REPORT ON THE ENVIRONMENTAL IMPACT ASSESSMENT OF THE BALTICA-1 OFFSHORE WIND FARM

APPENDIX 4

THE NUMERICAL MODELLING OF THE NOISE PROPAGATION FROM THE BALTICA-1 OWF OPERATION

AUTHORS:

Tamara Tarnoki, Jonas von Pein, Matthias Ram, Marta Nocoń, Irmina Balicka, Magda Chreptowicz, Urszula Sadowska-Maksym, Frank Thomsen

CONTRACTORS:

Justyna Edut, Natalia Kaczmarek, Mateusz Kunicki, Teresa Moroz-Kunicka, Juliusz Gajewski, Kamila Gałka, Dominika Górnowicz

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS AND DEFINITIONS

µPa	micropascal
dB	decibel – a logarithmic measure of sound intensity/pressure. The decibel value for sound pressure is 10 log10 (P^2/P_o^2) where P = the actual pressure and P_o = the reference pressure
EIA	Environmental Impact Assessment
HF	high frequency
HF-weighted SEL	sound exposure level with high-frequency weighting function according to susceptibility to noise-induced hearing damage in the harbour porpoise (based on NMFS 2018)
Hz	hertz – the unit of frequency, where 1 Hz is 1 cycle per second and 1 kHz is 1000 cycles per second
NMFS	The US National Marine Fisheries Service
NOAA	The US National Oceanic and Atmospheric Administration
OWF	Offshore Wind Farm
PTS	Permanent Threshold Shift – a permanent increase in hearing threshold due to a physical injury of hair cells because of exposure to sound
PTS (cum.)	the permanent shift in hearing threshold due to a cumulative dose of noise exposure
PTS (single blow)	the permanent shift of the hearing threshold as a result of a single pile driver blow
PW	pinnipeds in the water (here: the grey seal and the harbour seal)
PW-weighted SEL	sound exposure level with frequency weighting function according to the susceptibility to noise-induced hearing damage in seals (based on NMFS 2018, 2020)
RAM	Range-dependent Acoustic Model – a model based on the parabolic equation method, assuming that emitted energy dominates over back-scattered energy
SEL	Sound Exposure Level; it is often used when assessing the impact of noise on the marine environment as a measure of the total noise energy normalised to 1 second
SEL_{cum}	for a constant sound source such as operational noise, the cumulative sound exposure levels are expressed as follows: $$SEL_{cum} = SEL_{1s} + 10\ log_{10} t = SPL_{rms} + 10\ log_{10} t$$ where *SPL* is the operational root mean square level sound pressure and *t* is the total duration in seconds (24 hours for marine mammals and 12 hours for fish)

SPL	Sound Pressure Level [dB re 1µPa] – the sound pressure expressed in decibels [dB] relative to the reference pressure P_{ref} = 1µPa
SPL_{peak}	Peak Sound Pressure Level – the maximum value of a signal amplitude
SRC	source
TL	Transmission Loss (propagation loss) – reduction in sound intensity with the increase in distance
TTS	Temporary Threshold Shift – a temporary increase in hearing threshold after exposure to sound; the hearing threshold will return to pre-exposure state after some time
TTS (cum.)	a temporary shift in hearing threshold due to a cumulative dose of noise exposure
TTS (single blow)	Temporary Threshold Shift – a temporary shift in the hearing threshold as a result of a single pile driver blow

1 NON-SPECIALIST SUMMARY

Underwater sound is generated during all phases associated with the construction, operation, and decommissioning of an offshore wind farm (OWF).

For the purposes of this Report, the acoustic emission associated with piling in the area of the Baltica-1 OWF, which is located in the Polish exclusive economic zone, was examined. The modelling of underwater noise propagation during the operation stage was performed for the following scenarios:

- one WTG operating in the farm area in the summer season and winter season;
- all WTGs operating in the summer season and winter season.

Based on the acoustic modelling performed, the noise impact zones (in the form of the distance from the sound source expressed in kilometres) on marine mammals (porpoises and seals) and fish with swim bladders were estimated. The noise effects considered were behavioural responses (behavioural changes), hearing damage in the form of temporary and permanent shifts in the hearing thresholds (TTS, PTS) and reversible hearing loss in the case of fish. Therefore, the Report provides a factual basis for conducting an environmental impact assessment of the investment concerning marine mammals and fish.

For modelling purposes, 72 transects with a maximum length of 150 km, extending in all directions, were selected. Bathymetric data were obtained from the EMODnet platform. The geological profile of the seabed and the profiles of sound propagation velocity in the ground were determined using publicly available databases.

All ranges calculated for the harbour porpoise during the operation of a single WTG were low, reaching a maximum of 0.1 km for the behavioural response, TTS, and PTS. The impact ranges calculated for fish with swim bladders in relation to the TTS were similar to those obtained for the harbour porpoise, with a maximum range of 0.1 km in both the summer and winter seasons.

The results of the propagation of noise from the operation of all 64 WTGs did not show an increase in the impact ranges for both the harbour porpoise and fish. The sum of the impact ranges for all effects translated into impact zones of 1.9 km^2 each for both taxa, in both seasons analysed.

It should be emphasised that comparable results obtained for the harbour porpoise and fish, despite different threshold values or different seasons, can be attributed to the model resolution adopted. The range of 0.1 km is also the minimum range of impact generated by the model. Hence, the results are identical for all the effects considered.

2 INTRODUCTION

This Report constitutes Appendix 3 to the Report on the Environmental Impact Assessment of the Baltica-1 OWF, which concerns marine mammals and fish in the Polish part of the Baltic Sea. The Report contains the results of analyses relevant to the EIA in the scope of numerical modelling of the sound emitted by the operating OWF together with calculations of noise impact zones for marine mammals and fish with swim bladders.

2.1 SCOPE OF WORK

The scope of work included the modelling of underwater noise propagation during the operation of the Baltica-1 OWF and calculations of noise impact zones under two scenarios, the first of which included only one operating WTG, while in the second one, all WTGs were fully operating.

In the case of a single WTG, there was considered the worst-case scenario in terms of the potential range of impact from the operating turbine on the nearby Natura 2000 area (Hoburgs bank och Midsjöbankarna – SE330308), where the harbour porpoise is the protection objective. For this purpose, the same location was adopted for modelling as in the case of the analysis of noise from piling, i.e. the point with coordinates 55.641568 N; 17.61799 E. For all WTGs, an even distribution of 64 WTGs was assumed in the area of the Baltica-1 OWF development area.

The modelling methodology has been presented in Chapter 3. The modelling results for the winter and summer seasons are presented in Chapters 4.1 and 4.2, respectively.

3 METHODOLOGY

3.1 GENERAL APPROACH

The adopted approach to assessing the impact range and area has three stages:

- sound source definition (sound intensity and frequency spectrum);
- numerical noise modelling;
- calculations of biological effects using internationally accepted criteria.

The **definition of the sound source** during the OWF operation was based on empirical calculations obtained from publicly available measurement data.

The **numerical modelling of sound propagation** was performed using the proprietary MIKE software by DHI – Underwater Acoustic Simulator (UAS: MIKE DHI, 2023).

The model focuses on noise propagation in the far field. The UAS software applies the RAM code based on the sound propagation model developed by Collins (Collins, 1993). A detailed description of the underwater acoustic model, including the scientific basis of the model and its assumptions, can be found in the technical documentation for the UAS in the MIKE software (MIKE DHI, 2023).

The sound source properties were combined with a propagation model to calculate sound propagation in angular directions from the piling locations along 72 2D transects. Specific 1/3 octave bands with central frequencies varying from 20 Hz to 4 kHz were modelled. These bands cover most of the energy from piling. For higher frequencies, propagation losses at 4kHz were applied in combination with a correction for attenuation increasing with increasing frequency (Francois and Garrison, 1982a; 1982b). Based on the numerical model, maps were produced showing the sound exposure levels as a function of distance from the sound source.

As the marine mammals considered in this study use space across the entire water column, the maximum sound levels calculated in the water column for each distance range are presented.

To **calculate biological effects**, the scheme presented by Thomsen et al. (2021). There are, several respectively overlapping noise impact zones, the sizes of which depend mainly on the relative distance between the animals and the sound source location [Figure 3.1]. This study focuses on **behavioural response** and **hearing loss** (TTS, PTS, and reversible hearing loss), as these are the effects that should be considered due to the existing regulations. Impacts in the form of TTS, PTS, reversible hearing loss and behavioural response are included in internationally accepted guidelines for assessing the impact of underwater noise on marine organisms.

With this in mind, numerical modelling was conducted taking into account the zones in which the impact related to the organisms' ability to perceive sounds occurs (based on Thomsen et al., 2006). For this reason, the background SPL spectrum assumed in the calculations [Figure 3.2] is the lowest possible sound level in a given frequency range. Frequency ranges with sound levels lower than the acoustic background are not considered when summing up the acoustic energy of the broadband SEL. In addition, in the case of marine mammals, the so-called "effective silence" (Chapter 3.4), i.e. the lowest hearing threshold, was taken into account.

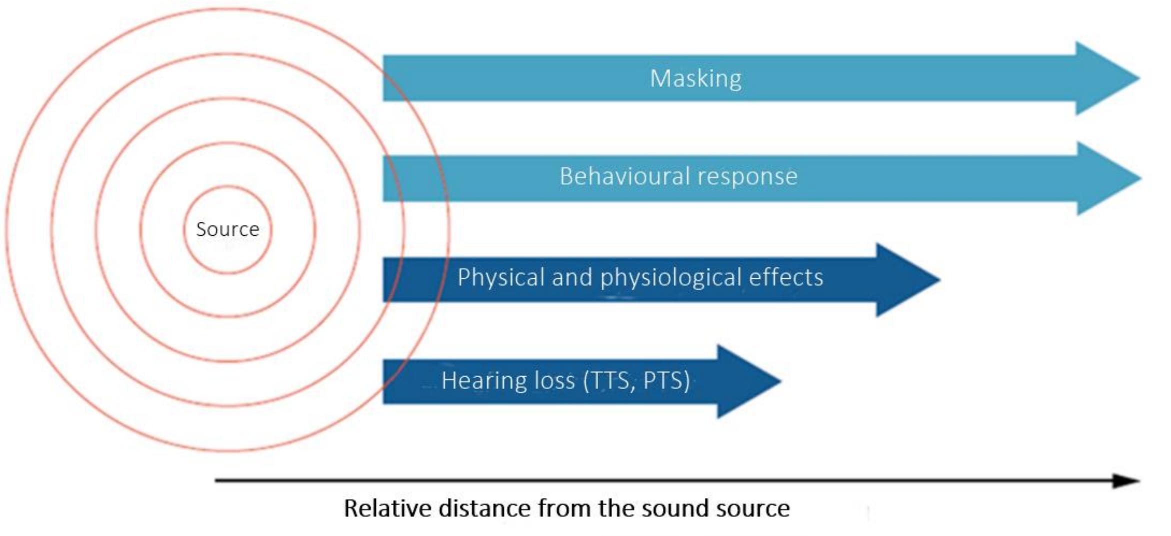

Figure 3.1. The potential effects of noise at different distances from the sound source (based on Thomsen et al., 2021)

[TTS = temporary threshold shift and PTS = permanent threshold shift (adapted from Thomsen et al., 2021)]

3.2 THE APPROACH TO THE OPERATION NOISE ASSESSMENT

3.2.1 Sound source definition

3.2.1.1 Information on the sound source

For the Baltica-1 OWF project, three types of foundations are considered, i.e. monopile, jacket foundation and gravity-based structure. The best database is available for the study of monopiles. As reported by Bellmann et al. (2023), there is no significant difference in noise generation between these types of foundations. A closer look at the available data, however, indicates that the levels measured for jacket foundations are slightly lower, while gravity-based foundations seem to be even quieter, although currently there is no empirical evidence for this. Therefore, the analyses performed for monopiles seem to be the worst-case scenario.

Tougaard et al. (2020) and Stöber and Thomsen (2021) found a relationship between the nominal power and the noise emitted by wind farms during the operational phase. In a publication that included a much broader set of measurement data compared to the two previous studies, Bellmann et al. (2023) were unable to confirm the previous finding that sound levels increased with nominal power (see also Holme et al., 2023). In fact, the sound emitted by an operating WTG was not only not dependent on the nominal power, but also unaffected by other variables such as whether a gear or direct drive was used and what type of foundation was chosen (Bellmann et al., 2023). To best match the measurement results with the scenario under investigation, the maximum measurement value resulting from the simultaneous use of a monopile and direct drive was selected, which is a conservative approach. The applied SPL^{SRC} level is 159 dB re 1 µPa.

3.2.1.2 Sound source spectrum

To distribute the acoustic energy in the frequency domain, the measured spectrum of the direct drive WTG was used as a reference level (Bellmann et al., 2023). This spectrum was adjusted to the changes in pile diameter between the measured and planned WTGs by assuming a scaling law with a frequency of up to 1 kHz. The scaling law was initially developed for pile-driving noise at sea (von Pein et al., 2023). According to the principle that low-frequency noise is emitted into the water with an efficiency that gets greater with increasing pile diameter, this law may find application also in this case.

The applied source spectrum is shown in the figure below [Figure 3.2].

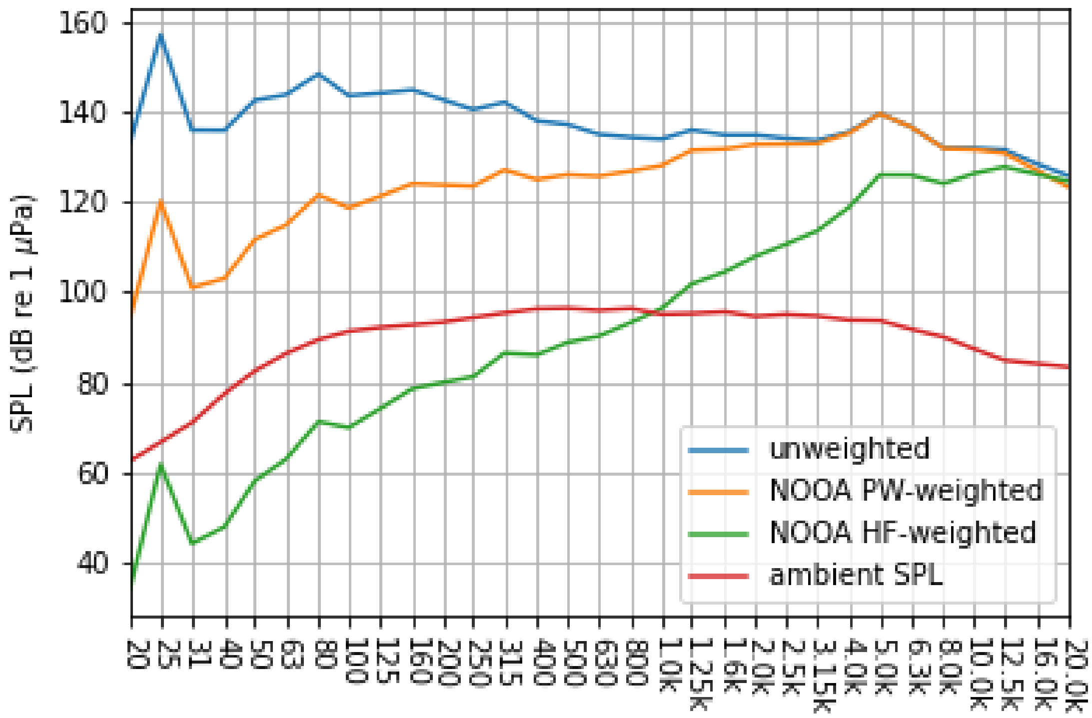

Figure 3.2. The considered source spectrum of the operational phase together with the HF- and PW-weighted spectra

3.2.2 Numerical modelling of noise

The modelling of the cumulative noise from the operational phase included the propagation of sound from all WTGs operating simultaneously. The basis for the cumulative model was the results obtained for a single location.

The criteria for assessing the effects (i.e. behavioural response, change in animal occurrence density, TTS, PTS, and reversible hearing damage) are identical to those for the considerations on a single location. If the sound field combination does not lead to overlapping of impact zones over the entire farm area, the impact zones are determined by multiplying the area of a single WTG by the appropriate number of WTGs.

3.2.2.1 Overlapping sound fields

The following approach is used to obtain the cumulative sound fields: the calculated field pressure from the modelled location is converted to the location of the analysed WTG and mapped onto a corrected rectangular grid using bilinear interpolation. The size of the target calculation grid is 100 m in the farm area, and it increases logarithmically outside its boundaries. The mapping is presented in

Figure 3.3, where for illustrative purposes, the cell sizes of both grids have been drawn much coarser than in the actual grids.

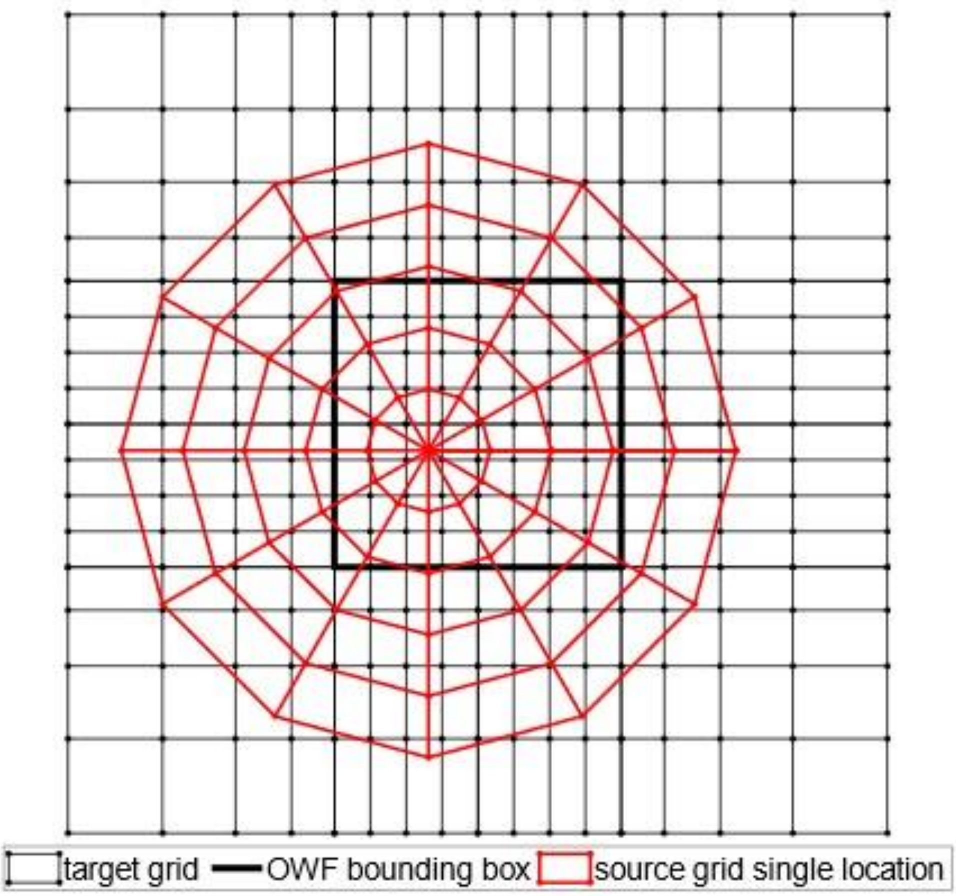

Figure 3.3. A simplified illustration of the interpolation grids used in the operational noise accumulation (not to scale)

The sound levels are then added in compliance with the following equation:

$$SEL_{cum}(x,y) = 10\ \log_{10}\left(\sum_{i=1}^{Nr} 10^{\left(\frac{SEL_i\,(x,y)}{10}\right)}\right)$$

This combination is routed directly to the maximum SEL value. Therefore, the dependence of the acoustic results on water depth is not taken into account. This assumption is another simplification and conservative estimate. The accumulation can only be routed if the modelled location results exist at the target calculation point of the grid. Therefore, on transects where islands or shallow waters occur, this approach may lead to an underestimation of the actual pressure field. However, if the propagation conditions are varied across the farm, the acoustic results may also be overestimated.

3.3 The calculation of biological impacts

3.3.1 Harbour porpoise

For porpoises, the acoustic thresholds for TTS and PTS were derived from the NMFS criteria (2018, 2023) for continuous noise. For seals, the NMFS threshold values are higher than the predicted operational noise level, and therefore, the potential impact ranges can be considered negligible.

For the harbour porpoise, behavioural response thresholds were accepted from Southall et al. (2007). For seals, there are no sufficient data to define a criterion for behavioural response resulting from exposure to operational noise from a wind farm.

A summary of operational noise exposure criteria applied in the case of the harbour porpoise is presented in the table below [Table 3.1].

Table 3.1. An overview of noise exposure criteria used to calculate the impact ranges at the operational phase for the group of high-frequency cetaceans

Animal species/group	Effect	Noise threshold	Source
Harbour porpoise	PTS	173 dB re. 1 µPa²s (weighted SEL cumulated for 24 hours)	NOAA National Marine Fisheries Service (2018)
	TTS	153 dB re. 1 µPa²s (weighted SEL cumulated for 24 hours)	
	Behavioural response	140 dB re 1 µPa (unweighted SPL)	Southall et al. (2007)

3.3.2 Fish

In relation to fish with swim bladders, there can be used the criteria for TTS and reversible hearing damage according to Popper et al. (2014).

Since the source level specified in Chapter 3.2.1, which is 159 dB re 1 µPa, is below the threshold for reversible hearing damage, this threshold was not included in this assessment and it can be assumed that the operation of the OWF will never lead to reversible hearing damage in fish with swim bladders. At the same time, it should be noted that the range of impact calculated for the TTS threshold value is located close to the source of sound. Therefore, it should be expected that only in the immediate vicinity of the WTGs, the effect in the form of TTS can occur in fish with swim bladders.

With no sufficient data, there is no criterion for the behavioural response of fish exposed to continuous noise.

A summary of the operational noise exposure criteria used in the model for fish with swim bladders is presented in the following table [Table 3.2].

Table 3.2. An overview of noise exposure criteria used to calculate the impact ranges at the operational stage for fish with swim bladders

Animal group	Effect	Noise threshold	Source
Fish with swim bladders used for hearing	TTS	158 dB re 1 µPa (unweighted SPL cumulated for 12 hours)	Popper et al. (2014)

For fish without swim bladders, a relevant stimulus is not the sound pressure, but rather the motion of sound wave particles (Popper and Hawkins, 2018). The existing noise criteria are defined by pressure values (see Popper et al., 2014). They are therefore extremely unreliable for fish without swim bladders, and it is not recommended to calculate impact ranges on their basis. This paper presents an overview of possible impacts based on a review of the existing literature.

3.4 ADDITIONAL PARAMETERS

3.4.1 "Effective quiet" – marine mammals

An important concept is the so-called "effective quiet", defined by Finneran (2015) as the highest SPL that will cause neither a significant TTS impact nor a return to TTS levels induced by previous exposure to higher levels. Further, Finneran (2015) indicates that this value may be 124 dB relative to 1 µPa for porpoises and in support of this conclusion, he cites a study by Kastelein et al. (2002). This study does not directly investigate "effective quiet", but rather shows that even very low sound exposures can lead to significant TTS impacts in harbour porpoises when the exposure duration is long. The lowest sound level leading to TTS in porpoises measured to date is 124 dB re 1 µPa. It can therefore be seen as a preliminary value until more accurate data can be obtained.

Effective quiet is applied in the 1/3 octave bands. Whenever the unweighted SPL of a band is less than 124 dB, it is ignored when summing the acoustic energy to the broadband SEL.

4 RESULTS

4.1 THE RESULTS OF NOISE MODELLING FOR THE OPERATION STAGE IN THE WINTER SEASON

4.1.1 The modelling of propagation of noise from a single wind turbine generator

This chapter presents the results of modelling carried out for the Baltica-1 OWF in the winter (see chapter 4.1) and summer seasons (see chapter 4.2). The impact ranges and areas for different threshold values are presented in the form of tables, and sound propagation maps are included as well.

4.1.1.1 Propagation loss calculation results

Propagation losses were estimated at different distances from the source in the range from 200 m to 5 km for the directions of north and south. According to the figure below [Figure 4.1], a typical increase in transmission losses at low and high frequencies can be clearly identified.

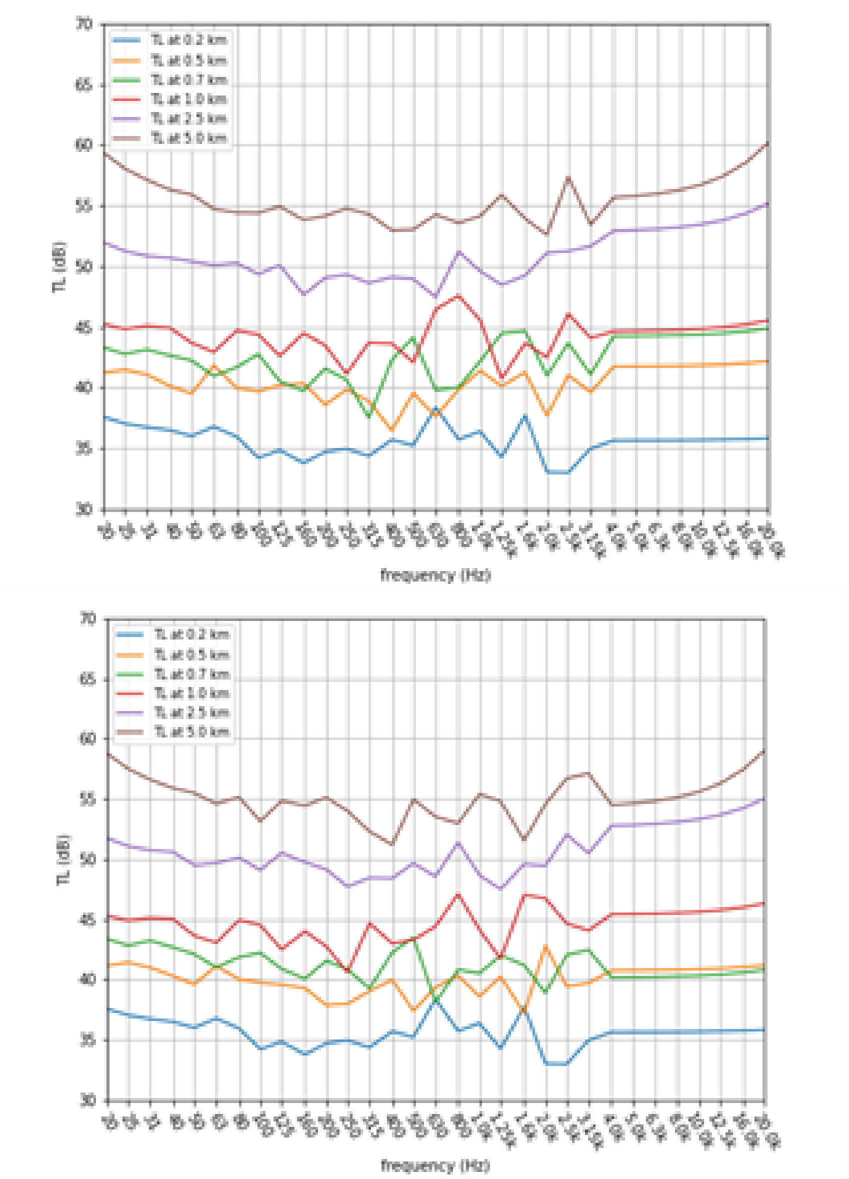

Figure 4.1. Transmission losses at different distances from the source estimated for the northern (top) and southern (bottom) directions

4.1.1.2 Impact ranges and areas

4.1.1.2.1 Harbour porpoise

The impact of noise from the operation of a single WTG is presented in the following table [Table 4.1] and figures [Figure 4.2, Figure 4.3]. In the case of the porpoise, all ranges were at a comparably low level of 0.1 km. This range is also the minimum range of impact generated by the model.

Table 4.1. The ranges and areas of impact on the harbour porpoise during the operation of a single WTG

Effect	Unit	Impact range [km]			Impact area [km²]
		R_{min}	R_{mean}	R_{max}	
Behavioural response	unweighted SPL	0.1	0.1	0.1	0.03
TTS (cumulative for 24 h)	HF-weighted SEL	0.1	0.1	0.1	0.03
PTS (cumulative for 24 h)	HF-weighted SEL	0.1	0.1	0.1	0.03

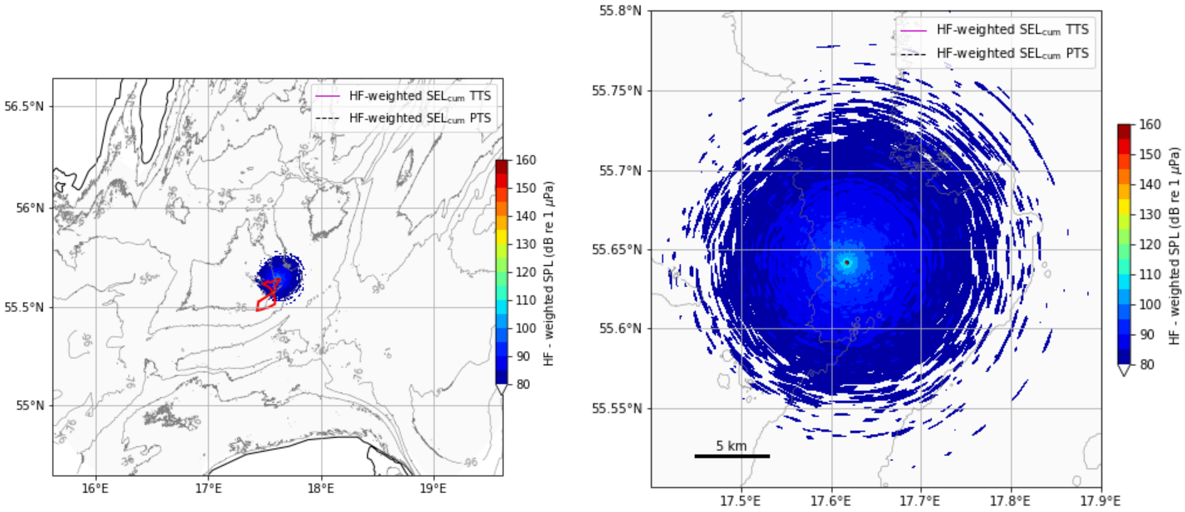

Figure 4.2. The map of HF-weighted SEL for one operating WTG in the Baltica-1 OWF area and the ranges of impact on the harbour porpoise (the map on the left shows a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

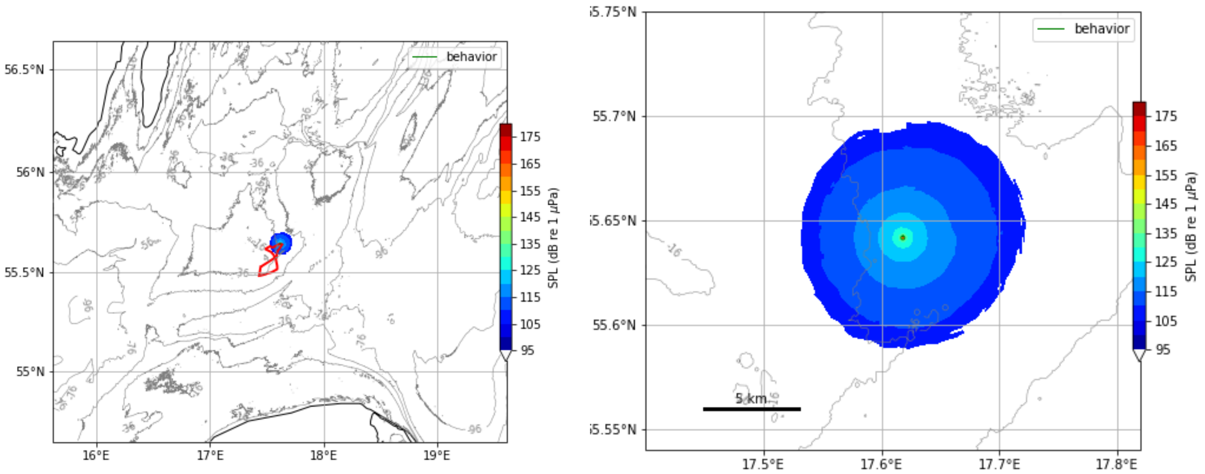

Figure 4.3. The map of unweighted SPL above the acoustic background for one operating WTG in the Baltica-1 OWF area and the range of impact for the harbour porpoise (the map on the left shows

a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

4.1.1.2.2 Fish with swim bladders

The impact of noise from the operation of one WTG is presented in the table [Table 4.2] and in the figure [Figure 4.4] below. The estimated range of TTS did not exceed 0.1 km.

Table 4.2. The ranges and areas of impact on fish with swim bladders during the operation of a single WTG

Effect	Unit	Impact range [km]			Impact area [km^2]
		R_{min}	R_{mean}	R_{max}	
TTS (cumulative for 12 h)	unweighted SPL	0.1	0.1	0.1	0.03

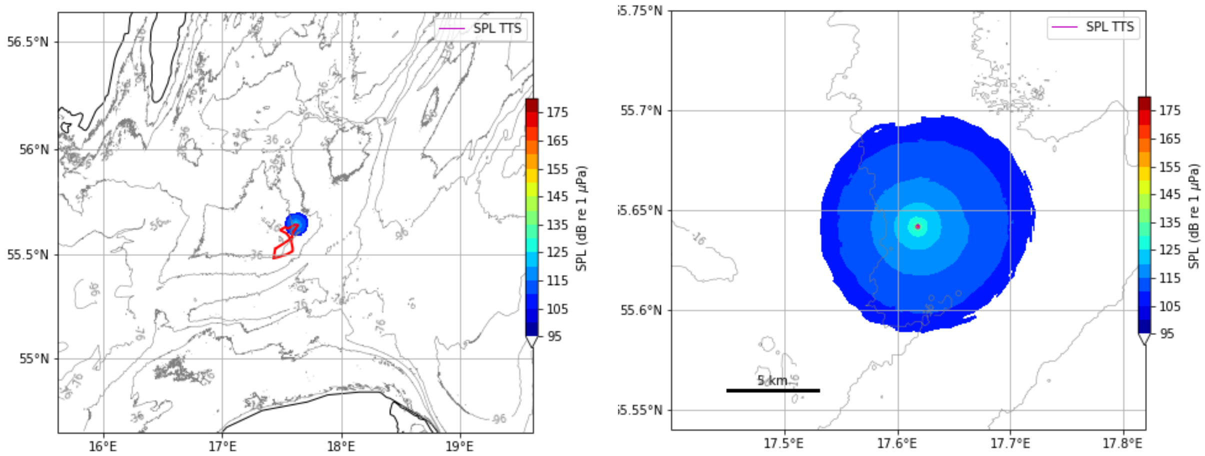

Figure 4.4. The map of unweighted SPL above the acoustic background for one operating WTG in the Baltica-1 OWF area and the ranges of impact on fish with swim bladders the map on the left shows a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

4.1.2 The modelling of propagation of noise from all wind turbine generators

4.1.2.1 Impact ranges and areas

4.1.2.1.1 Harbour porpoise

The results obtained for the harbour porpoise [Table 4.3, Figure 4.5, Figure 4.6] show that the individual areas of TTS and PTS impacts remained at the same level as estimated for a single WTG. However, it should be noted that the total area of impact consists of individual areas around each WTG included in the analysis and amounts to 1.9 km^2 for all the analysed effects.

Table 4.3. The areas of impact on the harbour porpoise during the operation of all WTGs

Effect	Unit	Impact area [km^2]
Behavioural response	unweighted SPL	1.9
TTS (cumulative for 24 h)	HF-weighted SEL	1.9
PTS (cumulative for 24 h)	HF-weighted SEL	1.9

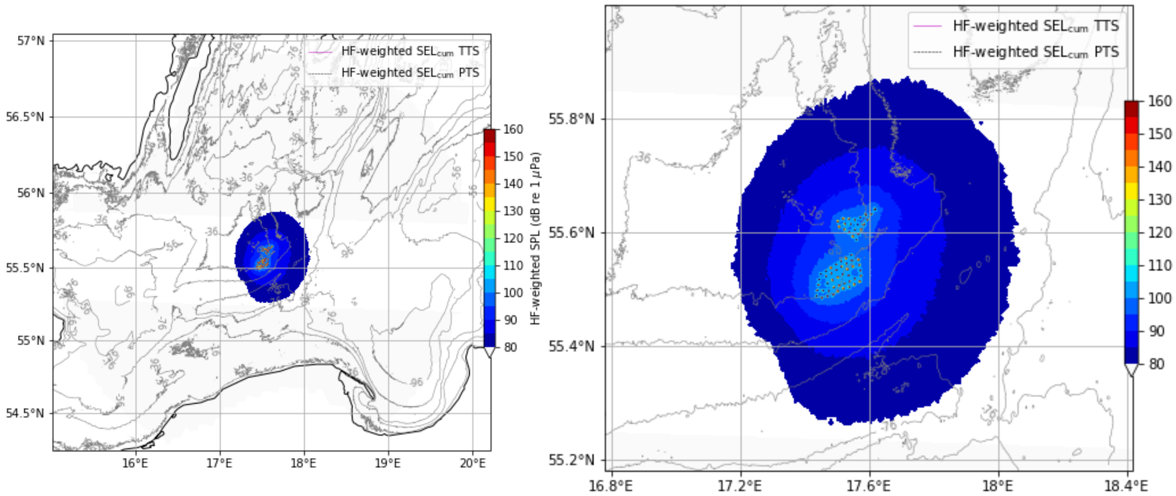

Figure 4.5. The map of HF-weighted SEL for all WTGs operating in the Baltica-1 OWF area and the range of impact on the harbour porpoise (the map on the left shows a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

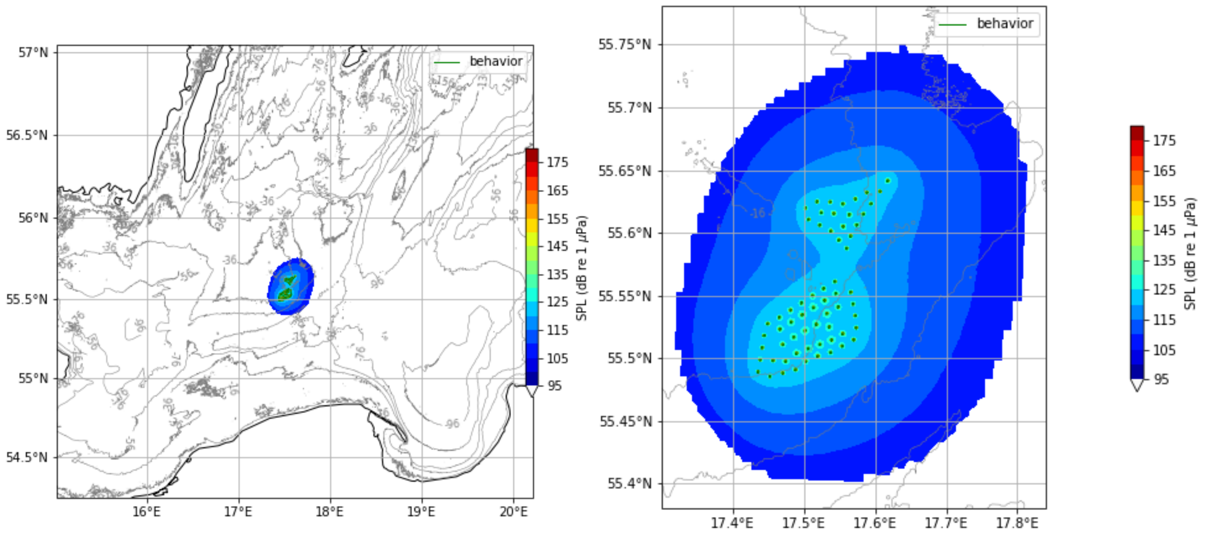

Figure 4.6. The map of unweighted SPL above the acoustic background for all WTGs operating in the Baltica-1 OWF area and the range of impact on the harbour porpoise (the map on the left shows a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

4.1.2.1.2 Fish with swim bladders

The results of the cumulative model for the stage of operation of all WTGs are presented in the table [Table 4.4] and in the figure [Figure 4.7] below. Similarly to the case of the harbour porpoise, the single TTS impact area did not increase compared to the analyses conducted for a single WTG, and the total impact area for the entire farm was 1.9 km^2.

Table 4.4. The areas of impact on fish with swim bladders during operation of all WTGs

Effect	Unit	Impact area [km^2]
TTS (cumulative for 12 h)	unweighted SPL	1.9

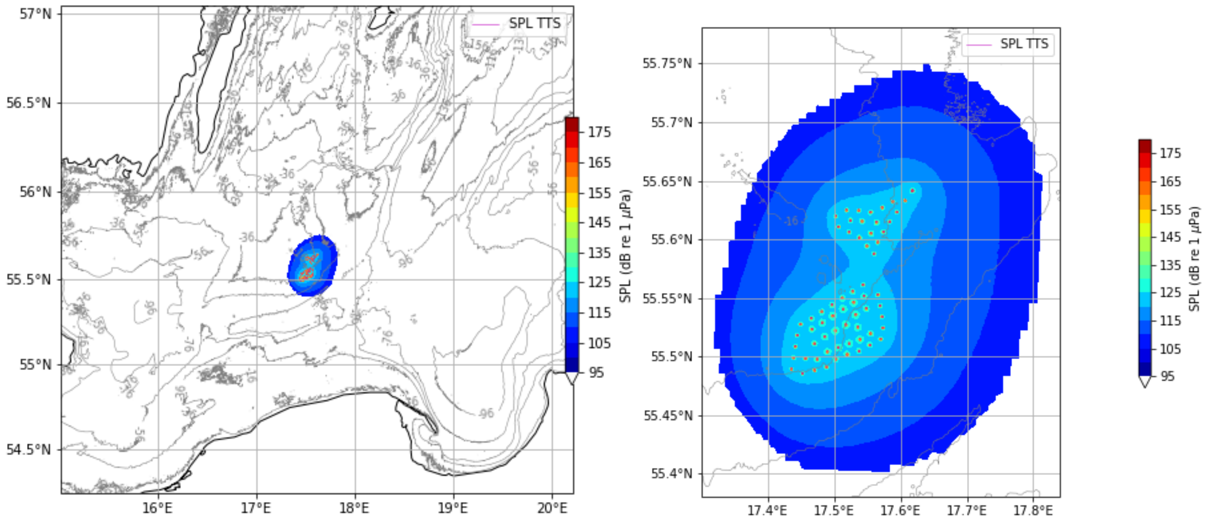

Figure 4.7. The map of unweighted SPL above the acoustic background for all WTGs operating in the Baltica-1 OWF area and the ranges of impact on fish with swim bladders (the map on the left shows a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

4.1.2.1.3 Fish without swim bladders

As indicated in Chapter 3.3.2, the assessment of the impact of offshore wind farms on fish without swim bladders is not possible because there is little information available on the particle motion associated with OWF activity. Sigray and Andersson (2011) measured particle motion caused by a smaller offshore WTG (Utgrunden, Sweden; 1.5 MW) and compared it to the audiograms of some local fish species. They concluded that an offshore WTG can be detected by the Atlantic cod (*Gadus morhua*) from a distance of 10 m. It is exceedingly difficult to extrapolate this information to larger, currently planned WTGs. The only conclusion that can be drawn from this information is that noise generated by offshore WTGs in the future will be audible to fish without swim bladders, but the exact ranges and areas of audibility cannot be estimated at this stage.

4.2 THE RESULTS OF NOISE MODELLING DURING THE OPERATION IN THE SUMMER SEASON

4.2.1 The modelling of propagation of noise from a single wind turbine generator

This chapter presents the results of modelling conducted for the Baltica-1 OWF in the summer season. The impact ranges and areas for different threshold values are presented in the form of tables, and sound propagation maps are included as well.

4.2.1.1 Transmission loss calculation results

Transmission losses were estimated at different distances from the source in the range from 200 m to 5 km for the directions of north and south. According to the figure below [Figure 4.8], a typical increase in transmission losses at low and high frequencies can be clearly identified.

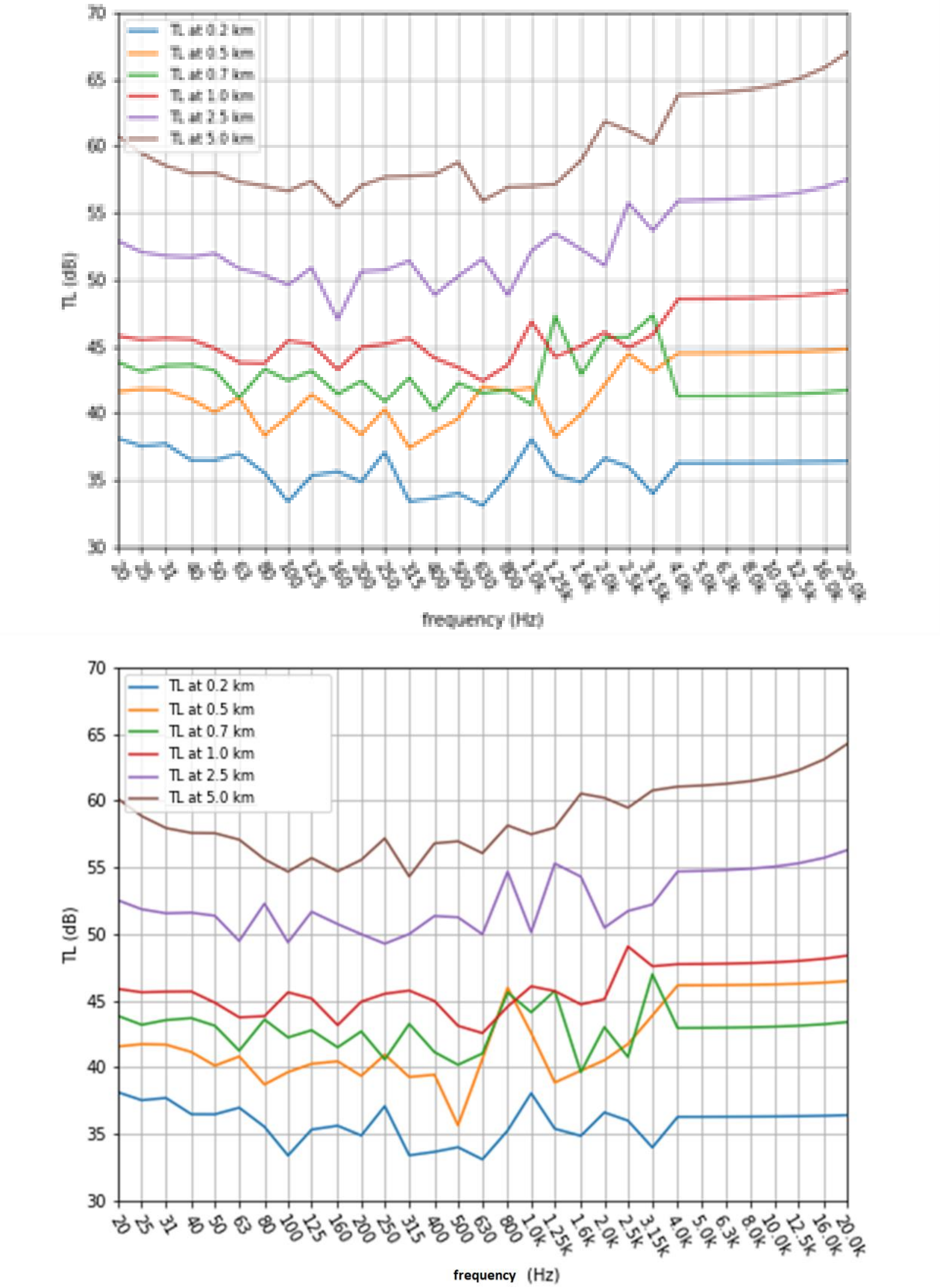

Figure 4.8. *Transmission losses at different distances from the source estimated for the northern (top) and southern (bottom) directions*

4.2.1.2 Impact ranges and areas

4.2.1.2.1 Harbour porpoise

The impact of noise from the operation of a single WTG is presented in the following table [Table 4.5] and figures [Figure 4.9, Figure 4.10]. In the case of the porpoise, all ranges were at a comparably low level of 0.1 km. This range is also the minimum range of impact generated by the model.

Table 4.5. The ranges and areas of impact on the harbour porpoise during the operation of a single WTG

Effect	Unit	Impact range [km]			Impact area [km^2]
		R_{min}	R_{mean}	R_{max}	
Behavioural response	unweighted SPL	0.1	0.1	0.1	0.03
TTS (cumulative for 24 h)	HF-weighted SEL	0.1	0.1	0.1	0.03
PTS (cumulative for 24 h)	HF-weighted SEL	0.1	0.1	0.1	0.03

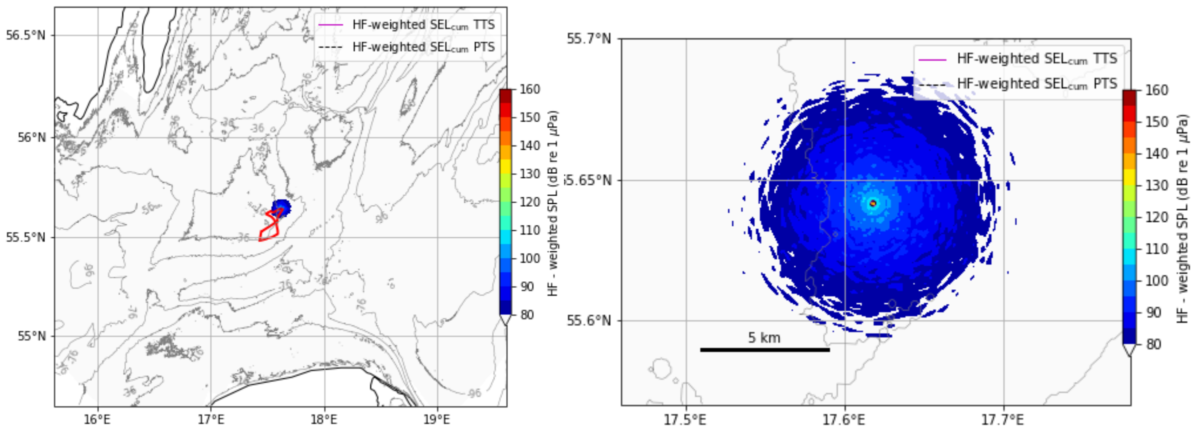

Figure 4.9. The map of HF-weighted SPL for one operating WTG in the Baltica-1 OWF area and the ranges of impact on the harbour porpoise (the map on the left shows a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

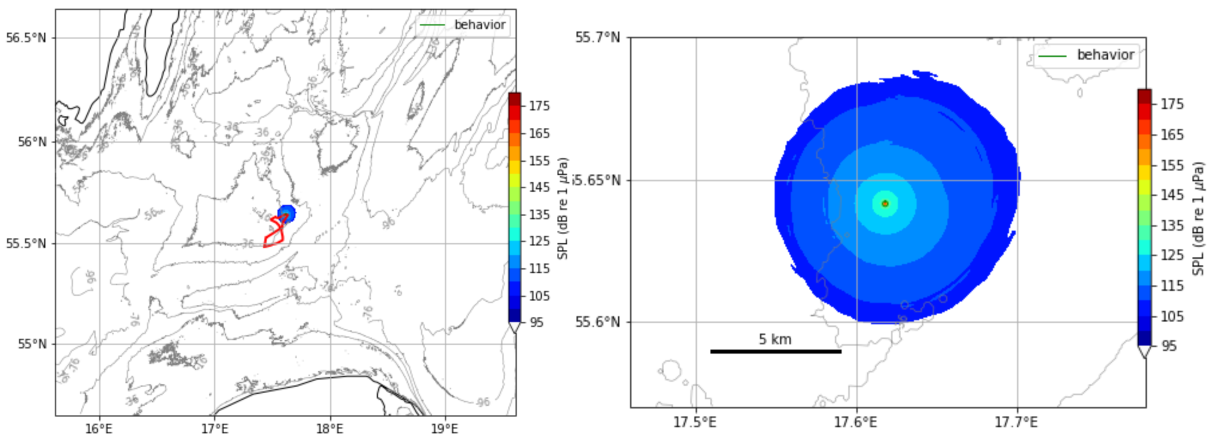

Figure 4.10. The map of unweighted SPL above the acoustic background for one operating WTG in the Baltica-1 OWF area and the range of impact for the harbour porpoise (the map on the left shows a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

4.2.1.2.2 Fish with swim bladders

The impact of noise from the operation of one WTG is presented in the table [Table 4.6] and in the figure [Figure 4.11] below. The estimated range of TTS did not exceed 0.1 km.

Table 4.6. The ranges and areas of impact on fish with swim bladders during the operation of a single WTG

Effect	Unit	Impact range [km]			Impact area [km²]
		R_{min}	R_{mean}	R_{max}	
TTS (cumulative for 12 h)	unweighted SPL	0.1	0.1	0.1	0.03

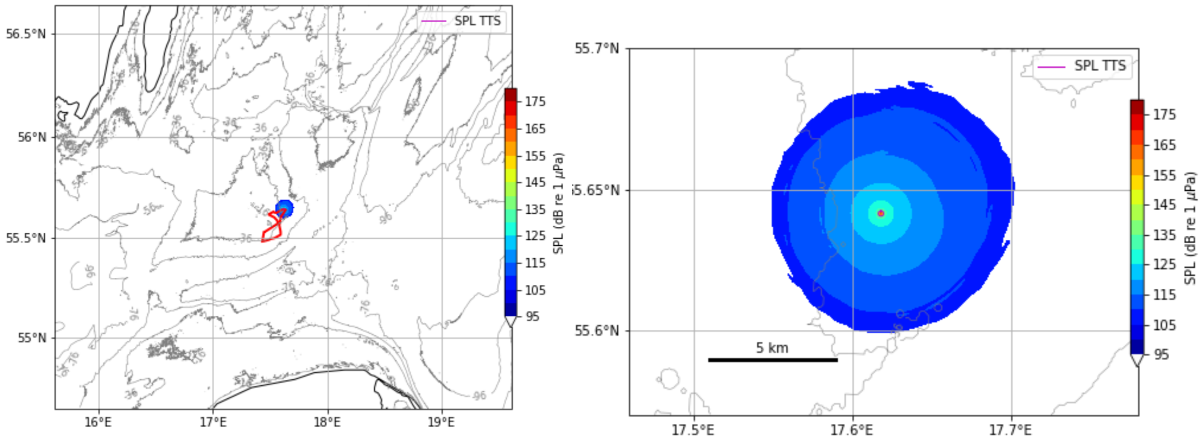

Figure 4.11. The map of unweighted SPL above the acoustic background for one operating WTG in the Baltica-1 OWF area and the ranges of impact on fish with swim bladders the map on the left shows a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

4.2.2 The modelling of propagation of noise from all wind turbine generators

4.2.2.1 Impact ranges and areas

4.2.2.1.1 Harbour porpoise

The results obtained for the harbour porpoise [Table 4.7, Figure 4.12, Figure 4.13] show that the individual areas of impact causing TTS, PTS, and behavioural response remained at the same level as estimated for a single WTG. However, it should be noted that the total area of impact consists of individual areas around each WTG included in the analysis and amounts to 1.9 km^2 for all the analysed effects.

Table 4.7. The areas of impact on the harbour porpoise during the operation of all WTGs

Effect	Unit	Impact area [km²]
Behavioural response	unweighted SPL	1.9
TTS (cumulative for 24 h)	HF-weighted SEL	1.9
PTS (cumulative for 24 h)	HF-weighted SEL	1.9

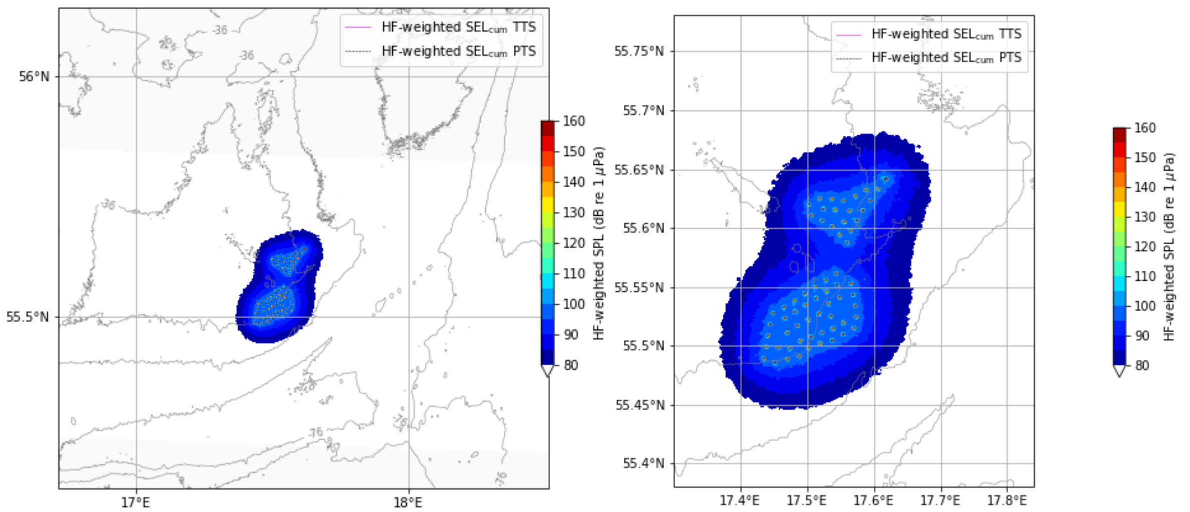

Figure 4.12. The map of HF-weighted SPL for all WTGs operating in the Baltica-1 OWF area and the range of impact on the harbour porpoise (the map on the left shows a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

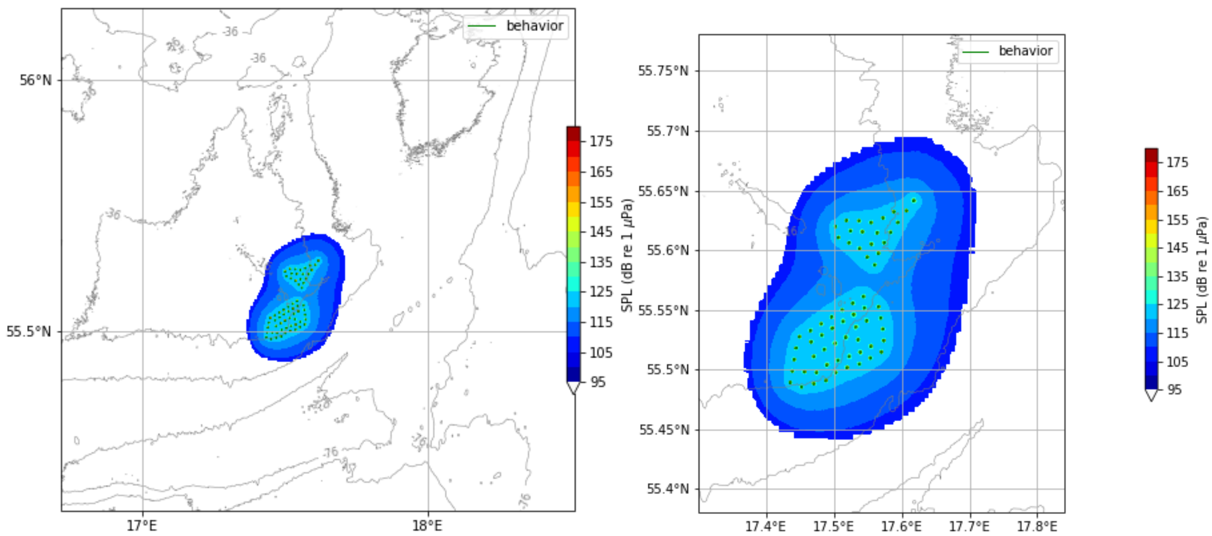

Figure 4.13. The map of unweighted SPL above the acoustic background for all WTGs operating in the Baltica-1 OWF area and the range of impact on the harbour porpoise (the map on the left shows the projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

4.2.2.1.2 Fish with swim bladders

The results of the cumulative model for the stage of operation of all WTGs are presented in the table [Table 4.8] and in the figure [Figure 4.14] below. Similarly to the case of the harbour porpoise, the single TTS impact area did not increase compared to the analyses conducted for a single WTG, and the total impact area for the entire farm was 1.9 km^2.

Table 4.8. The areas of impact on fish with swim bladders during operation of all WTGs

Effect	Unit	Impact area [km^2]
TTS (cumulative for 12 h)	unweighted SPL	1.9

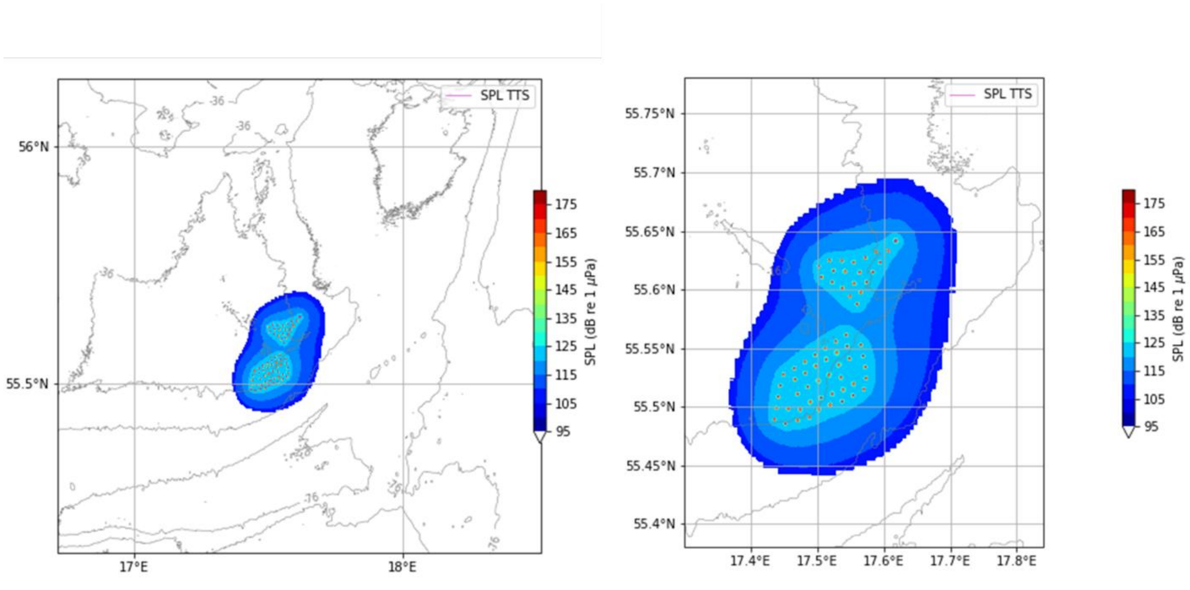

Figure 4.14. The map of unweighted SPL above the acoustic background for all WTGs operating in the Baltica-1 OWF area and the ranges of impact on fish with swim bladders (the map on the left shows a projection of the modelled area against the background of the Baltic Sea, and the map on the right shows the projection in close-up)

5 THE SUMMARY OF THE RESULTS AND CONCLUSIONS

The effects of noise impact from the operation of a single WTG and all WTGs in the winter season are presented in the table below [Table 5.1], while the results for the summer season are presented in the next table [Table 5.2]. All ranges calculated for individual effects, for both taxa, in both analysed seasons remained at a low level of 0.1 km, while the impact areas were 0.03 km^2 for a single WTG and 1.9 km^2 for all analysed WTGs, respectively.

Table 5.1. A summary of the impact ranges and areas for the harbour porpoise and fish, obtained for the Baltica-1 OWF during the operation of a single WTG and all WTGs in the winter season

Receptor	**Effect**	**SEL threshold [dB re 1 µPa²s].**	**SPL_{peak} threshold [dB re 1 µPa]**	**No mitigating measures applied**		
				The mean distance (SEL; SPL_{peak}) [km]	**The maximum SEL; SPL_{peak} distance [km]**	**Impact area [km^2]**
Harbour porpoise	Behavioural response	-	140	0.1/-	0.1/-	0.03/1.9
	TTS (cumulative for 24 h)	153	-	0.1/-	0.1/-	0.03/1.9
	PTS (cumulative for 24 h)	173	-	0.1/-	0.1/-	0.03/1.9
Fish with swim bladders	TTS (cumulative for 12 h)	-	158	0.1/-	0.1/-	0.03/1.9

Table 5.2. A summary of the impact ranges and areas for the harbour porpoise and fish, obtained for the Baltica-1 OWF during the operation of a single WTG and all WTGs in the summer season

Receptor	**Effect**	**SEL threshold [dB re 1 µPa²s].**	**SPL_{peak} threshold [dB re 1 µPa]**	**No mitigating measures applied**		
				The mean distance (SEL; SPL_{peak}) [km]	**The maximum SEL; SPL_{peak} distance [km]**	**Impact area [km^2]**
Harbour porpoise	Behavioural response	-	140	0.1/-	0.1/-	0.03/1.9
	TTS (cumulative for 24 h)	153	-	0.1/-	0.1/-	0.03/1.9
	PTS (cumulative for 24 h)	173	-	0.1/-	0.1/-	0.03/1.9
Fish with swim bladders	TTS (cumulative for 12 h)	-	158	0.1/-	0.1/-	0.03/1.9

The results of the modelling of noise from the wind farm operation indicate a small impact on porpoises, both in the case of the operation of one WTG and all WTGs simultaneously. Concerning a single WTG, the obtained impact ranges have negligible values. In the case of simultaneous operation of all WTGs, the obtained impact area of up to 1.9 km^2 is the sum of individual, smaller areas. This means that there is a large area in the entire wind farm where the noise level is below the analysed impact thresholds. The obtained results indicate that the area around the WTGs, in which changes in porpoise behaviour may occur, will not extend beyond a radius of 100 m. However, it should be remembered that knowledge about the impact of noise from operating wind farms on marine mammals is still limited. For this reason, the results obtained in this area should be treated with caution.

In relation to fish, the estimated sound source level is significantly below the threshold value determined for reversible hearing loss, and therefore, including it in the analysis is unjustified. Therefore, it is assumed that the noise generated during operation will not lead to reversible hearing loss in fish with swim bladders and this effect was excluded from the analyses. At the same time, the range of the TTS impact is close to the sound source, which means that TTS can only occur in the immediate vicinity of the sound source. The situation is similar in the case of the harbour porpoise, for which the area of impact of individual effects is 1.9 km^2, which is the sum of the impact areas around individual WTGs.

The similarity of the results obtained for the harbour porpoise and fish, despite different threshold values or different seasons, can be attributed to the assumed model resolution. The range of 0.1 km is also the minimum range of impact generated by the model. Hence, the results are identical for all the effects considered. The given areas of impact depend on the number of WTGs, which was assumed in this analysis for the RAV option, i.e. for 64 WTGs. Slight changes in the number of WTGs, such as those considered in the variant, will have a linear effect on the areas of impact if the distances between WTGs are similar.

6 References

Bellmann, M.A., Müller, T., Scheiblich, K. & Betke, K. (2023). Erfahrungsbericht Betriebsschall – Projektübergreifende Auswertung und Bewertung von Unterwasserschallmessungen aus der Betriebsphase von Offshore-Windparks (Field report on operational noise – Cross-project evaluation and assessment of underwater noise measurements from the operational phase of offshore wind farms), itap Bericht Nr. 3926, gefördert durch das Bundesamt für Seeschifffahrt und Hydrographie, Fördernummer 10054419.

Betke, K., Bellmann, M.A. (2023). Operational Underwater Noise from Offshore Wind Farms. [in Popper, A.N., Sisneros, J., Hawkins, A., Thomsen, F. (red.), The Effects of Noise on Aquatic Life. Springer, Cham; https://doi.org/10.1007/978-3-031-10417-6_15-1.

Collins, M. (1993). A split-step Padé solution for the parabolic equation method. The Journal of the Acoustical Society of America, 93: 1736–1742.

Finneran, J. (2015). Noise-induced hearing loss in marine mammals: A review of temporary threshold shift studies from 1996 to 2015. The Journal of the Acoustical Society of America 138 (3): 1702–1726; doi:10.1121/1.4927418.

Francois, R.E., Garrison, G.R. (1982a). Sound absorption based on ocean measurements. Part I: Pure water and magnesium sulphate contributions. Journal of the Acoustical Society of America, 72: 896–907.

Francois, R.E., Garrison, G.R. (1982b). Sound absorption based on ocean measurements. Part II: Boric acid contribution and equation for total absorption. Journal of the Acoustical Society of America, 72: 1879–1890.

Holme, C., Simurda, M., Gerlach, S., and Bellmann, M. (2023). Relationship between underwater noise and operating offshore wind turbine. The effects of noise on aquatic life.

Kastelein, R.B. (2002). Audiogram of a harbor porpoise (Phocoena phocoena) measured with narrow-band frequency modulated signals. J. Acoust. Soc. Am., 112: 334–344.

MIKE DHI. (2023). UAS in MIKE, Underwater Acoustic Simulation Module, Scientific Documentation.

NMFS. (2018). Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2.0): Underwater Thresholds for Onset of Permanent and Temporary Threshold Shifts. Technical Memorandum (No. NMFS-OPR-59): 167.

NMFS. (2023). National Marine Fisheries Service: Summary of Endangered Species Act acoustic thresholds (marine mammals, fishes and sea turtles).

Popper, A., Hawkins, A., Fay, R., Mann, D., Bartol, S., Carlson, T., Tavolga, W. (2014). Sound Exposure Guidelines for Fishes and Sea Turtles: A Technical Report prepared by ANSI-Accredited Standards Committee S3/SC1 and registered with ANSI. ASA S3/SC1.4 TR-2014.

Popper, A.N., and Hawkins, A.D. (2018). The importance of particle motion to fishes and invertebrates. The Journal of the Acoustical Society of America, 143: 470–488.

Popper, A.N., and Hawkins, A.D. (2019). An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. Journal of Fish Biology, 94, (5): 692–713.

Popper, A.N., Hice-Dunton, L., Jenkins, E., Higgs, D.M., Krebs, J., Mooney, A., Rice, A., Roberts, L., Thomsen, F., Vigness-Raposa, K., Zeddies, D., Williams, K.A. (2022). Offshore wind energy development: Research priorities for sound and vibration effects on fishes and aquatic invertebrates. J. Acoust. Soc. Am. 151: 205–215.

Sigray, R., and Andersson, M.H. (2011). Particle motion measured at an operational wind turbine in relation to hearing sensitivity in fish. Journal of the Acoustical Society of America, 130: 200–207.

Southall, B., Bowles, A., Ellison, W., Finneran, J., Gentry, R., Greene, J. C., Tyack, P. (2007). Marine mammal noise exposure criteria: initial scientific recommendations. Aquatic Mammals, 33: 411–521.

Stöber, U., Thomsen, F. (2021). How could operational underwater sound from future offshore wind turbines impact marine life? The Journal of the Acoustical Society of America, 149: 1791–1795.

Thomsen, F., Lüdemann, K., Kafemann, R., Piper, W., (2006). Effects of offshore wind farm noise on marine mammals and fish, biola. Hamburg, Germany on behalf of COWRIE Ltd. 2006.

Thomsen, F., Mendes, S., Bertucci, F., Breitzke, M., Ciappi, E., Cresci, A., dos Santos, M.E. (2021). Addressing underwater noise in Europe: Current state of knowledge and future priorities. Future Science Brief 7 of the European Marine Board (ed. by P. Kellett, R. van den Brand, B. Alexander, A. Muniz Piniella, A. Rodriguez Perez, J. van Elslander & J. Heymans). European Marine Board, Ostend, Belgium.

Tougaard, J., Hermannsen, L., & Madsen, P. (2020). How loud is the underwater noise from operational offshore wind turbines? J. Acoust. Soc. Am., 148: 2885–2893.

von Pein, J., Lippert, T., Lippert, S., & von Estorff, O. (2023). Frequency dependent scaling laws for offshore pile driving noise. Presentation at the Underwater Acoustics Conference and Exhibition in Kalamata, Greece.