JANUAR 2024
LILLEBÆLT VIND A/S

# MILJØKONSEKVENSVURDERING LILLEBÆLT SYD VINDMØLLEPARK

BILAG G2 UNDERVANDSSTØJ – EKSTRA LYDHASTIGHEDSSCENARIE

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| PROJECT NO. | DOCUMENT NO. |
|---|---|
| A234064 | A234064-ATR04-G2 |

| VERSION | DATE OF ISSUE | DESCRIPTION | PREPARED | CHECKED | APPROVED |
|---|---|---|---|---|---|
| 1 | 10.01.2024 | Technical report | RSLN | MNLR | MEAS |

# CONTENTS

# 1 Introduction

This document presents additional underwater noise results in continuation of the initial modelling report A234064-ATR04-G, which is Appendix G1 in the main report. Methods and software applied here remain the same. For detailed model set-up, please refer to the initial report.

Where the initial modelling report focussed on a water sound speed profile corresponding to the months of March-April, the present study investigates profiles along the full year. On that basis, a representative, conservative choice of sound speed profile is selected for the acoustic modelling.

Also, the initial modelling report only related the acoustic findings to the hearing of harbour porpoises, i.e. functional hearing group "VHF" (Very High Frequency) of (Danish Energy Agency 2022). In the present study, also harbour seals and grey seals are considered (hearing group "PCW" in both cases).

It is noted that in terms of acoustic criteria and modelling procedure, the two versions of the Danish Guideline for Underwater Noise (Danish Energy Agency 2022) and (Danish Energy Agency 2023) coincide.

# 2 Hearing properties for seals

The initial modelling report considered only harbour porpoises, applying frequency weighting and criteria according to the VHF functional hearing group (Danish Energy Agency 2023).

In the present study, also harbour seals and grey seals are considered, both characterized by the functional hearing group "PCW" (Phocid Carnivores in Water). It is noted that for this auditory group, the Danish Guideline for underwater noise presently states criteria for PTS/TTS (Permanent and Temporary Threshold Shift, respectively), while none are given for behavioural disturbance.

Figure 1 shows the frequency weighting functions applied in this study. It is seen that for frequencies below approximately 20 kHz the PCW auditory group has much better hearing abilities than VHF. According to the Danish Guideline for underwater noise, the PCW hearing group has indicative hearing range 40 Hz to 50 kHz, while the VHF group has 1 kHz to 150 kHz.

The PTS/TTS thresholds for seals are listed in Table 1 and assume frequency weighting according to the PCW auditory group. Due to the different frequency weighting, these values should not be compared directly to thresholds of e.g. the VHF group.

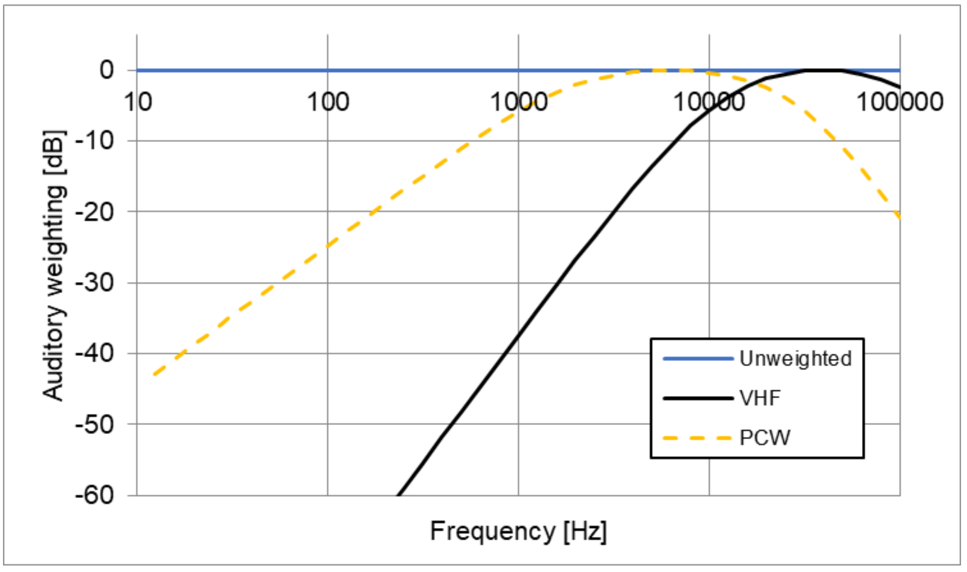


*Figure 1 Auditory frequency weighting functions* (Danish Energy Agency 2023).

*Table 1 Acoustic criteria for seals* (Danish Energy Agency 2023).

| Species and auditory group | Phase / Type of sound | Threshold | |
|---|---|---|---|
| | | PTS<br>SELcum,24h<br>[dB re 1µPa2s] | TTS<br>SELcum,24h<br>[dB re 1µPa2s] |
| Harbour and grey seals (PCW) | Construction: Impulsive | 185 dB | 170 dB |
| | Operation: Non-impulsive | 201 dB | 181 dB |

# 3 Alternative water sound speed profile

## 3.1 Acoustic features related to the sound speed profile

The variation of sound speed *c* [m/s] vs. depth below sea surface *D* [m] is commonly called a sound speed profile.

At the relative shallow water depth such as for the Lillebælt site, the sound speed profile affects the interaction between sound propagation and the seabed in mainly two ways (Farcas et al. 2016):

- The sound speed gradient causes **refraction of the sound wave**, i.e. "bending" of the direction of propagation. Particularly relevant cases as plotted in Figure 2 are:
  - Upward-refracting profiles: Profiles with a general slope having lowest sound speed near the sea surface. The sound propagation will tend to "bend" towards the sea surface. Offshore wind construction typically corresponds to little or no wind, which acoustically leads to no (or small) losses when the sound wave interacts with the sea surface. Hence, this type of profile will cause low propagation losses over distance. Upward-refracting profiles are commonly found during the cold times of the year, when the air is relatively cold and there is little heating of the upper water column by the sun.
  - Downward-refracting profiles: Profiles with a general slope having lowest sound speed near the seabed. This refracts the sound propagation down towards the seabed. The sound wave experiences significant losses when interacting with the seabed. Hence, downward-refracting profiles cause high propagation losses over distance. This type of profiles is often found in warmer times of the year, when the air is relatively warm and the sun heats the upper part of the water column.

  The diagram in Figure 3 shows single acoustic ray paths (may be seen as the direction of propagation of a sound wave) connecting a source and a particular receiver. It is illustrated how the ray is refracted either upwards or downwards depending on the two sound speed profiles.

  More complex profiles arise in case of e.g. stratification. Here, it is reminded that pieces of the profile having gradients will tend towards the above features.

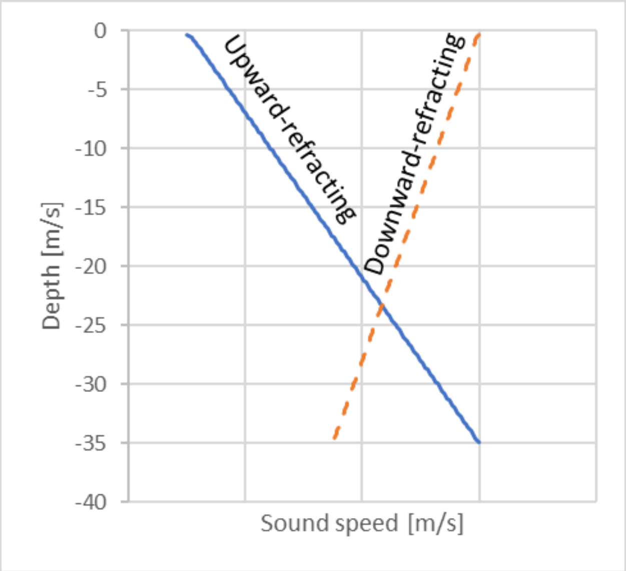


*Figure 2 Generic examples of sound speed profiles.*

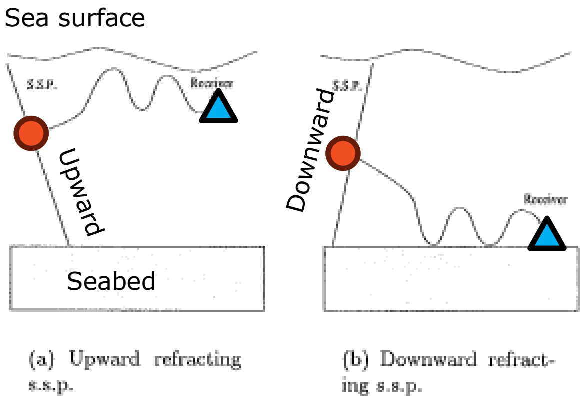


*Figure 3 Generic ray traces diagrams for upward- and downward refracting sound speed profiles (s.s.p.). Reworked from (Lützen 1998). Red dot is the sound source, and blue triangle is a receiver.*

- **Acoustic coupling** with seabed: For seabeds having acoustic properties similar to those of the water, a high degree of transfer of acoustic energy will take place from the water into the seabed. Broadly speaking, this will appear as energy lost to the seabed. Hence, high propagation losses over distance will be observed. Alternatively, seabeds with very contrasting properties will reflect a larger part of the sound back into the water, and hence lead to low propagation losses over distance.

  The governing properties for the coupling is the characteristic acoustic impedance $\rho \cdot c$ (density times sound speed) of water and the top seabed layer, respectively.

Taking a conservative approach for the study, priority is given to a sound speed profile with the following properties:

- Upward-refracting, to cause maximum interaction with the sea surface rather than with the seabed.
- General sound speed values far from the 1630 m/s of the top sand layer of the seabed. This will maximise reflection of the sound back into the water column and minimise energy lost into the seabed.

These features will correspond to conservative, low propagation loss over distance.

## 3.2 Sound speed profile from empirical data

The sound speed is conveniently calculated from measurements of temperature $T$ [$^{\circ}$C] and salinity $S$ [ppt], e.g. following Medwin's formula (Medwin 1975):

$$c = 1449.2 + 4.6T - 0.055T^2 + 0.00029T^3 + (1.34 - 0.010T)(S - 35) + 0.016D$$

Measurements of temperature and salinity were accessed from the ICES oceanographic database (International Council for the Exploration of the Sea (ICES) 2023). For the region between Als and Fyn, approximately 280 profile samples were obtained. These spanned the period April 2007 to December 2022, however with approximately 90% of these being from 2018 or later. Figure 4 shows selected profiles from the overall dataset, by means of example.

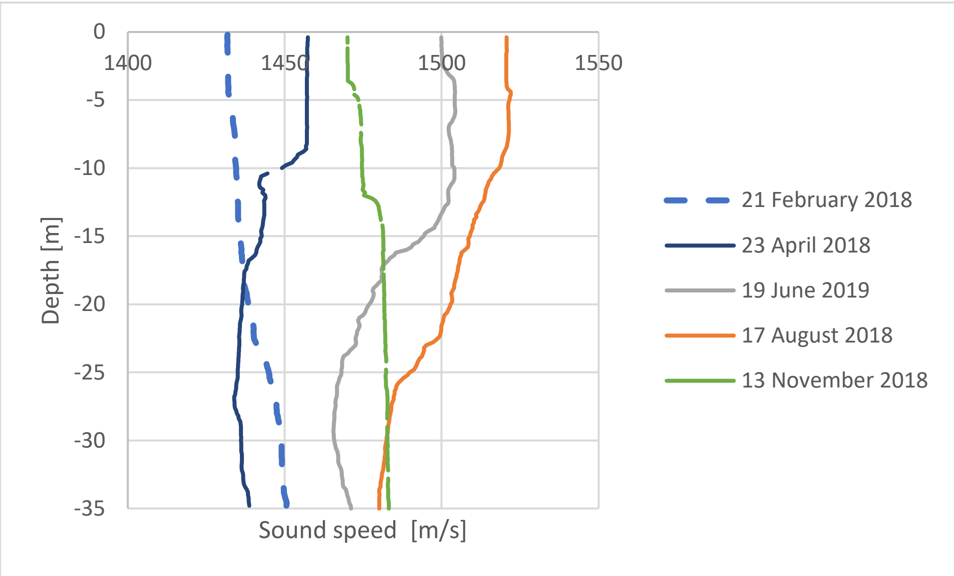


*Figure 4 Examples of sound speed profiles from the Lillebælt area. Dashed blue line "21 February 2018" is selected for the modelling".*

From inspection of the entire large data set, the sound speed profile labelled "21 February 2018" (dashed blue line in Figure 4) was found to meet the criteria by the end of Section 3.1 and serve the purpose of a conservative sound speed profile. It is seen to be generally upward refracting, as well as having generally low sound speed values compared to the other profiles.

# 4 Modelling results for seals and porpoise

In the following, "conservative sound speed profile" refers to the profile labelled "21 February 2018" (dashed blue line in Figure 4) of Section 3.2. Apart from this sound speed profile, model setup and configuration are the same as reported in the initial modelling report A234064-ATR04-G, which is Appendix G1 in the main report. Furthermore, results from the initial study were evaluated with frequency weighting and acoustic criteria for seals, which is the PCW auditory group.

## 4.1 Underwater noise from impact pile driving

The plots in Figure 5 and Figure 6 show graphically the modelling results for porpoises (auditory group VHF) and seals (both harbour and grey seals are auditory group PCW), respectively. The presented scenario includes 15 dB reduction corresponding to noise mitigation of a double Big Bubble Curtain (DBBC).

In the following two tables the results are presented in terms of:

- Table 2: **Cumulative SEL** corresponding to the unmitigated reference scenario of (Danish Energy Agency 2023). Results for the initial study are included as "March/April" profile. It is seen that the noise level increases by approximately 1 dB for the conservative choice sound speed profile.

- Table 3: **Impact ranges** according to Permanent Threshold Shift (PTS), Temporary Threshold Shift (TTS), and Behavioural impact of (Danish Energy Agency 2023). A general increase is seen, which for porpoises is most notable for behavioural impact going from 12.5 km in the initial study to 15 km when implementing the conservative sound speed profile. For seals, the distance-to-threshold is generally smaller than for porpoises.

    - It is noted that for seals, no criterion is given for behavioural impact, see Section 2.

*Table 2 Reference scenario for March/April vs. conservative sound speed profiles, in terms of $SEL_{cum}$ [dB re 1μPa²s] with initial distance 200 m, unmitigated piling.*

| Species and auditory group | $SEL_{cum}$, $L_{E,cum}$ for Reference scenario | |
|---|---|---|
| | March/April profile | Conservative profile |
| Porpoises (VHF) | 164.3 $dB_{VHF}$ | 165.3 $dB_{VHF}$ |
| Harbour and grey seals (PCW) | 192.4 $dB_{PCW}$ | 193.5 $dB_{PCW}$ |

*Table 3 Distance-to-threshold of PTS, TTS, and behavioural impact, assuming mitigated piling (15 dB). March/April sound speed profile and conservative sound speed profile.*

| Species and auditory group | Distance-to-threshold | | | | | |
|---|---|---|---|---|---|---|
| | March/April profile | | | Conservative profile | | |
| | PTS | TTS | Behaviour | PTS | TTS | Behaviour |
| Porpoises (VHF) | 75 m | 740 m | 12.5 km | 95 m | 776 m | 15 km |
| Harbour and grey seals (PCW) | 42 m | 544 m | - | 53 m | 570 m | - |

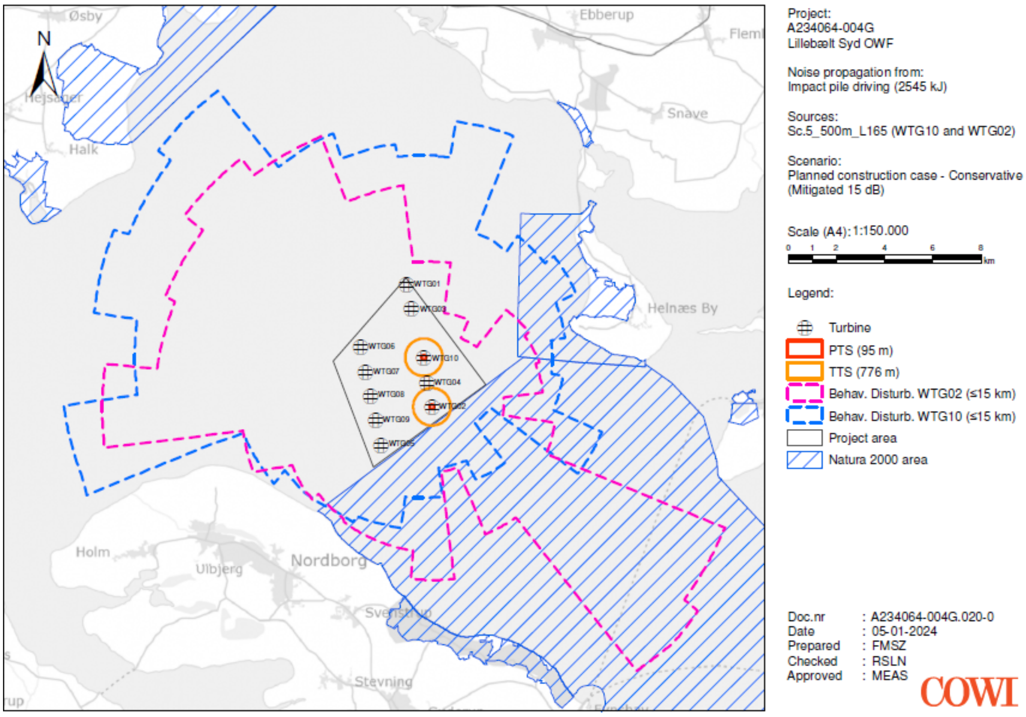


*Figure 5 Resulting impact areas for porpoises (VHF) for the conservative sound speed profile and with noise mitigation (15 dB). Results shown for WTG02 and WTG10.*

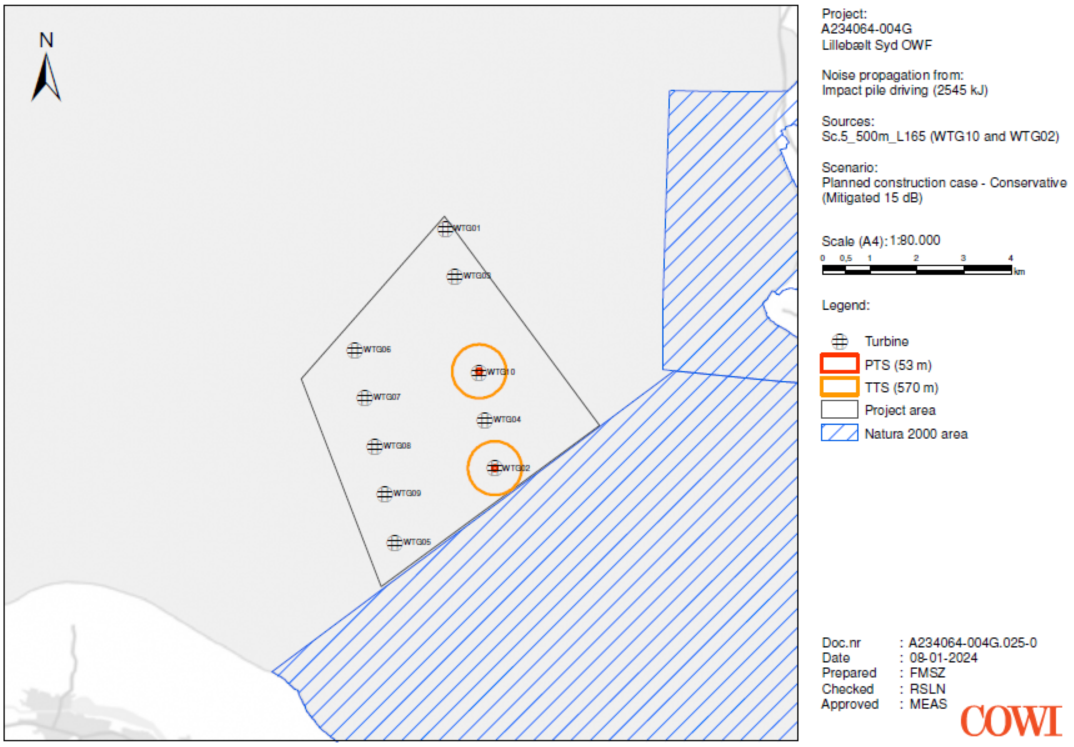


*Figure 6 Resulting impact areas for harbour seals and grey seals (both PCW) for the conservative sound speed profile and with noise mitigation (15 dB). Results shown for WTG02 and WTG10.*

## 4.2 Underwater noise from operational wind turbines

As listed in Section 2, Table 1 the acoustic thresholds of seals (PCW hearing group) for PTS and TTS increase by 16 and 11 dB, respectively, in case of non-impulsive noise compared to impulsive noise. Hence, the seals are much less sensitive to the continuous noise characterising the operational stage than to the construction stage involving impact piling. Similar tendencies are found for other marine mammals (Southall et al. 2019).

For seals, no excess compared to neither PTS nor TTS was found at any range from the noise source. Hence, the noise at all ranges was found to be less than the PTS and TTS criteria. It is noted that no criteria for seals are given for behavioural impact, see Section 2.

For harbour porpoises the assumption was made that the propagation properties are similar for both impact noise and continuous noise. Hence, approximately the same relative increase in distance to threshold is expected when changing from the initial sound speed profile to the conservative one of Section 3.2. On this basis, distance to threshold for PTS/TTS are coarsely assessed as 15 m and

170 m, respectively, for an animal remaining stationary for 24 hours. Similarly, distance to threshold for behavioural impact is 240 m.

On a general note, prediction of operational noise for future sized wind turbines is difficult. Semi-empirical work based on smaller wind turbines exists, such as e.g. (Tougaard et al. 2020) which was used for the present study. However, recent measurement experience for large turbines (foundation diameters 6 and 8 m) observed that predictions using the above semi-empirical framework tended to predict far higher noise levels than those actually measured (Holme et al. 2022). On this basis, the predictions in this section are considered conservative.

# 5 Conclusion

This study adds to the initial modelling report A234064-ATR04-G, which is Appendix G1 in the main report.

Based on a large quantity of historical sound speed profiles, a conservative approach was applied to select a representative sound speed profile. The model was re-run with this profile, and results were evaluated both according to harbour porpoises (VHF auditory group), and harbour and grey seas (both PCW group).

In the unmitigated reference scenario specified by the Danish Guideline for underwater noise, the $SEL_{cum}$ noise level increased by approximately 1 dB compared to the initial study. For both harbour porpoises and seals, the impact ranges (distance-to-threshold) increased. For harbour porpoises and pile driving noise, the main increase was observed for behavioural impact, which increased from 12.5 km in the initial study to 15 km using the more conservative sound speed profile.

For the operational stage of the wind turbines, the noise was compared to PTS and TTS criteria of seals. The noise was found to comply with these criteria at all ranges. For harbour porpoises, impact ranges for PTS/TTS were found to be 15 m and 170 m, and for behavioural impact the range was 240 m. It is stressed that operational noise for large wind turbines is associated with large uncertainties, and that the results presented here are regarded as conservative.

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