Noise modelling for UXO clearance has been undertaken using the methodology described in Soloway and Dahl (2014). The equation provides a simple relationship between distance from an explosion and the weight of the charge (or equivalent TNT weight) but does not take into account bottom topography or sediment characteristics.

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

Where W is the equivalent TNT charge weight and R is the distance from source to receiver.

Since the charge is assumed to be freely standing in mid-water, unlike a UXO which would be resting on the seabed and could potentially be buried, degraded or subject to other significant attenuation, this estimation of the source level can be considered conservative.

According to Soloway and Dahl (2014), the SEL can be estimated by the following equation:

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

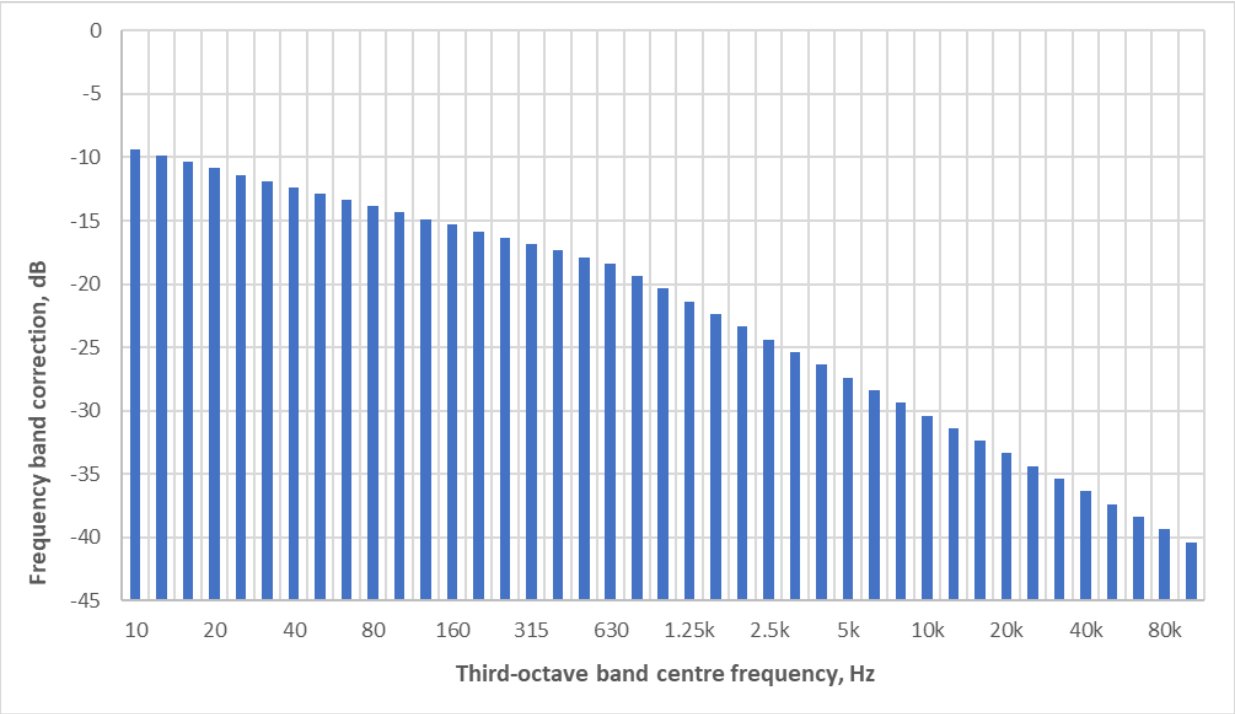

Figure 5.3: Assumed Explosive Spectrum Shape Used to Estimate Hearing Weighting Corrections to SEL

In order to compare to the marine mammal hearing weighted thresholds, it is necessary to apply the frequency dependent weighting functions at each distance from the source. This was accomplished by determining a transfer function between unweighted and weighted SEL values at various distances based on an assumed spectrum shape (see Figure 5.3) and taking into account molecular absorption at various ranges. A maximum of one UXO clearance event per day is assumed.

5.3.2 Deflagration

According to Robinson et al., (2020), low order deflagration results in a much lower amplitude of peak sound pressure than high order detonations. The study concluded that peak sound pressure during deflagration is due only to the size of the shaped charge used to initiate deflagration and, consequently, that the acoustic output can be predicted for deflagration as long as the size of the shaped charge is known.

Noise modelling for deflagration has therefore been based on the methodology described in above for detonations, using a smaller donor charge size.

6 Sound Modelling Results

6.1 Pre-construction Phase

The estimated ranges for injury to marine mammals due to various proposed activities invited in the pre-construction surveying phase of the operations are presented in this section. These include geophysical survey activities, UXO clearance and supported vessel activities.

The potential ranges presented for injury and disturbance are not a hard and fast 'line' where an impact will occur on one side and not on the other. Potential impact is more probabilistic than that; dose dependency in PTS onset, individual variations and uncertainties regarding behavioural response and swim speed/direction all mean that it is much more complex than drawing a contour around a location. These ranges are designed to provide an understandable way in which a wider audience can appreciate the potential spatial extent of the impact.

6.1.1 Geophysical Surveys

Geophysical surveying includes many sonar based operations and the resulting injury and disturbance ranges for marine mammals are presented in Table 6.1, based on a comparison to the non-impulsive thresholds set out in Southall et al. (2019).

The impact distances from these operations vary based on their frequencies of operation and source levels and are rounded to the nearest 5 m. It should be noted that, for the sonar-based surveys, many of the injury ranges are limited to approximately 100 m as this is the approximate water depth in the area. Sonar based systems have very strong directivity which effectively means that there is only potential for injury when a marine mammal is directly underneath the sound source. Once the animal moves outside of the main beam, there is no potential for injury. The same is true in many cases for TTS where an animal is only exposed to enough energy to cause TTS when inside the direct beam of the sonar. For this reason, many of the TTS and PTS ranges are similar (i.e. limited by the depth of the water). Any shallower waters surveyed would result in shorter injury ranges due to these directivity effects therefore these values represent a worst case assessment.

Table 6.1: Potential Impact Ranges (m) for Marine Mammals During the Various Geophysical Investigation Activities Based on Comparison to Southall et al. (2019) SEL Thresholds (N/E = threshold not exceeded)

Source	Potential Impact Range (m)										
	LF		HF		VHF		PCW		OCW		All
	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	Disturbance
SBP Innomar	125	120	205	125	530	330	125	120	125	75	1,425
MBES Kongsberg	125	120	125	120	175	135	125	120	125	120	855
MBES Reason	125	95	125	120	145	120	125	120	120	45	455
SSS Edgetech	25	N/E	50	50	125	120	50	5	N/E	N/E	235

6.1.2 UXO Clearance

Deflagration – Low Order Disposal

The predicted injury ranges for deflagration are presented in Table 6.2 and Table 6.3 whereas the predicted ranges for the clearance shot to remove any residual explosive material from the seabed are shown in Table 6.4 and Table 6.5.

All UXO injury and disturbance ranges are based on a comparison to the relevant impulsive sound thresholds as set out in section 4.2.2.

Table 6.2: Injury Ranges for Marine Mammals due to Detonation of 0.08 kg Donor Charge (Deflagration)

Group	PTS Range				TTS Range			
	SPL Peak		SEL (Weighted)		SPL Peak		SEL (Weighted)	
	Threshold	*Range (m)*	*Threshold*	*Range (m)*	*Threshold*	*Range (m)*	*Threshold*	*Range (m)*
LF	*219*	120	*183*	50	*213*	225	*168*	660
HF	*230*	40	*185*	N/E	*224*	75	*170*	25
VHF	*202*	685	*155*	190	*196*	1,265	*140*	1,495
PCW	*218*	135	*185*	10	*212*	250	*170*	125
OCW	*232*	30	*203*	N/E	*226*	60	*188*	10

Table 6.3: Injury Ranges for Fish due to Detonation of 0.08 kg Donor Charge (Deflagration)

Group	Mortality		Recoverable Injury	TTS
	Threshold	Range (m)		
Group 1 fish	*229 - 234*	30 - 45	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 2 fish	*229 - 234*	30 - 45	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 3 and 4 fish	*229 - 234*	30 - 45	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) High (Far) Low
Sea turtles	*229 - 234*	30 - 45	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low

Table 6.4: Injury Ranges for Marine Mammals due to Detonation of 0.5 kg Clearance Shot

Group	PTS Range				TTS Range			
	SPL Peak		SEL (Weighted)		SPL Peak		SEL (Weighted)	
	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)
LF	*219*	225	*183*	115	*213*	415	*168*	1,585
HF	*230*	75	*185*	5	*224*	135	*170*	60
VHF	*202*	1,265	*155*	425	*196*	2,325	*140*	2,435
PCW	*218*	250	*185*	22	*212*	455	*170*	300
OCW	*232*	60	*203*	N/E	*226*	110	*188*	15

Table 6.5: Injury Ranges for Fish due to Detonation of 0.5 kg Clearance Shot

Group	Mortality		Recoverable Injury	TTS
	Threshold	Range (m)		
Group 1 fish	*229 - 234*	50 - 80	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 2 fish	*229 - 234*	50 - 80	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 3 and 4 fish	*229 - 234*	50 - 80	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) High (Far) Low
Sea turtles	*229 - 234*	50 - 80	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low

Detonation – High Order Disposal

There is a small (10% to 20%) chance that low order deflagration could result in a high order detonation event. The predicted injury ranges for marine mammals and fish are shown in Table 6.6 and Table 6.7 for a realistic adverse case 300 kg UXO detonation and Table 6.8 and Table 6.9 for a maximum adverse case 1,000 kg detonation. It should be noted that, due to a combination of dispersion (i.e. where the waveform elongates), multiple reflections from the sea surface and bottom and molecular absorption of high frequency energy, the sound is unlikely to still be impulsive in character once it has propagated more than a few kilometres. Consequently, great caution should be used when interpreting any results with predicted injury ranges in the order of tens of kilometres. Furthermore, the modelling assumes that the UXO acts like a charge suspended in open water whereas in reality it is likely to be partially buried in the sediment. In addition, it is possible that the explosive material will have deteriorated over time meaning that the predicted noise levels are likely to be over-estimated. In combination, these factors mean that the results should be treated as precautionary impact ranges which are likely to be significantly lower than predicted.

Table 6.6: Potential Injury Ranges for Marine Mammals due to High Order Detonation of 300 kg UXO

Group	PTS Range				TTS Range			
	SPL Peak		SEL (Weighted)		SPL Peak		SEL (Weighted)	
	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)
LF	*219*	1,885	*183*	2,530	*213*	3,470	*168*	23,845
HF	*230*	615	*185*	90	*224*	1,130	*170*	935
VHF	*202*	10,630	*155*	3,045	*196*	19,590	*140*	7,690
PCW	*218*	2,085	*185*	480	*212*	3,840	*170*	4,520
OCW	*232*	505	*203*	20	*226*	925	*188*	298

Table 6.7: Potential Injury Ranges for Fish due to High Order Detonation of 300 kg UXO

Group	Mortality		Recoverable Injury	TTS
	Threshold	Range (m)		
Group 1 fish	*229 - 234*	410 - 680	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 2 fish	*229 - 234*	410 - 680	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 3 and 4 fish	*229 - 234*	410 - 680	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) High (Far) Low
Sea turtles	*229 - 234*	410 - 680	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low

Table 6.8: Injury Ranges for Marine Mammals due to High Order Detonation of 1,000 kg UXO

Group	PTS Range				TTS Range			
	SPL Peak		SEL (Weighted)		SPL Peak		SEL (Weighted)	
	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)	Threshold	Range (m)
LF	*219*	2,810	*183*	4,405	*213*	5,180	*168*	35,475
HF	*230*	920	*185*	160	*224*	1,690	*170*	1,420
VHF	*202*	15,880	*155*	3,895	*196*	29,260	*140*	9,040
PCW	*218*	3,115	*185*	835	*212*	5,735	*170*	6,665
OCW	*232*	750	*203*	40	*226*	1,380	*188*	525

Table 6.9: Potential Injury Ranges for Fish due to High Order Detonation of 1,000 kg UXO

Group	Mortality		Recoverable Injury	TTS
	Threshold	Range (m)		
Group 1 fish	*229 - 234*	610 - 1,015	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 2 fish	*229 - 234*	610 - 1,015	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) Moderate (Far) Low
Group 3 and 4 fish	*229 - 234*	610 - 1,015	(Near) High (Intermediate) High (Far) Low	(Near) High (Intermediate) High (Far) Low
Sea turtles	*229 - 234*	610 - 1,015	(Near) High (Intermediate) Low (Far) Low	(Near) High (Intermediate) Moderate (Far) Low

6.2 Construction Phase

6.2.1 Impact Piling

All impact piling injury and disturbance ranges are based on a comparison to the relevant impulsive sound thresholds as set out in section 3. All results for marine mammal injury ranges are shown with and without the use of an ADD for 15 minutes prior to the commencement of piling.

During impact piling the interaction with the seafloor and the water column is complex. In these cases, a combination of dispersion (i.e. where the waveform shape elongates), and multiple reflections from the sea surface and bottom and molecular absorption of high frequency energy, the sound will lose its impulsive shape after some distance (generally in order of several kilometres).

A recent article by Southall (2021) discusses this aspect in detail, and notes that *"…when onset criteria levels were applied to relatively high-intensity impulsive sources (e.g. pile driving), TTS onset was predicted in some instances at ranges of tens of kilometers from the sources. In reality, acoustic propagation over such ranges transforms impulsive characteristics in time and frequency (see Hastie et al., 2019; Amaral et al., 2020; Martin et al., 2020). Changes to received signals include less rapid signal onset, longer total duration, reduced crest factor, reduced kurtosis, and narrower bandwidth (reduced high-frequency content). A better means of accounting for these changes can avoid overly precautionary conclusions, although how to do so is proving vexing". The point is reenforced later in the discussion which points out that "…it should be recognized that the use of impulsive exposure criteria for receivers at greater ranges (tens of kilometers) is almost certainly an overly precautionary interpretation of existing criteria".*

Consequently, great caution should be used when interpreting any results with predicted injury ranges in the order of tens of kilometres.

Table 6.10: Injury and Disturbance Ranges Based on the Cumulative SEL Metric for Marine Mammals due to Impact Pile Driving of the Substation Jackets, with and without the Use of an ADD (N/E = threshold not exceeded)

Species/Group	Threshold (Weighted SEL)	Range (m)	
		Without ADD	With 15 mins ADD
LF	PTS - 183 dB re 1 μPa²s	1,085	N/E
	TTS - 168 dB re 1 μPa²s	*41,900**	*39,800**
HF	PTS - 185 dB re 1 μPa²s	N/E	N/E
	TTS - 170 dB re 1 μPa²s	N/E	N/E
VHF	PTS - 155 dB re 1 μPa²s	227	N/E
	TTS - 140 dB re 1 μPa²s	3,580	2,190
PCW	PTS - 185 dB re 1 μPa²s	N/E	N/E
	TTS - 170 dB re 1 μPa²s	1,245	N/E
OCW	PTS - 203 dB re 1 μ μPa²s	N/E	N/E
	TTS - 188 dB re 1 μPa²s	N/E	N/E
Behavioural disturbance	Mild - 140 dB re 1 μPa (rms)	46,705	
	Strong - 160 dB re 1 μPa (rms)	3,491	

Notes:

** These ranges are likely an overestimate due to the noise at this range no longer being impulsive as described above*

The injury ranges for marine mammals based on peak pressure are summarised in

Table 6.11 for both the first strike the animal experiences, and the phase of piling with the maximum sound energy. These ranges represent the potential zone for instantaneous injury. The injury ranges are therefore highly dependent upon the hammer energy, but independent of piling duration. It is assumed that, although the piling phase with the highest sound energy has larger injury ranges, the animal would have moved out of the ranges at the time those hammer energies are used. It is important to understand that a pile is a large and distributed source and therefore reporting injury ranges that are smaller than the physical size of the pile based on a point source sound level assumption (i.e. assumption of an infinitesimally small source size) could result in an overestimation of injury range.

Table 6.11: Summary of Peak Pressure Injury Ranges for Marine Mammals due to the Phase of Impact Piling Resulting in the Maximum Peak Sound Pressure Level, and due to the First Hammer Strike

Species/Group	Threshold (Unweighted Peak)	Range (m)	
LF	PTS - 219 dB re 1 μPa (pk)	49	35
	TTS - 213 dB re 1 μPa (pk)	85	62
HF	PTS - 230 dB re 1 μPa (pk)	18	13
	TTS - 224 dB re 1 μPa (pk)	31	22
VHF	PTS - 202 dB re 1 μPa (pk)	234	170

Species/Group	Threshold (Unweighted Peak)	Range (m)	
	TTS - 196 dB re 1 µPa (pk)	407	295
PCW	PTS - 218 dB re 1 µPa (pk)	54	39
	TTS - 212 dB re 1 µPa (pk)	93	68
OCW	PTS - 232 dB re 1µ Pa (pk)	15	11
	TTS - 226 dB re 1 µPa (pk)	26	19

The results of the noise modelling for fish and turtles are shown in Table 6.12 based on the cumulative sound exposure level thresholds, and in Table 6.13 based on the peak sound pressure thresholds. The tables show two results for Group 1 Fish, one based on the 0.5 m/s and another (in square brackets) showing the range for basking sharks using a higher swim speed of 1 m/s. Similarly, sea turtles have been assumed to swim at a speed of 0.5 m/s whereas fish eggs and larvae have been assumed to be static, resulting in a different impact range to reach the same numerical SEL criteria.

Table 6.12: Injury Ranges for Fish Based on the Cumulative SEL Metric due to Impact Pile Driving based on the Cumulative SEL Metric (N/E = threshold not exceeded)

Hearing Group	Response	Threshold (SEL, dB re 1 µPa^{2}s)	Range (m)
Group 1 Fish: No swim bladder (particle motion detection) – [basking shark ranges shown in square brackets].	Mortality	219	N/E
	Recoverable injury	216	N/E
	TTS	186	4,500 [2,550]*
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	N/E
	Recoverable injury	203	N/E
	TTS	186	4,500 [2,550]*
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	N/E
	Recoverable injury	203	N/E
	TTS	186	4,500 [2,550]*
Sea turtles	Mortality	210	N/E
Fish eggs and larvae (static)	Mortality	210	329

Notes:

** These ranges are likely an overestimate due to the noise at this range no longer being impulsive as described above*

Table 6.13: Summary of Peak Pressure Injury Ranges for Fish due to the Phase of Impact Piling Resulting in the Maximum Peak Sound Pressure Level, and due to the First Hammer Strike

Hearing Group	Response	Threshold (SPL_{pk}, dB re 1 µPa)	Range (m)	
			Max Peak Experienced	First Hammer Strike
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	85	62
	Recoverable injury	213	85	62
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	147	107
	Recoverable injury	207	147	107
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	147	107
	Recoverable injury	207	147	107
Sea turtles	Mortality	207	147	107
Fish eggs and larvae	Mortality	207	147	107

The disturbance range for fish, given by the 150 dB re 1 µPa SPL_{rms} contour is 13 km for impact pile driving.

6.2.2 Additional Construction Sources

The impact ranges from other construction related activities (such as cable trenching, cable laying and supporting jack-up rigs) on different marine mammal groups are presented in Table 6.14, and in Table 6.15 for fish.

Table 6.14: Estimated PTS and TTS Ranges from Different Vessels for Marine Mammals

Source/Vessel	Range (m)										
	LF		HF		VHF		PCW		OCW		All
	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	Disturbance
Cable trenching / cutting	N/E	N/E	N/E	N/E	N/E	55	N/E	40	N/E	N/E	9,284
Cable Laying	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	5,779
Jack up rig	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E

Table 6.15: Estimated Recoverable Injury and TTS Ranges from Vessels for Groups 3 and 4 Fish

Source/Vessel	Range (m)	
	Recoverable Injury	TTS
	170 dB rms for 48 hrs	158 dB rms for 12 hrs
Cable trenching / cutting	10	51
Cable Laying	16	66
Jack up rig	N/E	N/E

6.3 Operational Phase

Underwater noise from operational offshore wind turbines derives in the main from the moving mechanical parts in the nacelle, which is generally found to be of frequencies below 1 kHz (Pangerc *et al.*, 2016), and vessel noise associated with operational and maintenance activities.

Vibration of the wind turbine's gear box and generator is transmitted down the tower and radiated as sound from the tower wall. Sound radiation by surface waves is difficult to quantitatively predict, in particular for the boundary regions, and is highly dependent upon the conditions of both the wind turbine itself, including generator and tower condition, and on the seawater conditions. There have been few empirical investigations of operational offshore wind farms, and as such measurement data is also scarce. Those that have been measured in situ are almost exclusively from traditional foundation methods, rather than the floating foundations employed here. Due to the general lack of investigation into the subject, wind turbines of a variety of foundation types have been included in this section.

The distances and exposures of mammals and fish reported by studies that investigate the impact of operational offshore wind farms present a range of values, but the majority conclude that in the order of hundreds of metres distance from the wind turbines, sound levels would likely be audible but not at a level sufficient to cause injury or behavioural changes (Betke, 2006; Nedwell et al., 2007; Norro, et al., 2011; Ward, et al., 2006; Jansen, 2016). Norro et al. (2011) compared measurements of a range of different foundation types and wind turbine ratings in the Belgian part of the North Sea, as well as comparing those to other European waters. A summary of these studies is shown in Table 6.16. The authors found a slight increase in SPL compared to the ambient noise measured before the construction of the wind farms. They concluded that even the highest increases found within the dataset (20 to 25 dB re 1μ Pa) are unlikely to cause a significant impact and are significantly lower than those during the construction phase. They do however caution that this noise is of a much longer duration over the operational lifespan of the wind farm, and that little is known of the long-term impacts to aquatic life.

Table 6.16: Desktop Study of Operational Noise from Wind Turbines

Paper	Turbine	Foundation Type	Location	Notes
Betke, 2006	Vestas V80-2 MW 70 m hub height	Monopiles	Horns Rev	118 dB re 1 µPa @ 150 Hz
Nedwell et al., 2007	Vestas V80-2 MW	Monopiles	North Hoyle	Inside wind farm 128 dB re. 1 µPa Outside 120 dB re. 1 µPa No tonal components
	Vestas V80-2MW 68 m hub height	Steel monopiles 4.8 m diameter	Scroby Sands	Inside wind farm 130 dB re. 1 µPa Outside 132 dB re. 1 µPa States that the background level is higher inside the wind farm, perhaps due to shallow water No tonal component
	Vestas V90-3 MW 70 m hub height	Monopiles	Kentish Flats	Inside wind farm 114 dB re. 1 µPa Outside 113 dB re. 1 µPa Clear tonal components dependent upon separation
	Vestas V90-3 MW 75 m hub height	Steel monopiles 4.75 m diameter	Barrow	Inside wind farm 124 dB re. 1 µPa Outside 122 dB re. 1 µPa No tonal components. No consistent relationship between distance and level, thought due to wind noise

Paper	Turbine	Foundation Type	Location	Notes
Norro et al., 2011	Senvion (Repower) 5 MW 95 m hub height	Gravity base	Thorntonbank	Increase of 8 dB above background
	Vestas V90-3 MW 72 m hub height	Steel monopile foundations	Belwind Bligh Bank	Increase of 20 dB to 25 dB above background
Jansen and De Jong, 2016	Vestas V80-2 MW	Steel monopiles 4 m diameter	Princess Amalia wind farm	Noted to be next to busy shipping lanes - no difference in level between 100 m and 3.8 km

There is ongoing research into the particular area of floating wind is ongoing (Supergen, 2022). Given that sound is more readily transmitted from structures which are coupled together, the case of operational noise from piled foundation turbines is considered a worst case.

6.4 Vessel Noise (all phases)

Estimated ranges for injury to marine mammals due to the continuous noise sources (vessels) during different phases of the construction operations are presented below.

It should be borne in mind that there is a considerable degree of uncertainty and variability in the onset of disturbance and therefore any disturbance ranges should be treated as potentially over precautionary. Another important consideration is that vessels and construction noise will be temporary and transitory, as opposed to permanent and fixed. In this respect, construction noise is unlikely to differ significantly from vessel traffic already in the area.

The estimated median ranges for onset of TTS or PTS for different marine mammal groups exposure to different noise characteristics of different vessel traffic are shown in Table 6.1714. The exposure metrics for different marine mammal and flee speeds (as detailed in section 5.2) were employed.

Table 6.17: Estimated PTS and TTS Ranges from Different Vessels for Marine Mammals

Source/Vessel	Range (m)										
	LF		HF		VHF		PCW		OCW		All
	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	Disturbance
Anchor handling vessel	N/E	N/E	N/E	N/E	N/E	36	N/E	40	N/E	N/E	3,355
Main installation vessel, construction vessel (DP)	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	N/E	5,779
Survey vessel, crew transfer vessels and support vessels	N/E	N/E	N/E	N/E	N/E	55	N/E	40	N/E	N/E	9,284
Misc. small vessel (e.g. tugs, vessels carrying ROVs, dive boats, guard vessels and RIBs)	N/E	N/E	N/E	N/E	N/E	36	N/E	40	N/E	N/E	3,355

The ranges for recoverable injury and TTS for Groups 3 and 4 Fish are presented in Table 6.1815 based on the thresholds contained in Popper *et al.* (2014). It should be noted that fish would need to be exposed within these impact ranges for a period of 48 hours continuously in the case of recoverable injury and 12 hours continuously in the case of TTS for the effect to occur. It is therefore considered that these ranges are highly precautionary, and injury is unlikely to occur in reality.

Table 6.18: Estimated Recoverable Injury and TTS Ranges from Vessels for Groups 3 and 4 Fish

Source/Vessel	Range (m)	
	Recoverable Injury	TTS
	170 dB rms for 48 hrs	158 dB rms for 12 hrs
Anchor handling vessel	<10	18
Main installation vessel, construction vessel (DP)	16	66
Survey vessel, crew transfer vessels and support vessels	10	51
Misc. small vessel (e.g. tugs, vessels carrying ROVs, dive boats, guard vessels and RIBs)	<10	18

7 Mitigation and Residual Impact

7.1 Proposed Mitigation Measures

Without any mitigation measures in place, the noise causing activities were identified as having the potential to cause permanent threshold shift at a range of up to 1 km for impact piling for low frequency cetaceans, 234 m for very high frequency cetaceans, and 15 m for pocid carnivores. The impact ranges are much smaller for other sources employed in the study – cable laying, tugs, barges, support vessels, pile drilling, jack-up rigs, and other vessels.

In line with best practice, it is recommended that the following mitigation approach is followed:

Preconstruction works and survey

- The gradual start of works is a proposed mitigation measure that would allow the marine mammals, turtles and fish to move away from the work site and reduce the exposition to noise;
- A marine wildlife surveillance program could also be implemented during activities (e.g. MMO / PAM operators).
- Work would be suspended when cetaceans or turtles are sighted at less than 500 m from the site.

Piling Works

- Gradual start of piling activities to allow marine mammals, fish and turtles to move away from the work site and reduce the exposition to noise;
- Use behavioural deterrent devices to ensure there are no sensitive species within the area at the start of operations (e.g. acoustic deterrent devices);
- Use of an ADD for 15 minutes prior to the commencement of piling has shown that all PTS ranges can be reduced to below the threshold for injury;
- Piling works would be suspended when cetaceans or turtles are seen at less than 500 m from the piling site (i.e. MMO / PAM operators);
- Where practical, use of quieter alternative methods than pile driving.

Operational Phase

- There are no specific mitigation measures required for operation phase, however ongoing monitoring of the wind turbines would be beneficial to the general understanding of impacts.

7.2 Residual Impact

With mitigation measures in place as described above it is envisaged that the potential for injury to marine mammals, turtles and fish receptors will be minimised and is unlikely to occur even in close proximity to the works.

8 Conclusions

Noise modelling has been undertaken to determine the range of potential effects on marine mammals, fish, and sea turtles due to noise from piling activities associated with construction of the Proposed Development. The results are summarised in Table 8.1 which shows the maximum injury range for each group of mammals, fish, and sea turtles, for individual and simultaneous piling (the worst-case scenario of cumulative SEL or peak). The PTS impact range is typically dominated by nearest pile, so these ranges don't change for single or simultaneous pile driving (except for LF cetaceans).

Table 8.1: Summary of Maximum PTS Injury Ranges for Marine Mammals, and Mortality for Fish, and Turtles due to Impact Piling Based on Highest Range of Peak Pressure or SEL (N/E = Threshold Not Exceeded)

Species Group	Range (m)	
	Without ADD	With 15 mins ADD
Low frequency cetacean	1,085	49
High frequency cetacean	18	18
Very high frequency cetacean	234	234
Phocid carnivores	54	54
Other carnivores	15	15
Group 1 Fish: no swim bladder	85	85
Group 2 Fish: where swim bladder is not involved in hearing	147	147
Group 3 to 4 Fish: where swim bladder is involved in hearing	147	147
Sea turtles	147	147
Eggs and larvae	329	329

Underwater noise emissions from the pre-construction activities, operational noises, and vessels are unlikely to be at a level sufficient to cause injury or behavioural changes to marine mammals, fish, or sea turtles.

The use of ADD means that no PTS injury thresholds are exceeded for marine mammals.

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Appendix A. Impact of Particle Motion

Whilst the main report deals with the impact of sound on marine life, there remain uncertainties in relation to the presence of compression and interface waves at the water/ground substrate boundary during piling, and the potential effect on fish and invertebrates. Although the risk of injury to fish with and without swim bladders is addressed through the use of Sound Exposure Level (SEL) and peak pressure thresholds (Popper *et al.*, 2014), it is possible that fish that are only sensitive to particle motion. These fish could experience high levels of particle motion in close proximity to piling. However, the Popper *et al.* (2014) paper primarily addresses high amplitude sounds and high dynamic pressure, rather than particle motion.

Whilst the source measurements used to inform the subsea noise study included both direct radiated sound from the pile into the water, as well as ground-borne radiated sound, there are uncertainties with respect to how effectively the ground borne energy couples into the sea. If measurements were taken in an evanescent (non-propagating) field then high particle motion would not be reflected in the associated dynamic pressure measurements, particularly if those measurements were taken in shallow water and the energy is below the cut-off frequency. Consequently, it is possible that the effects on bottom fauna close to the pile could be under-estimated, particularly for species primarily sensitive to vibration of the seafloor sediment.

To put this issue into perspective, under section 5.1 entitled “Death or Injury”, Popper *et al.* (2014) states that “extreme levels of particle motion arising from various impulsive sources may also have the potential to injure tissues, although this has yet to be demonstrated for any source”. It would therefore appear that there is currently a lack of criteria for (or detailed measurements of) particle motion during piling operations for this issue to be currently assessed. Thus, in terms of potential damage to fish, the main report has addressed the impact as far as is practicable with the existing state of knowledge, based primarily on exposure to sound pressure.

GREEN VOLT

Flotation Energy Ltd | 12 Alva Street | Edinburgh EH2 4QG | Scotland
Tel: [redacted] | enquiries@flotationenergy.com | www.flotationenergy.com