BERWICK BANK WIND FARM **OFFSHORE ENVIRONMENTAL IMPACT ASSESSMENT**

APPENDIX 10.1, ANNEX B: SENSITIVITY ANALYSIS FOR DIFFERENT PILE SOURCE SEL ENERGY CONVERSION FACTORS

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1. INTRODUCTION

1. This technical note has been prepared to support the underwater noise technical assessment as part of the Berwick Bank Wind Farm Environmental Impact Assessment (EIA) Report. Following discussions with Marine Scotland Science (MSS), Marine Scotland Licencing and Operations Team (MS-LOT) and NatureScot, the stakeholders have asked for a sensitivity analysis to be carried out to determine the sensitivity of the results of underwater noise modelling to uncertainties in relation to the assumed source sound levels associated with impact piling.

2. A justification for the assumed source sound levels used in the assessment has been provided in volume 3, appendix 10.1, annex A. The assumption used in the noise modelling, as the most representative conversion factor, is that 4% of the hammer energy is converted into sound energy transmitted into the water at the start of the piling sequence, reducing to 0.5% as the pile is driven into the seabed.

3. To demonstrate the sensitivity of the model to conversion factors a range of different values have been explored, as recommended by the statutory consultees. These are:

- energy conversion factor of 4% reducing to 0.5% over the piling sequence;
- energy conversion factor of 1% throughout the piling sequence; and
- energy conversion factor of 10% reducing to 1% throughout the piling sequence.

4. These results are provided in this sensitivity analysis to allow comparison of results between conversion factors assumed, along with resultant ranges for potential injury to marine mammals (in the form of permanent threshold shift (PTS) and temporary threshold shift (TTS)).

2. BACKGROUND

5. For the purposes of the assessment, source sound exposure levels (SEL) were evaluated using the equation set out below (De Jong and Ainslie, 2008) during impact pile driving operation in each operation window.

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

6. In this equation:

- β is the percentage of the hammer energy transmitted through 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.

7. This equation demonstrates that the source SEL is directly related to the energy conversion factor β: as the conversion factor is increased, so too will the source sound level increase.

8. The source SEL is a theoretical construct which is useful in noise modelling to estimate the SEL in the far-field. In general, higher source SELs found in monitoring study reports for UK (including Scottish) offshore wind farms, and the conversion factors derived from them, are associated with (and indeed caused by) higher propagation coefficients as a result of extrapolating measurement data well beyond the measurement range, or simply due to errors introduced by measurements at larger ranges (see volume 3, appendix 10.1, annex A). Taking this into account, it is acknowledged that it is difficult to determine a preferred site or receiver location independent energy conversion factor for use in modelling a wide range of scenarios. Nevertheless, it is considered that greater emphasis should be placed on peer reviewed studies, and studies which utilise full acoustic modelling to determine the source SEL since these are less prone to errors introduced by extrapolating measured data beyond its range of validity.

9. Given that higher conversion factors are generally largely affected by long range propagation factors, it is considered that use of these higher numbers could lead to substantial overprediction of the far-field sound levels when using propagation models which do not correspond to the propagation coefficients used in the determination of the source SEL in the first place. High source SELs and energy conversion factors derived from these would only be appropriate if used in the same model as was used to derive the source level. In this respect, it is important to take into account that the Berwick Bank Wind Farm will be modelled using a full acoustic model (as opposed to a simple N log R relationship that would typically be used to derive the source SELs; see volume 3, appendix 10.1, annex A.

10. The assumption used for the modelling for Berwick Bank Wind Farm (the Proposed Development) is that the amount of sound radiated into the water column depends on both the hammer energy and the length of pile exposed in the water column above the seabed. Consequently, 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. The justifications for this assumption are:

- measurements of piles using above water impact hammers show approximately linear SEL to hammer energy relationship (e.g. Bailey *et al.*, 2010; Robinson *et al.*, 2007, 2009 and 2013; Lepper *et al.*, 2012);
- based on the peer reviewed literature which considers theoretical concepts, it is concluded that a representative energy conversion factor is likely to be in the range β ≈ 0.3% to 1.5% (Zampolli *et al.*, 2013), whereas Dahl *et al.* (2015) concluded β ≈ 0.5% based on a review of both theoretical considerations and measurement data by other studies 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 efficiencies being more likely throughout the remainder of the piling period where higher hammer energies are used. It is therefore concluded that an average hammer energy conversion factor of β ≈ 1% is a representative and precautionary average across the range of hammer energies used during a pile installation using an above water hammer;
- peer reviewed studies based on full scale 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);
- 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 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%, is considered likely to be an overestimate of the true energy radiated into the water column caused, at least in part, by differences between the theoretical noise modelling used to determine the conversion factor and real world propagation. True conversion factors are thought likely to be in the order of approximately half these values (as discussed in volume 3, appendix 10.1, annex A). Of these two studies (Lippert *et al.,* 2017 and Thompson *et al.,* 2020), the Lippert *et al.* (2017) study was considered more scientifically robust because of the very strong correlation between the detailed finite element modelling and measured data, compared to the Thompson *et al.* (2020) study where the conversion factors are a reflection of the differences between measured data and modelled data (as set out in the technical note on conversion factors in volume 3, appendix 10.1, annex A); and.
- it is recognised that for the Lippert *et al.* (2017) study, a substantial 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 would be approximately 3.5%.

11. Consequently, based on this review, taking into account the proposed piling methodology, best scientific evidence and professional judgement, a varying energy conversion factor of β = 4% at the start of piling to 0.5% at the end of piling has been used for subsea noise modelling associated with the Proposed Development and is presented in volume 3, appendix 10.1. A full review of the evidence and justification of the proposed energy conversion factor is provided in volume 3, appendix 10.1, annex A.

12. MS-LOT, MSS and NatureScot have requested an analysis be undertaken to examine the sensitivity of the injury ranges presented in volume 3, appendix 10.1 to different assumed values for the energy conversion factor. Specifically, they have requested the sensitivity analysis be performed using a conversion factor starting at 10%. The justification given by MSS and NatureScot for including the 10% conversion factor is that a study using a submersible impact hammer on pin-piling for Beatrice Offshore Wind Farm (Thompson *et al.*, 2020) found conversion factors of this magnitude for the first few strikes in the piling sequence. However, it is considered that the quoted conversion factors within this study were an artefact of differences between the propagation model used in the analysis compared to real world propagation, as opposed to a measure of true acoustic energy radiated into the water column. Consequently, this is considered likely to have resulted in overestimates of the conversion factors.

13. In light of these potential uncertainties in the derivation of source level, this document presents the results of a sensitivity analysis based on calculations using a conversion factor of β = 10% at the start of piling to 1% at the end of piling as well as a scenario utilising a conversion factor of 1% throughout the piling sequence. The results of this sensitivity assessment were presented to stakeholders during the pre-Application consultation (Road Map Meeting 3; 18 January 2022).

3. METHODOLOGY

14. The methodology for the noise assessment, including source determination, propagation modelling and assessment criteria and thresholds, is set out in full within the volume 3, appendix 10.1. In summary, the assessment methodology for piling is based on the following:

- Source SELs are derived using an energy conversion factor which assumes that a defined percentage of the energy from the hammer strike radiates through the pile into the water column as sound (De Jong and Ainslie, 2008).
- Sound propagation modelling is undertaken using the Weston Energy Flux method (Weston, 1976).
- Cumulative sound exposures are calculated based on assumed swim speeds of marine mammal species for animals moving away from the pile.
- Injury thresholds for marine mammals are based on those set out in Southall *et al.* (2019) for the dual metrics of peak sound pressure level (SPL_{pk}) and cumulative SEL (SEL_{cum}); and
- Ranges estimates were predicted on the basis of a single piling location (representing piling at the offshore substation platforms (OSPs)/Offshore convertor station platforms) and concurrent piling with two vessels piling at adjacent wind turbine locations (representing a maximum adverse scenario for piling at the wind turbine foundations).
- Ranges were estimated for both the absolute maximum hammer energy of 4,000 kJ and a more realistic maximum of 3,000 kJ for installation of piled foundations.

15. A representation of the three conversion factor cases considered is shown in Figure 3.1. The figure shows that in the two varying cases the SEL is highest during the start of the piling, which is consistent with the findings of Lippert *et al.* (2017).

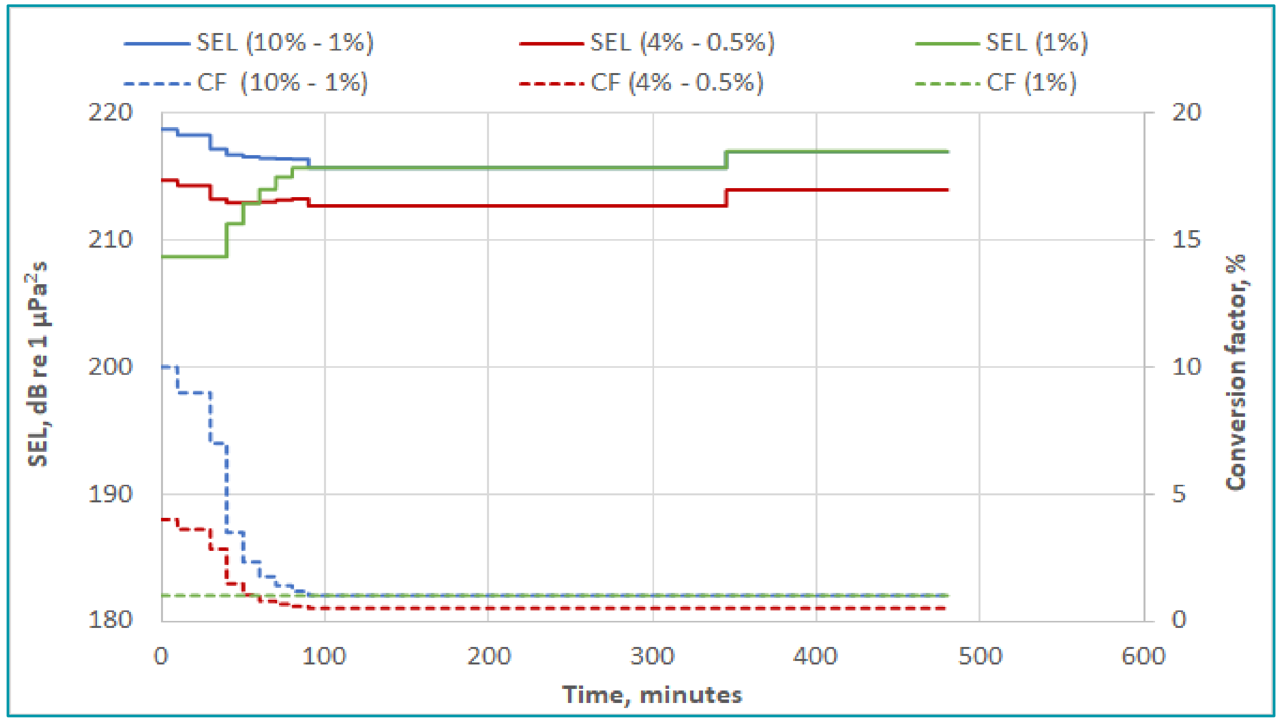

Figure 3.1: Relationship Between Three Conversion Factors and SEL Over the Piling Sequence for the 4,000 kJ Piling Scenario

16. 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 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).

4. RESULTS AND INTERPRETATION

17. The modelled PTS injury ranges based on the various conversion factors due to impact pile driving for the “maximum” pile driving scenario for wind turbine foundations for a single pile installation are

summarised in Figure 4.1. The injury ranges presented in Figure 4.1 are based on the dual metric thresholds for SPL_{pk}) and SEL_{cum} as set out in Southall *et al.* (2019), whichever is the highest for each hearing group. Full tabulated results are included in section 5.

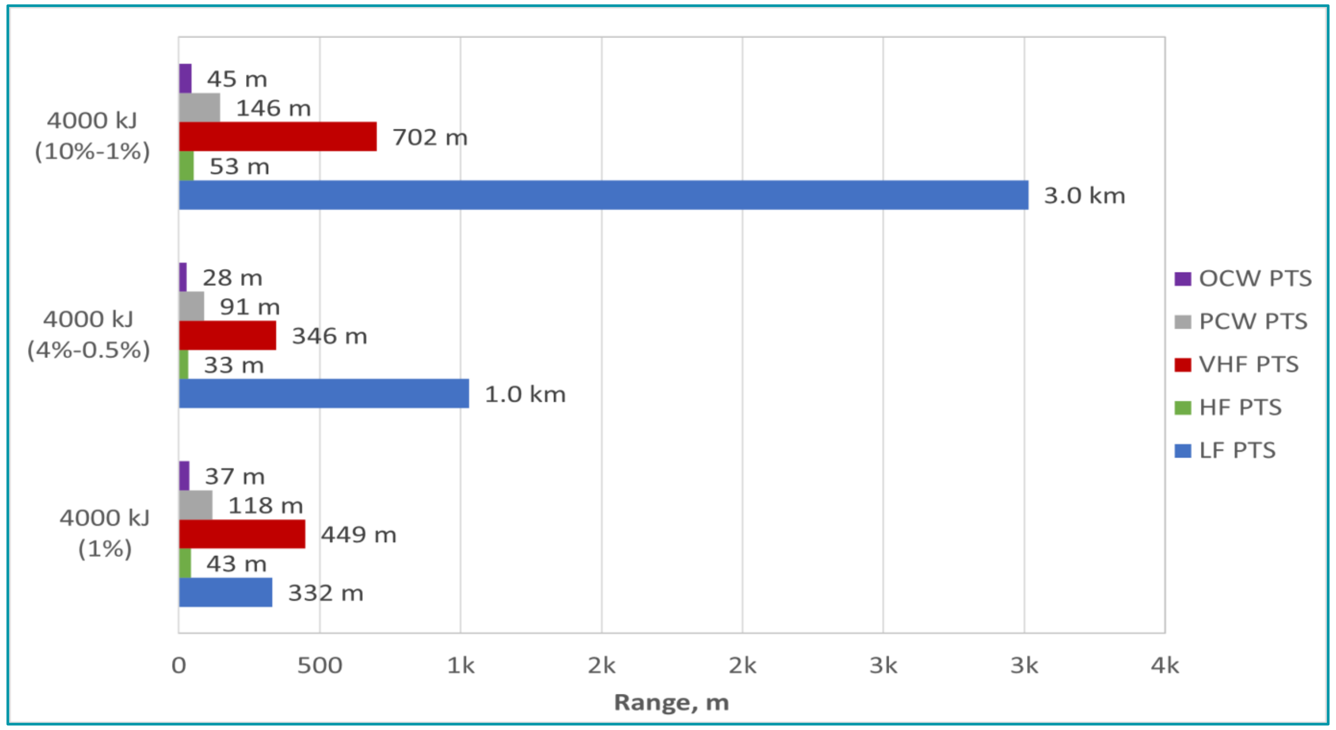

Figure 4.1: Modelled PTS Injury Ranges for Marine Mammals for Installation of a Single Pile Using Energy Conversion Factors of 1%, 4% Reducing to 0.5% and 10% Reducing to 1%

18. The range of potential PTS increases between the 1% conversion factor and the 4% to 0.5% conversion factor, and again between the 1% and 10% to 1% conversion factors (Figure 4.1). This is as would be expected considering the increase in source level resulting from considerably more energy being converted to sound energy, as shown in Figure 3.1. The difference between PTS range across the conversion factors is most marked for the Low Frequency (LF) cetacean category, which is due to the marine mammal frequency weighting curves. LF sound propagates further than high frequency sound, which attenuates relatively quickly, therefore mammals with hearing thresholds focussed on the lower frequency sounds will show a greater impact when that low frequency sound is increased. However, the impact of increasing the source level can still be seen across the other marine mammal hearing groups, with the Very High Frequency (VHF) group.

19. The sudden and rapid increase in the potential injury range is related to the properties of sound propagation, where moving away from a source, the relative sound levels drop-off more rapidly with distance at ranges closer to the source. At lower source levels a mammal can start relatively close to the source, for example at 100 m, and swim to double that distance in a short time reducing the sound it is exposed to by nominally 6 dB (swimming at conservative speed of 1.5 m/s a mammal can cover 100 m of distance in just over a minute). However, at higher source levels a mammal experiencing that same sound level would be considerably further from the source, for example 5 km, which would mean it would have to swim a further 5 km to reduce the sound level by the same magnitude (which would take over 55 minutes at the same swim speed). This increased time is what results in the greater sound exposure and consequently a greater range at which the PTS injury is predicted to occur.

20. A similar picture can be seen when looking at the TTS injury ranges, as shown in Figure 4.2.

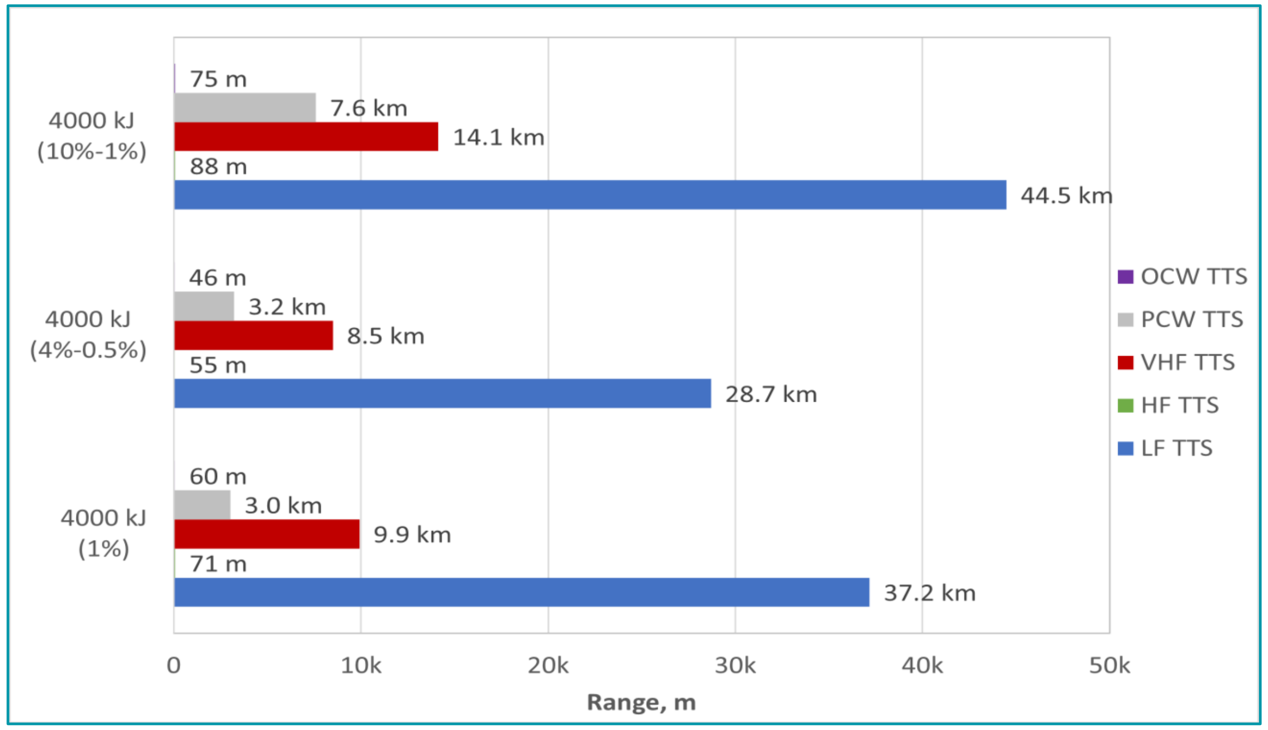

Figure 4.2: Modelled TTS Injury Ranges for Marine Mammals for Installation of a Single Pile Using Energy Conversion Factors of 1%, 4% Reducing to 0.5% and 10% Reducing to 1%

21. The injury ranges presented for all cases in this report include the same piling schedules as those listed in volume 3, appendix 10.1.

22. Figure 4.3 and Figure 4.4 show the results for the concurrent piling scenario for PTS and TTS injury ranges respectively. These figures show that the potential impact ranges for PTS and TTS increase with concurrent piling at two locations.

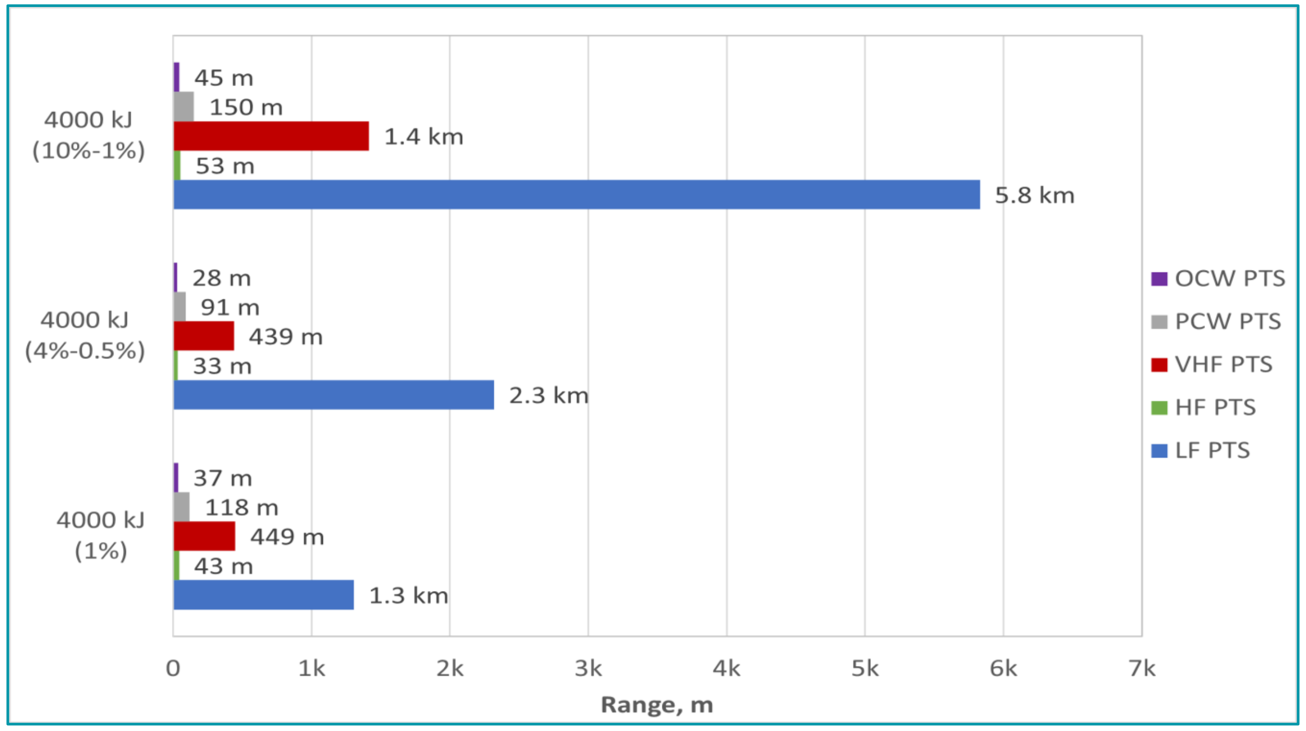

Figure 4.3: Modelled PTS Injury Ranges for Marine Mammals for Installation of Two Piles Concurrently, Using Energy Conversion Factors of 1%, 4% Reducing to 0.5% and 10% Reducing to 1%

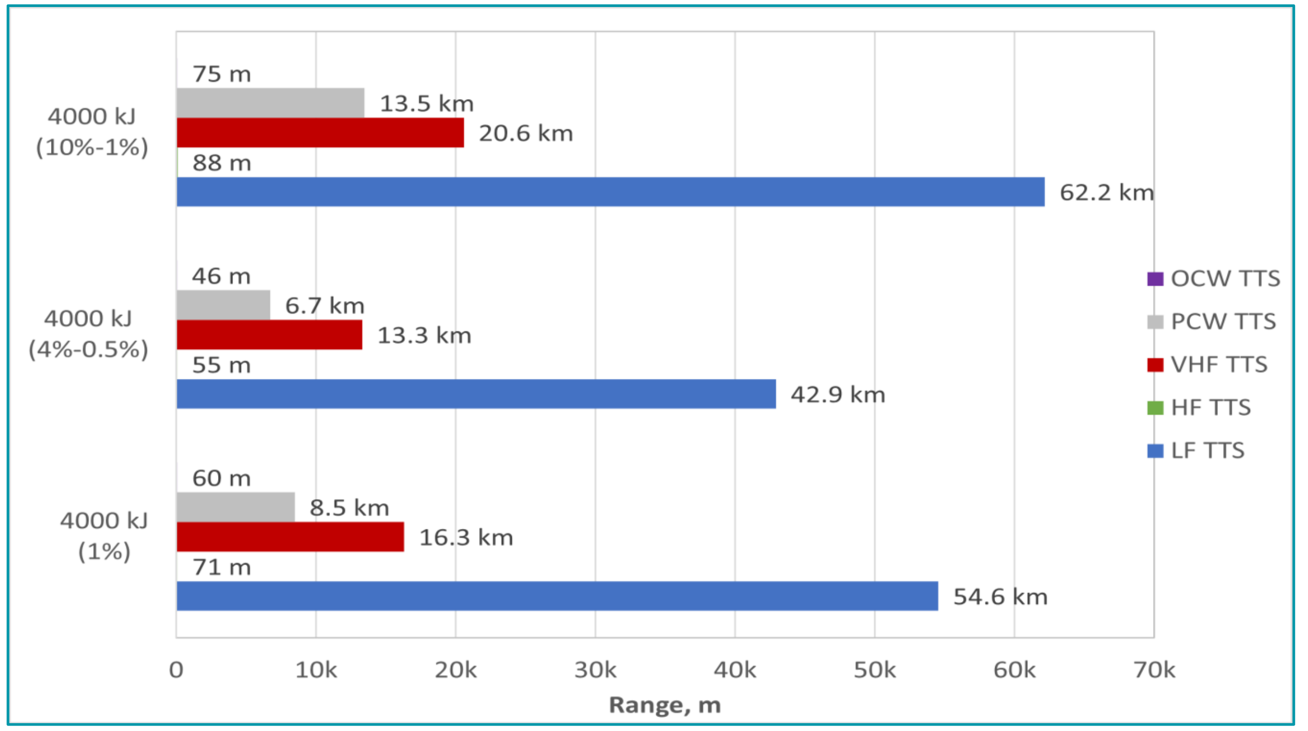

Figure 4.4: Modelled TTS Injury Ranges for Marine Mammals for Installation of Two Piles Concurrently, Using Energy Conversion Factors of 1%, 4% Reducing to 0.5% and 10% Reducing to 1%

23. When viewing the various injury ranges it is important to note that any injury ranges in the order of tens of kilometres are likely to be overestimates. This is because sound dispersion effects and loss of high frequency sound energy at these ranges will mean that the sound is no longer impulsive in character and is therefore unlikely to represent a higher injury risk compared to non-impulsive sound sources. Further information on this can be found in volume 3, appendix 10.1, annex A.

24. It is also important to note that neither the potential injury thresholds nor the noise propagation model takes account of the background noise environment. As such, there isn't a clear range from the source at which the anthropogenic noise level is equal to the background ambient sound level. At distances of multiple tens of kilometres from the noise source, the resultant noise level is unlikely to contribute to hearing damage for marine life, however the model still calculates an exposure based on summing these levels; adding up energy from sounds despite that fact that these sound levels may, in reality, be masked by the ambient sound in the ocean (described as "Effective Quiet" in National Marine Fisheries Service NMFS (2018)).

25. Even when taking account of the animals which start closer to the piling location, it is likely that the modelled exposure is an over estimation. For example, the minke whale *Balaenoptera acutorostrata*, a low frequency cetacean, has an assumed swim speed of 2.1 m/s, meaning that it can travel up to 75.6 km during the ten hours needed to install a pile. As stated in the previous paragraph, at such distances the noise due to piling activity is likely to be both continuous and masked by the background ocean noise.

26. At very high source noise levels, a change can be seen in which assessment parameters - cumulative SEL or peak sound level - results in the highest potential impact ranges. As can be seen in Table 4.1, at lower source sound levels, the potential for PTS due to peak sound level is the dominating parameter for all hearing groups other than low frequency cetaceans. In the low frequency hearing group cumulative SEL gives the highest potential impact ranges due to the greater proportion of low frequency sound.

Table 4.1: Parameter Resulting in the Greatest Injury Range for PTS and TTS by Conversion Factor (Single Pile Scenario)

Hearing Group	Parameter Which Causes Largest Potential Impact Ranges					
	1%		4% - 0.5%		10% - 1%	
	PTS	TTS	PTS	TTS	PTS	TTS
LF	SEL	SEL	SEL	SEL	SEL	SEL
HF	Peak	Peak	Peak	Peak	Peak	Peak
VHF	Peak	SEL	Peak	SEL	SEL	SEL
PCW	Peak	SEL	Peak	SEL	Peak	SEL
OCW	Peak	Peak	Peak	Peak	Peak	Peak

27. It is well understood that the size of the pile being installed will impact the way that sound is radiated into the surrounding water (e.g. Nehls *et al.*, 2007). For a given hammer blow energy, if the pile diameter is increased, the radiating surface increases. However, if the pile driver energy remains the same, the amplitude of the noise decreases. This is because the hammer energy must excite a larger number of surface elements (i.e. a greater surface area and mass) in the larger piles. Hence, a larger diameter for any given hammer energy is more likely to produce lower sound levels than a smaller diameter with the same energy (Nehls *et al.*, 2007). It is therefore likely that larger piles will result in a lower energy conversion factor than for installation of smaller piles of the same energy. In the context of this study, accounting for larger piles should not automatically suggest using a higher conversion factor.

4.1. INJURY RANGES WITH ACOUSTIC DETERRENT DEVICES

28. The analysis can be repeated including the use of acoustic deterrent devices (ADD) prior to commencement of the piling sequence. ADDs, originally developed for the fish farming industry, are sound sources used to deter marine mammals from an area and have subsequently been employed as part of mitigation strategies for the offshore wind industry to move marine mammals beyond injury zones prior to the start of piling. The modelled potential PTS injury ranges based on the conversion factor scenarios outlined in paragraph 3 as a result of impact pile driving for the "maximum" 4,000 kJ hammer energy for a single pile installation are summarised in Figure 4.5[1] and TTS in Figure 4.6. Activation of an ADD for discrete periods immediately prior to the start of piling was sufficient to mitigate the potential for PTS to occur, which in the case of 4% to 0.5% and 10% to 1% was 30 minutes and for 1% was 15 minutes. From Figure 4.5, it can be seen that, in the case of a single piling event, with application of ADD the PTS ranges are not exceeded in all cases or, in other words, the PTS injury range is 0 m.

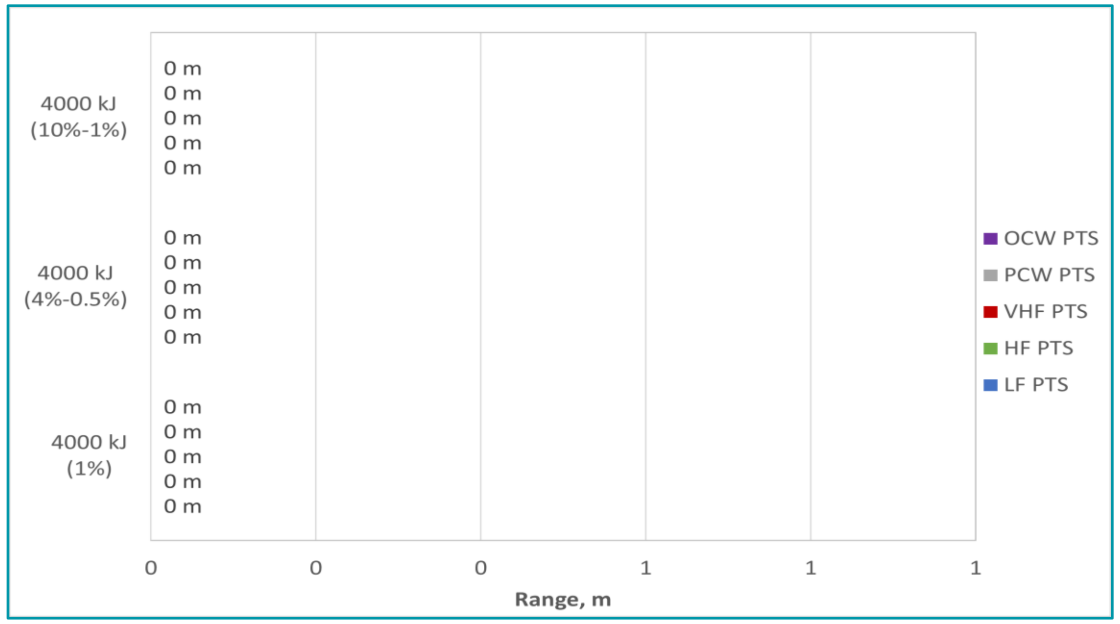

Figure 4.5: Modelled PTS Injury Ranges for Marine Mammals for Installation of a Single Pile Using Energy Conversion Factors of 1%, 4% Reducing to 0.5% and 10% Reducing to 1%, Including the Use of ADD

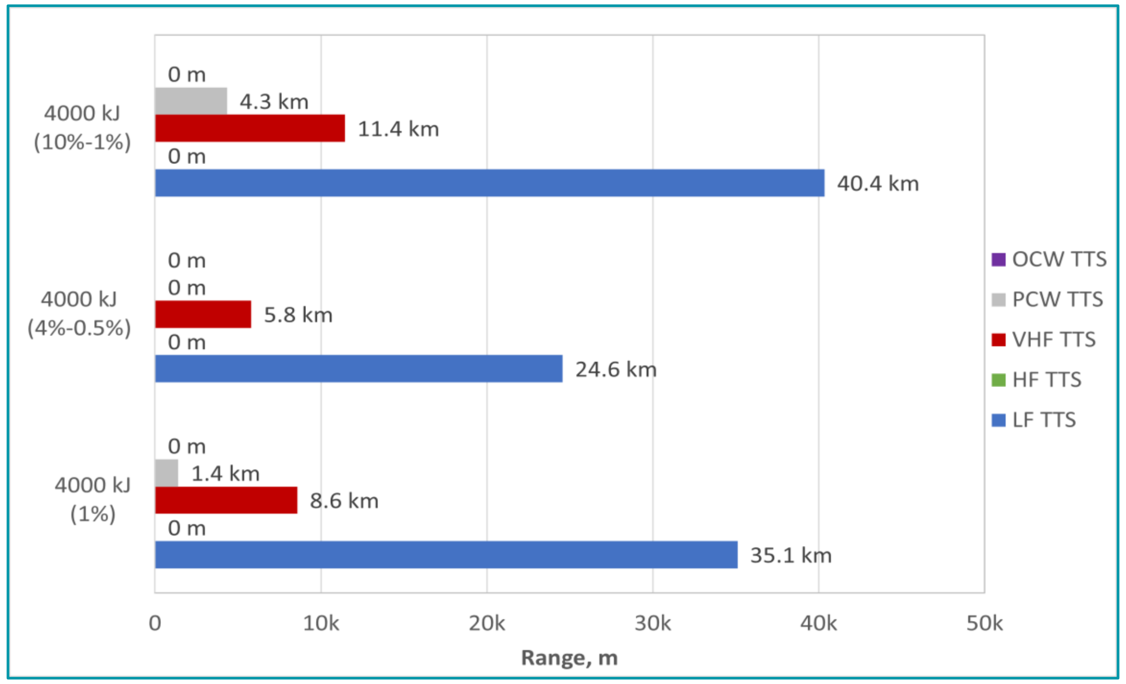

Figure 4.6: Modelled TTS Injury Ranges for Marine Mammals for Installation of a Single Pile Using Energy Conversion Factors of 1%, 4% Reducing to 0.5% and 10% Reducing to 1%, Including the Use of ADD

[1] It is worth noting that the ranges reduce to zero in Figure 4.5 which is why the figure looks "empty".

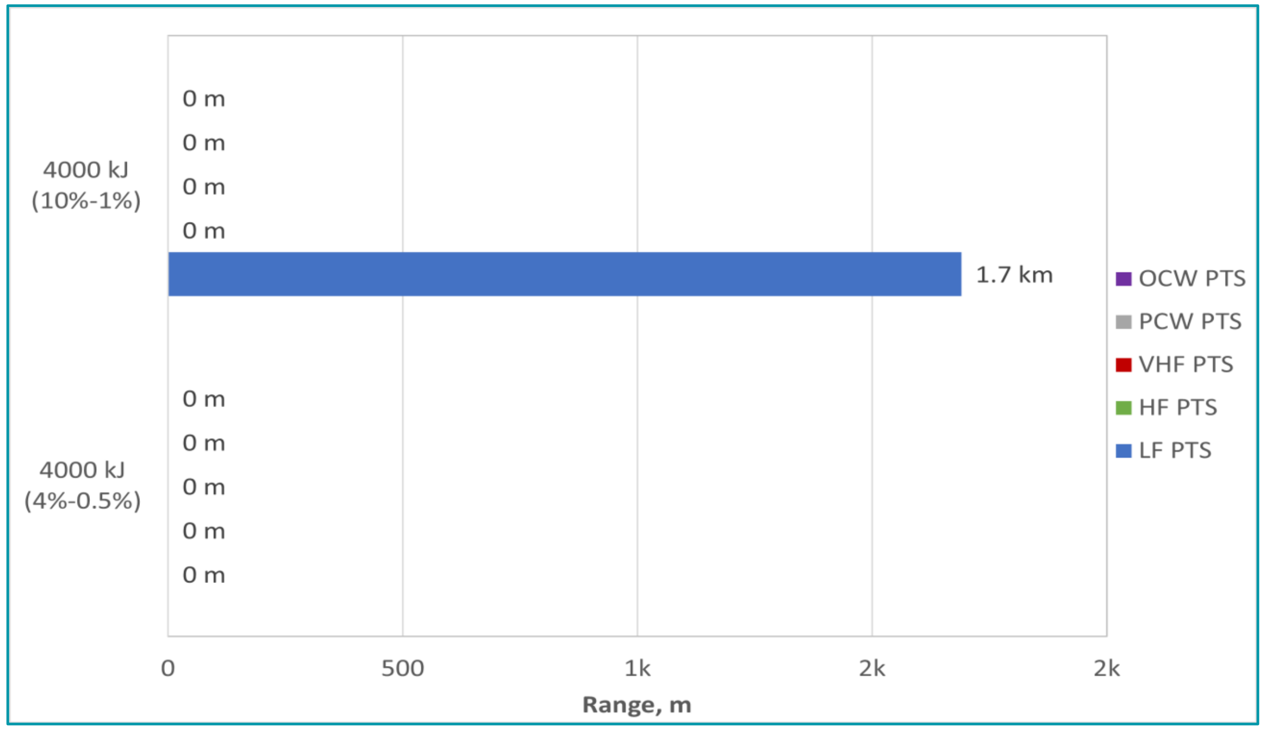

Figure 4.7: Modelled PTS Injury Ranges for Marine Mammals for Installation of Two Piles Concurrently, Using Energy Conversion Factors of 1%, 4% Reducing to 0.5% and 10% Reducing to 1%, Including the Use of ADD

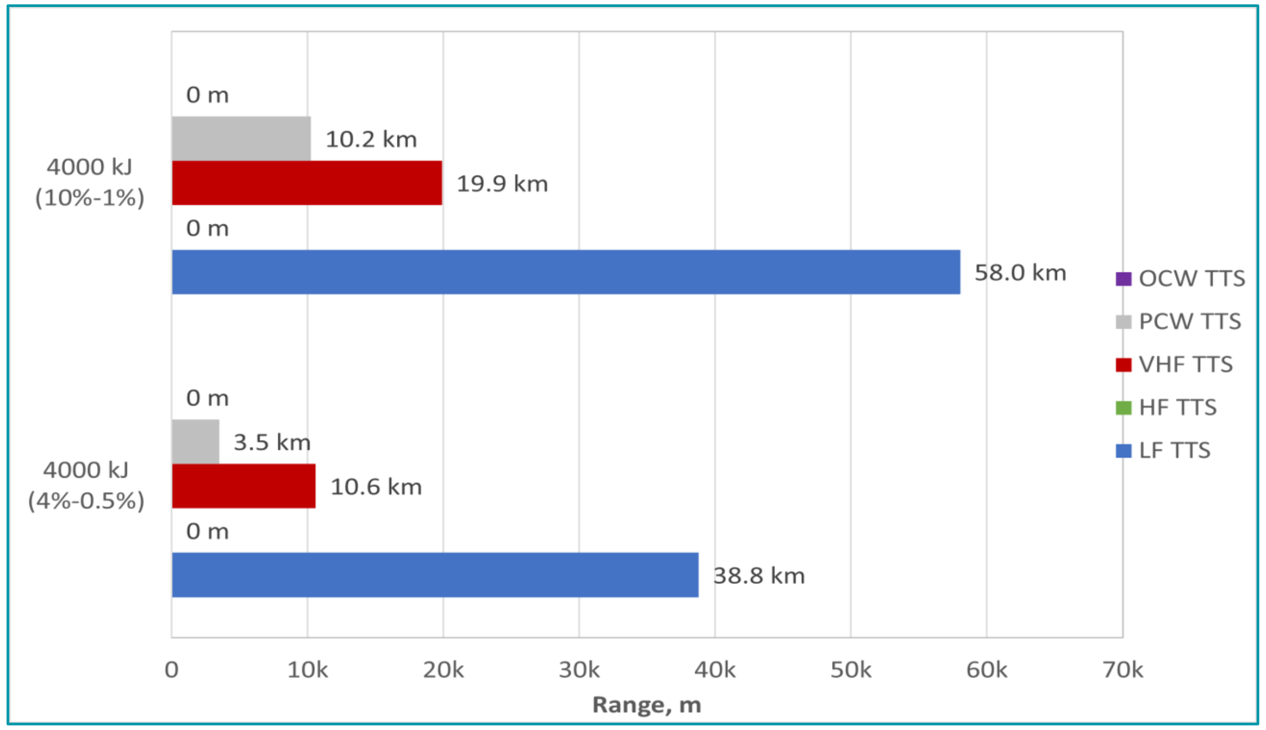

Figure 4.8: Modelled TTS Injury Ranges for Marine Mammals for Installation of Two Piles Concurrently, Using Energy Conversion Factors of 1%, 4% Reducing to 0.5% and 10% Reducing to 1% Reducing, Including the Use of ADD

29. From Figure 4.7 it can be seen that in the concurrent piling case, the use of ADD reduced PTS injury ranges to non-exceedances of the thresholds for all but the LF cetaceans group, for the conversion factor 10% to 1%. This scenario assumes piling at adjacent wind turbine locations with piling schedules commencing within 15 minutes of each other, representing a maximum spatial and temporal scenario (i.e. because the marine mammal is in close proximity to both piles towards the start of the piling sequences).

30. The use of ADD causes little difference in either of the TTS cases due to the impact ranges predicted, i.e. the use of an ADD gives a marine mammal receptor time to swim outside the range of PTS prior to commencement of piling activity, but not enough time to move out with the potential range of TTS.

5. SUMMARY

31. In this note, the results for three energy conversion factors have been presented:

- energy conversion fact of 4% reducing to 0.5% over the piling sequence;
- energy conversion fact of 1% throughout the piling sequence;, and
- energy conversion fact of 10% reducing to 1% throughout the piling sequence.

32. Full tabulated results are presented in section 5.

33. The results of the analysis are summarised as follows:

- all modelling results predict large TTS ranges; it is unrealistic to consider noise propagating over this distance to cause an adverse effect to marine life;
- contributions from strikes at tens of kilometres where the pulse duration of impulsive noise spreads such that it is no longer impulsive, and instead is non-impulsive in character ,is likely to lead to an overestimate of effect ranges (see appendix A); and
- noise that is no longer impulsive does not have as detrimental an impact on marine mammal receptors, and therefore the equivalent injury thresholds for continuous noise are comparatively lower.

34. As stated in the volume 3, appendix 10.1, annex A, a conversion factor of 10% is considered unrealistic due to the lack of substantiated evidence of this occurring. It is considered an overestimate of the true energy radiated into the water column caused by discrepancies between the noise modelling and real-world propagation.

35. It is considered, taking into account the proposed piling methodology, best scientific evidence and professional judgement, that 4% is a robust starting point for energy conversion factors for submersible impact hammers, reducing through the piling sequence, as set out in the technical note on conversion factors in volume 3, appendix 10.1, annex A and based on the detailed considerations in Lippert *et al.* (2017). For above water impact hammers a 1% conversion factor is considered reasonable.

36. Based on this sensitivity analysis, there is a relatively small difference in predicted modelled injury ranges for most marine mammal receptor groups between the 1% conversion factor throughout the piling sequency, and a conversion factor of 4% reducing to 0.5%.

6. FULL RESULTS

37. The full results of the sensitivity calculations are shown here in Annex A as follows, using a conversion factor of 1%, a conversion factor of 4% reducing to 0.5% as used in volume 3, appendix 10.1, and a conversion factor of 10% reducing to 1%:

- Injury ranges based on cumulative SEL thresholds for marine mammals, for the “maximum”, “realistic” and OSP/Offshore convertor station platform piling scenarios Table 6.1 to Table 6.3.
- Injury ranges based on peak SPL thresholds for marine mammals, for the “maximum”, “realistic” and OSP/Offshore convertor station platform piling scenarios – Table 6.4 and Table 6.5.
- Injury ranges based on cumulative SEL thresholds for fish, for the “maximum”, “realistic” and OSP/Offshore convertor station platform piling scenarios – Table 6.6 to Table 6.8.
- Injury ranges based on peak SPL thresholds for fish, for the “maximum”, “realistic” and OSP/Offshore convertor station platform piling scenarios – Table 6.9 and Table 6.10.
- Injury ranges based on cumulative SEL thresholds for marine mammals for piling of two foundations simultaneously, for the “maximum” and “realistic” piling scenarios – Table 6.11 and Table 6.12.
- Injury ranges based on cumulative SEL thresholds for fish for piling of two foundations simultaneously, for the “maximum” and “realistic” piling scenarios – Table 6.13 and Table 6.14.

Table 6.1: Injury Ranges for Marine Mammals due to Impact Pile Driving for the “Maximum” Pile Driving for Wind Turbine Foundations for the Three Energy Conversion Factors Assessed – “Maximum” Scenario Includes Piling up to 4,000 kJ (*N/E* Is Threshold not Exceeded)

Species/Group	Threshold (Weighted SEL)	Range (m)		
		1%	4% - 0.5%	10% - 1%
LF	PTS - 183 dB re 1 µPa^{2}s	332	1,030	3,015
	TTS - 168 dB re 1 µPa^{2}s	37,170	28,693	44,491
High Frequency (HF)	PTS - 185 dB re 1 µPa^{2}s	*N/E*	*N/E*	*N/E*
	TTS - 170 dB re 1 µPa^{2}s	*N/E*	33	75
VHF	PTS - 155 dB re 1 µPa^{2}s	104	286	702
	TTS - 140 dB re 1 µPa^{2}s	9,918	8,496	14,133
PCW	PTS - 185 dB re 1 µPa^{2}s	N/E	47	116
	TTS - 170 dB re 1 µPa^{2}s	3,020	3,228	7,584
OCW	PTS - 203 dB re 1 µPa^{2}s	*N/E*	*N/E*	*N/E*
	TTS - 188 dB re 1 µPa^{2}s	*N/E*	18	49

Table 6.2: Injury Ranges for Marine Mammals due to Impact Pile Driving for the “Realistic” Pile Driving for Wind Turbine Foundations for the Three Energy Conversion Factors Assessed – “Realistic” Scenario Includes Piling up to 3,000 kJ (*N/E* Is Threshold not Exceeded)

Species/Group	Threshold (Weighted SEL)	Range (m)		
		1%	4% - 0.5%	10% - 1%
LF	PTS - 183 dB re 1 µPa^{2}s	229	707	2,165
	TTS - 168 dB re 1 µPa^{2}s	30,249	23,376	37,521
HF	PTS - 185 dB re 1 µPa^{2}s	*N/E*	*N/E*	*N/E*
	TTS - 170 dB re 1 µPa^{2}s	*N/E*	26	58
VHF	PTS - 155 dB re 1 µPa^{2}s	81	223	514
	TTS - 140 dB re 1 µPa^{2}s	7,671	6,869	11,796
PCW	PTS - 185 dB re 1 µPa^{2}s	*N/E*	35	88
	TTS - 170 dB re 1 µPa^{2}s	1,562	2,220	5,754
OCW	PTS - 203 dB re 1 µPa^{2}s	*N/E*	*N/E*	*N/E*
	TTS - 188 dB re 1 µPa^{2}s	*N/E*	*N/E*	37

Table 6.3: Injury Ranges for Marine Mammals due to Impact Pile Driving for the Pile Driving for OSP/Offshore Convertor Station Platform Foundations for the Three Energy Conversion Factors Assessed – OSP/Offshore Convertor Station Platform Scenario Includes Piling up to 4,000 kJ (*N/E* Is Threshold not Exceeded)

Species/Group	Threshold (Weighted SEL)	Range (m)		
		1%	4% - 0.5%	10% - 1%
LF	PTS - 183 dB re 1 µPa^{2}s	325	1,023	2,977
	TTS - 168 dB re 1 µPa^{2}s	35,030	27,519	42,801
HF	PTS - 185 dB re 1 µPa^{2}s	*N/E*	*N/E*	*N/E*
	TTS - 170 dB re 1 µPa^{2}s	*N/E*	33	75
VHF	PTS - 155 dB re 1 µPa^{2}s	103	285	699
	TTS - 140 dB re 1 µPa^{2}s	9,460	8,317	13,791
PCW	PTS - 185 dB re 1 µPa^{2}s	*N/E*	47	116
	TTS - 170 dB re 1 µPa^{2}s	2,781	3,148	7,385
OCW	PTS - 203 dB re 1 µPa^{2}s	*N/E*	*N/E*	*N/E*
	TTS - 188 dB re 1 µPa^{2}s	*N/E*	18	49

Table 6.4: Summary of Injury Ranges due to the Maximum Peak Pressure over the Piling Sequence for Marine Mammals due to Impact Piling for Wind Turbine Foundations ("Maximum" Scenario) and OSP/Offshore Convertor Station Platform Foundations

Species/Group	Threshold (Unweighted Peak)	Range (m)		
		1%	4% - 0.5%	10% - 1%
LF	PTS - 219 dB re 1 µPa (pk)	109	83	134
	TTS - 213 dB re 1 µPa (pk)	180	138	222
HF	PTS - 230 dB re 1 µPa (pk)	43	33	53
	TTS - 224 dB re 1 µPa (pk)	71	55	88
VHF	PTS - 202 dB re 1 µPa (pk)	449	346	554
	TTS - 196 dB re 1 µPa (pk)	741	568	920
PCW	PTS - 218 dB re 1 µPa (pk)	118	91	146
	TTS - 212 dB re 1 µPa (pk)	195	150	241
OCW	PTS - 232 dB re 1 µPa (pk)	37	28	45
	TTS - 226 dB re 1 µPa (pk)	60	46	75

Table 6.5: Summary of Injury Ranges due to the Maximum Peak Pressure Over the Piling Sequence for Marine Mammals due to Impact Piling for Wind Turbine Foundations ("Realistic" Scenario)

Species/Group	Threshold (Unweighted Peak)	Range (m)		
		1%	4% - 0.5%	10% - 1%
LF	PTS - 219 dB re 1 µPa (pk)	94	72	116
	TTS - 213 dB re 1 µPa (pk)	155	119	191
HF	PTS - 230 dB re 1 µPa (pk)	37	29	46
	TTS - 224 dB re 1 µPa (pk)	61	47	76
VHF	PTS - 202 dB re 1 µPa (pk)	388	298	478
	TTS - 196 dB re 1 µPa (pk)	638	490	788
PCW	PTS - 218 dB re 1 µPa (pk)	102	78	126
	TTS - 212 dB re 1 µPa (pk)	168	129	208
OCW	PTS - 232 dB re 1 µPa (pk)	31	24	39
	TTS - 226 dB re 1 µPa (pk)	52	40	64

Table 6.6: Injury Ranges for Fish due to Impact Pile Driving for the "Maximum" Pile Driving for Wind Turbine Foundations for the Three Energy Conversion Factors Assessed – "Maximum" Scenario Includes Piling up to 4,000 kJ (*N/E* Is Threshold not Exceeded)

Hearing Group	Response	Threshold (SEL, dB re 1 µPa²s)	Range (m)		
			1%	4% - 0.5%	10% - 1%
Group 1 Fish: No swim bladder (particle motion detection) – [*basking shark ranges shown in square brackets*].	Mortality	219	*N/E*	*N/E*	*N/E*
	Recoverable injury	216	*N/E*	*N/E*	*N/E*
	TTS	186	5,852 [*2,235*]	4,161 [*2,219*]	7,442 [*4,829*]
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	*N/E*	19	39
	Recoverable injury	203	25	67	150
	TTS	186	5,852	4,161	7,442
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	*N/E*	33	66
	Recoverable injury	203	25	67	150
	TTS	186	5,852	4,161	7,442
Sea turtles	Mortality	210	*N/E*	19	39
Fish eggs and larvae (static)	Mortality	210	677	495	718

Table 6.7: Injury Ranges for Fish due to Impact Pile Driving for the "Realistic" Pile Driving for Wind Turbine Foundations for the Three Energy Conversion Factors Assessed – "Realistic" Scenario Includes Piling up to 3,000 kJ (*N/E* Is Threshold not Exceeded)

Hearing Group	Response	Threshold (SEL, dB re 1 µPa²s)	Range (m)		
			1%	4% - 0.5%	10% - 1%
Group 1 Fish: No swim bladder (particle motion detection) – [*basking shark ranges shown in square brackets*].	Mortality	219	*N/E*	*N/E*	*N/E*
	Recoverable injury	216	*N/E*	*N/E*	*N/E*
	TTS	186	4,367 [*1,298*]	3,183 [*1,609*]	5,938 [*3,709*]
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	*N/E*	*N/E*	31
	Recoverable injury	203	20	53	114
	TTS	186	4,367	3,183	5,938
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	*N/E*	26	53
	Recoverable injury	203	20	53	114
	TTS	186	4,367	3,183	5,938
Sea turtles	Mortality	210	*N/E*	*N/E*	31
Fish eggs and larvae (static)	Mortality	210	542	400	579

Table 6.8: Injury Ranges for Fish due to Impact Pile Driving for the Pile Driving for OSP/Offshore Convertor Station Platform Foundations for the Three Energy Conversion Factors Assessed –OSP/Offshore Convertor Station Platform Scenario Includes Piling up to 4,000 kJ (*N/E* Is Threshold not Exceeded)

Hearing Group	Response	Threshold (SEL, dB re 1 µPa²s)	Range (m)		
			1%	4% - 0.5%	10% - 1%
Group 1 Fish: No swim bladder (particle motion detection) – [*basking shark ranges shown in square brackets*].	Mortality	219	*N/E*	*N/E*	*N/E*
	Recoverable injury	216	*N/E*	*N/E*	*N/E*
	TTS	186	5,363 *[2,058]*	3,943 *[2,165]*	7,058 [*4,679*]
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	*N/E*	19	39
	Recoverable injury	203	25	67	149
	TTS	186	5,363	3,943	7,058
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	*N/E*	33	66
	Recoverable injury	203	25	67	149
	TTS	186	5,363	3,943	7,058
Sea turtles	Mortality	210	*N/E*	19	39
Fish eggs and larvae (static)	Mortality	210	592	439	638

Table 6.9: Summary of Injury Ranges due to the Maximum Peak Pressure Over the Piling Sequence for Fish due to Impact Piling for Wind Turbine Foundations ("Maximum" Scenario) and OSP/Offshore Convertor Station Platform Foundations

Hearing Group	Response	Threshold (SPL_{pk}, dB re 1 µPa)	Range (m)		
			1%	4% - 0.5%	10% - 1%
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	180	138	222
	Recoverable injury	213	180	138	222
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	297	228	366
	Recoverable injury	207	297	228	366
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	297	228	366
	Recoverable injury	207	297	228	366
Sea turtles	Mortality	207	297	228	366
Fish eggs and larvae	Mortality	207	297	228	366

Table 6.10: Summary of Injury Ranges due to the Maximum Peak Pressure Over the Piling Sequence for Fish due to Impact Piling for Wind Turbine Foundations ("Realistic" Scenario)

Hearing Group	Response	Threshold (SPL_{pk}, dB re 1 µPa)	Range (m)		
			1%	4% - 0.5%	10% - 1%
Group 1 Fish: No swim bladder (particle motion detection)	Mortality	213	155	119	191
	Recoverable injury	213	155	119	191
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	207	255	196	315
	Recoverable injury	207	255	196	315
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	255	196	315
	Recoverable injury	207	255	196	315
Sea turtles	Mortality	207	255	196	315
Fish eggs and larvae	Mortality	207	255	196	315

Table 6.11: Injury Ranges for Marine Mammals due to Concurrent Impact Pile Driving at Two Locations for the "Maximum" Pile Driving for Wind Turbine Foundations for the Three Energy Conversion Factors Assessed – "Maximum" Scenario includes Piling up to 4,000 kJ (*N/E* Is Threshold not Exceeded)

Species/Group	Threshold (Weighted SEL)	Range (m)		
		1%	4% - 0.5%	10%-1%
LF	PTS - 183 dB re 1 µPa²s	1,305	2,319	5,830
	TTS - 168 dB re 1 µPa²s	54,550	42,931	62,172
HF	PTS - 185 dB re 1 µPa²s	*N/E*	*N/E*	*N/E*
	TTS - 170 dB re 1 µPa²s	18	35	84
VHF	PTS - 155 dB re 1 µPa²s	201	439	1,415
	TTS - 140 dB re 1 µPa²s	16,298	13,300	20,581
PCW	PTS - 185 dB re 1 µPa²s	25	53	150
	TTS - 170 dB re 1 µPa²s	8,490	6,731	13,476
OCW	PTS - 203 dB re 1 µPa²s	*N/E*	*N/E*	*N/E*
	TTS - 188 dB re 1 µPa²s	*N/E*	20	58

Table 6.12: Injury Ranges for Marine Mammals due to Concurrent Impact Pile Driving at Two Locations for the "Realistic" Pile Driving for Wind Turbine Foundations for the Three Energy Conversion Factors Assessed – "Realistic" Scenario Includes Piling up to 3,000 kJ (*N/E* Is Threshold not Exceeded)

Species/Group	Threshold (Weighted SEL)	Range (m)		
		1%	4% - 0.5%	10%-1%
LF	PTS - 183 dB re 1 µPa²s	675	1,556	4,439
	TTS - 168 dB re 1 µPa²s	45,893	35,991	53,519

Species/Group	Threshold (Weighted SEL)	Range (m)		
		1%	4% - 0.5%	10%-1%
HF	PTS - 185 dB re 1 µPa²s	*N/E*	*N/E*	*N/E*
	TTS - 170 dB re 1 µPa²s	13	27	64
VHF	PTS - 155 dB re 1 µPa²s	150	307	984
	TTS - 140 dB re 1 µPa²s	13,259	10,997	17,536
PCW	PTS - 185 dB re 1 µPa²s	18	38	106
	TTS - 170 dB re 1 µPa²s	5,713	4,966	10,523
OCW	PTS - 203 dB re 1 µPa²s	*N/E*	*N/E*	*N/E*
	TTS - 188 dB re 1 µPa²s	*N/E*	14	41

Table 6.13: Injury Ranges for Fish due to Concurrent Impact Pile Driving at Two Locations for the "Maximum" Pile Driving for Wind Turbine Foundations for the Three Energy Conversion Factors Assessed – "Maximum" Scenario Includes Piling up to 4,000 kJ (*N/E* Is Threshold not Exceeded)

Hearing Group	Response	Threshold (SEL, dB re 1 µPa²s)	Range (m)		
			1%	4% - 0.5%	10% - 1%
Group 1 Fish: No swim bladder (particle motion detection) – [*basking shark ranges shown in square brackets*].	Mortality	219	*N/E*	*N/E*	*N/E*
	Recoverable injury	216	*N/E*	*N/E*	*N/E*
	TTS	186	9,912 [*5,441*]	7,106 [*4,342*]	11,660 [*8,264*]
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	*N/E*	21	44
	Recoverable injury	203	46	89	274
	TTS	186	9,912	7,106	11,660
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	20	37	86
	Recoverable injury	203	46	89	274
	TTS	186	9,912	7,106	11,660
Sea turtles	Mortality	210	*N/E*	21	44
Fish eggs and larvae (static)	Mortality	210	978	708	1,038

Table 6.14: Injury Ranges for Fish Due To Concurrent Impact Pile Driving at Two Locations for the "Realistic" Pile Driving for Wind Turbine Foundations for the Three Energy Conversion Factors Assessed – "Realistic" Scenario Includes Piling up to 3,000 kJ (*N/E* Is Threshold not Exceeded)

Hearing Group	Response	Threshold (SEL, dB re 1 µPa²s)	Range (m)		
			1%	4% - 0.5%	10% - 1%
Group 1 Fish: No swim bladder (particle motion detection) – [*basking shark ranges shown in square brackets*].	Mortality	219	*N/E*	*N/E*	*N/E*
	Recoverable injury	216	*N/E*	*N/E*	*N/E*
	TTS	186	7,722 [*3,837*]	5,612 [*3,259*]	9,404 [*6,523*]
Group 2 Fish: Swim bladder not involved in hearing (particle motion detection)	Mortality	210	*N/E*	16	34
	Recoverable injury	203	35	65	185
	TTS	186	7,722	5,612	9,404
Group 3 and 4 Fish: Swim bladder involved in hearing (primarily pressure detection)	Mortality	207	16	29	64
	Recoverable injury	203	35	65	185
	TTS	186	7,722	5,612	9,404
Sea turtles	Mortality	210	*N/E*	16	34
Fish eggs and larvae (static)	Mortality	210	777	571	831

6.2. SUPPLEMENTARY INFORMATION

38. At the request of stakeholders, additional modelling was undertaken to determine the maximum injury ranges based on constant conversion factors at the maximum hammer energy of 4,000kJ for the SPL_{pk} metric only. These are presented in Table 6.15. Modelled values at which instantaneous injury in the form of PTS could occur based on SPL_{pk} thresholds were highest for the 10% conversion factor at the maximum hammer energy of 4,000 kJ. However, these were considered over precautionary for this metric as an animal is likely to flee the area starting from the first strike of the hammer and throughout soft start as the hammer energy ramps up. In addition, as described, a conversion factor of 10% is considered unlikely at the maximum hammer energy as the pile would be embedded and therefore the proportion of energy converted to sound would be reduced (thus the use of a reducing conversion factor).

Table 6.15: Summary of Injury Ranges due to the Maximum Peak Pressure over the Piling Sequence for Marine Mammals due to Impact Piling for Wind Turbine Foundations ("Maximum" Scenario) and OSP/Offshore Convertor Station Platform Foundations Using Range of Conversion Factors

Hearing Group	Threshold (Unweighted Peak)	Range (m)				
		1% Constant	4% Constant	10% Constant	4% - 0.5% Reducing	10% - 1% Reducing
LF	PTS - 219 dB re 1 µPa (pk)	109	223	359	83	134
HF	PTS - 230 dB re 1 µPa (pk)	43	89	143	33	53
VHF	PTS - 202 dB re 1 µPa (pk)	449	928	1,519	346	554
PCW	PTS - 218 dB re 1 µPa (pk)	118	243	390	91	146

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