Guidelines for underwater noise, Prognosis for EIA and SEA assessments, Energistyrelsen maj 2022

1 Introduction

On May 2022, the Danish Energy Agency published "Guidelines for underwater noise – installation of impact or vibratory driven piles" [Energistyrelsen, 2022], specifying requirements for documentation of underwater noise emission from offshore wind farm construction, as part of the application for construction permit as well as for the construction period itself.

This document has the purpose of providing corresponding guidelines tailored to development stages prior to the construction permit application; including, but not limited to Environmental Impact Assessments (EIA) and Strategical Environmental impact Assessment (SEA). For such project development stages, the developer must prAepare an underwater noise prognosis following the procedures and requirements outlined in this document, as part of the assessment to be submitted to the relevant authorities.

2 Contents

The present guidelines cover impact as well as vibratory pile driving. Other installation techniques, operational wind turbine noise, and vessel noise are beyond the scope of the guidelines. The guidelines cover installation of both single-type foundations such as monopiles, as well as multi-pile foundations such as jackets and tripods.

The guidelines contain acoustic criteria corresponding to Permanent Threshold Shift (PTS) and Temporary Threshold Shift (TTS) for species relevant to Danish waters. These criteria are stated as cumulative sound exposure level (abbreviated as SEL_{cum}), weighted by appropriate auditory frequency weighting functions.

Also, threshold values for the evaluation of behavioural reactions to underwater noise in harbour porpoises are presented. These are stated as root-mean-square sound pressure levels over 125 ms ($L_{rms,125ms,VHF}$).

The prognosis must be submitted as part of the impact assessments.

3 Prognosis requirements

The purpose of the prognosis is to provide the basis for an assessment of the impact of underwater noise on marine mammals, applying best-available knowledge in combination with project specific parameters. If necessary to comply with the impact thresholds, the prognosis must include appropriate noise mitigation measures.

The main components of the underwater noise prognosis are:

A. Detailed source model, based on best-available knowledge, empirical data and/or appropriate models.
B. A site specific underwater sound propagation loss model, based on best-available knowledge, environmental data, either through a semi-empirical approach or through appropriate sound propagation models.
C. Compliance with species specific impact thresholds according to auditory groups.

4 Prognosis procedure

In the following, a step-by-step procedure for carrying out the prognosis is provided, followed by individual sections specifying the detailed requirements for each step.

The procedure for the prognosis is as follows:

1) (Developer) chooses an appropriate number of prognosis locations, in line with requirements in section 4.1.
2) (Developer) designs a detailed source model to be used as input for the prognosis. The source model must follow requirements in section 4.2.
3) (Developer) uses source model "2)" in a site specific underwater sound propagation model in line with requirements in section 4.3.1 for a semi-empirical model approach, or in section 4.3.2 for a numerical model approach.
4) The acoustic criteria for compliance must be calculated using the results from the sound propagation model "3)", as detailed in section 4.4, and Distance-To-Threshold (DTT), as defined in [Energistyrelsen, 2022] for all relevant species is calculated and documented.

4.1 Prognosis extent

The following requirements must be fulfilled and documented through the prognosis:

1. A suitable number of locations within the project area must be selected for the prognosis including:
   1.1. Positions within the site likely to have the lowest sound propagation loss.
   1.2. Positions in close proximity to protected areas for marine species, such as relevant Natura 2000 appointed to protect marine mammals, to determine the extent of noise overlapping the area.
   1.3. For large scale projects, such as offshore wind farms, at least 4 locations must be included.
   1.4. For small scale projects, such as harbour expansion, at least 2 locations must be included.
2. If different pile types, and/or pile installation methods, are used, an evaluation of each combination must be conducted, identifying the worst-case combination, from an

underwater noise emission perspective. Argumentation should consider frequency content, source level, installation procedure and installation time. The identified worst-case combination must be used for the prognosis. Evaluation must consider limitations in available noise mitigation measures for each pile type.

3. Documentation of chosen source positions must include georeferenced maps, as well as coordinates for each position in an appropriate Coordinate Reference System (CRS) such as EPSG: 4326 or EPSG: 25832.

4.2 Detailed source model

The following requirements must be fulfilled and documented:

4. Source level and spectrum for the proposed pile installation.
   - 4.1. Source Level for a transient source (impact piling) is defined as $L_{S,E}$ $[dB\ re\ 1\ \mu Pa^2 m^2 s]$, as defined in ISO 18405 [DS/ISO 18405, 2017]. Abbreviation is SEL
   - 4.2. Source Level for a continuous source (vibratory piling) is defined as L_S $[dB\ re\ 1\ \mu Pa^2 m^2]$, as defined in ISO 18405 [DS/ISO 18405, 2017]. Abbreviation is SPL
   - 4.3. Source Level must be specified for the source without any Noise Abatement Systems (NAS) active.
   - 4.4. Source Level is presented as both broadband level and in 1/3 octave bands, with and without frequency weighting of each relevant marine mammal species, as per hearing group specifications in [NOAA, April 2018], [Southall, et al., 2019].
     - 4.4.1. Frequency range for Source Level representation must cover at least 12.5 Hz – 25 kHz, and should ideally cover 12.5 Hz – 128 kHz. If no data is available for the 25 kHz – 128 kHz frequency range, an extrapolation of the trend from 1 kHz – 25 kHz may be assumed.
     - 4.4.2. Reported source level must represent the maximum utilized hammer energy (impact piling) or driving force (vibratory piling).
   - 4.5. A discussion of the source level and frequency spectrum along with assumptions and uncertainties must be provided, based on best-available knowledge, and should, to the extent possible, consider relevant parameters, such as bathymetry, sediment composition, pile penetration depth.
   - 4.6. The source model is allowed to include an active NAS.
     - 4.6.1. If one such is included, the assumed effectiveness (insertion loss, as defined in [Energistyrelsen, 2022]) must be specified in 1/3 octave bands without frequency weighting. The broadband effectiveness must be reported in broadband values for all relevant auditory group frequency weightings. Assumed effectiveness must be justified within the documentation.
5. The pile installation procedure used for cumulative impact thresholds must be specified.
   - 5.1. For impact piling, this includes hammer energy, e.g. as presented in the simplified hammer protocol example of Table 4.1. This can be thought of as a proposed driving “history” and may be provided both as tables or curves including planned non-driving intervals if any. For multiple-pile foundations, the protocol must include all piles installed within a 24 hour window.
   - 5.2. For vibratory driving, this is driving force. A time/depth-varying force amplitude may be accounted for, as in the impact piling example.
   - 5.3. The assumed relationship between applied hammer energy/driving force, and source level must be reported.

Table 4.1. Example of coarse hammer protocol for impact driving without planned periods of inactivity. The sequence is chronological, from top to bottom. This is an example only and shall not be used for prognosis purposes. Note that non-constant time intervals, or ramming frequency, between strikes may also occur.

Hammer energy [kJ]	Blow count	Hammer energy relative to max energy, S_i	Ramming frequency (blows/sec)
600	400	15%	0.5
800	1400	20%	0.5
1600	1400	40%	0.5
2400	1400	60%	0.5
3200	1400	80%	0.5
4000	1200	100%	1.0
Total:	7200		

4.3 Site specific propagation model

The prognosis must be based on a site specific sound propagation model to determine sound emission from the pile installation procedure. The sound propagation model can be based on either:

- A semi-empirical approach, where previous measurements form the base of the assumed sound propagation loss, or
- A numerical model approach, where sound propagation models (e.g. Finite element, Parabolic Equation, Ray/Beam tracing, Normal modes,…) are used.

Separate requirements for the two approaches apply as follows:

4.3.1 Semi-Empirical model

In order for a semi-empirical model approach to be used, the following conditions must be complied with:

6. The oceanographic conditions during the measurements, on which the semi-empirical prognosis will be based, must be comparable to those for the area to be investigated. That includes at minimum comparable:
   6.1. Bathymetry
   6.2. Sediment soil acoustic properties of uppermost layers
   6.3. Water temperature and salinity profiles
7. An assessment of the local influence of seasonality must be added, relating the conditions during measurement to those of the intended installation period. E.g. the influence of measurement results obtained during summer months, relative to an intended installation in winter months for the project area. This assessment must be supported by best-available knowledge on local salinity and temperature changes over the year.

7.1. If measurements are performed during significantly different sound speed conditions, than the assessment finds to be likely conditions during installation, the measurements are not considered valid as a basis for the prognosis.

8. The characteristics of the sound source used to obtain measurements must comply with the following:
   8.1. The frequency content of the source must cover the frequency range of the source model, fulfilling all requirements in requirement 4, section 4.2.
   8.2. The frequency content must be measurable above ambient noise level within each frequency band in the entire frequency range.
   8.3. The spectral shape of the emitted noise must resemble that of the intended pile installation method (impact or vibratory).
9. A sound propagation curve fit for the measurements in the form $\Delta L = X \cdot \log_{10}(r) + A \cdot r\ dB$, where X [-] is a positive and A [m^{-1}] a positive or negative constant, and r the distance [m].
   9.1. The transect bathymetry for which the curve fit is supplied, must be illustrated graphically.
10. The curve fit must be supplied as a broadband curve fit, provided unweighted and for each of the frequency weightings as per requirement 4.4, section 4.2.
    10.1. The curve fit can optionally also be provided as individual unweighted curve fits for each 1/3 octave band.
11. The curve fit documentation must include all measurement data points supporting the curve fit. The metric used must be SEL_{SS} for impact piling and SPL for vibratory driving, as defined in ISO 18406 [DS/ISO 18406, 2017].
12. The uncertainty of the prognosis must be discussed.

4.3.2 Numerical model

A numerical model approach can be used if the following conditions are met:

13. An appropriate numerical model, or a combination of multiple models, is used. Argumentation for choice of model must be reported, with reference to model benefits and limitations relative to the site specific environmental conditions.
14. A non-exclusive list of exemplary model types is Finite Element (FE), Parabolic Equation (PE), Normal Modes (NM), Wavenumber Integration (WI), Ray/Beam Tracing (RT/BT).
15. The used software must be stated, including program version and date.
16. A site specific acoustic environmental model must be used and reported using a combination of tables and maps, including site specific knowledge, to the extent available, detailing at least:
    16.1. Bathymetry
    16.2. Sediment soil acoustic properties of uppermost layers, including:
        16.2.1. Absorption
        16.2.2. Density
        16.2.3. Sound Speed
17. It must be specified what assumptions are used in the model regarding:
    17.1. Air-water interface conditions: Calm water or surface roughness
    17.2. Sea water volume attenuation, including assumed temperature and salinity
    17.3. Water temperature and salinity profiles
    17.4. Sound speed profile(s)
18. It is recommended that the model accounts for:
    18.1. Shear and compressional waves in the seabed.

19. A sound propagation curve fit resulting from the model must be documented.
    19.1. The curve fit must be based on a Max-Over-Depth (MOD) approach, as defined in [Energistyrelsen, 2022], where sound propagation model output at each range step is the maximum level at that range at any water depth
    19.2. The curve fit of at least the worst-case transect must be supplied
    19.3. The curve fit must be documented both unweighted and for each of marine mammal auditory group frequency weightings.
    19.4. Curve fit documentation is recommended to include a distance vs. level plot with all data points as well as the used curve fit.
    19.5. The curve fit must be documented in either:
        19.5.1. The form $\Delta L = X \cdot \log_{10}(r) + A \cdot r\ dB$, where X [-] is a positive and A [m^{-1}] a positive or negative constant, and r the distance [m], or
        19.5.2. using a more accurate curve fit model.
20. The metric used must be SEL_{SS} for impact piling and SPL for vibratory driving, as defined in ISO 18406 [DS/ISO 18406, 2017].
21. Number of transects modelled must be at least 18 for projects in open water. For projects located within 10 km of land in any direction, the number of transects must be higher.
22. The horizontal resolution of the model should reflect the site specific conditions and choice of sound propagation model. Recommended spacing is 25 m or shorter.
23. The vertical resolution of the model should be 1 m or finer. Justification for choice must be provided.
24. Sound propagation model must cover at least 10 km radius, however may be reduced if land is reached in all directions before 10 km distance.
25. The uncertainty of the prognosis must be discussed, based on environmental parameters and sound propagation model choice.

4.4 Acoustic criteria for compliance

The prognosis must include calculation of underwater noise impact on all relevant marine mammal species. In this regard, best-available knowledge on species-specific hearing thresholds and impact levels must be used. At the time of writing, this is considered to be represented by auditory group thresholds outlined in [Tougaard, 2021] and [Tougaard, 2021] as summarized in [Energistyrelsen, 2022]. These thresholds are shown in Table 4.2 for impulsive sounds (impact piling) and in Table 4.3 for other sounds (vibratory installation).

Note that behaviour disturbance thresholds are only available for harbour porpoise at the time of writing. If supported by best-available knowledge at the time of the prognosis, revised and/or threshold levels for other species should be used.

Table 4.2. Species of marine mammals commonly occurring in Danish waters with corresponding auditory groups and respective acoustic thresholds stated as SEL_{cum} in dB re 1 µPa^{2}s and SPL in dB re 1 µPa. Only thresholds for Impulsive sounds (impact pile driving) are shown. Source: [Energistyrelsen, 2022]

Impulsive sounds (impact piling)					
Species (English)	Species (Danish)	Weighting (xx)	Threshold type		
			PTS	TTS	Behavioural Disturbance

			SELcum $L_{E,p,xx,24h}$	SELcum $L_{E,p,xx,24h}$	SPL $L_{p,rms,125ms}$
Harbour porpoise	Marsvin	VHF	155	140	103
White-beaked dolphin	Hvidnæse	HF	185	170	-
Pilot whale	Grindehval	HF	185	170	-
Minke whale	Vågehval	LF	183	168	-
Harbour seal	Spættet sæl	PCW	185	170	-
Grey seal	Gråsæl	PCW	185	170	-

*Table 4.3. Species of marine mammals commonly occurring in Danish waters with corresponding auditory groups and respective acoustic thresholds stated as SEL_{cum} in dB re 1 µPa²s and SPL in dB re 1 µPa. Only thresholds for other sound types, such as vibratory installation methods, are shown. *) Threshold for Behavioural Disturbance is a coarse estimate, to be used only until better data become available. Source: [Energistyrelsen, 2022]*

Other sounds (vibratory installation)					
Species (English)	Species (Danish)	Weighting (xx)	Threshold type		
			PTS	TTS	Behavioural Disturbance
			SELcum $L_{E,p,xx,24h}$	SELcum $L_{E,p,xx,24h}$	SPL $L_{p,rms,125ms}$
Harbour porpoise	Marsvin	VHF	173	153	*)103
White-beaked dolphin	Hvidnæse	HF	198	178	-
Pilot whale	Grindehval	HF	198	178	-
Minke whale	Vågehval	LF	199	179	-
Harbour seal	Spættet sæl	PCW	201	181	-
Grey seal	Gråsæl	PCW	201	181	-

The following process for achieving compliance with the acoustic criteria must be followed.

26. The auditory group cumulative sound exposure level, $L_{E,cum,xx}$ is calculated through Equation 1 (impact piling) or Equation 2 (vibratory installation) for each of the relevant marine mammal auditory groups (xx).
    26.1. The calculation must at least be carried out for the transect with the lowest sound transmission loss for each respective marine mammal auditory group. It is encouraged to carry out calculations for additional transects.
    26.2. A fleeing speed v_f of 1.5 m/s should be used. Any use of an alternative fleeing speed can be used if supported by best-available knowledge, in which case this must be documented and justified.
    26.3. Marine mammal starting distance, r_0 is set to 200 m, see [Energistyrelsen, 2022].
    26.4. The calculation is carried out for one auditory group's specific frequency weighting at a time. This implies the use of auditory group specific transmission loss coefficients and source level.

Equation 1: Impact piling cumulative impact leve.l Source: [Energistyrelsen, 2022]

$$L_{E,cum,xx} = 10 \cdot \log_{10} \sum_{i=1}^{N} \frac{S_i}{100\%} \cdot 10^{\frac{L_{S,E,xx} - X_{xx} \cdot \log_{10}(r_0 + v_f \cdot t_i) - A_{xx} \cdot (r_0 + v_f \cdot t_i)}{10}} \, dB$$

Where

- $L_{E,cum,xx}$ [dB] is the auditory group frequency weighted cumulative sound exposure level of a foundation installation, including all piles installed within a 24 time frame,
- xx is the auditory group frequency weighting, LF, HF, VHF or PCW.
- i [-] is the current pile strike number, from 1 to N,
- N [-] is the total number of pile strikes for the pile installation,
- S_i [%] is the percentage of full hammer force applied for pile strike "i",
- $L_{S,E,xx}$ [dB re 1 µPa^{2}m^{2}s] is the auditory group frequency weighted source level at 100% hammer energy, as defined in ISO 18405,
- X_{xx} [-] is the auditory group frequency weighted curve fit coefficient obtained through sound propagation modelling.
- A_{xx} [m^{-1}] is the auditory group frequency weighted curve fit coefficient obtained through sound propagation modelling.
- r_0 [m] is the start distance of the marine mammal at the first pile strike,
- v_f [m/s] is the fleeing speed of the marine mammal,
- t_i [s] is the total time elapsed at pile strike "i" since the first pile strike, which occurs at $t_1 = 0$.

Equation 2: Vibratory piling cumulative impact level Source: [Energistyrelsen, 2022]

$$L_{E,cum,xx} = 10 \cdot \log_{10} \sum_{s=1}^{T} \frac{S_s}{100\%} \cdot 10^{\frac{L_{S,xx} - X_{xx} \cdot \log_{10}(r_0 + v_f \cdot t_s) - A_{xx} \cdot (r_0 + v_f \cdot t_s)}{10}} \, dB$$

Where

- $L_{E,cum,xx}$ [dB] is the auditory group frequency weighted cumulative sound exposure level of a foundation installation, including all piles installed within a 24 time frame,
- s [second] is the time between onset of piling and current time elapsed, from 1 to T,
- T [second] is the total time of pile installation,
- S_i [%] is the percentage of full vibratory driving force applied at time "s",
- $L_{S,xx}$ dB re 1 µPa^{2}m^2] is the auditory group frequency weighted source level at full driving force, as defined in ISO 18405,
- X_{xx} [-] is the auditory group frequency weighted curve fit coefficient obtained through sound propagation modelling.
- A_{xx} [m^{-1}] is the auditory group frequency weighted curve fit coefficient obtained through sound propagation modelling.
- r_0 [m] is the start distance of the marine mammal at the first pile strike,
- v_f [m/s] is the fleeing speed of the marine mammal,
- t_s [s] is the total time elapsed at time "s" since the onset of piling, which occurs at $t_1 = 0$.

27. For each auditory group frequency weighting "xx", the difference, $\Delta L_{xx} = L_{E,cum,xx} - L_{E,p,xx,24h}$ is calculated, where $L_{E,p,xx,24h}$ is the PTS threshold value provided in Table 4.2 for impulsive sounds (impact piling) or Table 4.3 for other sounds (vibratory installation). The calculated ΔL_{xx} is documented for all relevant marine mammal species.
    27.1. If ΔL_{xx} is positive, the value of ΔL_{xx} represents the auditory group minimum mitigation requirement for compliance with the acoustic criteria.

27.2. A mitigated source level $L_{S,E,mit,xx} = L_{S,E,xx} - \Delta L_{xx}$ $[dB]$ for impact piling, or $L_{S,mit,xx} = L_{S,xx} - \Delta L_{xx}$ $[dB]$ for vibratory pile driving is calculated.

27.3. Using an iterative process for each frequency weighting, Equation 1 (impact piling) or Equation 2 (vibratory installation) is then used to calculate "r_0" as the safe starting distance for the marine mammal for the PTS and TTS thresholds. Here, the source level $L_{S,E,xx}$ or $L_{S,xx}$ is replaced by the corresponding mitigated version from requirement 27.2, and the cumulative noise dose $L_{E,cum,xx}$ is replaced by the respective threshold value $L_{E,p,xx,24h}$ for PTS and TTS, available from Table 4.2 for impulsive sounds (impact piling) or Table 4.3 for other sounds (vibratory installation).

27.4. For impact piling, behavioural disturbance distance for harbour porpoise must be calculated as the distance, within which the rms sound pressure level, $L_{p,rms,125ms} \leq 103\ dB$, where: $L_{p,rms,125ms} = L_{E,p} + 10\log_{10}(0.125) = L_{E,p} + 9\ dB$, where $L_{E,p}$ is the VHF frequency weighted sound exposure level of a single pile strike at 100% hammer force.

27.4.1. If a behavioural disturbance criteria is available for any other relevant species, the DTT must also be calculated for those.

27.5. For vibratory piling, behavioural reaction distance for harbour porpoise may be calculated as the distance, at which the rms sound pressure level, $L_{p,rms,125ms} \leq 103\ dB$, at maximum driving force.

27.5.1. If behavioural disturbance criteria is available for any other relevant species, the impact range must also be calculated for those.

5 Bibliography

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