OKTOBER 2023
LILLEBÆLT VIND A/S

MILJØKONSEKVENSVURDERING LILLEBÆLT SYD VINDMØLLEPARK

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CONTENTS

1 Introduction

On behalf of Lillebælt Vind A/S, COWI has carried out a series of underwater noise calculations for the Lillebælt Syd Offshore Wind Farm (OWF). The project is currently planned to produce between 154 and 166 MW, depending on the final scenario. The Lillebælt Syd OWF is projected between the islands of Als and Funen in Denmark, at about 4 km from both coasts (see Figure 1). Connected with the southern border of the project area, there is the Natura 2000 area number 197 ("Flensborg Fjord, Bredgrund og farvandet omkring Als").

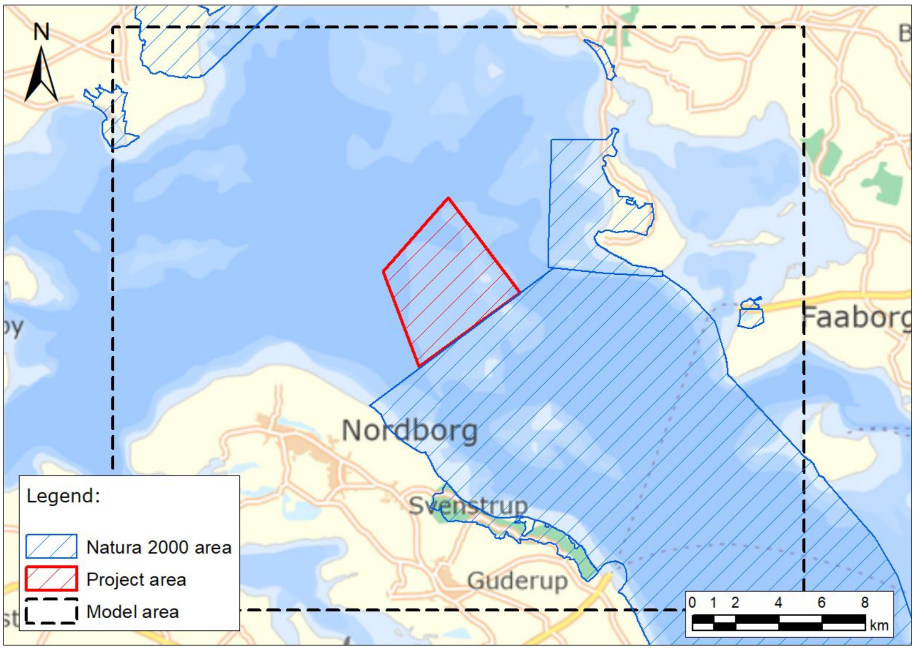

Figure 1 Overview map of Lillebælt Syd OWF

The modelled activities include:

- Construction phase: Installation noise for impact-driven monopiles.
- Operational phase: Turbine noise.

Several scenarios are currently considered for this OWF (see Table 1). The layouts range between 10 and 23 windmills and have single wind turbine power outputs between 7.2 to 15 MW

Table 1 Summary of the scenario layouts. Red: scenarios and parameters used in the calculations.

Parameter	Scenario layout 1	Scenario layout 3	Scenario layout 4	Scenario layout 5
Number of turbines	11	14	23	10
Power per turbine (MW)	14	11	7.2	15
Total power (MW)	154	154	165.6	150
Rotor diameter (m)	222	200	172	236
Monopile diameter (m)	7.5			

Since the installation of monopiles is assumed similar for all scenarios, scenario layouts 4 and 5 have been considered for the construction phase due to the number and location of their turbines. Scenario layout 5 has been considered for the operational noise, since it has the largest turbines. The impact of the remaining scenario layouts 1 and 3 is expected to be similar or lower than the calculated layout scenarios 4 and 5.

A previous underwater noise prediction for this project was carried out by Lloyd's Register (LR) in May 2018 (Lloyd's Register, 2018). That prediction was based on the now obsolete Danish Energy Agency (ENS) ”Guideline for underwater noise – Installation of impact driven piles” (Energistyrelsen, 2016). A new ”Guideline for underwater noise – Installation of impact or vibratory driven piles” was released by ENS in May 2022 (Danish Energy Agency, 2022). This report uses many of the same assumptions made in the LR report but updates the calculation method to follow the requirements of the latest guideline from ENS.

The results from these calculations are used by the marine fauna specialists to complete the Environmental Impact Assessment (EIA) on the relevant species (COWI, 2022).

2 Underwater noise

The propagation of sound in water is more efficient than in the air, due to a lower absorption of acoustic energy and the potentiality of cylindrical spreading of energy (Kinsler, 1982). The speed of sound is also different in water, with typical values between 1450 and 1550 m/s, which is over four times higher than in air. With longer propagation distances, an area can be potentially impacted several kilometres away from a powerful noise source.

Sound propagation can be simplified as:

$$L_p(r) = L_S - N_{PL}(r)$$

Equation 1

In Equation 1, L_p is the received level that depends on r, the distance to the source. L_S is the source level and N_{PL} is the propagation loss, that also depends on the distance between source and receiver. All are measured in decibels (dB).

The calculation software computes the propagation loss for many different receiving points by using several input data as described in section 3.3.

However, the received level is not enough to assess the impact of noise on marine animals, since different groups of animals have different hearing systems. The new guideline (Danish Energy Agency, 2022) describes different functional hearing groups for marine mammals based on available data from experiments and studies. Hearing sensitivity varies with frequency, and this is corrected in the received level by using weighting functions, like the ones shown in Figure 2.

In these calculations, one weighting function has been used:

- W_{VHF} for harbour porpoises.

Furthermore, unweighted (linear or uncorrected) levels are used for fish, fish eggs and fish larvae. Unless specified otherwise, all presented results apply to the harbour porpoise's species.

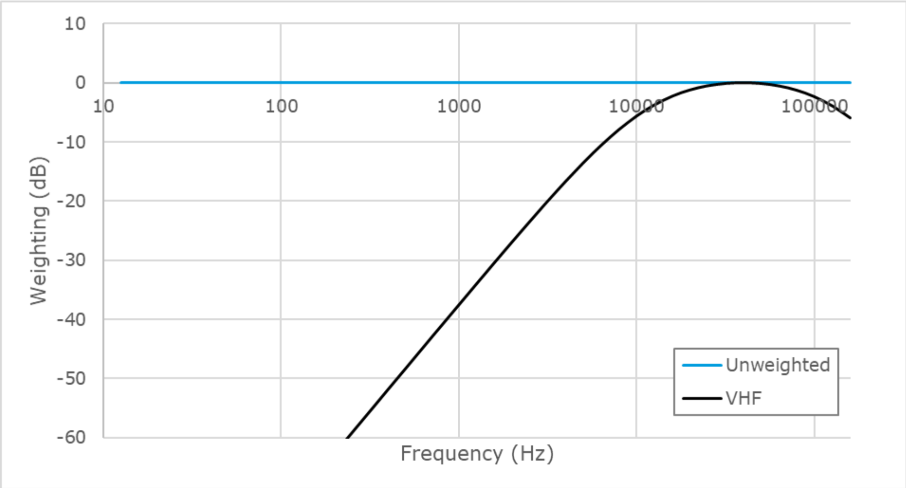

Figure 2 Weighting functions used in this project.

For harbour porpoises, Figure 2 shows that their practical hearing range is limited to approximately 1,000 to 150,000 Hz.

Sound pressure is a magnitude that fluctuates with time. Normally expressed as a level, it can be represented with different parameters depending on the type of sound:

- For sources where the sound is sustained over time, like turbine noise, $L_{p,rms}$ (known as SPL), is typically used:

$$SPL: L_{p,rms} = 20 \cdot log_{10}\left(\frac{p_{RMS}}{p_{ref}}\right)$$

Equation 2

In Equation 2, *SPL* stands for Sound Pressure Level and *RMS* for Root Mean Square, a statistical indicator of the signal. p_{RMS} is the RMS sound pressure of the sound and p_{ref} is the reference pressure (1 μPa in water). In air, the reference pressure is 20 times larger than in water. Having different reference pressures, underwater and air noise levels cannot be compared directly.

- For impulsive sources, like pile driving, the Sound Exposure Level $L_{E,p}$ (known as SEL) is preferred for comparison purposes:

$$SEL: L_{E,p} = 10 \cdot log_{10}\left(\frac{\int_{t_5}^{t_{95}} p^2(t)dt}{E_0}\right)$$

Equation 3

In Equation 3, $p^2(t)$ is the squared instantaneous pressure, t_{95}-t_5 is the time period that contains the 90% of the energy of the integrated signal, and E_0 is the reference value of 1 μPa²s.

For pile driving noise, SEL_{SS} (single strike) is used. It corresponds to a period of observation of one single strike of the hammer. To represent the level over more than one hammer strike, the cumulative SEL (SEL_{cum}, symbol $L_{E,cum}$) is used:

$$SEL_{cum}: L_{E,cum} = 10 \cdot log_{10}\left(\frac{\sum_{n=1}^{N} E_n}{E_0}\right)$$

Equation 4

In Equation 4, E_n is received sound exposure of each hammer strike. Therefore, the received SEL_{cum} is simply the logarithmic addition of all the received SEL_{SS} during the accumulation period.

For the evaluation of the behavioural response of porpoises to noise, the SPL averaged over a time period of 125 ms is used. For hammer strike pulses shorter than 125 ms, this SPL can be directly estimated from the SEL_{SS} according to the following equation (Danish Energy Agency, 2022):

$$SPL_{125ms}: L_{p,rms,125ms} = L_{E,p} + 9dB$$

Equation 5

2.1 Acoustic criteria for compliance

Maximum noise limits are defined for several adverse effect on fauna, like the Permanent Threshold Shift (PTS) or the Temporary Threshold Shift (TTS), for which an animal would lose hearing capabilities permanently and temporarily, respectively. Table 2 and Table 3 present the noise limits considered in this report:

Table 2 Acoustic criteria for harbour porpoises (Danish Energy Agency, 2022).

		Threshold		
Species and weigthing	*Phase / type of sound*	PTS $SEL_{cum,24h}$ (dB re $1\mu Pa^2s$)	TTS $SEL_{cum,24h}$ (dB re $1\mu Pa^2s$)	Behavioural Disturbance SPL_{125ms} (dB re $1\mu Pa$)
Harbour porpoise (VHF)	Construction: impulsive	155	140	103
	Operation: non impulsive	173	153	103

Table 3 Acoustic criteria for fish (Andersson, 2016).

		Threshold		
Species and weighting	*Risk*	*SPL_{125ms} (dB re 1μPa)*	*SEL_{SS} (dB re 1μPa²s)*	*$SEL_{cum,24h}$ (dB re 1μPa²s)*
Fish (unweighted)	Organ damage /death	207	174	204
Fish eggs and fish larvae (unweighted)	Damage /death	217	187	207

3 Methodology

This section describes the approach followed for the calculations. It lists the calculated scenarios, the applied calculation methods, and the input parameters.

3.1 Scenarios

The calculated scenarios model the installation of monopile foundations for the windmills during the construction phase and the turbine noise expected during operation. No other type of noise has been calculated for this report (vessel traffic, dredging, drilling, etc.).

Furthermore, this assessment is limited to desktop work with no additional data collection of underwater noise levels nor other survey data.

3.1.1 Construction noise

The installation of monopiles using a hydraulic impact hammer is part of the activities described by the new guideline (Danish Energy Agency, 2022). The criterion used to evaluate the noise impact of this activity is the cumulative SEL that a porpoise would receive when swimming away from the noise source. Four different monopile positions have been calculated separately. Based on the results of these calculations, the propagation path with the smallest propagation loss has been used in the scenarios described below.

Within the construction phase, two scenarios have been calculated:

Reference case

This scenario represents a Worst-Case Scenario (WCS) without any noise mitigation and without using an Acoustic Deterrent Device (ADD). In the new guideline, this scenario is used to calculate the minimum amount of noise mitigation that is required. It assumes that the animals are at 200 m away from the pile during the first strike of the hammer.

Planned construction case

This scenario assumes that the activities are carried out as planned. This includes the mitigation measures calculated in the reference case. The outcome of this calculation is used to decide if the pilling activities can be allowed. In this case, there is not an assumption for the initial distance for the animals, but instead, it is calculated at what initial distance the porpoises would get a Permanent Threshold Shift (PTS) or hearing loss.

3.1.2 Operational noise

Turbine noise is not within the scope of the new guideline (Danish Energy Agency, 2022). Therefore, this assessment has been based on the existing literature and previous measurements of turbines. The prediction of noise levels has been done for the layout scenario no. 5 with all 10 turbines operating at the same time.

3.2 Model

The underwater noise modelling is carried out using dbSea from Marshall Day Acoustics[1]. With dbSea, underwater sound propagation is predicted in dependence of range, bathymetry, temperature profile and salinity profile. The software implements several numerical methods of calculation: parabolic equation method, normal mode method and ray tracing method. Each modelling approach is valid for a different domain and frequency range. The calculation software allows to combine two calculation methods by calculating the lower frequencies with one method and the higher frequencies with another.

The model parameters used in this project are:

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[1] COWI's calculations have been carried out in accordance with guidelines published by ENS, ASA and CMS, and use best practices and state-of-the-art methods for underwater noise calculation. COWI has furthermore controlled both input data and results. However, the core of the calculation software is a "black-box" from which COWI can only control the calculation results by sampling. COWI does not take responsibility for later identified malfunctions in software systems that may affect the calculated results and assessments. COWI has used dBSea Underwater Noise Modelling, version v2.3.0 build 297 64bit.

- Geometry and mesh:
  - Model size (km): X= 32; Y= 27; Z= 0,05
  - Result grid resolution (m): dx: 20; dy: 20; dz= 1
  - Source result range step (m): 20
  - Number of radial transects per source:
    - Construction phase: 24 (15° slice step angle)
    - Operational phase: 18 (20° slice step angle)
  - Number of calculated source positions:
    - Construction phase: 4
    - Operational phase: 10
- Solver:
  - Frequency range: 12,5 Hz to 160 kHz in 1/3 octave bands
  - LF solver: dBSeaPE (Parabolic Equation - PE)
  - HF solver: dBSeaRay (Ray tracing - RT)
  - Crossover frequency between LF and HF solvers: 2500 – 3200 Hz

A realistic WCS modelling approach has been used to ensure that results remain conservative under most circumstances. Therefore, the presented results should not be considered as average values but as the possible maximum. The specific decisions taken regarding this approach are described in 3.3 and 4.1.

3.2.1 SEL_{cum} calculation

The new guideline (Danish Energy Agency, 2022) describes a methodology to predict the cumulative SEL received by a fleeing animal. In this calculation, it is assumed that the animal is swimming with a constant speed of 1.5 m/s in a straight line away from the source. Meanwhile the animal is escaping, it receives the noise from the impact hammer with a SEL_{SS} that depends both on the propagation loss (and therefore on the range or distance to the source) and on the hammer strike energy as described in the pile driving protocols.

At any time, t_i [s], the distance from the animal to the source is:

$$r_i = r_0 + v_f \cdot t_i$$

Equation 6

Where r_0 is the initial distance for the animal during the first strike of the hammer and v_f is 1.5 m/s.

On one hand, the received SEL_{SS} will decrease as the animal escapes because the transmission loss typically tends to increase with range. On the other hand, the hammer energy will be increased as the pile penetrates the seabed, and that will yield a larger SEL_{SS} at the source. The three simultaneous phenomena (animal fleeing, propagation loss and driving protocols) are combined to calculate the SEL_{SS} received by the animal for all strikes involved in the installation of one monopile. SEL_{cum} is then calculated as:

$$SEL_{cum}\colon\ L_{E,cum} = 10 \cdot \log_{10} \sum_{i=1}^{N} \frac{S_i}{100} 10^{\frac{L_{S,E} - N_{PL,E}(r_i)}{10}}$$

Equation 7

Where:

- N is the total number of strikes required per monopile.
- i is the index for each single strike that is considered.
- S_i is percentage of full hammer energy used for the strike *i.*
- $N_{PL,E}$ is the transmission loss that depends on the position of the animal.
- r_i is the range of the animal during each strike *i* as calculated in Equation 6.

Equation 7 is a modification of Equation 4 presented in the introduction. It also includes the possibility that SEL_{ss} may change for each strike *i* due to the piling protocol and the movement of the animal.

As explained in section 4.1, the realistic WCS approach in this case has involved:

- Choosing the radial transect among all calculated sources, with the transmission loss $N_{PL,E}$ that results in the highest SEL_{cum}.
- Choosing the pile driving protocol that results in the highest SEL_{cum}.

3.3 Input data

The software uses two types of input data: acoustic data and environmental data. The acoustic data includes a description of the activities, their source levels, and the positions of sources and receivers.

The environmental data includes bathymetry, water temperature, salinity and geotechnical data obtained from surveys in the area. Using the water column data, the speed of sound and attenuation in water are also estimated.

3.3.1 Acoustic data

The acoustic data includes the documentation of the source levels and their positions. For the construction phase, it also includes the hammer protocol that describes how the hammer energy evolves with time. The pile driving source levels are consistent with the previous noise calculations (Lloyd's Register, 2018).

Receiver and source locations

The positions of the scenario layout number 5 were chosen as the source locations. This was the chosen scenario for the operational phase because it features the largest turbines. The results from the operational phase were subsequently used to inform the selection of source locations for the construction phase. The sources showing the lowest $N_{PL,E}$ were calculated. The locations of these sources are presented in Table 4 and shown in Figure 3:

Table 4 Source coordinates calculated in the operational phase. The positions in bold were also calculated in the construction phase.

WTG ID	***Lon [°]***	***Lat [°]***	***E [m]***	***N [m]***	***Depth (mMSL)***
WTG01	9,871767	55,150438	555556,1	6111879,1	-20,7
WTG02	**9,887200**	**55,104523**	**556604,5**	**6106782,2**	**-16,7**
WTG03	9,874854	55,141254	555765,6	6110859,6	-19,0
WTG04	9,884110	55,113705	556394,4	6107801,4	-16,9
WTG05	9,853726	55,090677	554487,7	6105214,8	-19,8
WTG06	**9,841380**	**55,127408**	**553650,5**	**6109292,6**	**-20,5**
WTG07	**9,844467**	**55,118225**	**553859,7**	**6108273,1**	**-20,9**
WTG08	9,847552	55,109042	554068,8	6107253,6	-19,6
WTG09	**9,850636**	**55,099859**	**554278,0**	**6106234,2**	**-16,8**
WTG10	9,882378	55,122986	556270,9	6108832,8	-19,3

All sources have been modelled at 50% water depth.

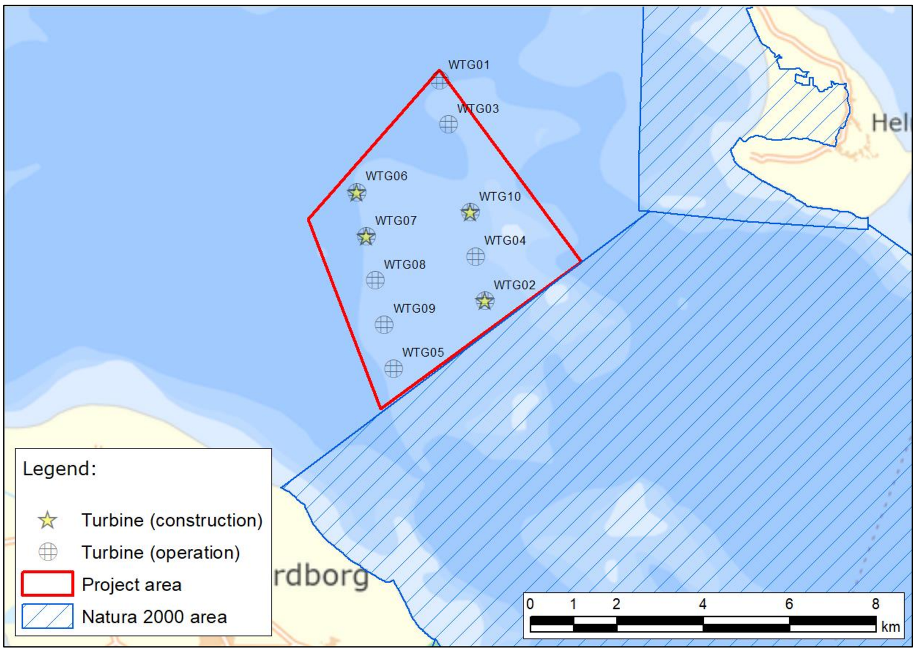

Figure 3 Location of turbines for Scenario number 5 used in the operational noise calculation.
Construction noise has been calculated for WTG02, 06, 07 and 10.

The receiver locations constitute the whole domain, as it is assumed that animals could be anywhere. However, the nearby Natura 2000 areas represent habitats that are especially important for harbour porpoises. To study the propagation in this area in more detail, WTG02 was also included in the calculations.

Pile driving noise

The noise generated by the hydraulic hammer impacting the metallic monopile foundation is expected to generate the highest noise levels of all the activities required for this project. The vibrations introduced by the hammer travel down the monopile and are transmitted to the adjacent water and seabed. These perturbations propagate in all directions over distances of several kilometres.

The level of this source depends on the energy used by the hammer, the characteristics of the monopile itself and geotechnical conditions like the soil resistance of the seabed where it is installed. The design plan for this activity is described in the driveability analysis report (C2WIND, 2022). This document includes a calculation of the expected employed hammer energy and number of hammer strikes that will be required for the installation of the OWF's foundations. The overall parameters extracted from this report are presented in Table 5:

Table 5 Summary of results from the driveability analysis

Parameter	*Value*
Monopile diameter (m)	7.5
Hammer model	MENCK MHU 3500S
Studied borehole locations	5
Maximum impact hammer energy (kJ)	812-2545
Installation time per monopile (min)	63-92
Number of strikes per monopile	4923-7187

In (C2WIND, 2022), the driveability analyses were performed for five borehole locations within the project area with different soil conditions and target penetration depths, which explains the broad ranges in Table 5. For each location, a different piling sequence was designed to install the monopile into its final position. The controlled hammer energy pile driving logs for each position are presented in the appendices of (C2WIND, 2022) and summarised in Figure 4.

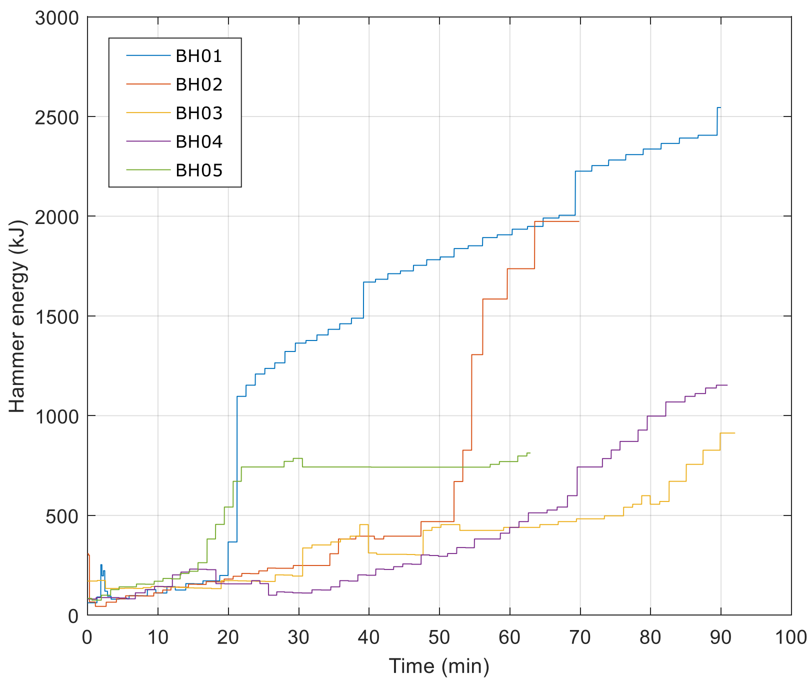

Figure 4 Driving logs showing the hammer energy as a function of time for each of the five calculated borehole positions. Extracted from (C2WIND, 2022).

The report (C2WIND, 2022) also includes another scenario named ”maximum hammer energy” where the number of strikes required to install a pile is minimum. In this scenario, the hammer operator would not ramp up the hammer energy and instead use a maximum hammer energy up to 3016 kJ from the piling start. The report describes this scenario as conservative but unrealistic. From the noise point of view, this scenario would be unacceptable because of the risk of exceeding the noise limits when the soft-start procedure is not used, even with the currently available most effective mitigation measures.

The pile driving source level for the maximum hammer energy of 2545 kJ is presented in Figure 5. It corresponds to the previous calculations in (Lloyd's Register, 2018), which had an overall SEL_{SS} of 220.5 dB re 1 μPa^2m^2s. The frequencies over 2 kHz have been assumed to decrease with 6 dB per octave. This is an estimation based on the typical trends from 2 kHz – 64 kHz found in several high-frequency measurements reported in the literature (De Jong & Ainslie, 2008), (Robinson, Theobald, & Lepper, 2012), (Leunissen & Dawson, 2018).

The VHF-weighted values show a maximum level of 170 dB re 1 μPa^2m^2s at the 1/3 oct. band of 10 kHz. In fact, most of the contribution to the VHF-weighted levels comes from the extrapolated frequency range. This source of uncertainty is reviewed in section 5 Discussion.

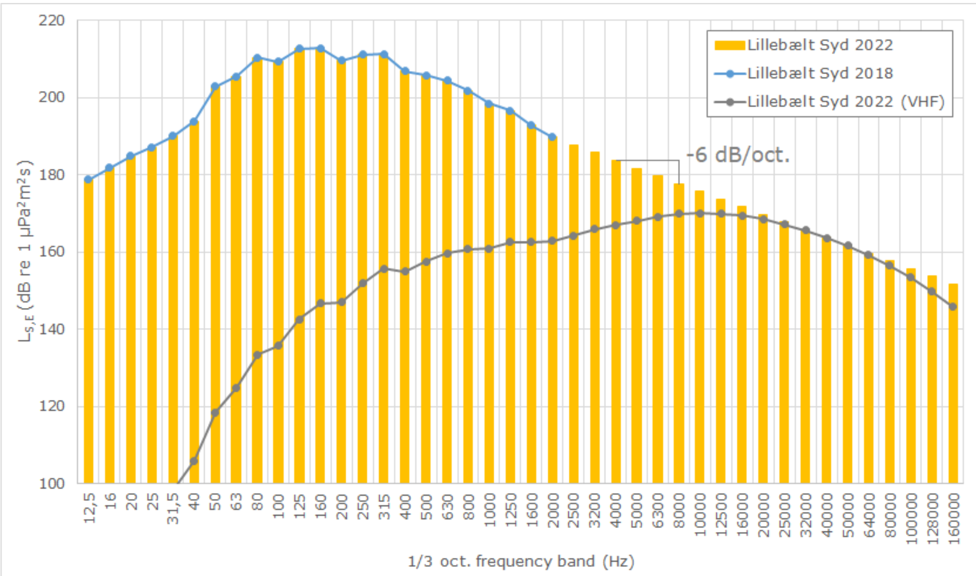

Figure 5 Source SEL_{SS} at 1 m. Yellow: unweighted levels. Blue: unweighted levels used in the previous report (Lloyd's Register, 2018). Gray: VHF-weighted levels. Unweighted broadband level: 220.5 dB re 1 μPa^2m^2s. VHF-weighted broadband level: 179.8 dB_{VHF} re 1 μPa^2m^2s. Hammer energy: 2545 kJ.

Turbine operation noise

During operation, the noise generated by the turbine typically comes from the nacelle and has a tonal characteristic due to the mechanical revolutions in the gearbox and the generator. Other sources of noise like the wind load excitation of resonances in the blades and tower may also contribute to the emission. This structure-borne sound is transmitted down from the tower and into the surrounding water via the foundation.

Most reported measurements mainly show pure tone components below 1 kHz, with lower levels at other frequencies, typically 20 dB below the tonal peaks. However, the literature is currently missing measurements for large turbines, since most published measurements are for turbines below 6 MW. The source levels used in the calculation have been obtained by extrapolating measurement levels from smaller turbines. The references used in this assessment include (Tougaard, Hermannsen, & Madsen, 2020) and (ITAP GmbH, 2006). These levels are shown in Figure 6.

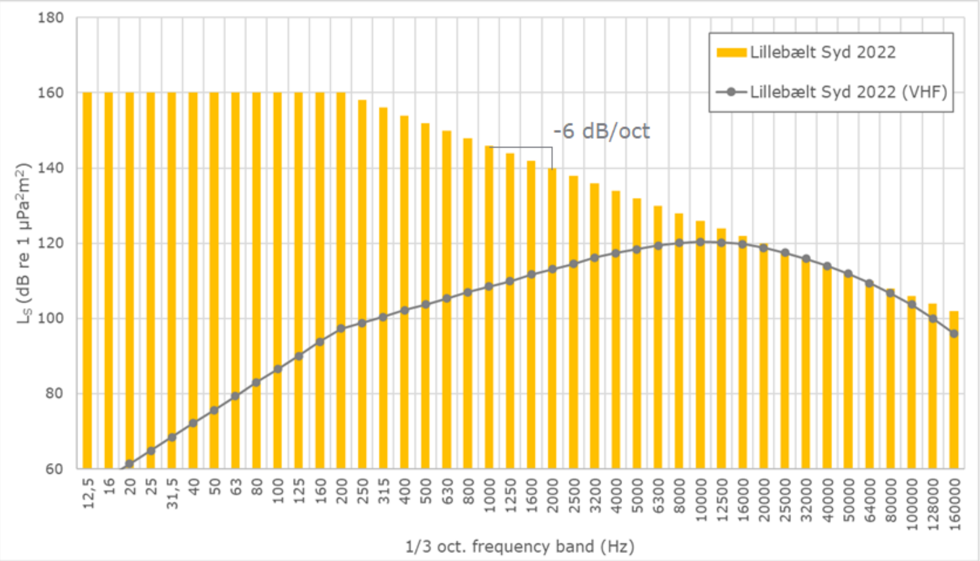

Figure 6 Source SPL at 1 m. Yellow: unweighted levels. Gray: VHF-weighted levels. Unweighted broadband level: 171.7 dB re 1 µPa^{2}m^2. Turbine power: 15 MW.

Background noise

The baseline noise levels less than 5 km away from the project area were measured in 2018 and are reported in (Nielsen, Sørensen, & Tougaard, 2019). In the 10 Hz-10 kHz frequency range, levels fluctuate between 80 and 107 dB re 1 µPa2.

3.3.2 Environmental data

The environmental data is used in the calculation software to model the propagation of sound in water. The seawater and seabed conditions correspond to the previous noise calculations (Lloyd’s Register, 2018).

Bathymetry

The bathymetry of the model and the coastline are shown in Figure 7. It covers an area of 32x27 km around the project area. The mesh is not uniform and contains a greater detail in the project area. The maximum grid size (distance between data points) is 50 m outside the project area and 5 m inside.

The bathymetry has been built based on the following datasets:

- Farvandsvæsenet (resolution of 50x50m).
- Detailed survey of the project area (resolution of 5x5 m).
- GeoDanmark (Datafordeler).

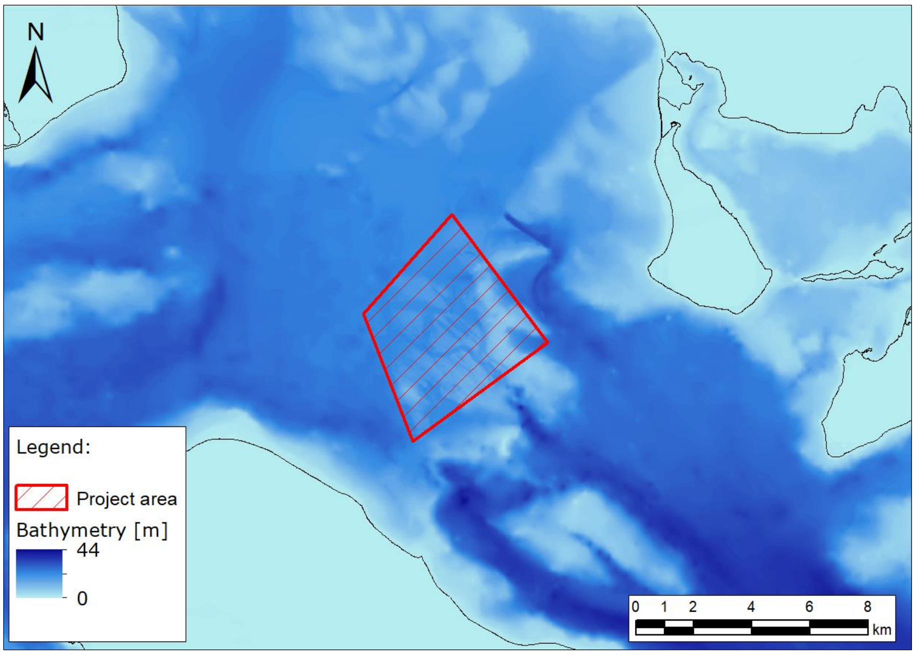

Figure 7 Bathymetry model. Depth reference DVR90.

A more detailed description of the bathymetry data collection is provided in COWI's "Hydrografi og vandkvalitet report" (EIA Appendix F).

The tidal range has been neglected in the calculations since it is not expected to produce significant changes in the noise results.

Seawater conditions

The sound speed profile extracted from (Lloyd's Register, 2018) was estimated based on historical measurements of temperature and salinity in the waters south of Sønderborg for the months of March-April.

The mean temperature ranges between 6°C at the surface and 4°C at the seabed. The mean salinity ranges between 16 ‰ at the surface and 18 ‰ at the seabed. Based on these values, the sound speed profile in Figure 8 was used in the calculations.

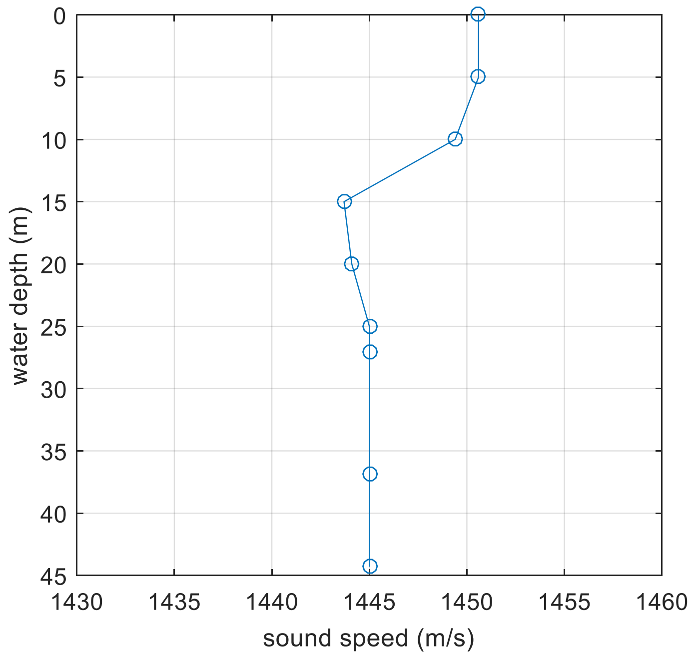

Figure 8 Derived sound speed profile (m/s) from (Lloyd's Register, 2018).

Geotechnical data

The seabed was modelled using data collected in geophysical investigations of the area as described in (Lloyd's Register, 2018). The same approach as the previous calculations was followed, and the following parameters were used in the model:

Table 6 Geotechnical data used in the calculations

Depth of the seabed layer [m]	*Material*	*Geophysical parameters:*
0 - 2	Sand	C_p= 1630 m/s ρ= 1850 kg/m³ α= 0.4 dB/λ
2 - ∞	Moraine	C_p= 1900 m/s ρ= 2050 kg/m³ α= 0.3 dB/λ

The substrate study is presented in the COWI's "Marin habitatkortlægning" (EIA Appendix C).

4 Results

This section describes the outcomes of the prognosis. However, the graphical results are all gathered in Appendix A: Noise maps and a summary of the results is presented in section 5.

4.1 Construction phase

The procedure to calculate the cumulative SEL described in section 3.2.1 was implemented using the sound field calculated with dBSea for the four source locations and the communicated pile driving protocols for the five boreholes mentioned in section 3.3.1.

For each source, the propagation was calculated in 24 radial directions uniformly separated by 15°. Each direction may represent the escape route of a fleeing porpoise. Therefore, the WCS approach implies selecting the direction that yields the highest SEL_{cum}. The 96 calculated radials (24 per source) are presented in Figure 9, with the selected transect result highlighted in red. The values between the calculated ranges have been interpolated linearly.

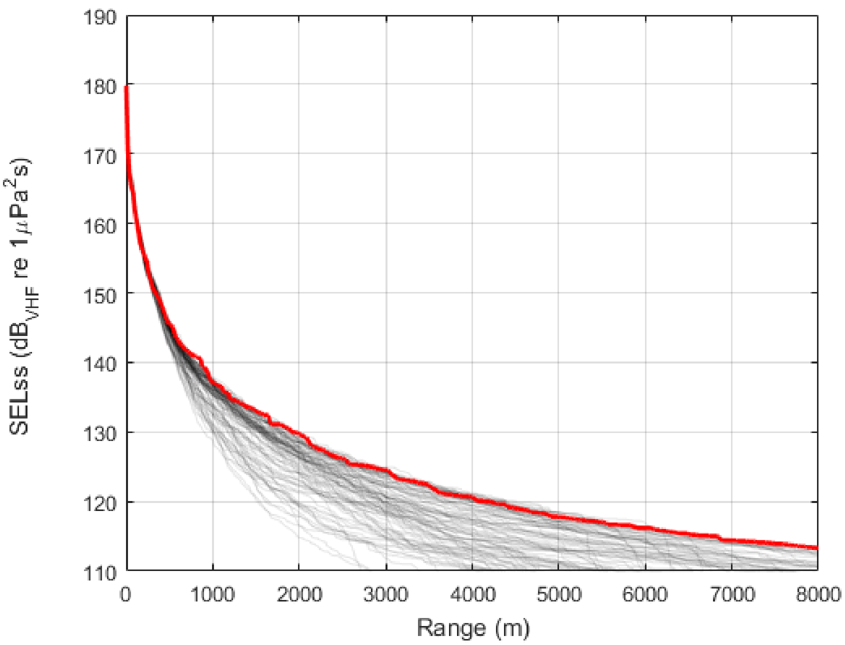

Figure 9 Ensemble of SEL_{ss} as a function of range for the 96 calculated transects. Red: radial transect WTG10, 270° which gives the highest SEL_{cum}

The selected radial transect belongs to the WTG10 position in the 270° (west) direction. A porpoise fleeing in this direction would receive a higher SEL_{cum} than another porpoise fleeing in any of the other 95 directions. This radial transect is shown in Figure 10:

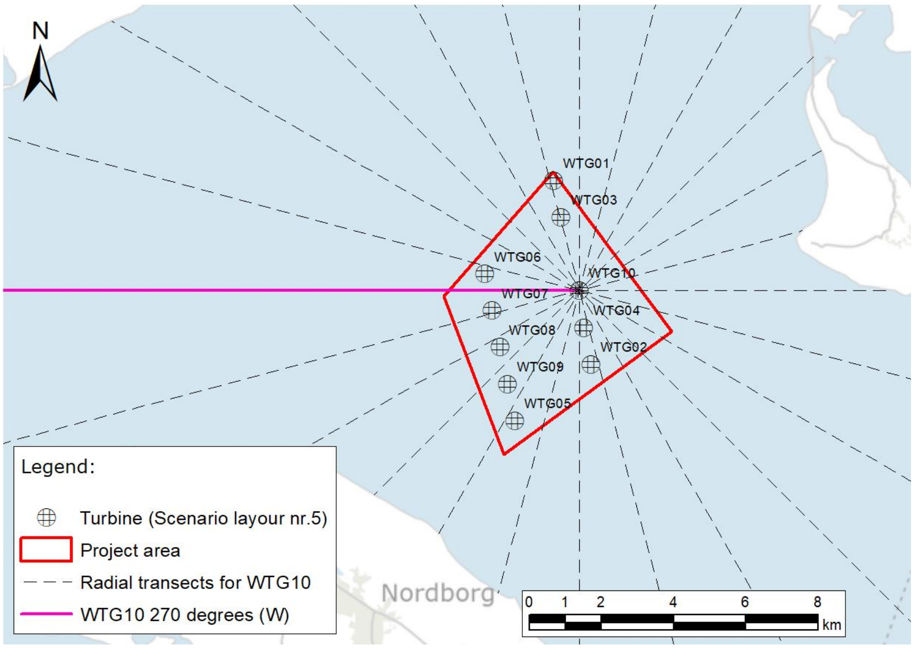

Figure 10 Radial transect used in the calculations.

All driving protocols were also considered in the calculations and the protocol for BH03 resulted in the highest SEL_{cum}. Therefore, the rest of the prognosis is made based on the radial 270° from WTG10 and the BH03 protocol.

In the reference case, the initial position of the porpoise is assumed at 200 m according to the guideline. Without any mitigation, this would result in a $L_{E,cum}$=164.3 dB_{VHF} re 1µPa^{2}s. Considering the PTS of 155 dB_{VHF} re 1µPa^{2}s, at least 9.3 dB of attenuation at the source would be required.

Based on the severity of the excess, a single big bubble curtain is estimated to mitigate the noise levels below the limit. Measurements of a single big bubble curtain report an overall attenuation of at least 10 dB (Bellmann, 2014). The Concession Holder has decided to use a double big bubble curtain, for which attenuations between 14 and 18 dB have been reported (Bellmann, 2014).

Including a mitigation of 15 dB, the calculations were repeated as part of the planned construction case. The initial position of the animal was iterated until the PTS was reached again, this time at a distance of 75 m from the source. This calculation as a function range is shown in Figure 11:

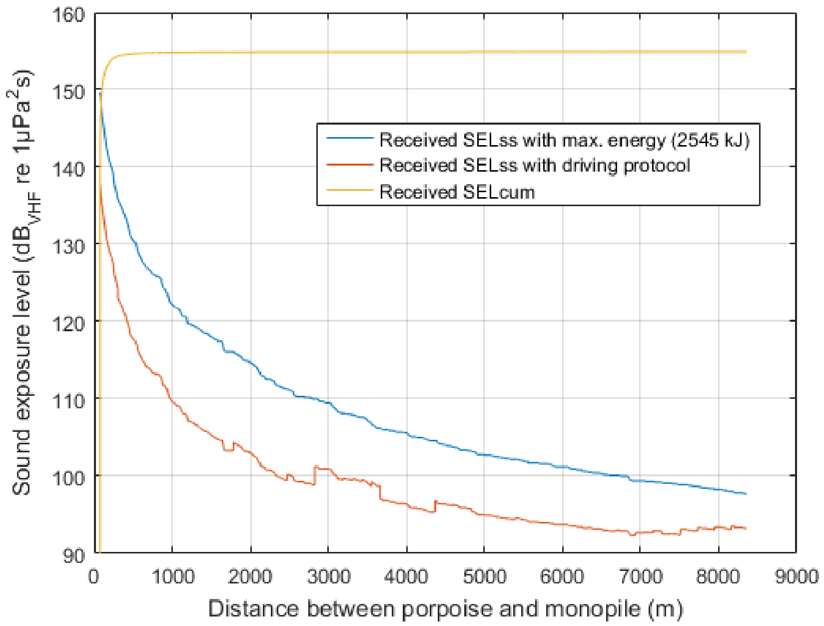

Figure 11 Calculation of SEL_{cum} under mitigated conditions (15 dB) for a porpoise with an initial distance of 75 m. Blue: Received SEL_{ss} if all hammer strikes were done at 100% energy (2945 kJ). Red: Correction of the blue plot with the actual driving protocol BH03. Yellow: SEL_{cum} calculated from the red plot as received by the animal.

The Distances to Thresholds (DTT) for porpoises in the Planned construction case are presented in Table 7:

Table 7 Threshold ranges including mitigation for the VHF group. Thresholds units are dB re 1μPa²s for PTS and TTS (SELcum), and dB re 1μPa for the Behavioural Disturbance ($SPL_{125\ ms}$)

Group	***PTS***	***DTT***	***TTS***	***DTT***	***Behavioural***	***DTT***
VHF	155	**75 m**	140	**740 m**	103	**12,5 km**

Figure 20 in Appendix A displays the buffer ranges around two calculated foundations (WTG2 and WTG10) on a map. Porpoises inside these buffers during the impact driving are at risk of exceeding the corresponding threshold.

It is important to note that the buffers for the two foundations are depicted together in the same plot, even though the installation events are not simultaneous.

The DTT for fish, fish eggs and fish larvae in the Planned construction case are presented in Table 8:

Table 8 Threshold ranges including mitigation for the unweighted group.

Impact	***SEL_{ss} (dB re 1µPa₂s)2***	***DTT (m)***
Risk of organ damage/death of fish	*174*	***300 m***
Damage/death of fish eggs and fish larvae	187	**50 m**

4.2 Operational phase

The turbine noise from the 10 windmills of scenario layout no. 5 was calculated. The results of these calculations are shown in Figure 21 and

Figure 22 Operational noise map: SP in Appendix A: Noise maps.

As an SPL weighted for VHF, the levels are barely over the background level, as presented in

Figure 22 Operational noise map: SP. The Behavioural Disturbance threshold of $L_{p,rms,125ms}$=103 dB_{VHF} re 1 µPa is marked in pink at a distance of 200 m or less. Due to the separation in frequency between the emission and the hearing range, the harbour porpoise may not hear the turbine noise until relatively close to the OWF.

The low levels also mean that damaging limits are unlikely to be reached. At 160 m or less, a harbour porpoise would need to remain static over a 24 h period to reach the TTS at 153 dB_{VHF} re 1 μPa^2s. For the PTS at 173 dB_{VHF} re 1 μPa^2s, the static receiver would need to be at 10 m or less from a turbine. The 24-hours cumulative SEL is shown in Figure 21.

None of the unweighted noise limits for fish are expected to be triggered.

5 Discussion

There are several sources of uncertainty for this calculation. These have been presented below in two categories: input data and model.

Uncertainties related to the input data:

- The source modelling is one of the most important factors affecting the noise results. This calculation uses a series of assumptions based on literature and previous professional experience to estimate the sources levels. Nevertheless, the actual source may deviate from these assumptions due to unforeseen circumstances. Seeking to minimize this uncertainty, the used source data has been comprehensively compared with the existing literature and a conservative option has been always chosen.

- In the construction phase, the source levels from LR's report (Lloyd's Register, 2018) have been used in the calculations. These were based on empirical experience for the designed hammer energy and pile size. The spectral information above 2 kHz has been extrapolated based on existing measurements of the high-frequency range.

- For the operational phase, the source level has been extrapolated from existing measurements of less powerful turbines. The broadband level 171.4 dB re 1 μPa^2m^2 has been overestimated to ensure that all the typical frequencies of emission are excited at the extrapolated level of 160 dB re 1 μPa^2m^2.

- The general lack of measurement data at high frequencies constitutes an uncertainty that will be reduced as new information becomes available. Until then, the WCS approach that adds security margins to the existing data may cause results that overestimate the actual noise levels.

- Deviations in other input data (bathymetry, water column and geotechnical surveys) can also have an important influence on the results. Special care has been taken to ensure that the possible deviations will not trigger exceedances in the noise limits.

Uncertainties related to the model:

- The variability of the seabed along the transect has not been modelled and the geotechnical parameters are assumed constant with range. This implies that, for example, reflections from stone reefs could be neglected for some transects.

- The calculation of cumulative SEL described in the new guideline (Danish Energy Agency, 2022) assumes an animal fleeing with a constant speed of 1.5 m/s in a straight line away from the source. For some animals, this escaping trajectory may not be available. For example, the animal may reach land before the piling has finished. Nevertheless, the calculation shows that the first 1200 m account for 95% of the received dose, and none of the source positions are closer than 2 km from the coast.

- Other uncertainties of the calculation method correspond to the model's assumptions: flat sea surface/roughness, omission of shear waves and vibrations in the seabed. They are described in the scientific documentation published by dBSea Ltd., UK.

6 Conclusion

A series of underwater noise calculations of the Lillebælt Syd OWF have been carried out with dBSea. The input data to the noise model and a description of the calculation method is presented, as required by the new guideline (Danish Energy Agency, 2022). The results of the calculation and noise contour maps are also provided in this document. However, the final assessment on marine fauna is presented in the main EIA document (COWI, 2022), in which this document is included as a technical appendix.

For the construction phase (impact pile driving), it is concluded that mitigation measures are required to not exceed the PTS for porpoises for type-I (impulsive) sounds (155 dB_{VHF} re 1 $\mu Pa^2 s$). The results show that a reduction of 10 dB is estimated to be sufficient to keep the cumulative SEL values below the requirement. A double Big Bubble Curtain (DBBC) is expected to fulfil that reduction, but other methods could also be used as long as they provide at least 10 dB of reduction in the relevant frequency range (1 to 150 kHz). A calculation with a DBBC has been included, assuming an attenuation of 15 dB.

For the operational phase (turbine noise), it is concluded that the predicted levels will not disturb the behaviour of harbour porpoises except at less than 200 m from the foundations. Within that distance, a porpoise would only reach a TTS at 153 dB_{VHF} re 1 $\mu Pa^2 s$ when remaining stationary over a 24 h period. Under similar conditions, the PTS at 173 dB_{VHF} re 1 $\mu Pa^2 s$ would only be reached at 10 m.

7 References

Andersson, M. A. (2016). *A framework for regulating underwater noise during pile driving.* Stockholm: Swedish Environmental Protection Agency.

Bellmann, M. A. (2014). Overview of existing Noise Mitigation Systems for reducing Pile-Driving Noise. *Inter-noise.* Melbourne.

C2WIND. (2022). *Lillebælt Syd Offshore Wind Farm - Initial Monopile Design and driveability – Alm&Hamre (20010-7).*

COWI. (2022). *Lillebælt Syd Vindmøllepark - Miljøkonsekvensrapport for vindmøllepark og kabler til havs (In Danish).*

Danish Energy Agency. (2022). *Guidelines for underwater noise, Prognosis for EIA and SEA.*

De Jong, C., & Ainslie, M. A. (2008). Underwater radiated noise due to the piling for the Q7 Offshore Wind Park. *Euronoise.* Paris.

Energistyrelsen. (2016). *Guideline for underwater noise – Installation of impact-driven piles.*

ITAP GmbH. (2006). *Measurement of underwater noise emitted by an offshore wind turbine at Horns Rev .*

Kinsler, L. E. (1982). *Fundamentals of acoustics, (3rd edition).* Wiley.

Leunissen, E. M., & Dawson, S. M. (2018). Underwater noise levels of pile-driving in a New Zealand harbour, and the potential impacts on endangered Hector's dolphins. *Marine Pollution Bulletin*, 195-204.

Lloyd’s Register. (2018). *Piling noise prediction - Lillebælt Syd OWF.*

Nielsen, M. L., Sørensen, P. M., & Tougaard, J. (2019). *Undervandsstøj i Indre Danske farvande 2018 (In Danish).* Aarhus Universitet.

Robinson, S., Theobald, P. D., & Lepper, P. A. (2012). Measurement of underwater noise generated from marine piling during construction of a UK offshore windarm. *Proceedings of the 11th European Conference on Underwater Acoustics.* Edinburgh.

Tougaard, J., Hermannsen, L., & Madsen, P. T. (2020). How loud is the underwater noise from operating offshore wind turbines? *The Journal of the Acoustical Society of America*, 148, 2885.

Appendix A: Noise maps

List of figures:

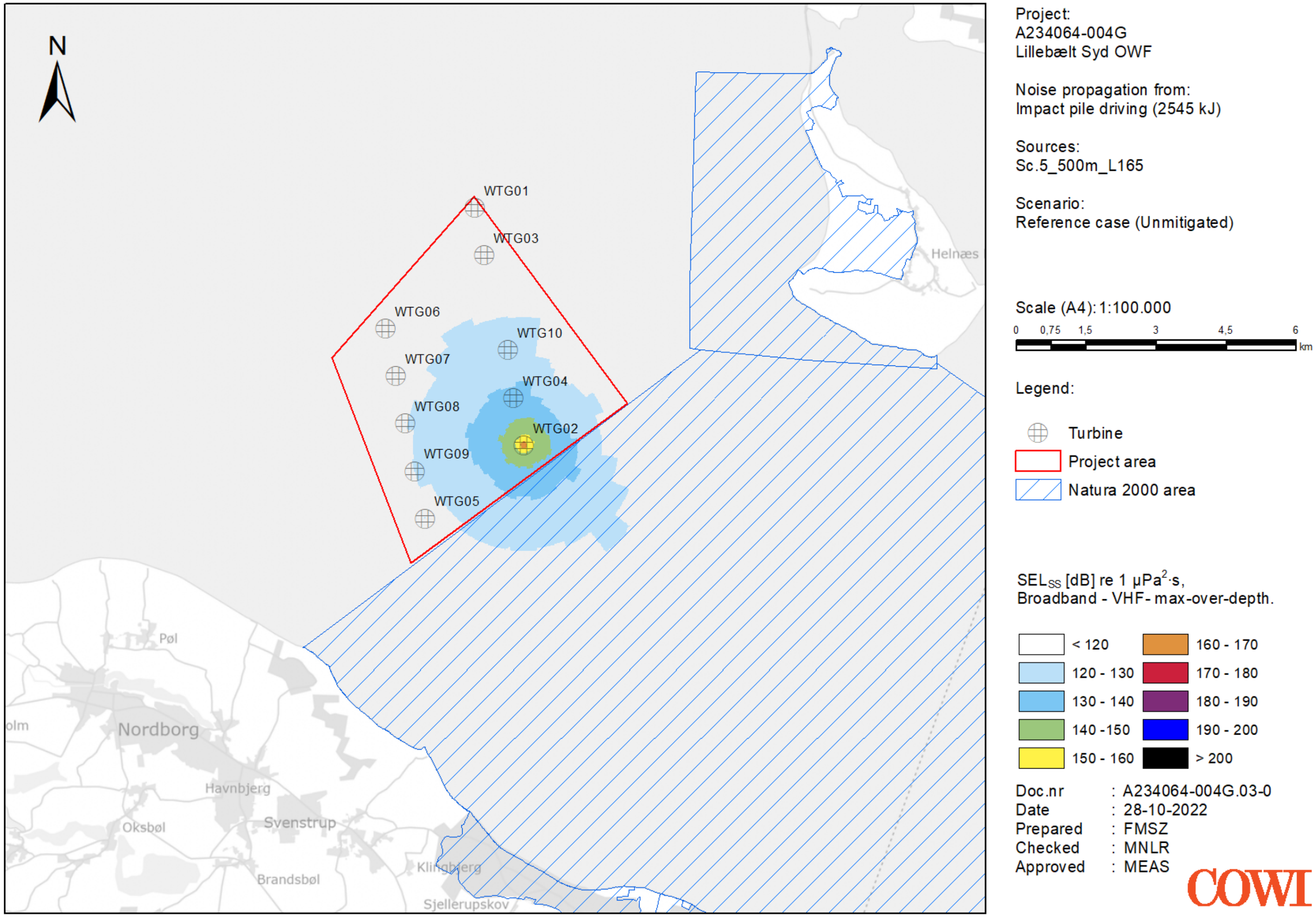

Figure 12 Construction noise map: Unmitigated SEL_{SS} at position WTG02

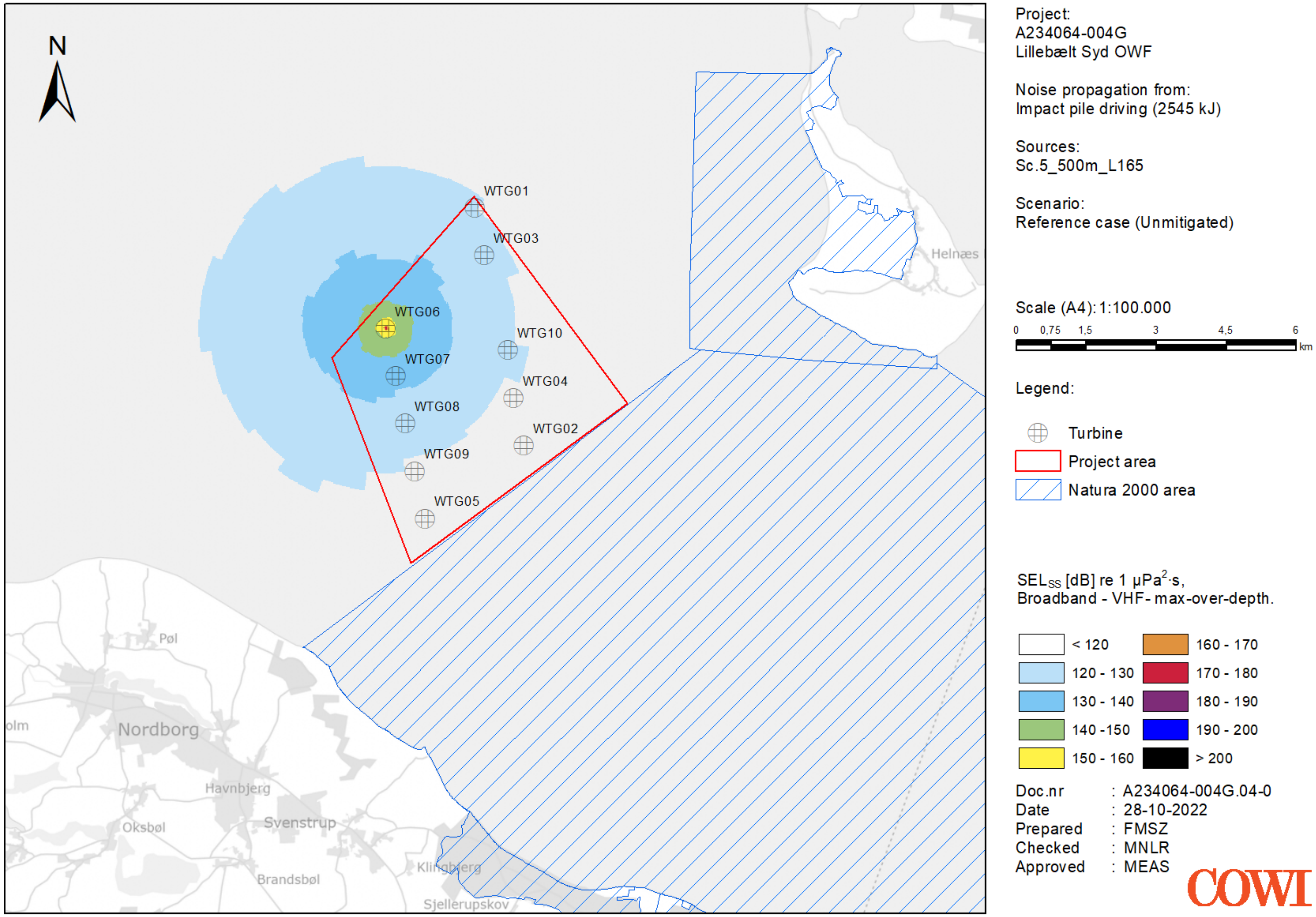

Figure 13 Construction noise map: Unmitigated SEL$_{SS}$ at position WTG06

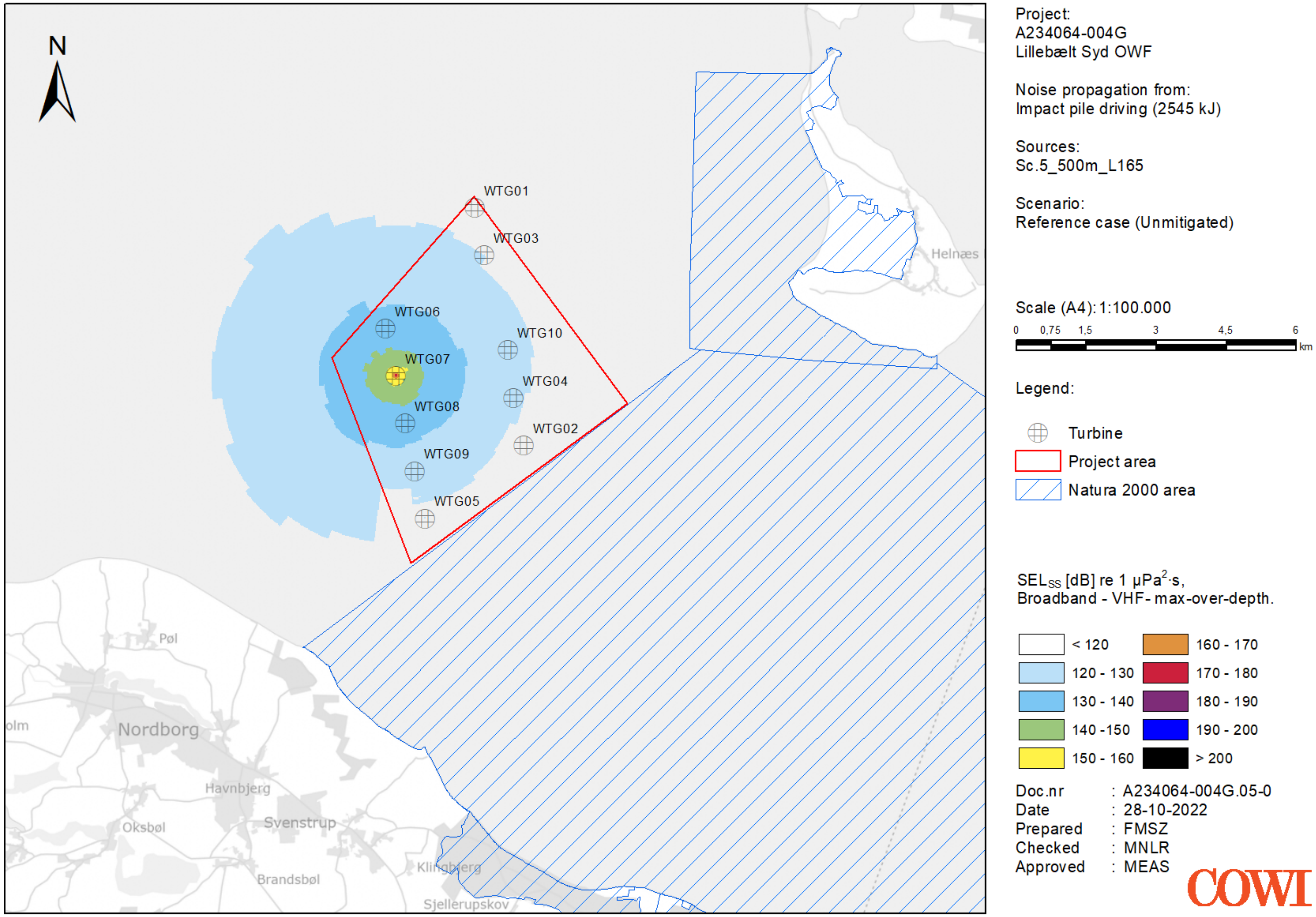

Figure 14 Construction noise map: Unmitigated SEL_{SS} at position WTG07

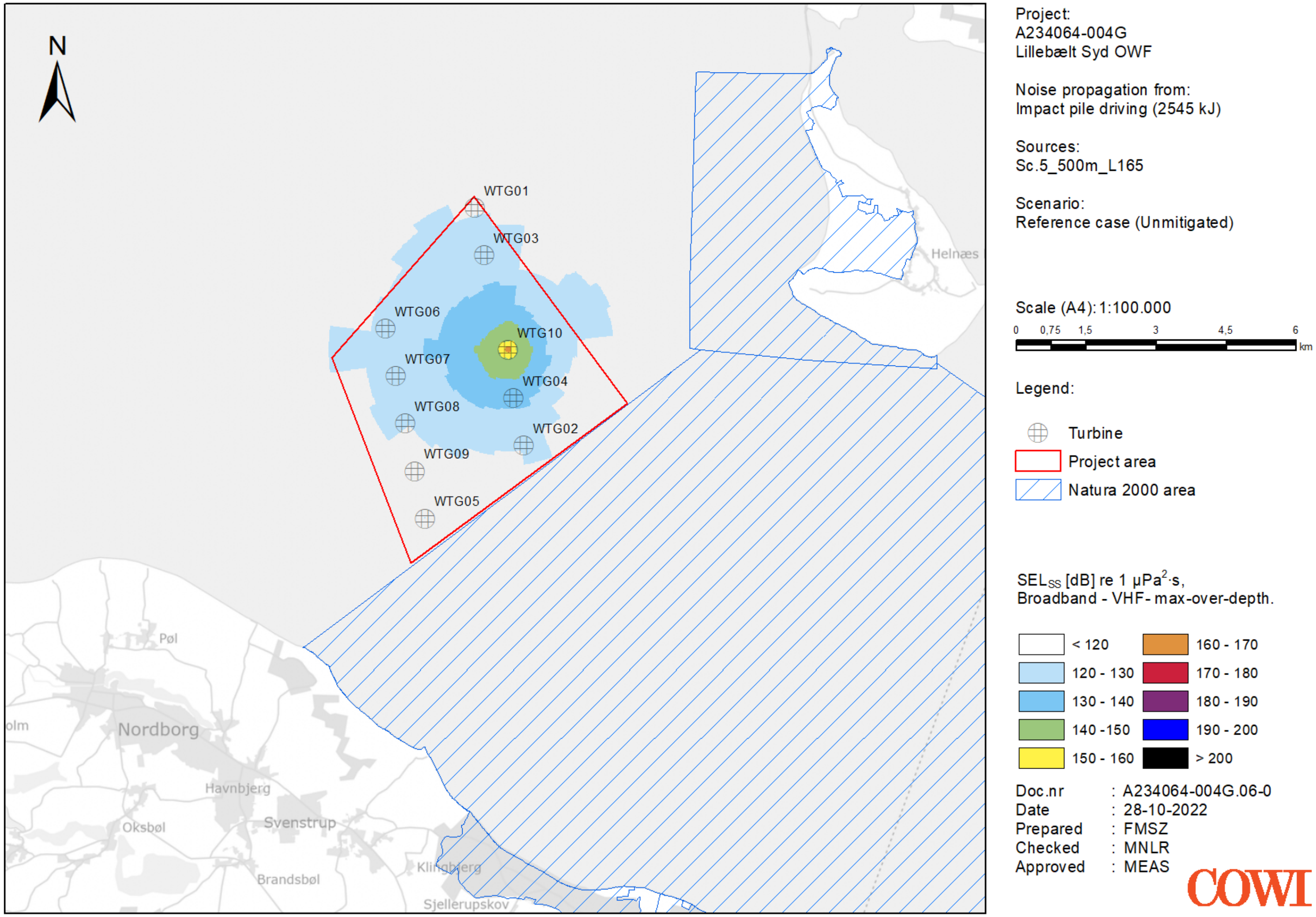

Figure 15 Construction noise map: Unmitigated SEL$_{SS}$ at position WTG10

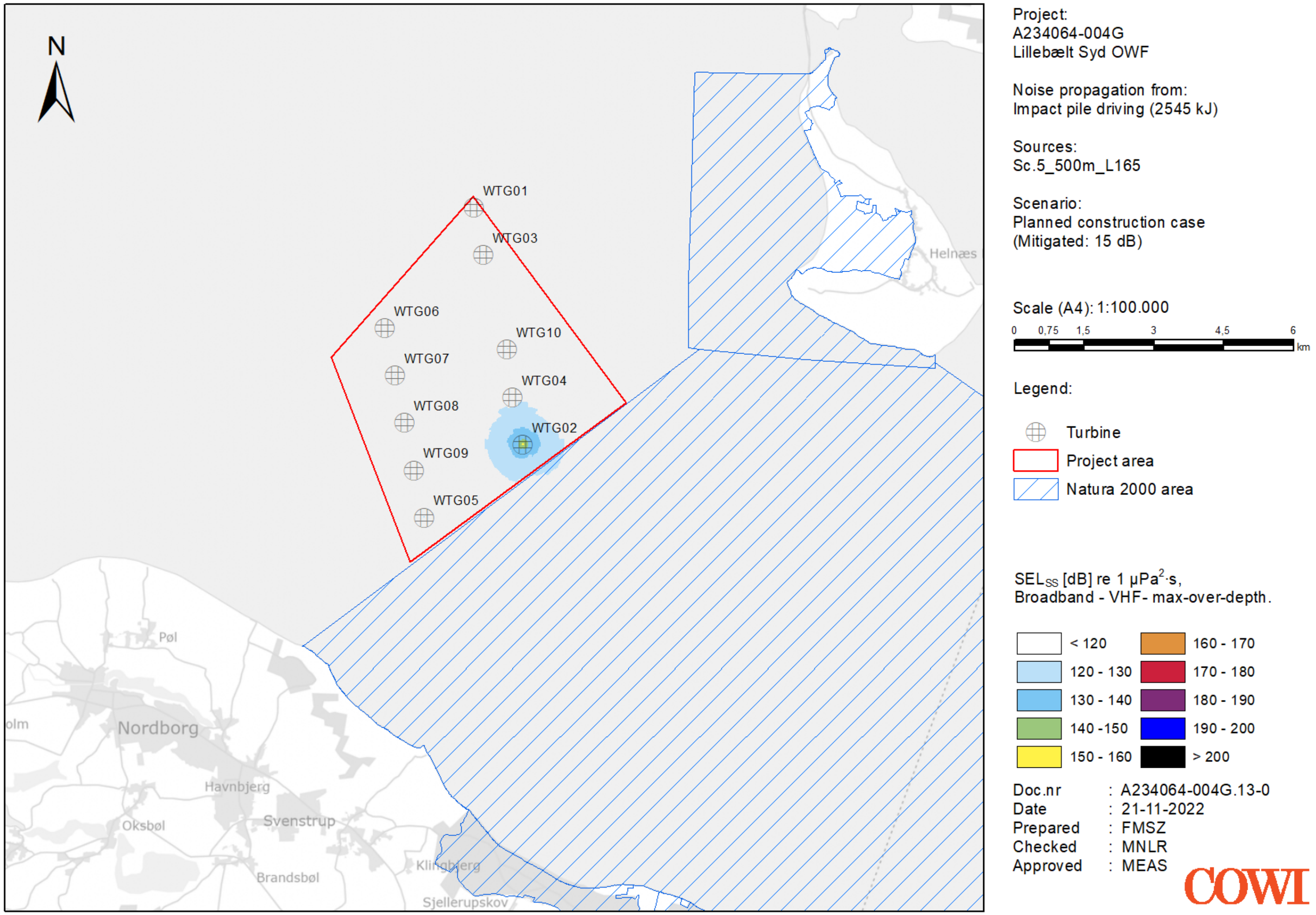

Figure 16 Construction noise map: Mitigated (15 dB) SEL_{SS} at position WTG02

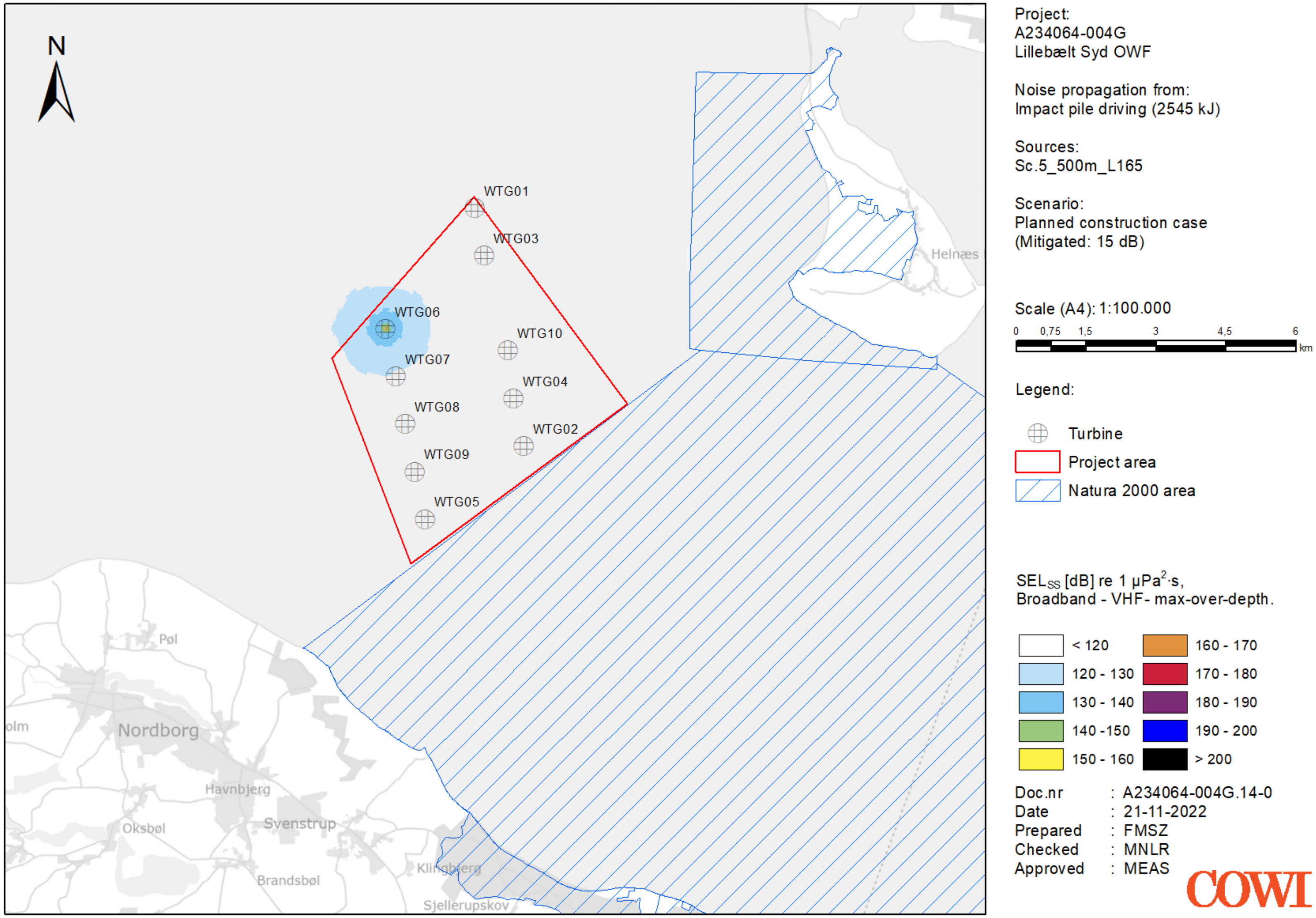

Figure 17 Construction noise map: Mitigated (15 dB) SEL_{SS} at position WTG06

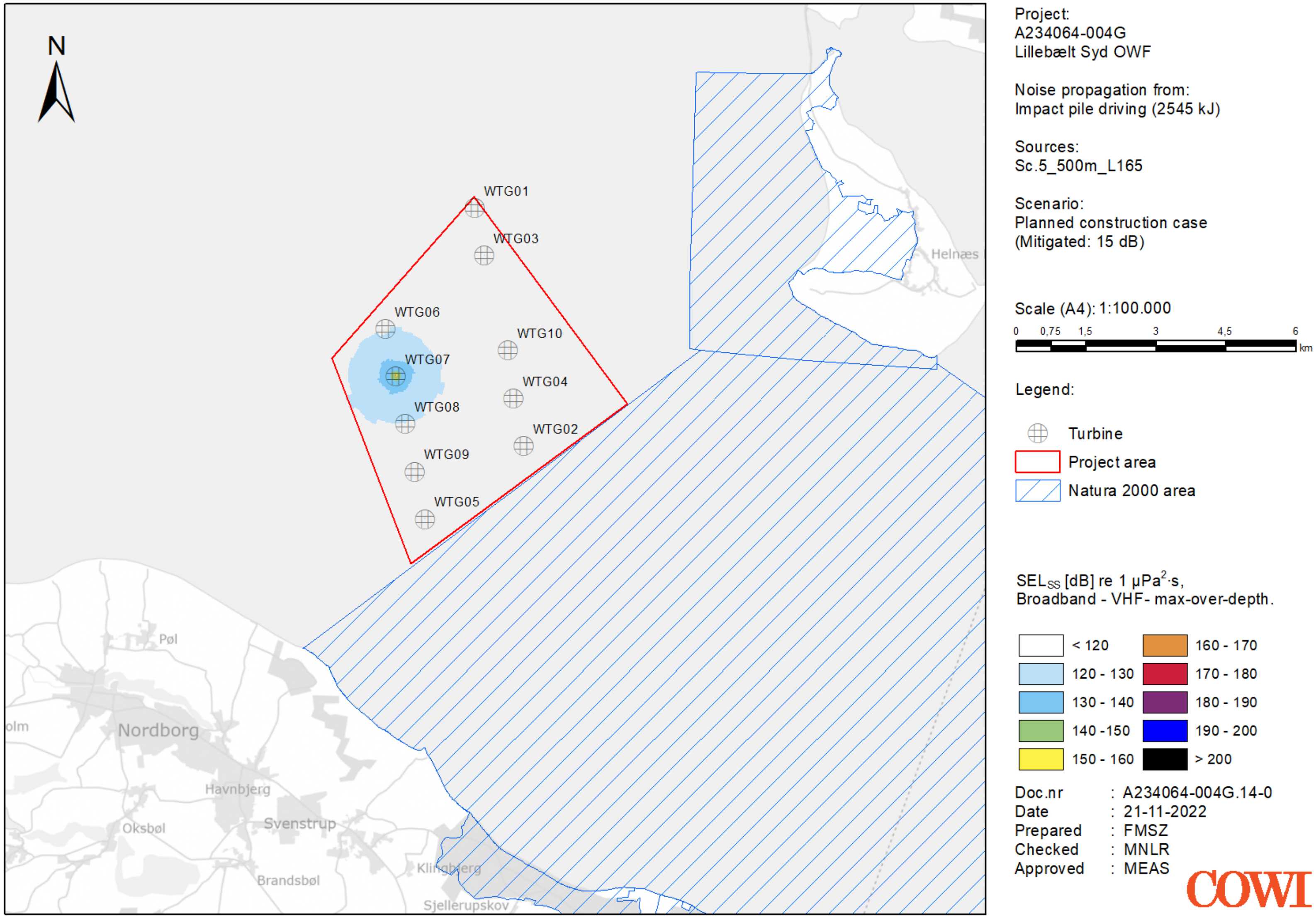

Figure 18 Construction noise map: Mitigated (15 dB) SEL$_{SS}$ at position WTG07

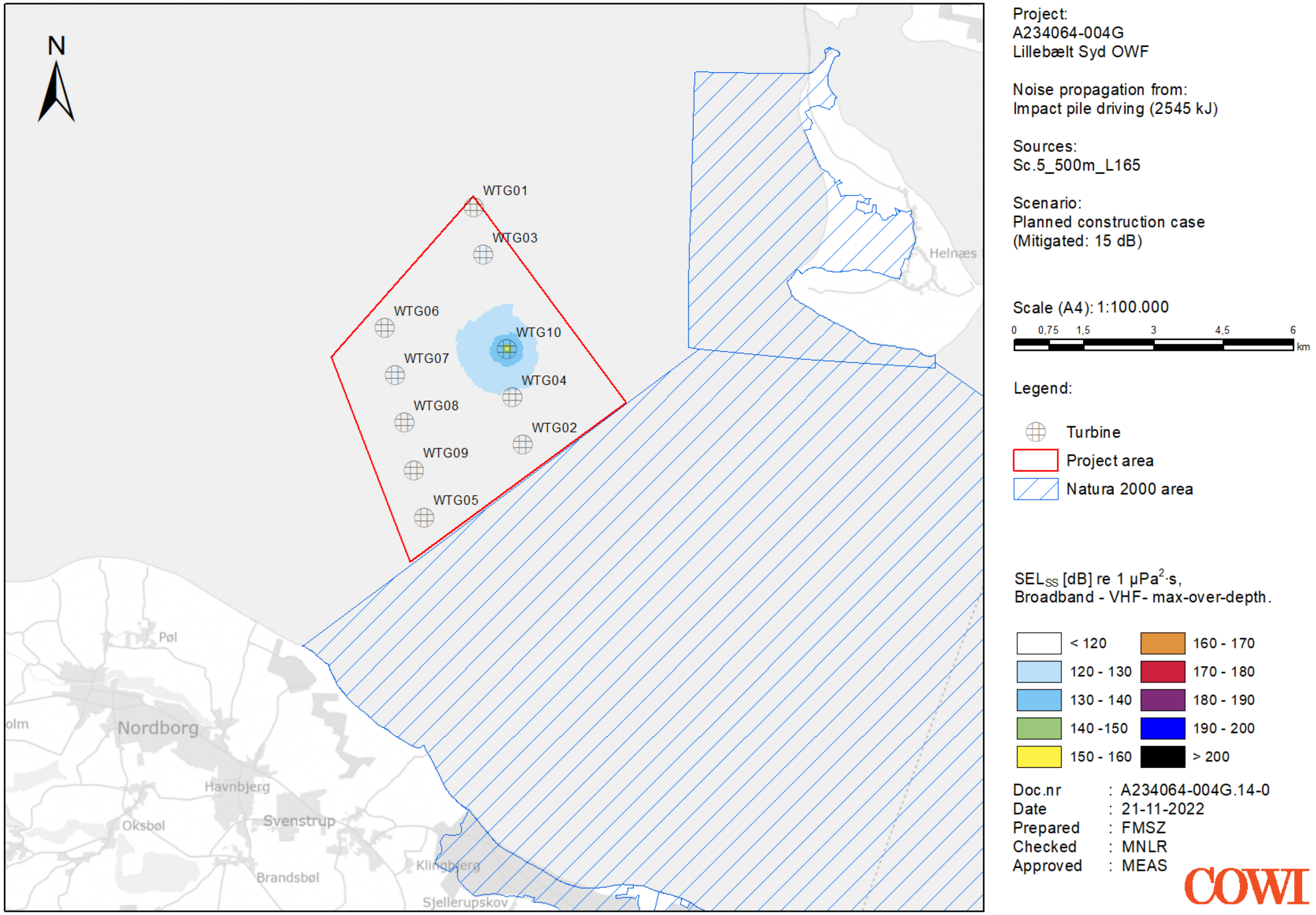

Figure 19 Construction noise map: Mitigated (15 dB) SEL$_{SS}$ at position WTG10

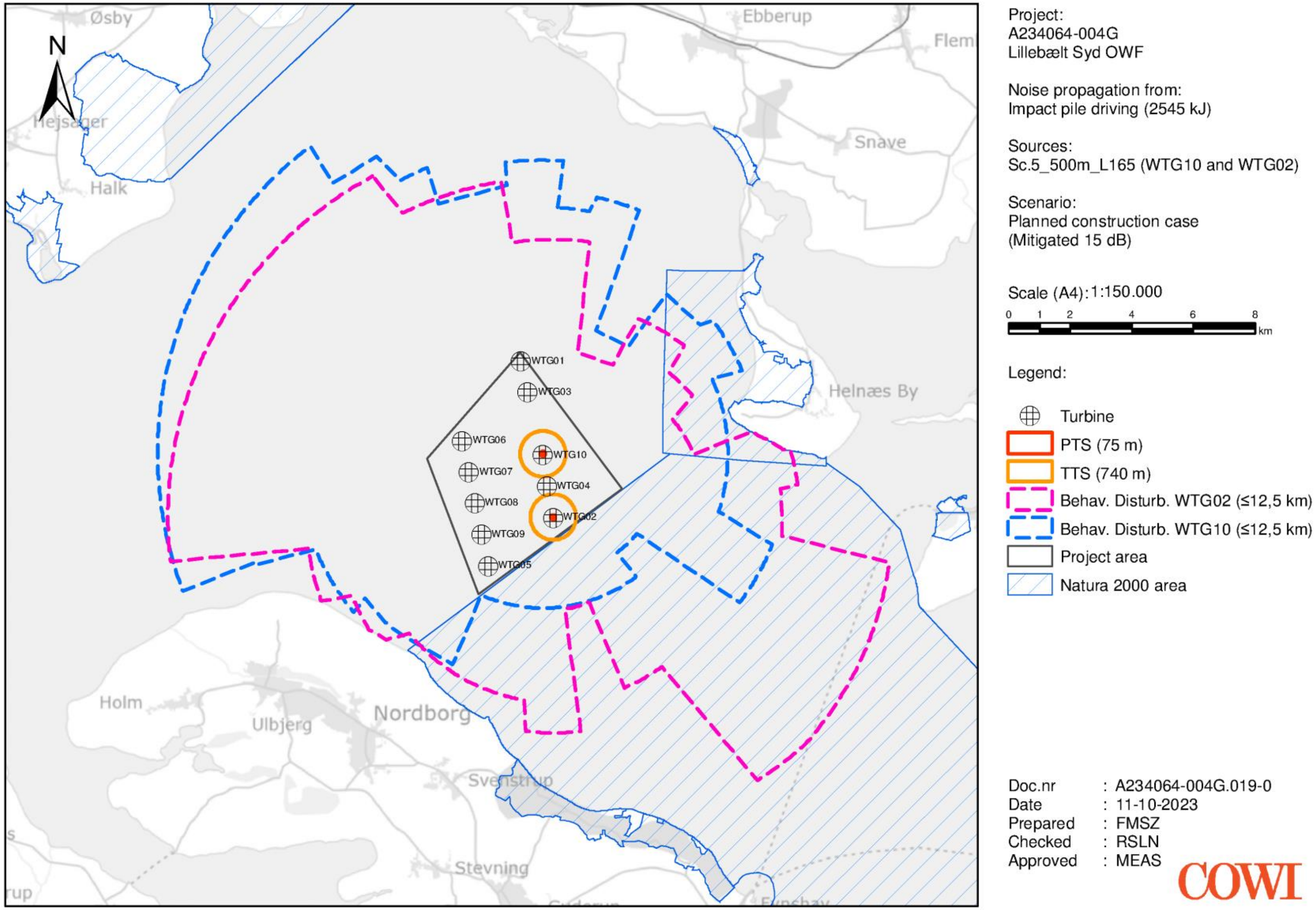

Figure 20 Construction noise map: Buffer to main thresholds depending on the porpoise's initial position. Based on SEL_{cum} and SPL calculations for a planned, mitigated (15 dB) scenario layout nr. 5. Positions WTG02 and WTG10. PTS: >155 dB_{VHF} re 1µPa^{2}s, TTS: >140 dB_{VHF} re 1µPa^{2}s, Behavioural Disturbance: >103 dB_{VHF} re 1µPa.

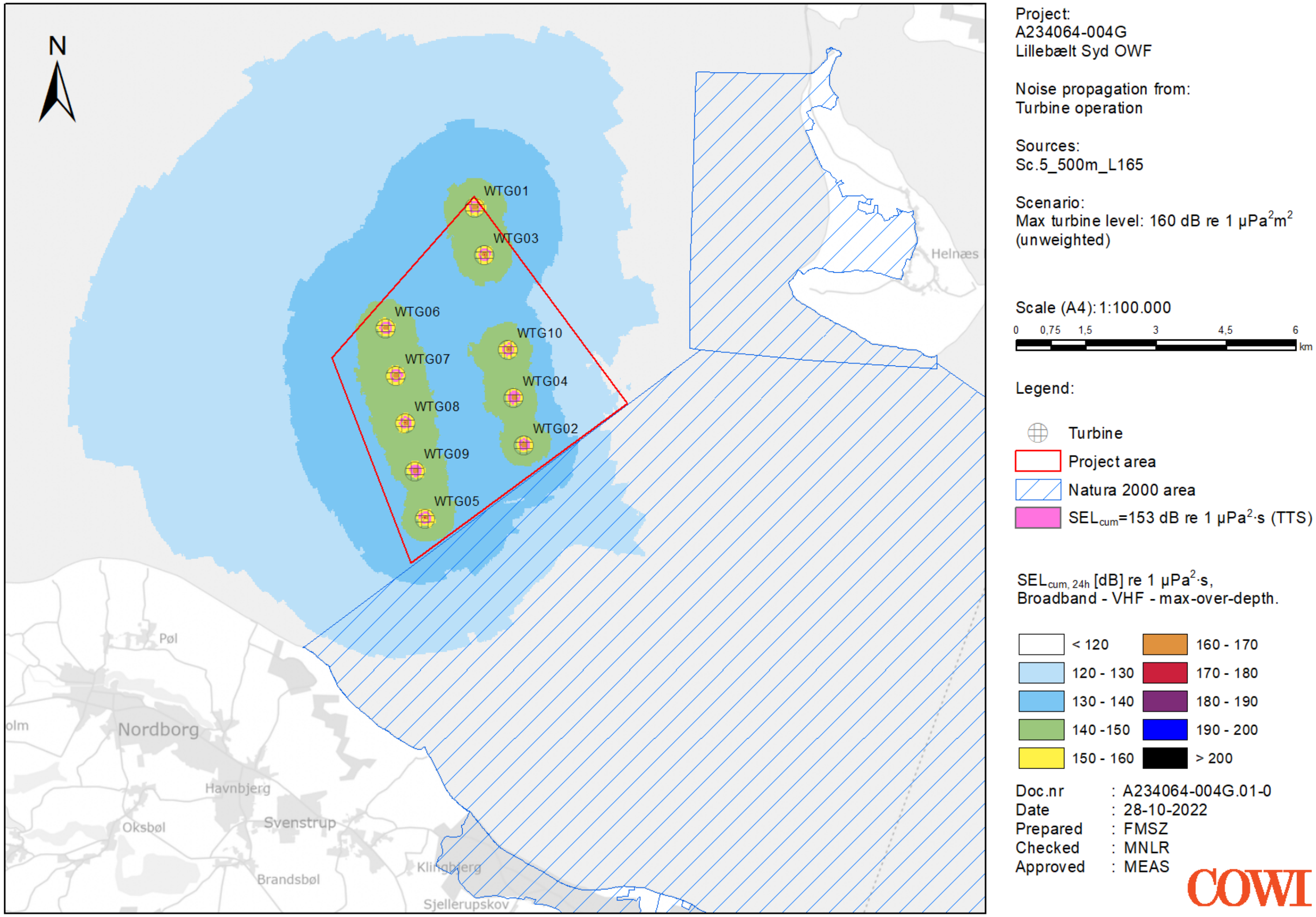

Figure 21 Operational noise map: $SEL_{cum\ 24h}$

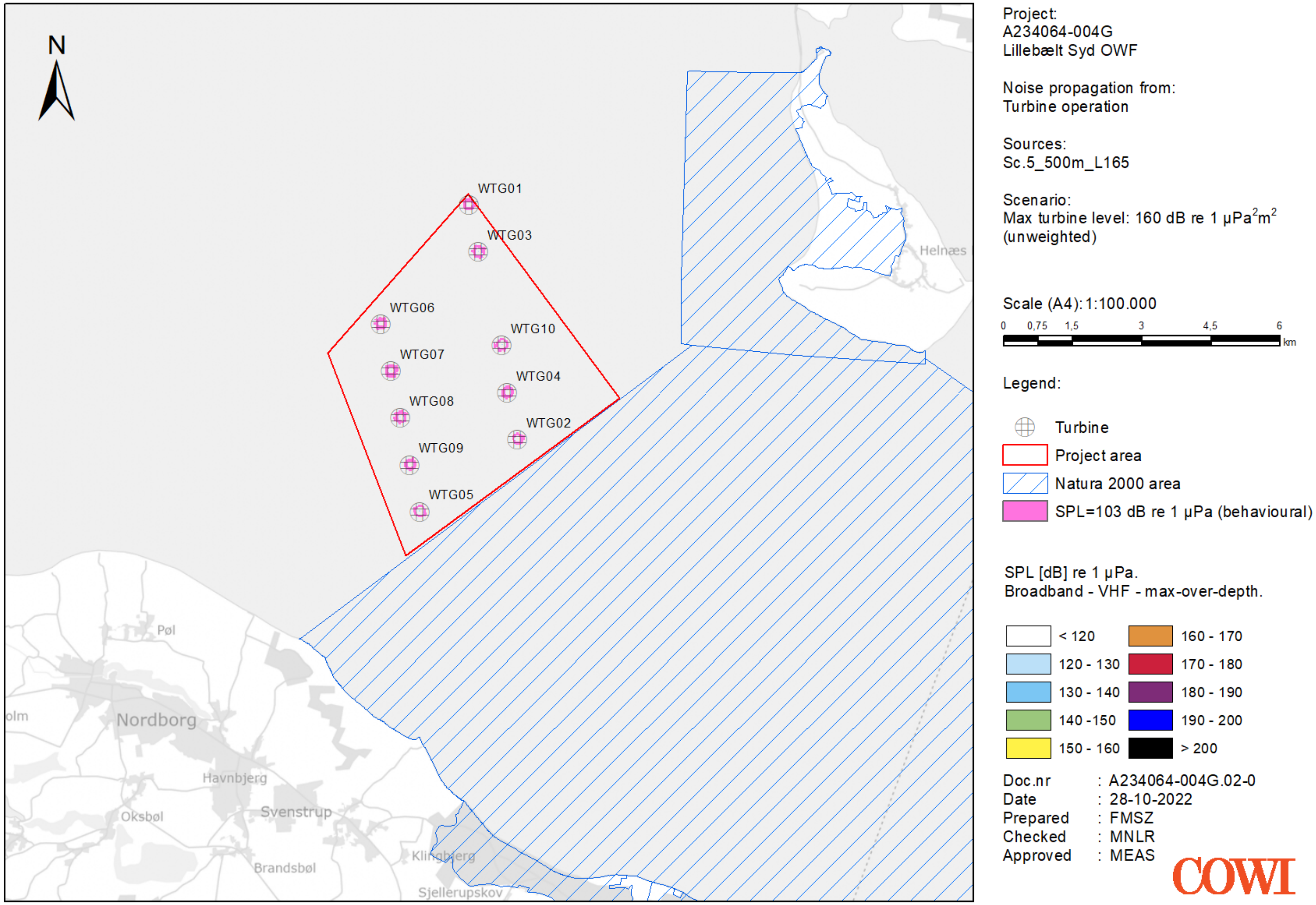

Figure 22 Operational noise map: SPL

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