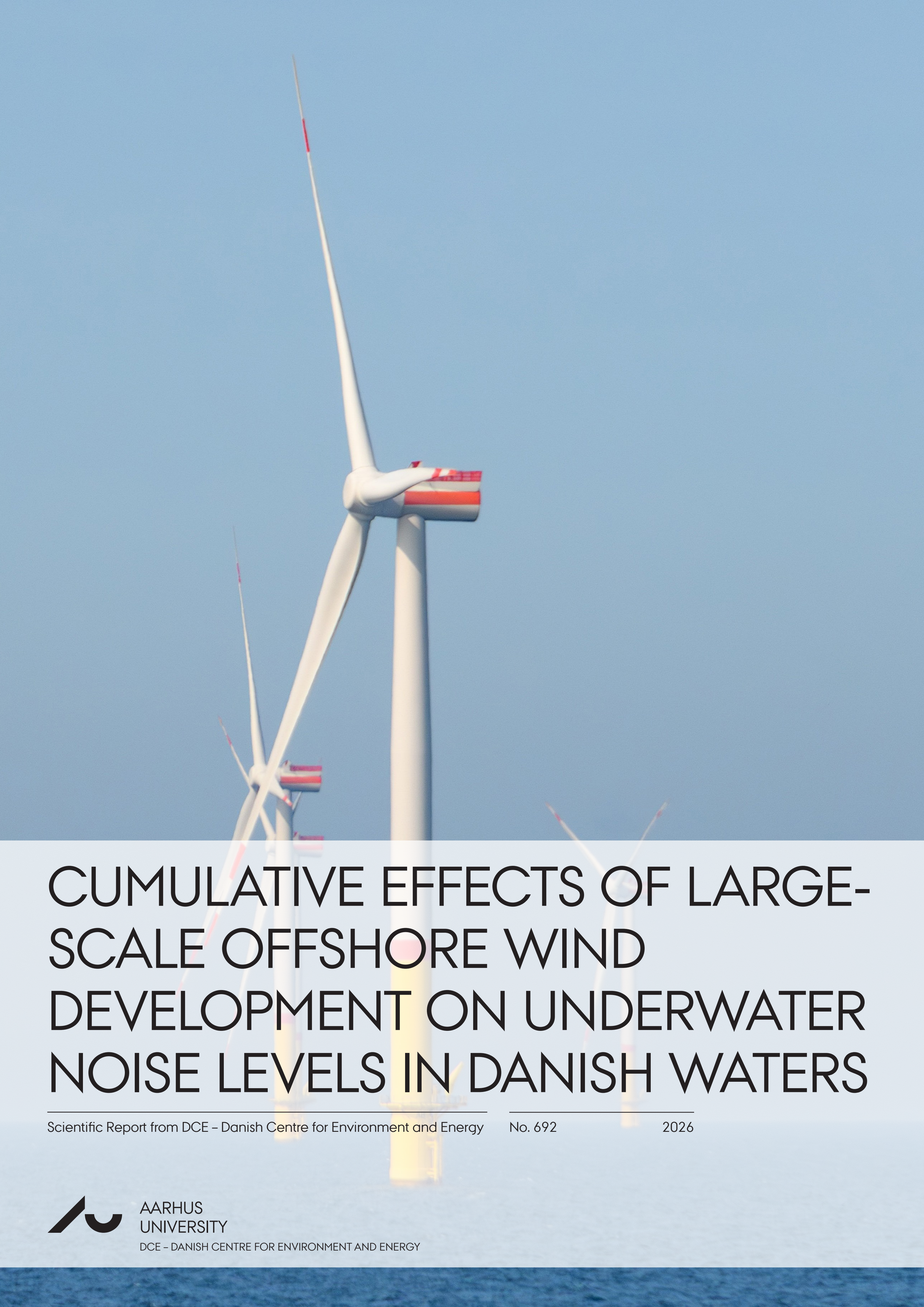

CUMULATIVE EFFECTS OF LARGE-SCALE OFFSHORE WIND DEVELOPMENT ON UNDERWATER NOISE LEVELS IN DANISH WATERS

Scientific Report from DCE – Danish Centre for Environment and Energy | No. 692 | 2026

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Data sheet

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Abstract: Current (2023) and projected future (2030) underwater noise conditions were modelled for Danish marine waters, to understand the relative contribution of future offshore wind development on cumulative underwater noise levels. Underwater noise was modelled for three areas surrounding Denmark separately (North Sea, Western Baltic, and Bornholm) in two or three frequency bands centered at 125 Hz, 315 Hz and – for North Sea - 500 Hz. The results showed that expanding offshore wind energy in Danish marine waters is likely to negatively affect the indicators used to assess Good Environmental Status in the framework of the Danish Marine Strategy, thereby making it more difficult to achieve and/or maintain Good Environmental Status. Underwater noise from operation of offshore wind farms should be included in future assessments of new projects and appropriate measures to reduce the radiated noise levels, particularly from services vessels, should be considered. However, the main contributor to the continuous noise indicators is likely to remain commercial shipping.

Keywords: Offshore Wind Farms, Underwater Noise, Soundscape Modelling, Marine Mammals

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Content

Preface

This report contributes to the project "*Environmental mapping and screening of areas for offshore wind in Denmark*" initiated in 2022 by the Danish Energy Agency. The project aims to support the long-term planning of offshore wind farms by providing a comprehensive overview of the combined offshore wind potential in Denmark. It is funded under the Finance Act 2022 through the programme "Investeringer i et fortsat grønnere Danmark" (Investing in the continuing greening of Denmark). The project is carried out by NIRAS, DCE (Aarhus University, Department of Ecoscience) and DTU Wind.

The overall project consists of four tasks defined by the Danish Energy Agency (https://ens.dk/ansvarsomraader/vindmoeller-paa-hav/planlaegning-af-fremtidens-havvindmoelleparker):

1. Sensitivity mapping of nature, environmental, wind and hydrodynamic conditions.
2. Technical fine-screening of areas for offshore wind based on the sensitivity mapping and relevant technical parameters.
3. Assessment of potential cumulative effects on the environment from large-scale offshore wind development in Denmark and neighbouring countries.
4. Assessment of barriers and potentials in relation to coexistence.

This report addresses one component of Task 3, namely the cumulative impact of large-scale offshore wind development on underwater noise in Danish marine waters (territorial waters and economic exclusive zone). The report provides an assessment of how noise levels across Danish territorial waters are predicted to change due to the expected offshore wind expansion. The assessment is divided into three regions: 1) the Danish part of the North Sea and Western Skagerrak, 2) the Danish part of the Western Baltic (covering Eastern Skagerrak, the Kattegat, the Belt Seas, the Sound and Western Baltic), 3) the Danish waters around Bornholm (the Arkona and Bornholm basins) (Table 2.1). The assessment focuses on operational noise from offshore wind farms, including noise from wind turbine generators and service vessels, i.e. no contribution of noise from construction of the anticipated new wind farms is included, as this contribution is temporary. Additionally, the assessment framework incorporates existing ship traffic as well as natural wind-generated ambient noise as a baseline.

The assessment presented in this report consists of a comparison of anthropogenic contributions to underwater noise modelled in a baseline scenario (2023) and a future scenario (2030). All input parameters of the two models were kept the same with the exception of the presence of a larger number of offshore wind farms in the future scenario and minor changes to the shipping routes caused by the new wind farms. Locations, sizes and other parameters for the future wind farms were provided by the Energy Agency. No new data was obtained specifically for this report. This project was supported by the Danish Energy Agency and in part by Energinet.

Summary

Denmark has set ambitious goals to become more reliant on green energy sources, with a keen focus to tender the construction of multiple offshore windfarms (OWF) by 2030. While the planned construction of offshore windfarms will aid in Denmark's green energy transition, changes to environmental pressures caused by wind farms must be considered. This includes underwater noise resulting from both operational and planned windfarms. Descriptor 11 of the EU Marine Strategy Framework Directive (2008/56/EC) calls for nation states to address the negative effects of noise on the marine environment and assure Good Environmental Status (GES) in their waters. With respect to continuous noise, the median noise levels cannot exceed the Level of Onset of Biologically Adverse Effects (LOBE) for 20% of a target species habitat in any month or quarterly assessment within a given year, which allows 80% of the species carrying capacity.

Here, the Danish marine waters were split into three distinct areas: North Sea (west of Denmark), Western Baltic (between Denmark and Sweden), and the area around Bornholm (see map in Table 2.1). For each of these areas, both the current and the projected future noise conditions were modelled for Danish waters with the addition of 17 OWF currently under tender for development by the Danish Energy Agency. Modelled noise maps included natural ambient noise overlaid with projected noise from the OWF, from the OWF + associated service vessels, and the total noise from OWF, service vessels, and regular shipping traffic. Maps provided the absolute modelled noise, as well as the excess noise above modelled ambient conditions. In each location, at least the 125 Hz and the 315 Hz decidecade band were calculated.

The North Sea area experienced the smallest impact, though it was averaged over the largest area, while the Bornholm area measured the largest LOBE exceedance. In Figure A, median excess noise (L_{50}) above LOBE (20 dB) exceeded 20% in both frequency bands during Q1 (winter) when the hydrographic conditions are favourable for increased sound propagation, and are at 20% for the 315 Hz band during Q3 (summer), the decidecade band selected to better predict noise originating from OWFs. Additional noise from the OWF turbines and service vessels is above LOBE between 25-50% of the area for the lower exceedance levels in the future scenario.

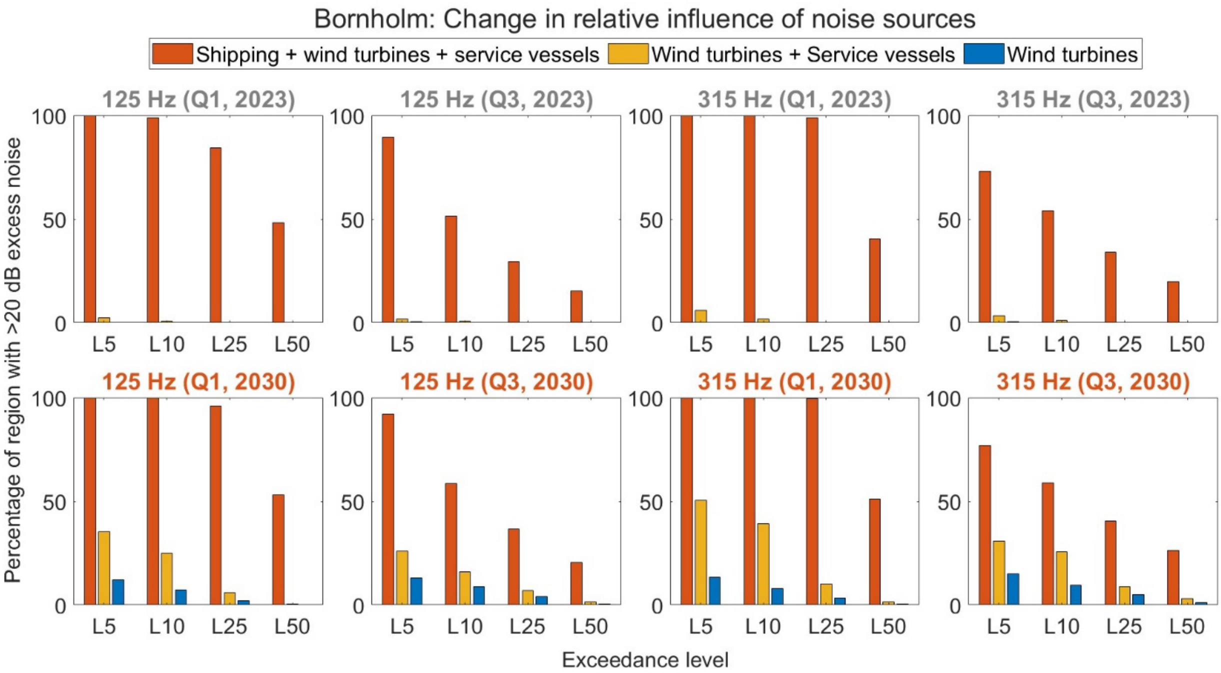


Figure A. The percentage of the Danish EEZ around Bornholm where excess noise was higher than the 20 dB LOBE under different exceedance levels, parsed out by noise source and plotted for current (2023, top) and future (2030, bottom) scenarios.

Overall, shipping traffic was the highest contributor to underwater noise in all three regions, in both current and future scenarios. When shipping noise was removed from the analysis, median noise levels did not exceed LOBE in 20% or more of any of the three modelled regions. While cumulative noise levels do increase for lower exceedance levels, the source of this noise comes mostly from service vessels, and steps can be taken to reduce this impact such as slow down speeds or coordination in service schedules.

Resumé

Danmark har fastsat ambitiøse målsætninger for en øget anvendelse af vedvarende energikilder, herunder med et betydeligt fokus på udbud og etablering af flere havvindmølleparker (Offshore Wind Farms, OWF) frem mod 2030. Selvom den planlagte udbygning af havvindmøllekapacitet vil bidrage væsentligt til den grønne omstilling, er det nødvendigt at inddrage undervandsstøj fra både eksisterende og planlagte havvindmølleparker i vurderingen af god miljøtilstand i danske havområder. Deskriptor 11 i EU's havstrategirammedirektiv (2008/56/EF) fastlægger, at medlemsstaterne skal forebygge og begrænse negative effekter af undervandsstøj på det marine miljø. For kontinuerlig støj gælder, at mediane støjniveauer ikke må overstige niveauet for biologisk skadelige effekter (Level of Onset of Biologically Adverse Effects, LOBE) i mere end 20 % af en arts levested i nogen måned eller kvartalsvis vurdering inden for et kalenderår, hvilket svarer til, at mindst 80 % af artens bæreevne opretholdes.

I denne analyse er Danmarks eksklusive økonomiske zone opdelt i tre geografiske delområder: Nordsøen (vest for Danmark), den vestlige Østersø (mellem Danmark og Sverige) samt området omkring Bornholm (jf. kort i tabel 2.1). For hvert delområde er både de aktuelle og de forventede fremtidige støjforhold modelleret for danske farvande under inddragelse af 17 havvindmølleparker, som på analysetidspunktet er i udbud hos Energistyrelsen. De modellerede støjkort inkluderer støjbidrag fra havvindmølleparker alene, fra havvindmølleparker og tilknyttede servicefartøjer samt den samlede støjbelastning fra havvindmølleparker, servicefartøjer og eksisterende skibstrafik. Både absolutte støjniveauer og støjniveauer som overskyder baggrundsstøj (excess noise) er modelleret. For alle områder er kumulative støjniveauer beregnet for mindst to frekvensbånd, tredjedelsoktavbåndene centreret omkring 125 Hz og 315 Hz.

Resultaterne viser, at Nordsøområdet samlet set er mindst påvirket, om end vurderingen her er baseret på det største geografiske areal. Området omkring Bornholm udviser derimod de største overskridelser af LOBE. Som vist i figur A overstiger den mediane overskydende støj (L50) over LOBE (20 dB) 20% af arealet i begge frekvensbånd i første kvartal (vinter), hvor de hydrografiske forhold generelt er gunstige for øget lydudbredelse. Endvidere når overskridelsen 20% for 315 Hz-båndet i tredje kvartal (sommer), hvilket er det tredjedelsoktavbånd, der anvendes som indikator for støj fra havvindmølleparker. I fremtidsscenariet overstiger den ekstra støj fra vindmølleturbiner og servicefartøjer LOBE i ca. 25–50 % af arealet ved lavere overskridelsesniveauer.

På tværs af alle tre delområder udgør skibstrafik den væsentligste kilde til kontinuerlig undervandsstøj, både for det nuværende og fremtidige scenarie. Når støj fra skibstrafik udelades overstiger de mediane støjniveauer ikke LOBE i 20% eller mere af nogle af de tre modellerede områder. Selvom de planlagte vindmølleparker fører til at kumulative støjniveauer øges ved lavere overskridelsesniveauer skyldes denne stigning primært støj fra servicefartøjer. Der vurderes at være mulighed for at reducere denne påvirkning, for eksempel gennem hastighedsbegrænsninger og øget koordinering af service- og vedligeholdelsesaktiviteter.

1 Introduction

Large-scale offshore wind development is a central component of Denmark's strategy towards achieving net zero emissions while also strengthening national energy security. This large-scale development of offshore wind introduces anthropogenic pressures on the marine environment that must be managed. One of these pressures is underwater noise, which is generated during all phases of offshore wind farm development, from site surveys and construction through to operation and eventual decommissioning. Underwater noise impacts marine life in various ways – for operating wind farms disturbance of animal behaviour, masking of biologically important sounds used for communication and foraging, and long-term exposure to elevated noise levels is also believed to induce physiological stress and cardiovascular effects.

Recognizing the impacts of underwater noise on marine ecosystems, EU has established a comprehensive regulatory framework through the Marine Strategy Framework Directive (MSFD, 2008/56/EC), where Descriptor 11 specifically addresses the introduction of underwater noise from human activities. Quantitative criteria for assessing Good Environmental Status (GES) are based on the concept of the Level of Onset of Biologically adverse Effects (LOBE), which is defined as "the noise level at which individual animals start to have adverse effects that could affect their fitness" (Borsani et al. 2023). For continuous underwater noise from shipping or operational wind turbine generators (WTG), OSPAR guidelines define GES as no more than 20% of a target species' habitat exposed to noise levels above the LOBE in any month of the assessment year.

Sustainable large-scale offshore wind development therefore requires evaluating the expected cumulative effects of planned offshore wind development projects on national underwater noise levels. While individual projects undergo environmental impact assessments that consider their isolated effects, the combined impact of large-scale offshore wind development may result in noise levels that exceed acceptable thresholds across a much larger area and therefore compromise GES. Cumulative effects assessment is particularly important in regions where multiple OWFs are planned, potentially leading to additive impacts on marine fauna.

This report presents an assessment of the potential effects of Denmark's planned offshore wind farm development on underwater noise levels, specifically addressing likely effects of these projects on indicators for GES under MSFD criterion D11C2. The assessment focuses on continuous noise associated with operation of OWF, including noise from wind turbines as well as associated service vessels. By quantifying the spatial and temporal extent of noise exposure across Denmark's marine waters, and how these are altered given expected offshore wind developments by 2030, this report aims to inform decision-making processes and identify potential areas of concern to ensure that Denmark's renewable energy ambitions are realized in a manner that is ecologically sustainable and compliant with objectives of the Danish Marine Strategy.

2 Methods

2.1 The Quonops Model

Modelling of the contribution of operational wind farms to the anthropogenic sound in the ocean was performed by the Quonops modelling tool, developed and maintained by Quiet Oceans, Plouzané, France (Folegot et al., 2016). This modelling framework has been used extensively, also in Danish waters, including modelling for the HOLAS 3 assessment (J. Tougaard, M. Ladegaard, E. Griffiths, & C. Marcolin, 2023). Briefly, the model calculated statistical estimates of the natural ambient noise, ship noise, and noise generated from the offshore wind farms (OWF), both the wind turbine generators themselves (WTG) and the associated service and crew exchange vessels. Natural ambient noise was estimated from the relationship between wind speed and natural condition noise level (Knudsen-Wenz curves). Three anthropogenic noise contributions were modelled: WTG noise alone, WTG + OWF service vessels, and the total noise generated from WTG, service vessels, shipping traffic, and wind noise. Finally, both total noise level (sum of anthropogenic and natural noise) and excess noise level (level of anthropogenic noise above natural noise) was estimated for each modelling scenario.

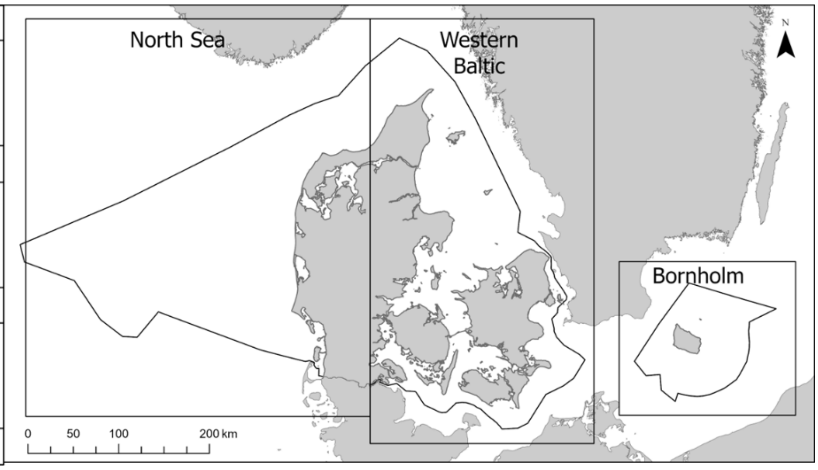
2.1.1 Modelling Area

Modelling covered the entire Danish marine waters, i.e. territorial waters and economic exclusive zone (EEZ). For technical reasons, the modelling was subdivided into three rectangles covering 1) North Sea (including the Danish part of the North Sea as well as Western Skagerrak), 2) Western Baltic (covering Eastern Skagerrak, the Kattegat, the Belt Seas, the Sound and Western Baltic), 3) Bornholm (including the Arkona and Bornholm basins). Bounding polygons are indicated in Table 2.1, together with the spatial resolution of the output maps. Projection and datum of the model is latitude/longitude, WGS84 (EPSG 4326).

To study the impacts of noise decidecade bands were modelled, bandwidths of 1/10th of a decade or a decidecade (for all practical purposes identical to 1/3 of an octave). For the North Sea area, three decidecade frequency bands were selected, with centre frequencies of 125 Hz, 315 Hz, and 500 Hz. For both the Western Baltic and Bornholm area, modelled decidecade bands were 125 Hz and 315 Hz.

Table 2.1. Details including bounding box coordinates and spatial resolution of the three modelled areas. Rectangles of the three areas are illustrated on the map to the right. Within each rectangle, parts that are within the Danish EEZ are outlined with a black line. For more information about offshore wind farm locations, see Figure 2.3.

North Sea	
Latitude	54.8°N – 58.3°N
Longitude	3.2°E – 9.5°E
Resolution	341 x 369 m
Western Baltic	
Latitude	53.9°N – 58.5°N
Longitude	9.5°E – 13.1°E
Resolution	300 x 300 m
Bornholm	
Latitude	54.5°N – 55.8°N
Longitude	13.1°E – 16.9°E
Resolution	150 x 150 m
Datum: WGS84 (EPSG 4326)	



2.1.2 Input parameters to the models

Table 2.2 lists the input parameters for the model. Some of these are standard Quonops input parameters, some have been extracted from additional sources for this project, and some have been developed as part of the project. All are further described in the following sections.

Table 2.2. List of input data and sources.

Parameter	**Source(s)**	**Comments**
Bathymetry	EmodnetQO50m	Standard Quonops layer
Sediment properties	SHOM	Standard Quonops layer
Hydrography	CMENS	Standard Quonops layer
Wind and wave statistics	CMENS/NCEP	Standard Quonops layer
AIS ship data	Marine Traffic, Danish Shipping Authority	QO AIS database
VMS ship data	Danish Fisheries Agency	Provided by AU
Ship source model	RANDI 3.1C JE	(MacGillivray & de Jong, 2021)
Turbine source model	Project specific	See description below
Service vessel source model	Project specific	See description below
Existing wind farms	Energistyrelsen (2024)	See description below
2030 model scenario	Energistyrelsen (2024)	See description below

The standard Quonops layers within the model are the basis for modelling the natural ambient noise conditions and were sourced from larger databases and weather hindcast models. Bathymetric data was extracted from EMODnet at a spatial resolution of 27m x 49m. Benthic sediment dynamics were extracted from the French Service Hydrographique et Océanographique de la Marine (SHOM) at a spatial resolution of 102m x 185m. Vertical sound speed profiles and wave height were hindcasted by E.U. Copernicus Marine Service Information, or CMENS (https://doi.org/10.48670/moi-00054 and https://doi.org/10.48670/moi-00055, respectively). Sound speed profiles were extracted on a daily basis, while wave height was extracted on an hourly basis, and both at a 2km x 3km spatial resolution. Wind speed came from the NCEP global forecast at a 3-hour temporal resolution and 31km x 56km spatial resolution.

2.1.3 Recordings for model calibration

Ambient and ship noise recordings were supplied to Quiet Oceans for calibration of the sound propagation models in each of the three model regions. These recordings were provided by DCE/ECOS and consisted of data from the Danish national monitoring program for underwater noise (Marine Strategy Framework Directive criterion D11C2; see for example J. Tougaard, M. Ladegaard, E. Griffiths, & C. Marcolin, 2023), the strategic impact assessment for the Energy Island North Sea (Kyhn et al., 2024), and the strategic impact assessment for North Sea I (Sveegaard et al., 2024). Table 2.3 lists the amount of data supplied. Recordings were supplied to Quiet Oceans as calibrated decidecade levels with a temporal resolution of 1 second.

Table 2.3. Measured decidecade levels used to calibrate the Quonops model. Each band was first assessed if the noise data collected was sufficient for calibration. Bands were excluded if the root mean square error (RMSE) was greater than 2 dB, or if there was an abnormal noise source such as self-noise from the recording rig. Therefore, if a band was used for calibration, it is marked with a green 'OK', and if it was not it is marked with a red 'EXCL' for excluded. Within these data, all 'DKMst' stations refer to NOVANA (National Monitoring and Assessment Programme for the Aquatic and Terrestrial Environments) Danish noise monitoring stations, 'NS' refers to data collected at a North Sea I project station, and 'NSE' refers to data collected at a North Sea Energy Island project station. For more information about these stations, please refer to Tougaard et al. (2024), Sveegaard et al. (2024), and Kyhn et al. (2024) for the three projects, respectively. All NOVANA stations, as well as the Fehmarn Belt data, were downloaded from the ICES continuous noise database: https://underwaternoise.ices.dk/continuous

Area	Station	Begin	End	Coverage (days)	Status 125Hz	Status 315Hz	Status 500Hz
North Sea	DKMst202 Gule Rev East	4/5/2021	15/08/2021	104	OK	OK	OK
North Sea	DKMst202 Store Rev East	4/5/2021	6/7/2021	64	EXCL	OK	OK
North Sea	DKMst202 Store Rev West	5/5/2021	15/08/2021	103	OK	OK	OK
North Sea	NS02	19/04/2023	24/10/2023	160	OK	OK	OK
North Sea	NS06	22/04/2023	1/11/2023	123	OK	OK	OK
North Sea	NS13	20/04/2023	13/02/2024	163	OK	OK	OK
North Sea	NS14	22/04/2023	12/2/2024	259	OK	OK	OK
North Sea	NS16	20/04/2023	10/2/2024	229	OK	OK	OK
North Sea	NS25	21/04/2023	12/2/2024	202	OK	OK	OK
North Sea	NSE-02	15/11/2021	24/08/2022	267	OK	OK	OK
North Sea	NSE-03	15/11/2021	22/08/2022	279	OK	EXCL	EXCL
North Sea	NSE-06	9/6/2022	25/08/2022	78	EXCL	EXCL	OK
North Sea	NSE-08	2/6/2023	15/02/2023	466	OK	OK	OK
North Sea	NSE-09	16/11/2021	25/08/2022	252	OK	EXCL	EXCL
North Sea	NSE-12	20/05/2022	29/08/2023	445	OK	OK	OK
North Sea	NSE-13	15/11/2021	24/08/2022	164	OK	OK	EXCL
W. Baltic	DKMst038 Stevns	25/05/2018	6/12/2020	492	OK	OK	-
W. Baltic	DKMst103 Hjelm	27/05/2018	6/6/2020	416	OK	OK	-
W. Baltic	DKMst104 Anholt	27/05/2018	29/12/2021	535	OK	OK	-
W. Baltic	Fehmarn Belt	16/09/2017	15/09/2021	1120	OK	OK	-

2.2 Ships and ship source model

2.2.1 AIS ship data

AIS data was available from the Quiet Oceans' database and sources were Marine Traffic and the Danish Maritime Authority.

2.2.2 VMS ship data

VMS data included in the modelled areas, including a surrounding 20 km buffer, was supplied from the Danish Fisheries Agency through DCE/ECOS. The information consisted of individual positions received through the VMS system. To ensure anonymization of data, vessel identification was automatically replaced by a random identifier upon retrieval from the database to prevent later identification of ships. The data retrieved from the VMS-database for each data point were:

- Date and time (UTC)
- Anonymized vessel ID
- Position longitude (WGS84)
- Position latitude (WGS84)
- Speed over ground (knots)
- Course over ground (degrees true north)
- Length of vessel (m, if available)

An example of VMS and AIS data used in the North Sea area is shown in Figure 2.1.

2.2.3 Ship source model

The ship source characteristics, consisting of frequency source spectrum and source level, were modelled in Quonops by the RANDI 3.1c JE model framework, also known as the JOMOPANS-ECHO model (MacGillivray & de Jong, 2021). The model provides average ship noise spectra for 13 different ship types, scalable with ship length and speed. The substantial inter-ship variation in parameters is encompassed in the model by randomly adding an offset (positive or negative) drawn from a distribution around the mean with a variance obtained from the measured data behind the model. This particular implementation of the RANDI3 framework was specifically developed for the North Sea as part of the JOMOPANS project that supplied modelled noise maps for the most recent OSPAR Quality Status Report (Kinneging, 2022). A comparison between the JOMPANS-ECHO model and other current models is shown in Figure 2.2.

Figure 2.1. Map of combined AIS and VMS data from April 2023 in the North Sea study area used in this study. Highlighted in purple are existing offshore wind-farms (OWF) in 2023 in Danish and German waters. Visible are the straight shipping routes into the Baltic around Skagen. Isolated high-density spots in the central North Sea are due to ship traffic connected to the oil and gas fields, and larger areas of higher densities are aggregations of fishing vessels on major fishing grounds.

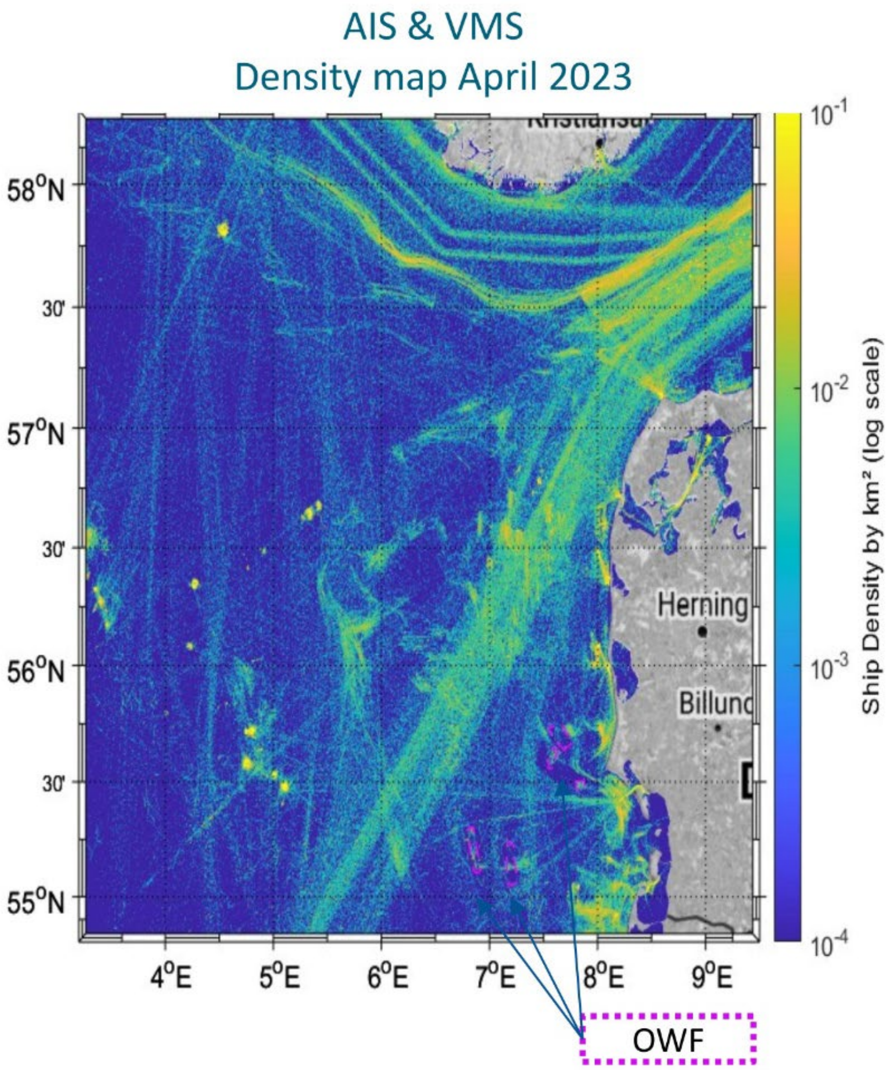
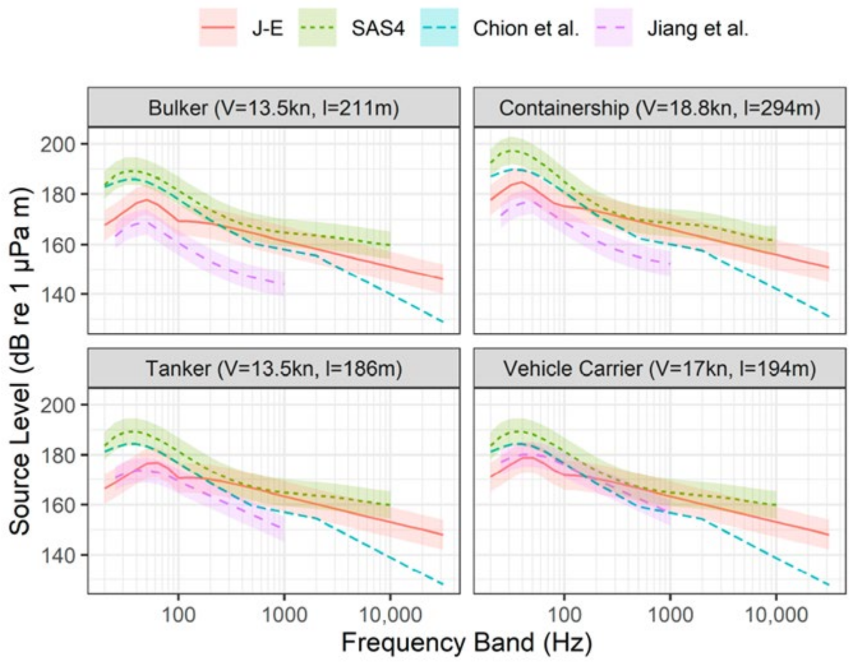


Figure 2.2. Examples of predicted source spectra for four different ship types and four different source models. The source model used in Quonops is the J-E model (red curve), which is the model developed and used by Quiet Oceans. The coloured band around the curves indicate +/- one standard deviation. From MacGillivray and de Jong (2021).



2.3 Wind farm scenarios

WTG sources were modelled as individual sources in the same way as ships, with the difference that WTG are stationary. Two scenarios were modelled: the present (2023) condition, and a predicted scenario for 2030 that was provided by the Danish Energy Agency (Energistyrelsen, 2024) (see Figure 2.3).

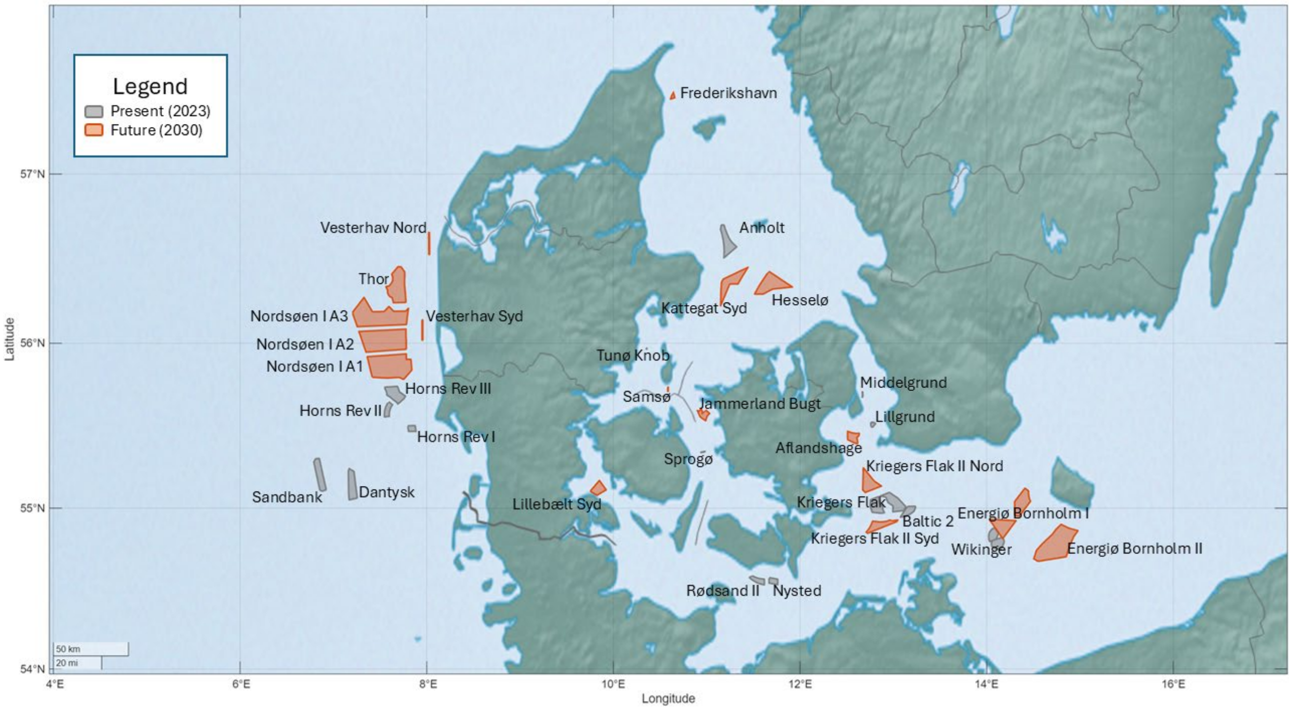


Figure 2.3. Map of wind farms of the present (2023) scenario (in gray) and additional planned wind farms in the future (2030) scenario (in orange) included in this analysis, as originally provided by the Danish Energy Agency.

2.3.1 Present scenario (2023)

The present scenario includes Danish offshore wind farms operational in 2023 (listed in Table 2.3 and indicated with red polygons in figure 2.3). The time frame covered by the present scenario covers twelve months from April 2023 to March 2024, but this is collectively referred to as the 2023 scenario within this document.

Three smaller existing wind farms were omitted: Rønland, Avedøre Holme and Frederikshavn. These turbines are technically offshore but located on the coast in very shallow water and are not believed to contribute significantly to the underwater noise further offshore.

Table 2.4. Wind farms included in the present (2023) scenario. Note: Wind farms included in the modelled scenario are based on information provided by the Danish Energy Agency at the start of this project.

Name	Region	OWF size	Turbine model, nominal capacity, gear type	Country
Horns Rev 1	North Sea	160 MW	Vestas V80-2.0 MW; gearbox	DK
Horns Rev 2	North Sea	209 MW	Siemens SWT-2.3-93, 2.3 MW; gearbox	DK
Horns Rev 3	North Sea	407 MW	Vestas V164-8.0 MW; gearbox	DK
Vesterhav Syd[1]	North Sea	344 MW	Siemens-Gamesa SG 8.0-167; 8 MW; Direct drive	DK
Anholt	Western Baltic	400 MW	Siemens SWT-3.6-120; 3.6 MW, gearbox	DK
Tunø Knob	Western Baltic	5 MW	Vestas V39-500kW; gearbox	DK
Samsø	Western Baltic	23 MW	Siemens SWT-2.3-82; 2.3 MW; gearbox	DK
Middelgrund	Western Baltic	49 MW	Bonus B76/2000; 2 MW; gearbox	DK
Nysted	Western Baltic	166 MW	Siemens SWT-2.3-82; 2.3 MW; gearbox	DK
Rødsand 2	Western Baltic	207 MW	Siemens SWT-2.3-93; 2.3 MW; gearbox	DK
Kriegers Flak	Western Baltic	605 MW	Siemens-Gamesa SG 8.0-167; 8 MW; Direct drive	DK
DanTysk	North Sea	288 MW	Siemens SWT-3.6-120; 3.6 MW, gearbox	DE
Sandbank	North Sea	288 MW	Siemens SWT-4.0-130; 4.0 MW, gearbox	DE
Lillgrund	Western Baltic	110 MW	Siemens SWT-2.3-93; 2.3 MW; gearbox	SE

2.3.2 Future scenario (2030)

A scenario for large-scale offshore wind development in Danish waters in 2030 was supplied by the Danish Energy Agency. The future scenario was modelled from April 2030 through March 2031, subsequently referred to as the 2030 scenario. The scenario consisted of all conditions present during the 2023 scenario, in addition to the planned offshore windfarms and service vessel traffic expected to be operational by 2030. Therefore, these modelled conditions include the wind farms listed in Table 2.3 and Table 2.4, or OWF shown in Figure 2.3.

All other parameters in the model were kept constant between the 2023 and 2030 scenario, including weather, hydrography, ship traffic, and ship source model. This essentially means that the 2030 scenario models how the underwater noise conditions would have been in 2023 if all wind farms in the 2030 scenario were in operation. This choice allows a direct analysis of the cumulative impact of the wind farms in 2030 and addresses what additional pressure they may exert on the marine environment. The only change in other parameters from the 2023 scenario to the 2030 scenario was that service vessel traffic associated with the new wind farms was added, and that ship traffic was diverted around new wind farms.

It was assumed that all wind farms operational in 2023 continue to be in operation in 2030 even though some of these are reaching the end of their projected lifetime (Tunø Knob, established 1995; Middelgrund, established 2000; Nysted, established 2002; Horns Reef 1, established 2003). Some of these wind farms may be decommissioned by 2030, others may be upgraded with different turbines in 2030, but as this is presently unknown, it is assumed that they will remain in service as they are. Several wind farms from other nations are also currently planned very close to the Danish EEZ. Some of these are relatively far in the process, including Galathea-Galene North, Kattegat South, and Swedish Kriegers Flak (all Sweden), and Gennaker (Germany), but these have not been included in the 2030 scenario as planning was not controlled by the Danish Energy Agency. Therefore, their noise contribution, if completed by 2030, was not included in the model.

Table 2.5. Wind farms included in the 2030 scenario in addition to the wind farms operational in 2023. For many of the OWF the size and turbine type which will be implemented is unknown or yet to be decided. In this case, a generic 15 MW model was used.

Name	Country	Region	Size and type
Nordsøen I A1	DK	North Sea	Generic 15 MW, direct drive
Nordsøen I A2	DK	North Sea	Generic 15 MW, direct drive
Nordsøen I A3	DK	North Sea	Generic 15 MW, direct drive
Thor	DK	North Sea	Siemens-Gamesa SG 14-236 direct drive
Vesterhav Nord	DK	North Sea	Siemens-Gamesa SG 8.0-167 direct drive
Frederikshavn	DK	Western Baltic	Generic 15 MW, direct drive
Kattegat Syd	DK	Western Baltic	Generic 15 MW, direct drive
Hesselø	DK	Western Baltic	Generic 15 MW, direct drive
Lillebælt Syd	DK	Western Baltic	Generic 15 MW, direct drive
Jammerland Bugt	DK	Western Baltic	Generic 15 MW, direct drive
Samsø	DK	Western Baltic	Generic 15 MW, direct drive
Aflandshage	DK	Western Baltic	Generic 15 MW, direct drive
Kriegers Flak 2 Syd	DK	Western Baltic	Generic 15 MW, direct drive
Kriegers Flak 2 Nord	DK	Western Baltic	Generic 15 MW, direct drive
Energiø Bornholm I	DK	Bornholm	Generic 15 MW, direct drive
Energiø Bornholm II	DK	Bornholm	Generic 15 MW, direct drive

2.4 Noise exposure from OWF model

Within the North Sea I project the noise source properties of two different turbine types were measured and characterized – an 8 MW turbine fitted with a gear box (Horns Rev 3) and an 8 MW turbine without gearbox (direct drive). A dynamic calculation of the source level of a wind turbine in operation, depending on wind speed, was used to model the operational noise of wind turbine generators based on pre-existing measurements (Bellmann et al., 2023) and measurements of underwater noise from operating turbines in the North Sea (Sveegaard, et. al., 2024). Noise emissions from WTGs were thus interpolated from these measurements and the general scaling with generator size, assuming that the noise from direct drive turbines scale with generator capacity in the same way as seen for turbines with gearbox. Direct drive systems generate electricity at much lower speeds; they do not require a gearbox and therefore have fewer moving parts. However, direct drive systems require heavier generators than geared machines for a given turbine capacity. Therefore, there is a predicted increase in noise output from each individual WTG which corresponds to the size of the generator. For the 2030 scenario it was assumed that all new installations would be with direct drive turbines. It was assumed that the radiated noise from turbines is independent of the type of foundation (monopile, jacket, gravity structure). For the 2023 scenario, the actual size of the turbines were be used. For the 2030 scenario, it was assumed that the nominal capacity of all new turbines installed would be 15 MW.

Ship noise related to wind farm maintenance is emitted by larger service operation vessels (SOVs) and smaller crew transfer vessels (CTVs). For the 2023 scenario, information about these vessels was available in the AIS data. For the 2030 scenario, both SOV and CTV activity for future wind farms had to be simulated by an AIS generator already developed by Quiet Oceans in the framework of a separate project.

2.5 Modelled output

For each scenario, decisions had to be made on which frequency bands to model, the temporal resolution and time span, and the statistical parameters to extract. The model output for the North Sea area was delivered by the North Sea I project and parameters were thus determined by this project. For the two remaining areas where modelling was undertaken as part of the current project and in order to reduce cost, only two of the three frequency bands used for the North Sea were included and modelling was restricted to two 3-month periods of the year rather than 12 consecutive months.

2.5.1 Frequency Bands

Noise was modelled to best assess the impact of noise from different anthropogenic sources, in either two or three frequency bands per area:

- Band A: 125 Hz decidecade band. This band has become a de facto reference band for ship noise, due to the requirements of the Marine Strategy Framework Directive to monitor this frequency band. Including this band ensures that results are comparable to outputs from other models (such as the models that have been used for the recently completed HELCOM HOLAS 3 and OSPAR QSR assessments).
- Band B: Wind turbine band, 315 Hz decidecade band. This band was chosen to represent the operational noise from wind turbines.
- Band C: Service vessel band, 500 Hz decidecade band. This band was chosen to represent underwater radiated noise from service vessels that are typically smaller vessels and therefore has proportionally less energy at 125 Hz band.

All three frequency bands were modelled in the North Sea area. For the two other areas, only 125 Hz and 315 Hz were modelled.

2.5.2 Time frame

For the North Sea area, noise levels were modelled monthly over a full year from April to March (2023/2024 and 2030/2031, for the present and future scenario, respectively). For the two other areas, a 'summer' and 'winter' quarter were selected, each covering three months: Q3 (July 1-September 31, 2023/2030) and Q1 (January 1-March 31, 2024/2031). These two periods were selected based on the most extreme hydrographical conditions so as to cover a worst-case and a best-case sound propagation scenario.

2.5.3 Conditional parameters modelled

Two main parameters were modelled for each decidecade band: the absolute sound pressure level ($L_{p,ddec}$) in units of dB re. 1 µPa, and the excess sound pressure level (L_{excess}) above natural sources, in units of dB. $L_{p,ddec}$ represents the rms-averaged (rms = root mean square) sound pressure level in the particular decidecade band. Output of Quonops are statistics of the modelled parameters aggregated over long time intervals (the temporal assessment period, cf. Borsani et al., 2023), 1 month for the North Sea and 3 months for the two other areas. More specifically, the statistics are aggregated from single noise maps, referred to as "snap shots", each with a time resolution of about 10 seconds (the temporal analysis window, cf. Borsani et al., 2023), modelled for each hour of the temporal assessment period. L_{excess} represents the difference between the total sound pressure level and the sound pressure level from natural sources alone (i.e. wind): $L_{excess} = L_{p,total} - L_{p,wind}$. The excess therefore represents the amount (in dB) that the ships and turbines contribute to the total noise, above the natural wind noise. L_{excess} has a lower bound of 0 dB, indicating no contributions from ships and turbines. Modelled values are the distribution of $L_{p,ddec}$ and L_{excess} over a month or quarter.

Table 2.6. Depth resolution for sound propagation modelling, optimized to fit within the CPU memory limits of the modelling computer.

North Sea	Western Baltic	Bornholm
Up to 50 m: 2m between 50/100m: 5 m between 100/500m: 10 m more than 500 m: 30 m	Up to 100 m: 3m between 100/200m: 5 m more than 200 m: 25 m	Up to 10 m: 1 m between 10/50m: 5 m more than 50 m: 10 m

Both parameters were modelled in depth layers based on the depth of the grid cell (Table 2.5). Within each grid cell, the statistical distribution of each parameter (Table 2.6) over the modelling period (one month or one quarter) was characterized by 7 exceedance levels (Table 2.6). These percentiles, or exceedance levels (L_x), are the 5th, 10th, 25th, 50th, 75th, 90th and 95th upper percentiles. L_5 therefore represents the level exceeded in 5% of the observations within the grid cell and L_{50} represents the median.

Table 2.7. Description of the output layer maps per timeframe/frequency band. For each layer, exceedance levels (L_x) calculated are the 5th, 10th, 25th, 50th, 75th, 90th and 95th upper percentiles.

Parameter	Layer
L_{total}	Shipping + service + turbines
$L_{excess, total}$	Excess level of the above over ambient
$L_{turbines}$	Turbine noise alone
$L_{excess, turbines}$	Excess level of the above
$L_{turbines + service vessels}$	Turbines and service vessels alone
$L_{excess, turbines + service vessels}$	Excess level of the above

2.6 Modelled maps processing

The potential impact on noise levels from the increase in windfarms around Denmark was examined across the Danish EEZ for each of the three areas. Procedures and criteria for assessing anthropogenic underwater noise are continuously being developed by international working groups such as TG Noise (European Commission), ICG-Noise (OSPAR) and EG-Noise (HELCOM). The most recent recommendations regarding assessment of Good Environmental Status (GES) for continuous underwater noise (EU Marine Strategy Framework Directive criterion D11C2). The assessment is based on evaluating the spatio-temporal exceedance of noise levels considered harmful to marine life (Level of Onset of Biological Effects, LOBE, see Borsani et al, 2024). Two different metrics are recommended for LOBE in such assessments: 1) the overall increase in noise levels caused by the presence of anthropogenic sources (excess level, L_{excess}), and the absolute sound pressure level (L_p) in a relevant or proxy frequency band. The particular choices of LOBE and tolerable fraction of time where LOBE can be exceeded have significant impact on the outcome of the assessment, as illustrated in Figure 2.4. In evaluation of the present and future scenarios for offshore wind, we used LOBE values identical to, or consistent with, the most recent national assessment of underwater noise in Danish marine waters (J. Tougaard, M. Ladegaard, E. Griffiths, & C. Marcolin, 2023), thereby following recommendations from HELCOM and OSPAR.

The final step in assessment of GES is evaluation of the fraction of each spatial assessment unit (so-called Marine Reporting Units, MRUs) where the median excess level or the median sound pressure level exceeds LOBE. If this fraction exceeds 20%, the MRU is not considered to be in Good Environmental Status (Borsani et al., 2024). Application of the 20% area threshold for GES has not been applied in this analysis as it is beyond the scope of the work, but as the analysis was performed with a method and choice of assessment parameters consistent with D11C2 assessment, the results are indicative of how realization of the 2030 scenario for offshore wind could affect a future assessment of GES in Danish marine waters.

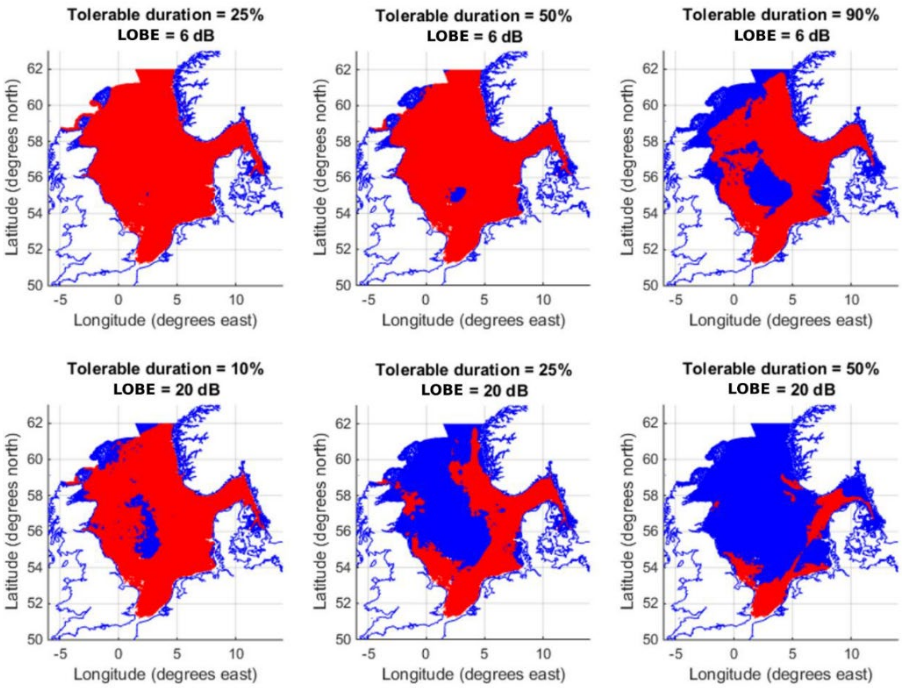


Figure 2.4. Modelled maps from the JOMOPANS project (Kinneging et al., 2023) used to illustrate the importance of choice of LOBE and tolerable duration. In each map the red area indicates where LOBE is exceeded for longer than the tolerable duration (expressed as percent of the time). Two different values of LOBE were used: 6 dB excess level, corresponding roughly to the lowest exceedance that can be modelled reliably and would result in roughly a halving of communication range, and 20 dB excess level, corresponding to a substantial (approximately 1/10th) reduction in effective communication distances for animals. From Borsani et al. (2023).

2.6.1 LOBE for masking

LOBE for excess level was set to 20 dB following recent assessments both in HOLAS 3 (HELCOM, 2023) and the North Sea Quality Status Report (OSPAR, 2023). An increase in ambient noise by 20 dB, everything else being equal, will result in a general reduction of the maximal communication range by 90% and thus indicates a substantial potential for impact on all animals communicating in the particular frequency band.

2.6.2 LOBE for behavioural response

LOBE for behavioural responses (usually deterrence by the noise) is expressed as a sound pressure level and is dependent on the frequency band in question. Substantial empirical evidence supports that harbour porpoises – the sole species where a reliable LOBE value has been set – respond to received sound pressure levels ($L_{p,125ms,\ VHF}$) at and above roughly 100 dB re 1µPa auditory frequency weighted with the VHF-weighting curve (Tougaard, 2025; Wisniewska et al., 2018). The poor low-frequency hearing of harbour porpoises means that they are unlikely to respond directly to the noise in the frequency bands modelled, but due to the stereotypic nature of the source spectra of ship noise (MacGillivray & de Jong, 2021) it is possible to extrapolate from the higher frequencies to LOBE values in the modelled bands that can function as proxies. Thus, for the 125 Hz and 500 Hz decidecade bands LOBE values used in the Danish D11C2 assessment were used: 115 dB re 1 µPa and 109 dB re 1 µPa, respectively (Tougaard et al., 2023), as these values were also used in the HOLAS 3 assessment and are considered the current standard. For the 315 Hz decidecade band a proxy LOBE value of 112 dB was interpolated (Figure 2.5). It should be kept in mind that these values are proxies for the actual impact and interpretation towards actual impact on porpoises must be done with great caution.

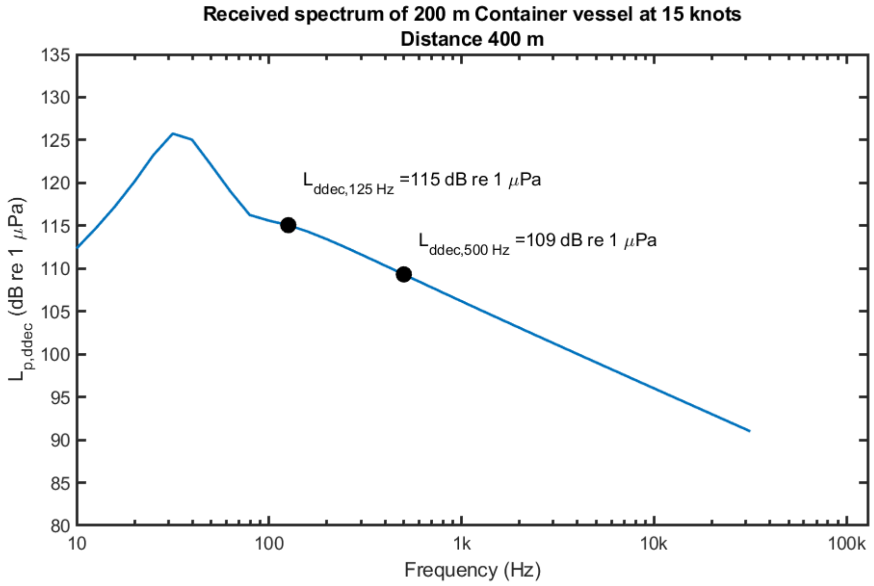


Figure 2.5. Received decidecade levels of a 200 m container vessel 400 m from a porpoise – a level predicted to be at the mean threshold for behavioural response to the noise. From the curve we can derive proxy levels in the 125 Hz, 315 Hz, and 500 Hz decidecade bands as 115 dB re 1 µPa, 112 dB re. 1 µPa, and 109 dB re. 1 µPa, respectively. The ship noise was modelled from the standard source model of MacGillivray and de Jong (2021). Figure adapted from Tougaard et al. (2023)

3 Results

For all three regions, the fraction of the region where median excess noise and median total sound pressure level exceeded LOBE was determined. Although the current guidance recommends using the median noise or excess noise levels (Borsani et al, 2024), lower exceedance levels were also visualized here to provide additional information. We note that the regions used here are different from the MRUs selected for D11C2 assessments, such as the OSPAR QSR2024 and HELCOM's HOLAS 3, and are only used to illustrate the regional changes in noise exposure due to large-scale offshore wind expansion. Unless otherwise noted, all plots represent the full accumulative noise, i.e. the sum of natural ambient, shipping, service vessels and turbines.

3.1 North Sea

3.1.1 Excess noise level

The spatial distribution of high excess noise levels was very similar across the three modelled frequency bands (Figures 3.1-3.3) with the shipping lane remaining prominent even as the exceedance level increases, particularly within the 125 Hz band. In the future scenarios, the wind farms and associated service vessels are more prominent within the 315 Hz band maps. For the 500 Hz band, which was selected to focus on service vessel radiated noise, noise values dissipate rapidly as exceedance levels increase, except at the new windfarm location sites.

In the 125 Hz band, the impact of offshore wind farms modelled in the 2030 scenario was very small across all months (Figure 3.4). The overall excess noise levels are high in the North Sea, with several months when median noise levels exceed the 20 dB LOBE criterion.

In the 315 Hz band, excess noise levels were also generally high. The impact of offshore wind farms and associated service vessels is still reasonably small but more pronounced in this frequency band. For example, in April median (L_{50}) noise levels in the 2030 scenario exceed the LOBE threshold in 20% of the modelled area within the Danish North Sea.

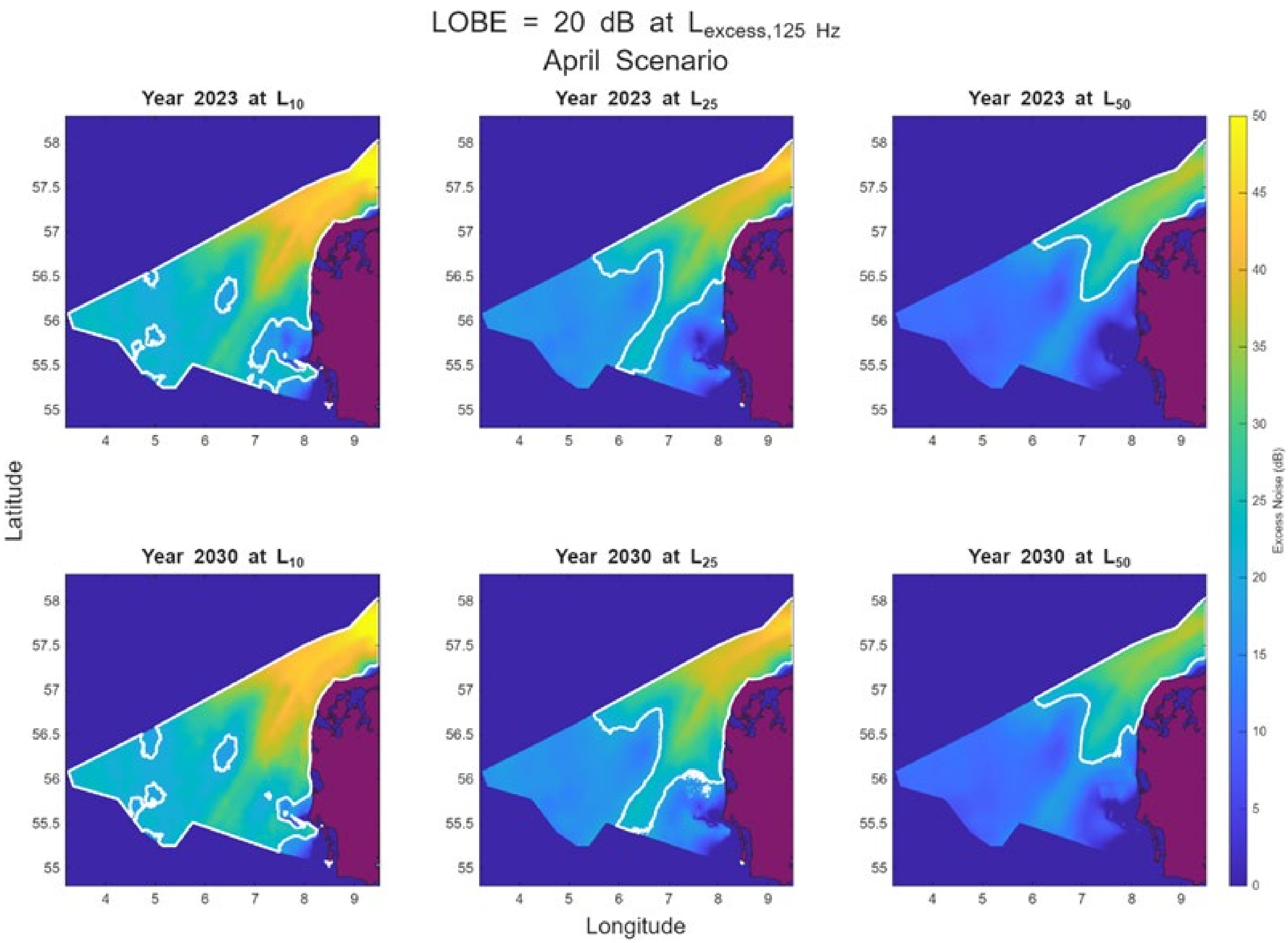


Figure 3.1. North Sea modelled excess noise levels for the 125 Hz decidecade band in the April scenario. Top row shows present (2023) scenario, bottom row shows future (2030) scenario. Each column shows a different exceedance level (L_{10}, L_{25}, and L_{50}). White boundary indicates areas that exceed a LOBE of 20 dB. For data from other months, please see Figure 3.4.

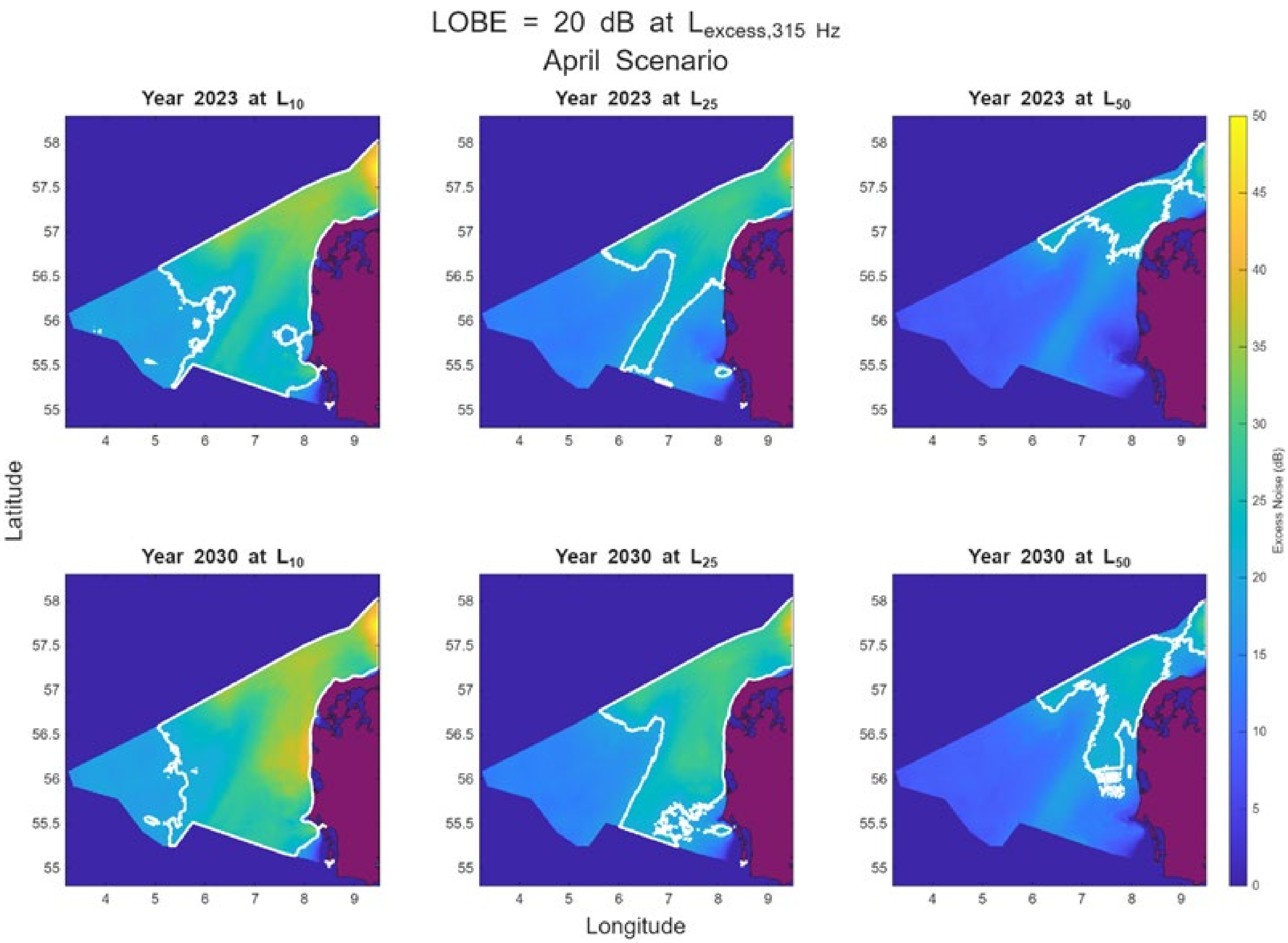


Figure 3.2. North Sea modelled excess noise levels for the 315 Hz decidecade band in the April scenario. Top row shows present (2023) scenario, bottom row shows future (2030) scenario. Each column shows a different exceedance level (L_{10}, L_{25}, and L_{50}). White boundary indicates areas that exceed a LOBE of 20 dB. For data from other months, please see Figure 3.5.

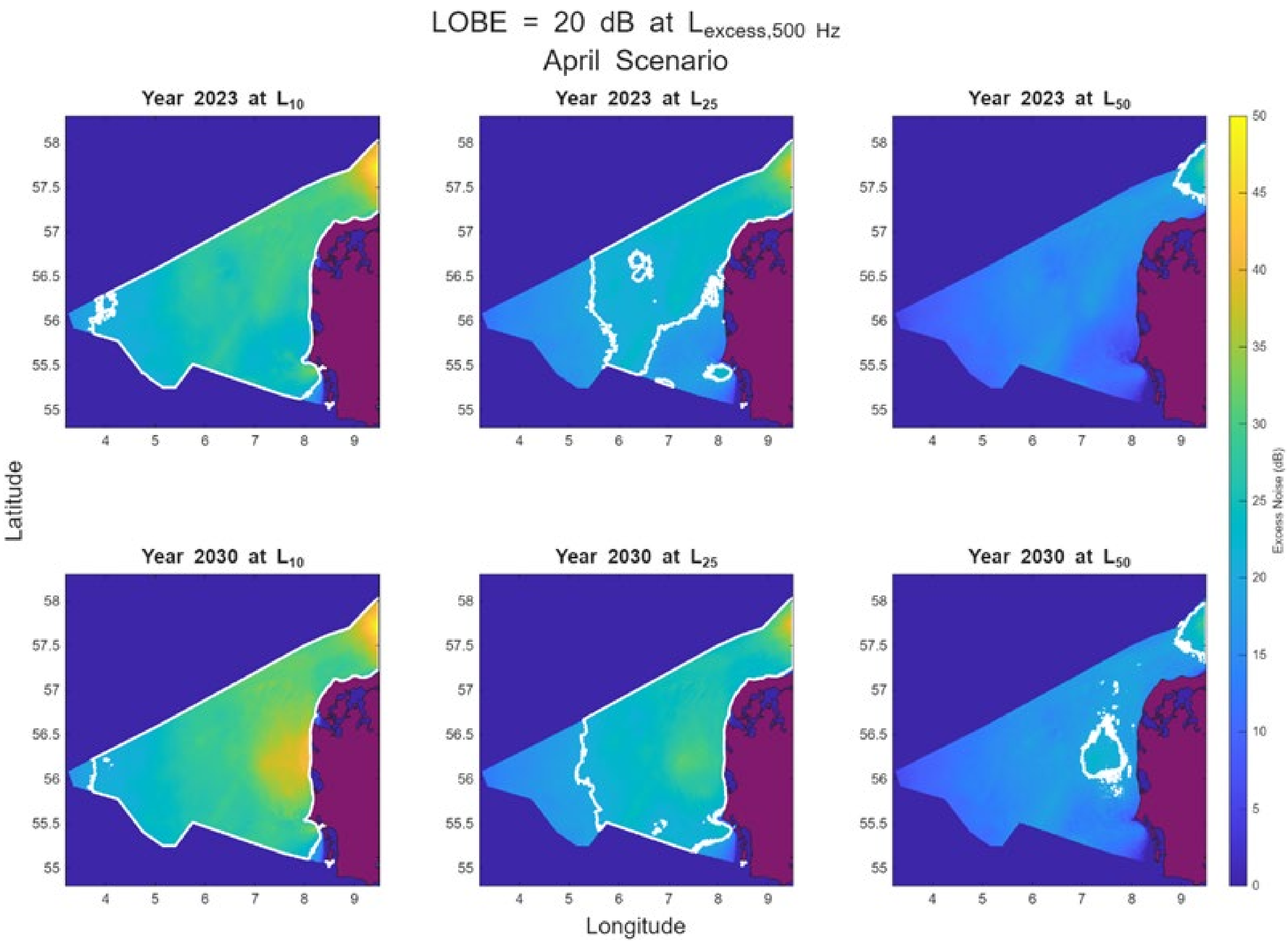
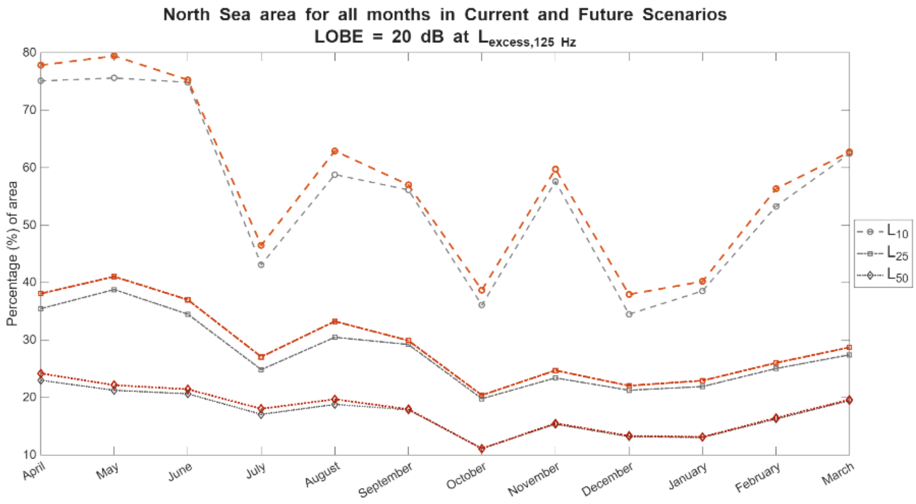


Figure 3.3. North Sea modelled excess noise levels for the 500 Hz decidecade band in the April scenario. Top row shows present (2023) scenario, bottom row shows future (2030) scenario. Each column shows a different exceedance level (L_{10}, L_{25}, and L_{50}). White boundary indicates areas that exceed a LOBE of 20 dB. For data from other months, please see Figure 3.6.

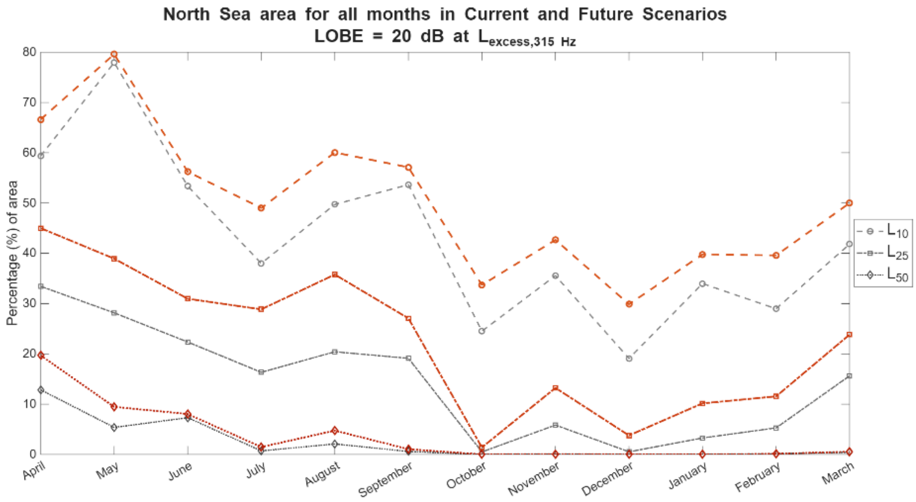
In the 125 Hz band, the effect of the additional offshore wind farms in the 2030 scenario on the median excess noise level was very small across all months (Figure 3.4). The overall excess noise levels were high in the North Sea, with median noise levels exceeding a 20 dB LOBE value above 20% of the modelled area in several of the months modelled. If lower exceedance levels than the median are used, such as the L_{10} and L_{25}, exceeded 10% and 25% of the time, respectively, the fraction of the modelled area where LOBE is exceeded increases substantially (Figure 3.4). For all three exceedance levels, however, the difference between the 2023 scenario and the 2030 scenario is very small, seen as the difference between the orange and the grey lines in Figure 3.4.

Figure 3.4. Monthly percentages of the North Sea region where the excess noise level in the 125 Hz decidecade band exceeded LOBE = 20 dB. Three exceedance levels are shown: L_{10}, L_{25}, and L_{50} (median). Gray lines indicate the current (2023) scenario and orange lines indicate the future (2030) scenario.



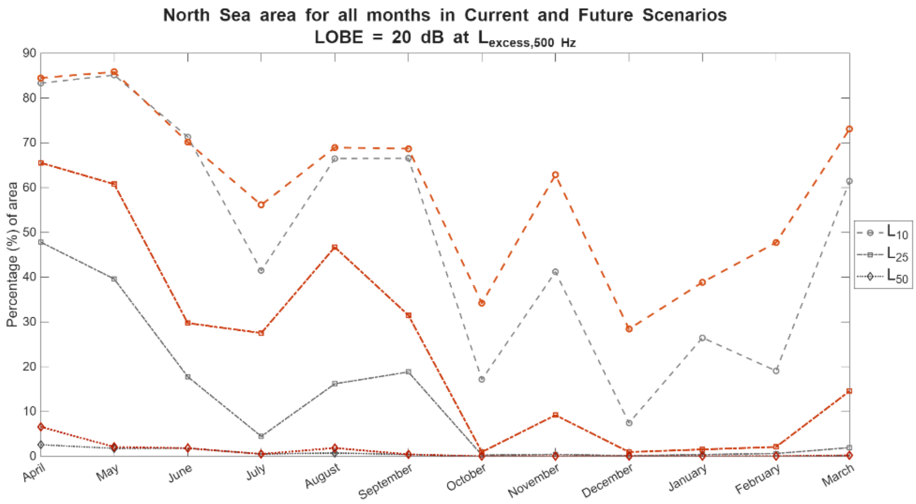
In the 315 Hz band, excess noise levels are generally lower than for the 125 Hz band and the median level exceeding LOBE remains under 20% of the area for a majority of the months of the year. The effect of the additional offshore wind farms in the 2030 scenario is larger than in the 125 Hz band. (Figure 3.5).

Figure 3.5. Monthly percentages of the North Sea EEZ area where excess noise in the 315 Hz decidecade band exceeded LOBE = 20 dB. Three exceedance levels are shown: L_{10}, L_{25}, and L_{50} (median). Gray lines indicate the current (2023) scenario and orange lines indicate the future (2030) scenario.



The median excess noise level in the 500 Hz band remained low throughout the year but L_{10} and L_{25} exceeded LOBE in considerable parts of the modelled area in parts of the year and the additional wind farms in the 2030 scenario added substantially to the size of the exposed area, seen as the difference between the orange and the grey lines in figure 3.6. (Figure 3.6).

Figure 3.6. Monthly percentages of the North Sea EEZ area where excess noise in the 500 Hz decidecade band exceeded LOBE = 20 dB. Three exceedance levels are shown: L_{10}, L_{25}, and L_{50} (median). Gray lines indicate the current (2023) scenario and orange lines indicate the future (2030) scenario.



3.1.2 Absolute sound pressure level

North Sea median noise levels (L_{50}) in the 125 Hz band were almost always below LOBE and the fraction of the modelled area where it was exceeded was therefore uninformative. However, the L_{10} exceeded LOBE in some parts of the modelled area (Figure 3.7). Underwater noise levels are generally higher in March, April and May, and lower the rest of the year. A small increase in the fraction of the modelled area above LOBE is seen for L_{10} and L_{25} data, but no difference for L_{50} or higher exceedance levels.

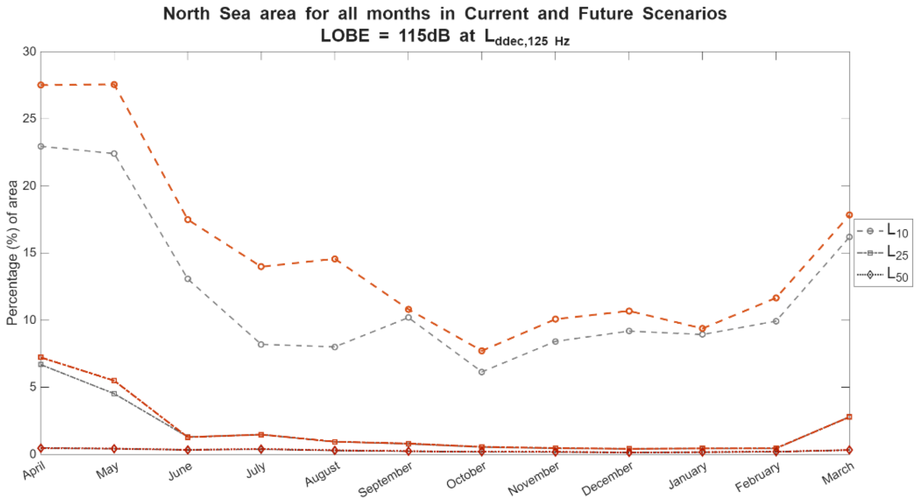


Figure 3.7. Monthly percentages of the North Sea EEZ area where absolute noise in the 125 Hz decidecade band exceed LOBE = 115 dB for three exceedance levels: L_{10}, L_{25}, and L_{50} (median). Gray lines indicate current (2023) scenario, where orange lines indicate the future (2030) scenario.

For the 315 Hz decidecade band, which captures more wind turbine noise, a larger difference can be seen between current and future scenarios across all months (Figure 3.8) for L_{10} and L_{25}, but not the median level. A similar pattern was seen for the 500 Hz band (Figure 3.9).

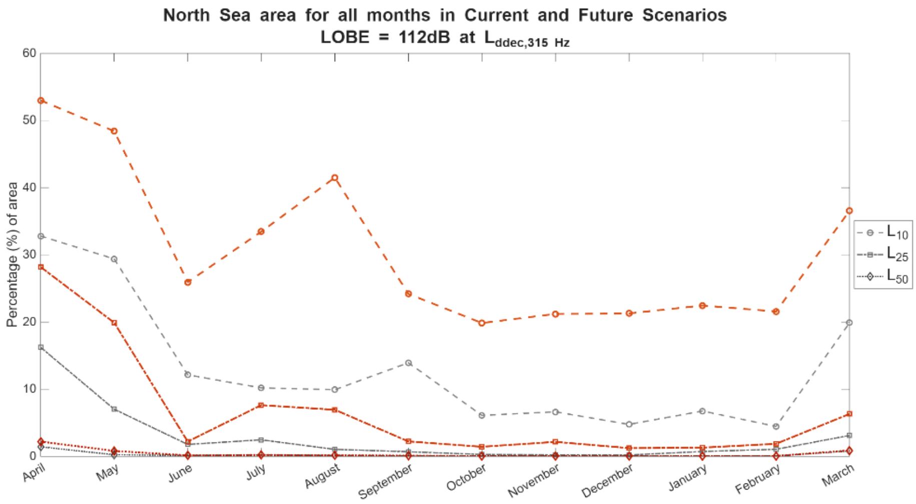
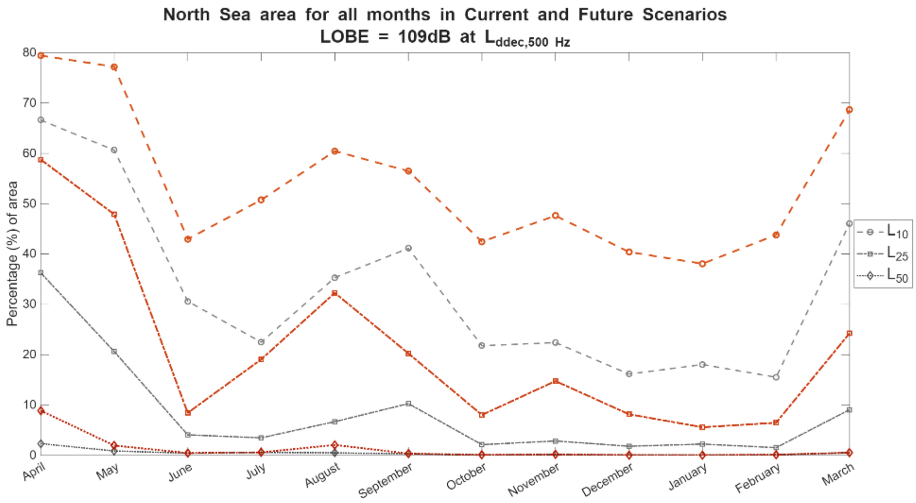


Figure 3.8. Monthly percentages of the North Sea EEZ area where absolute noise in the 315 Hz decidecade band exceed LOBE = 115 dB for three exceedance levels: L_{10}, L_{25}, and L_{50} (median). Gray lines indicate current (2023) scenario, where orange lines indicate the future (2030) scenario.

Figure 3.9. Monthly percentages of the North Sea EEZ area where absolute noise in the 500 Hz decidecade band exceed LOBE = 115 dB for three exceedance levels: L_{10}, L_{25}, and L_{50} (median). Gray lines indicate current (2023) scenario, where orange lines indicate the future (2030) scenario.



3.2 Western Baltic

For the Western Baltic modelling area, we investigated two periods, winter and summer, modelled for both the current and future scenarios. The summer period, or Q3, was modelled between 1/7/2023 – 30/9/2023 and the winter, or Q1, modelled between 1/1/2024 – 31/3/2024 in the current scenario. For the future scenario, the same date ranges were used in 2030 and 2031.

Predictably, the regions which exceed LOBE within the Western Baltic are mostly concentrated along existing shipping lanes and busy ports. Also, the contribution from the fast ferry connection between Aarhus and Odden and the ferries across Fehmarn Belt are clearly visible on the higher exceedance levels. Q1 overall experienced louder noise conditions, in both scenarios. While some of this may be attributed to more ships, it may largely be due to differences between the two periods in the complex hydrographic conditions in the Kattegat and the Belt Seas. These waters is a complex and dynamic mixing zone between a dense, bottom layer of high-saline water flowing from the North Sea combined with a less saline upper layer of run-off from the rivers of the large Baltic Sea drainage area (Leppäranta & Myrberg, 2009). In winter and spring, a strong pycnocline forms in the Kattegat, which creates a minimum sound speed in the upper half of the water column due to sound being refracted upwards by the dense bottom layer below the pycnocline. The ship noise is thus concentrated in a surface duct creating favourable conditions for long-range sound propagation. In summer, the opposite is the case, where the formation of a thermocline typically separates the warmer upper layer from the cold bottom layer, creating a sound speed minimum below the thermocline, which leads to a downward-refracting condition and reduced propagation.

3.2.1 Absolute sound pressure level

The median sound pressure level in the 125 Hz band was below LOBE throughout almost all the modelled area both in the 2023 and the 2030 scenarios (Figure 3.10). Higher exceedance levels (L_{10} and L_{25}) exceeded LOBE mainly in the large shipping lanes through the straits. A similar pattern was seen for the 315 Hz band, with the additional larger areas around offshore wind farms where median and higher percentiles exceeded LOBE. (Figure 3.11).

Figure 3.10. Absolute noise in the 125 Hz decidecade band for current (2023) and future (2030) scenarios. White polygons indicate when noise levels exceed the behavioural disturbance threshold for harbour porpoise at different exceedance levels. The 125 Hz band is a good indicator for disturbances originating from shipping traffic.

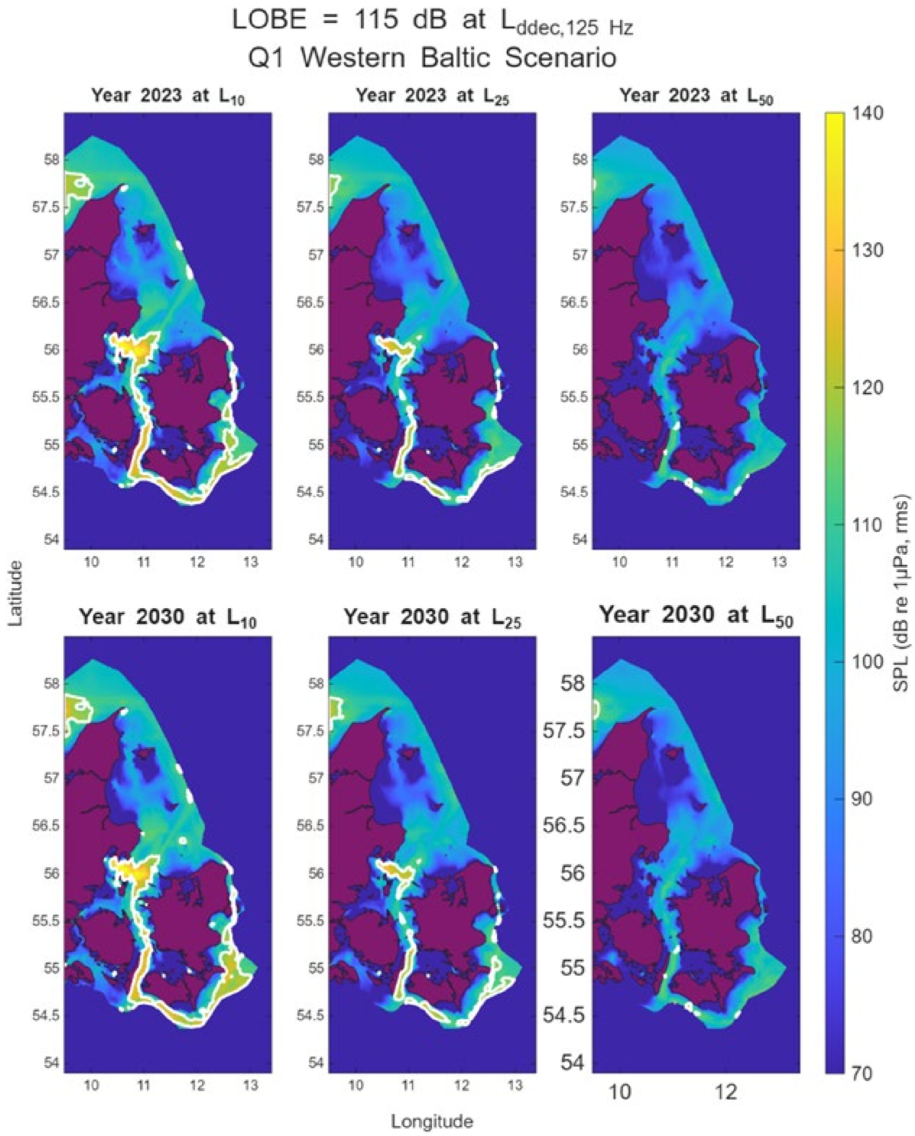
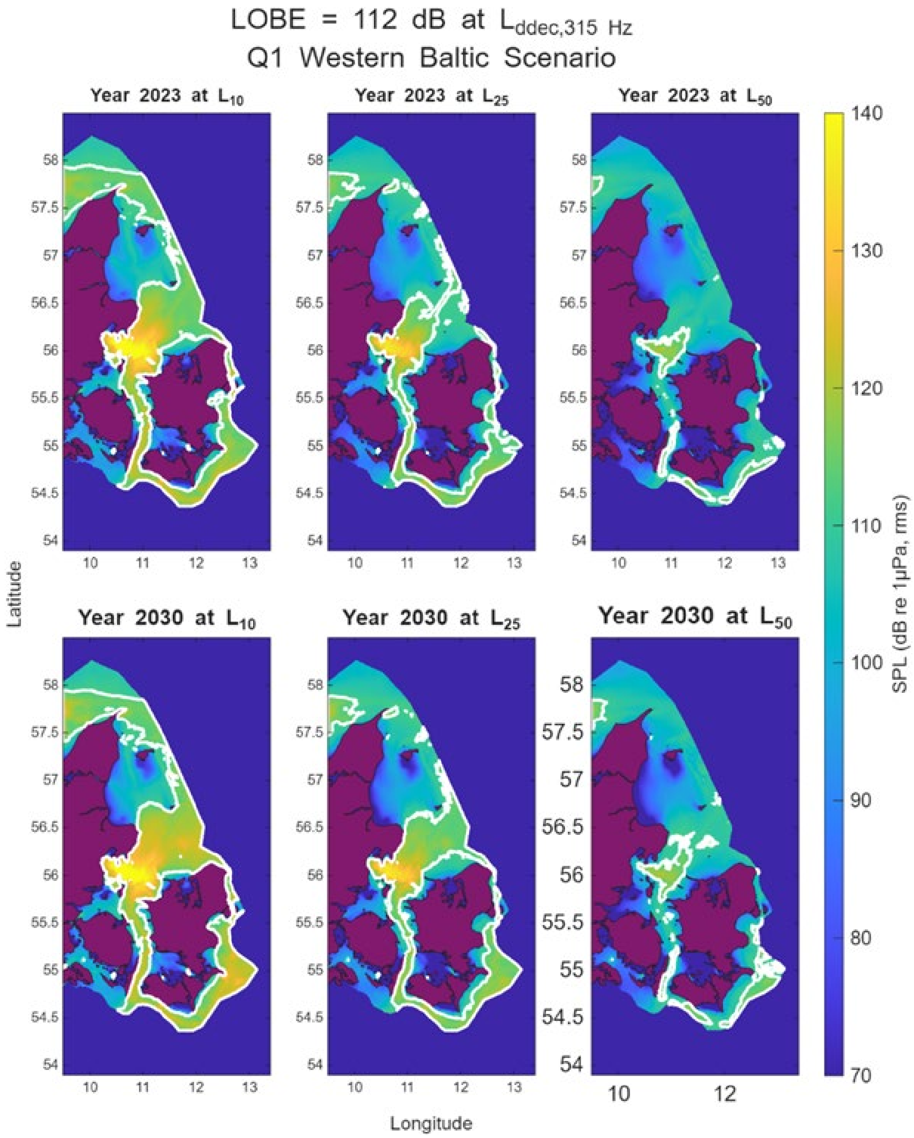
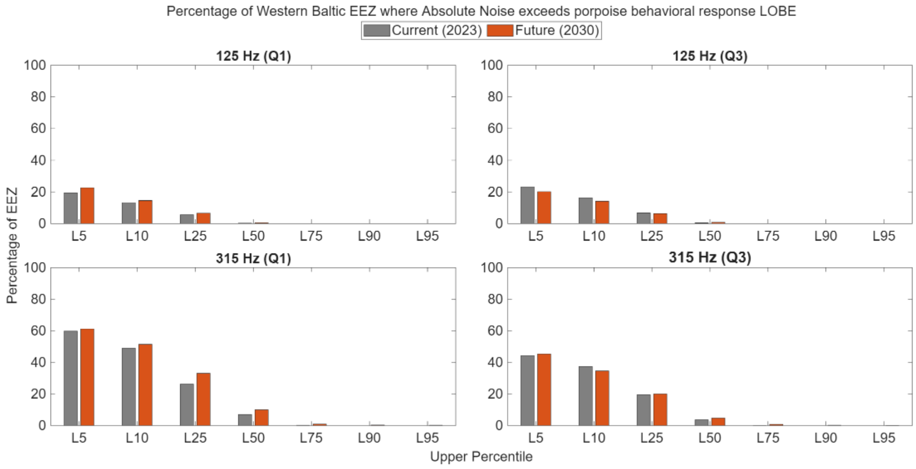


Figure 3.11. Absolute noise in the 315 Hz decidecade band for current (2023) and future (2030) scenarios. White polygons indicate when noise levels exceed the behavioural disturbance threshold for harbour porpoise at different exceedance levels. The 315 Hz band is a good indicator for noise disturbance originating from turbines and service vessel traffic.



The effect on sound pressure levels of adding additional offshore wind farms in the 2030 scenario compared to the 2023 scenario is shown in Figure 3.12. In most cases the fraction of the modelled area where exceedance levels where higher than LOBE increased from the present 2023 scenario to the future 2030 scenario, indicating higher levels of underwater noise from anthropogenic sources in 2030, consistent with the fact that more sources (offshore wind farms and associated service vessels) were added to the 2030 scenario, while no other sources were removed. For a few of the lower exceedance levels in the Q3 period (L_5 and L_{10} for 125 Hz and L_{10} for 315 Hz) the area above LOBE paradoxically decreases when additional sources (wind farms) were added. This effect is likely spurious and linked to the need to adjust shipping lanes from 2023 to 2030 around the future wind farms and likely therefore linked to moving noise sources further apart or into areas with poorer conditions for sound propagation. The fact that the effect is only seen in Q3 supports that it is related to sound propagation conditions.

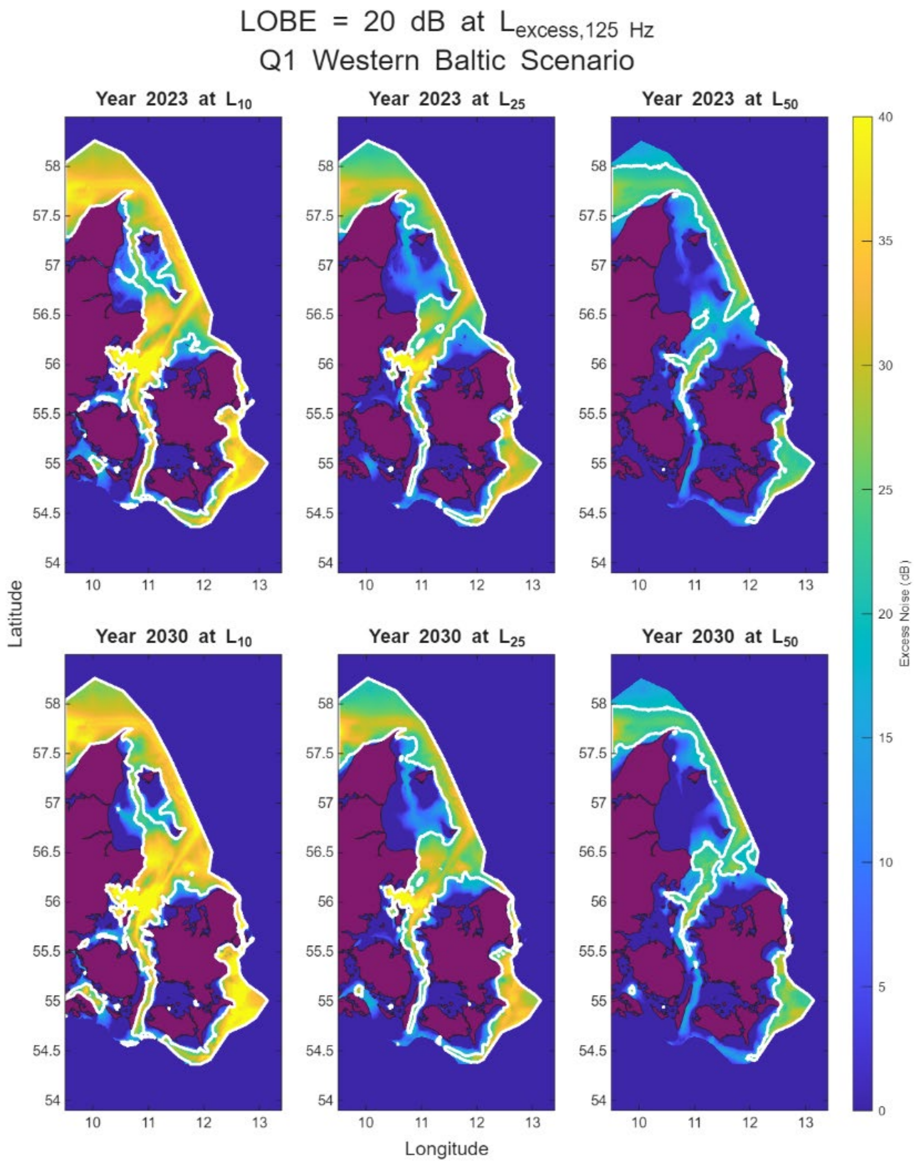
Figure 3.12. The percentage of Western Baltic EEZ area where the behavioural LOBE criteria is exceeded for different exceedance levels, contrasting current (2023) against future (2030) scenario. Note that the slight decrease for Q3 125 Hz noise is likely due to rerouting of shipping routes.



3.2.2 Excess noise level

As for the maps of sound pressure levels, also the maps for excess levels in the 125 Hz and 315 Hz bands are dominated by the shipping lanes, large ports, and ferry routes (Figures 3.13 and 3.14).

Figure 3.13. Excess noise in the 125 Hz decidecade band for 2023 and 2030 scenarios. White polygons indicate when the 20 dB LOBE threshold was exceeded across different exceedance levels. The 125 Hz band is a good indicator for disturbances originating from shipping traffic.



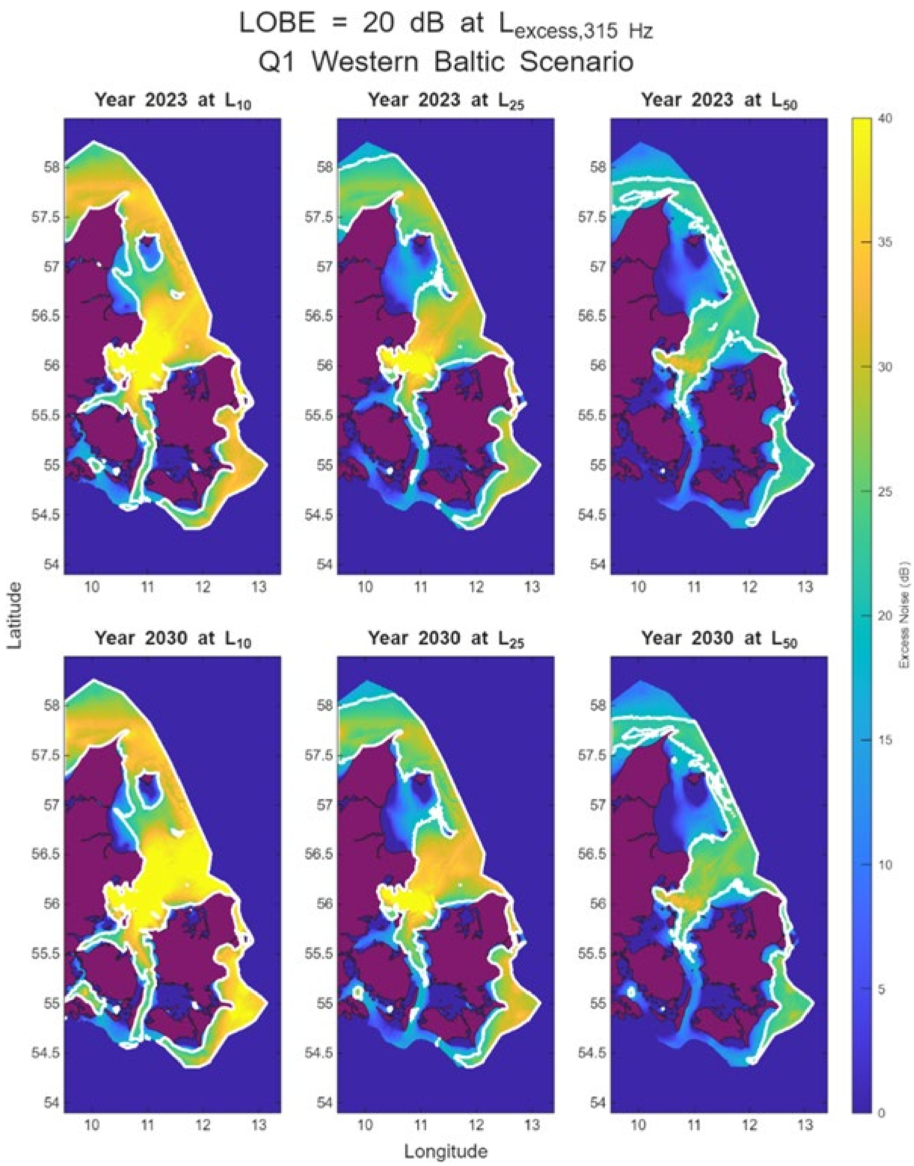
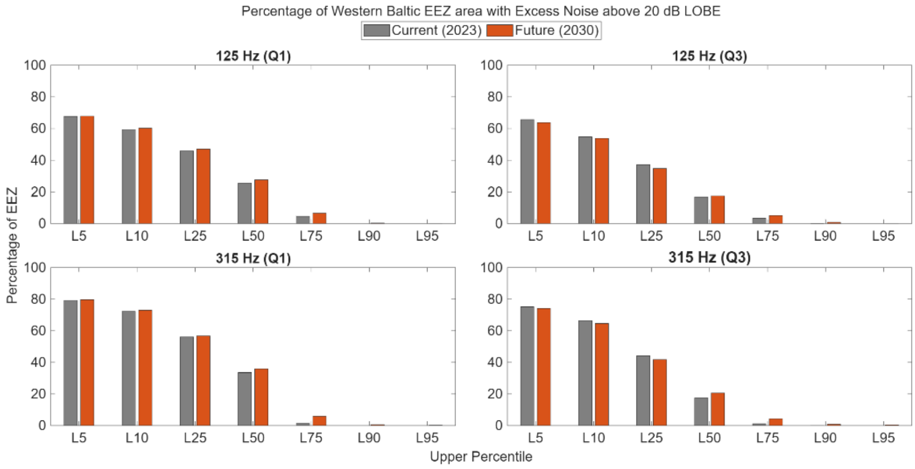


Figure 3.14. Excess noise in the 125 Hz decidecade band for 2023 and 2030 scenarios. White polygons indicate when the 20 dB LOBE threshold was exceeded across different exceedance levels in first quarter. The 315 Hz band is a good indicator noise originating from OWF and associated service vessels.

Median excess noise levels (L_{50}) exceeded LOBE in a substantial part of the modelled area (roughly 20-30%) in both the 125 Hz and the 315 Hz bands (Figure 3.15). The change in area exposed above LOBE from 2023 to 2030 was small, however (difference between grey and orange bars). As for the sound pressure levels, there were paradoxical decreases in exposed area for some of the lower exceedance levels in Q3 in 2030 compared to 2023. This is almost certainly due to the same effect seen for sound pressure levels, i.e. related to moving shipping lanes out of the areas of the future wind farms.

Figure 3.15. The percentage of Western Baltic EEZ where the excess noise exceeds the 20 dB LOBE criteria for different exceedance levels, contrasting current (2023) against future (2030) scenario.



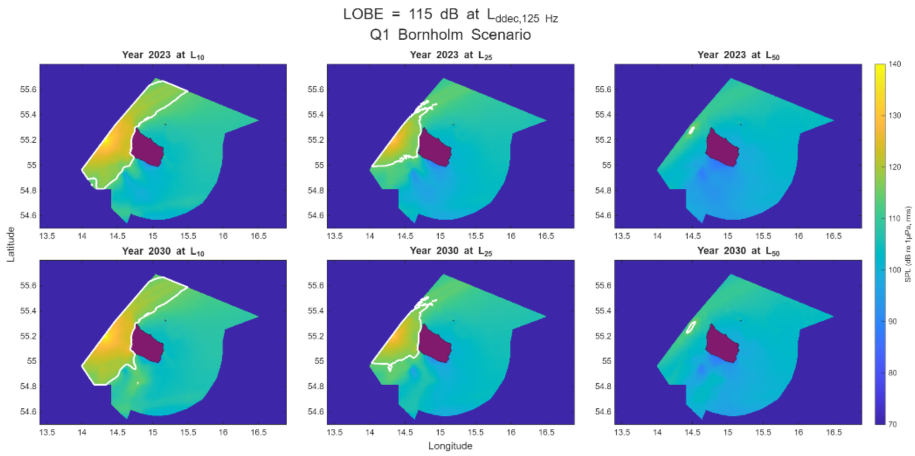
3.3 Bornholm

The waters around Bornholm are hydrographically different from the rest of the Danish waters, being part of what is often referred to as the Baltic Proper and characterized by deeper basins (Arkona and Bornholm Basins) filled with high-saline waters, separated from the Kattegat by the shallow Danish Straits. Above the saline pockets and separated by an often extreme halocline is the almost brackish run-off waters from the rivers draining into the Baltic. (Leppäranta & Myrberg, 2009). As in Kattegat, the nature of the halocline has a substantial effect on sound propagation conditions, which therefore can change substantially between summer and winter.

3.3.1 Absolute sound pressure level

Figures 3.16 and 3.17 provide an overview of the modelled noise around Bornholm for the 125 and 315 Hz noise bands and indicate the areas with noise levels exceeding LOBE. Noise levels are highest in and around the shipping lane.

Figure 3.16. Absolute noise in the 125 Hz decidecade band for current (2023) and future (2030) scenarios. White polygons indicate when noise levels exceed the behavioural disturbance threshold for harbour porpoise (LOBE) at different excess noise levels in Q1. The 125 Hz band is a good indicator for disturbances originating from shipping traffic.



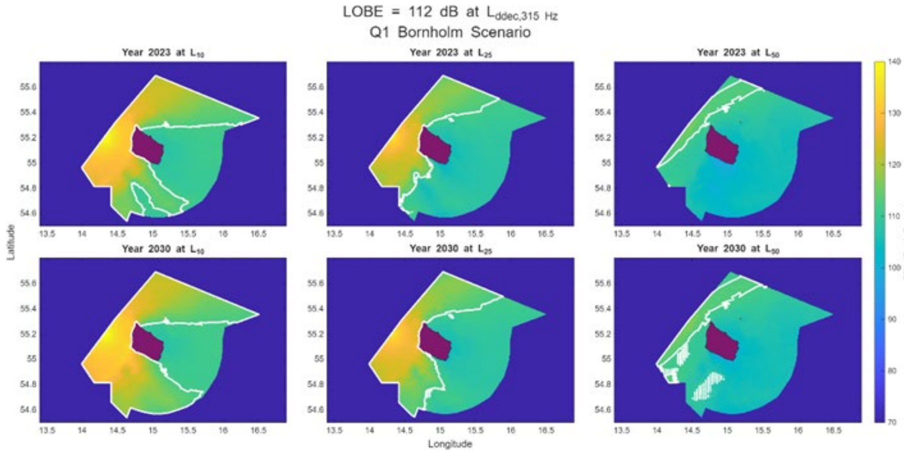


Figure 3.17. Absolute noise in the 125 Hz decidecade band for current (2023) and future (2030) scenarios. White polygons indicate when noise levels exceeded the behavioural disturbance threshold for harbour porpoise (LOBE) at different excess noise levels in the first quarter. The 315 Hz band is a good indicator for noise originating from wind turbines and associated service vessels.

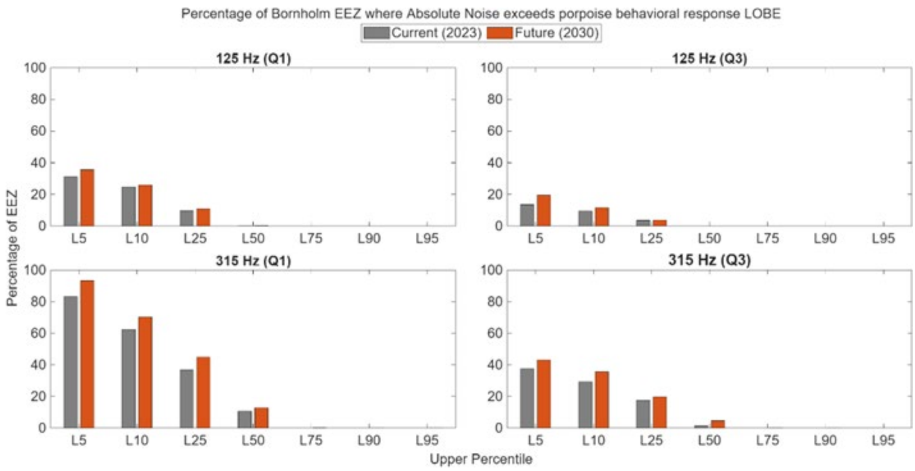


Figure 3.18. The percentage of the Danish area around Bornholm where the behavioural LOBE criteria was exceeded for different exceedance levels, contrasting current (2023) against future (2030) scenario.

The fraction of the modelled area where the median sound pressure level exceeded LOBE was virtually zero for the 125 Hz band, but roughly 5-15% in the 315 Hz band. At lower exceedance levels the area where LOBE was exceeded, for 315 Hz in Q1, increased to more than 80% of the area. As seen in the two other areas, the additional wind farms in the 2030 scenario increases the area where LOBE is exceeded, but not dramatically.

3.3.2 Excess noise level

As for the sound pressure level, the shipping route northeast of Bornholm is the most visible area of high excess levels of noise, both in the 125 Hz and the 315 Hz bands. However, and in contrast, also the Energy Island windfarm in the areas southwest of Bornholm is visible as an identifiable source of noise (Figures 3.19 and 3.20).

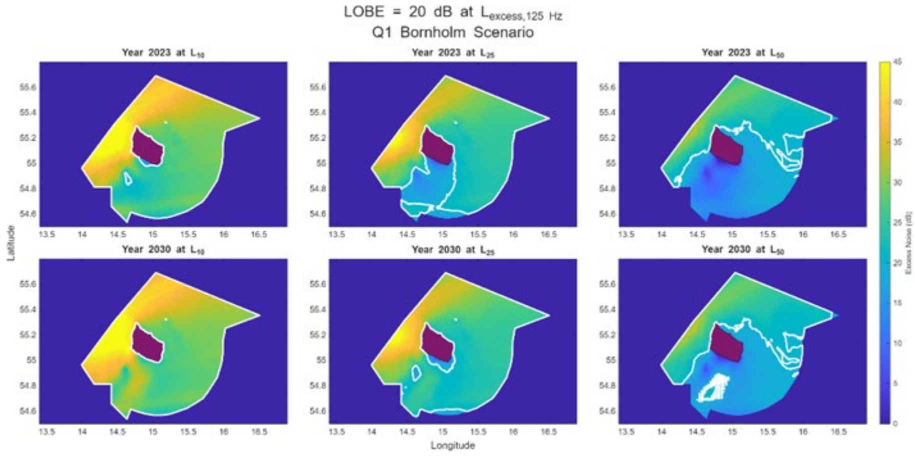


Figure 3.19. Excess noise in the 125 Hz decidecade band present (2023) and future (2030) scenarios in first quarter. White polygons indicate when the 20 dB LOBE threshold was exceeded across different exceedance levels. The 125 Hz band is a good indicator of noise originating from shipping traffic.

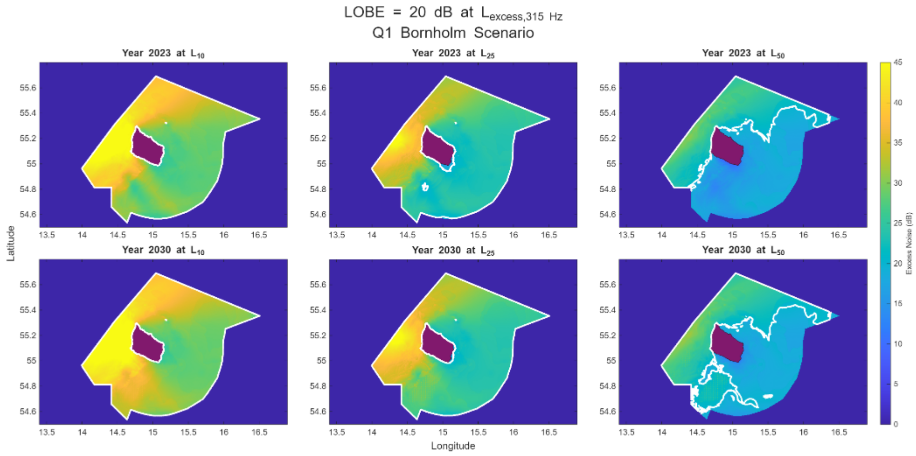


Figure 3.20. Excess noise in the 315 Hz decidecade band for present (2023) and future (2030) scenarios in first quarter. White polygons indicate when the 20 dB LOBE threshold was exceeded across different exceedance levels. The 315 Hz band is a good indicator of noise originating from OWF and associated service vessels.

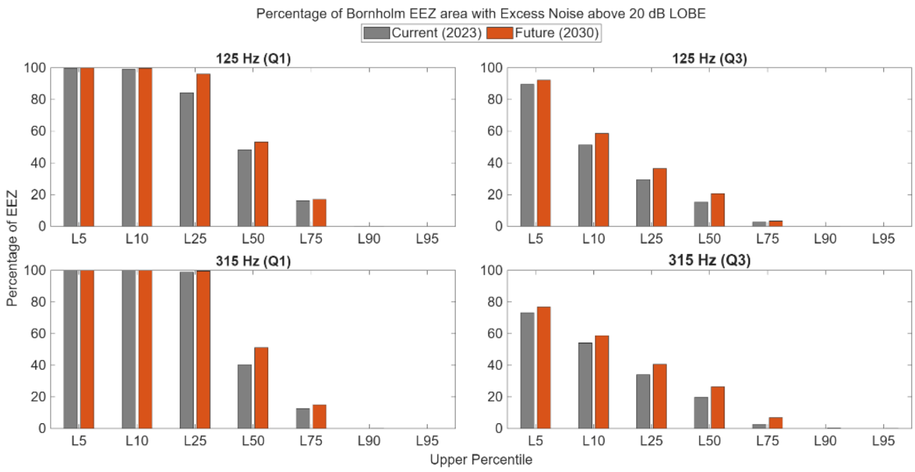


Figure 3.21. The percentage of the Danish area around Bornholm where the LOBE criteria is exceeded for different exceedance levels, contrasting current (2023) against future (2030) scenario for the winter (Q1) and summer (Q3) quarters.

The fraction of the modelled area where excess noise levels were above LOBE were the highest of all the three areas covered in this assessment. Q1 was generally noisier than Q3, which exceeded the 20 dB LOBE in almost the entire modelled area for 25% of the time (Fig. 3.21). Even median excess noise levels (L_{50}) exceed LOBE in 15-20% (Q3) and 40-50% (Q1) of the modelled area.

3.4 Relative contribution of anthropogenic noise sources

The relative contribution of individual sound sources to existing and future cumulative underwater noise levels is essential information when reduction/regulation of the noise is required. This was done for the two scenarios in this study, and results are shown in Figures 3.22 & 3.23. The relative contribution of noise from the operating turbines themselves was almost zero in the 2023 scenario, but non-negligible in the 2030 scenario (blue bars). However, the contribution from the associated service vessels (orange bars) were larger than the turbine noise. In 2023 the service vessels' contribution was much larger than the turbines, in 2030, the contribution, when expressed as percent area where LOBE was exceeded, was roughly twice the contribution of the turbines themselves. In all cases, however, the most significant contribution came from the shipping traffic not associated with the wind farms.

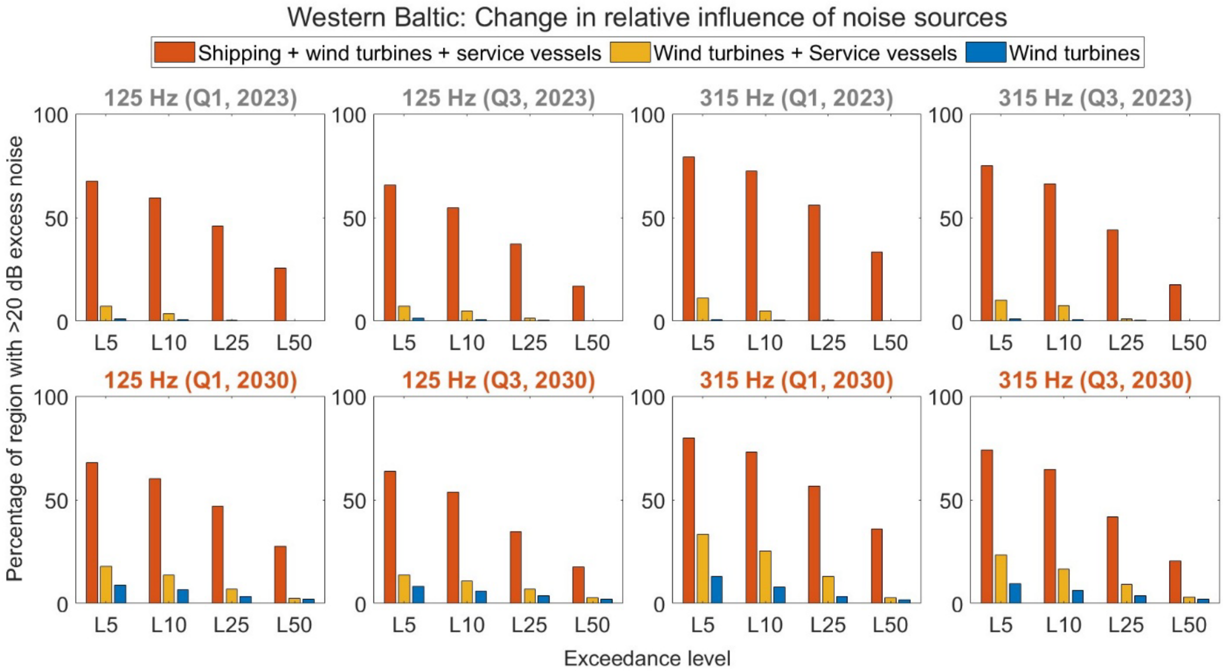


Figure 3.22. The percentage of the Danish area within the Western Baltic where excess noise was higher than the 20 dB LOBE under different exceedance levels, parsed out by noise source, and shown for current (2023, top) and future (2030, bottom) scenarios.

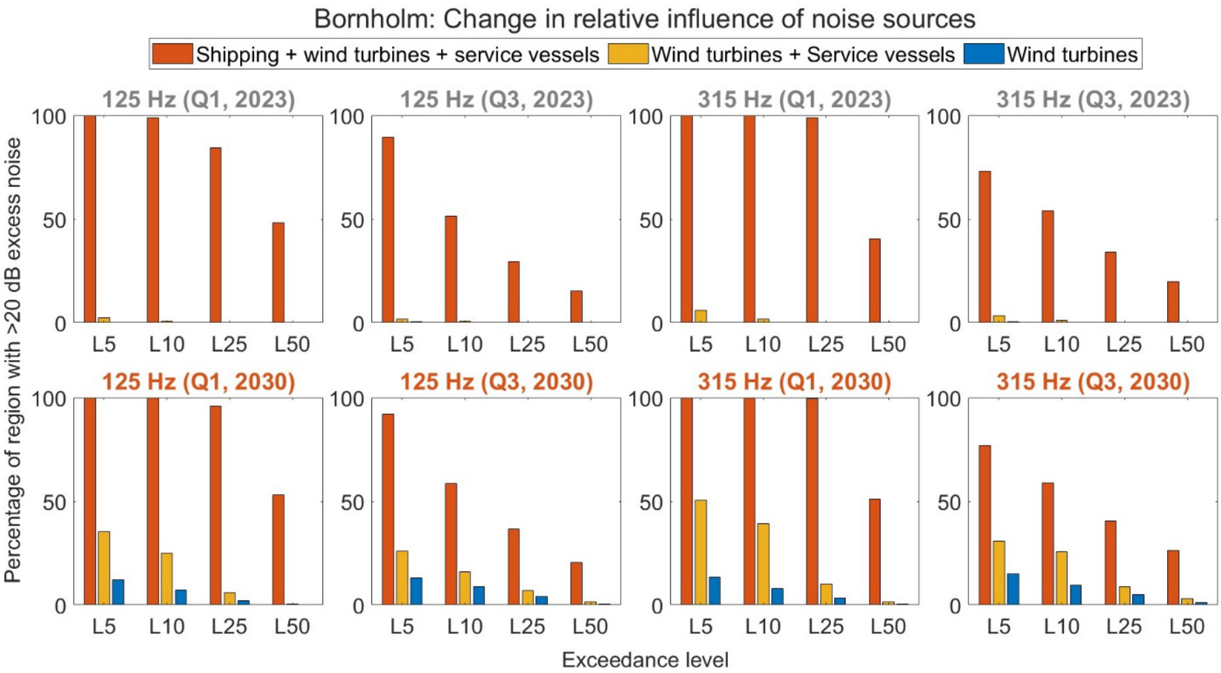


Figure 3.23. The percentage of the Danish area around Bornholm where excess noise was higher than the 20 dB LOBE under different exceedance levels, parsed out by noise source, and shown for current (2023, top) and future (2030, bottom) scenarios.

4 Conclusions

The modelling of underwater noise presented here provides an overview of how Denmark's planned offshore wind expansion is expected to influence underwater noise levels in Danish marine waters, particularly relevant for the Marine Strategy Framework Directive GES criterion D11C2. The results demonstrate that large-scale offshore wind development is likely to add levels of anthropogenic noise that will affect the D11C2 criterion negatively (i.e. make it more difficult to obtain or maintain GES). The additional noise associated with the expansion of offshore wind is primarily due to the service vessels and secondarily from the wind turbines themselves. However, by far the most significant component of anthropogenic noise on a regional level is likely to remain commercial shipping traffic.

The modelled underwater noise, expressed both as absolute sound pressure levels and as excess levels, were generally high across all three modelled regions, with the lowest levels in the North Sea, higher levels in the Western Baltic, and the highest levels around Bornholm. These results are consistent with previous modelling of underwater noise in the same areas, most significantly conducted by the JOMOPANS project for the North Sea (Kinneging et al., 2023) and Kattegat and the BLUES project for the Baltic sea (Klauson et al., 2024), used in the recent assessment of OSPAR area 2 (Kinneging, 2022) and HOLAS 3 (HELCOM, 2023), respectively, as well as the Danish reporting of the D11C2 criterion (J. Tougaard, M. Ladegaard, E. Griffiths, & C. Marcolin, 2023). The most recent assessment concluded that GES is not achieved with respect to criterion D11C2 in the two Marine Reporting units used in the assessment (Danish part of the North Sea + Kattegat, and Danish Straits + the Baltic Sea around Bornholm, respectively).

Elevated sound pressure levels and correspondingly high excess noise levels were modelled in and around main shipping corridors and ferry routes, reflecting the persistent contribution of low-frequency ship noise within the 125 Hz decidecade band. Seasonal variability in sound propagation, particularly in the Kattegat and Bornholm areas, further accentuates wintertime noise conditions. During winter, stratified hydrographic conditions create surface ducts that enhance horizontal sound transmission, effectively increasing the spatial footprint of anthropogenic noise sources. Conversely, during summer, the formation of thermoclines tends to limit propagation, resulting in lower regional excess noise levels.

Across all three regions, future large-scale offshore wind farm developments had limited influence on cumulative noise levels, seen by comparing the 2023 present day scenario with the 2030 future scenario, highlighting the dominant overall contribution of cargo ships and ferries to the anthropogenic noise. However, on a smaller spatial scale, the contribution of future wind farms was substantial. Thus, offshore wind farms in operation do lead to local increases in noise levels that can further exacerbate already high noise levels from shipping. The additional noise from offshore wind farms can be separated into the contribution from operating turbines and the contribution from associated service and crew exchange vessels, showing that the vessels amount to roughly 2/3 of the impact from the wind farms, when expressed as area exposed to levels above LOBE. As there are several efficient methods available to reduce the radiated noise from such vessels, including technical modifications to the ships, speed restrictions, optimizing vessel routes and time scheduling (see for example Findlay et al., 2023), there is regulatory room for managing the additional noise caused by the expansion of marine wind energy.

The overall results confirm the need for including noise from the operational phase of wind farms (both the turbines and the associated vessels) in strategic and environmental impact assessments for future offshore wind farms. This should be supported by actual measurements before and after construction of the wind farms, producing better baseline data and allowing for BACI-studies to quantify the actual contribution of the wind farms. Furthermore, the results of the present modelling emphasise the need for including offshore wind energy, and likely also other offshore activities, such as oil-and-gas extraction, in future assessments of criterion D11C2.

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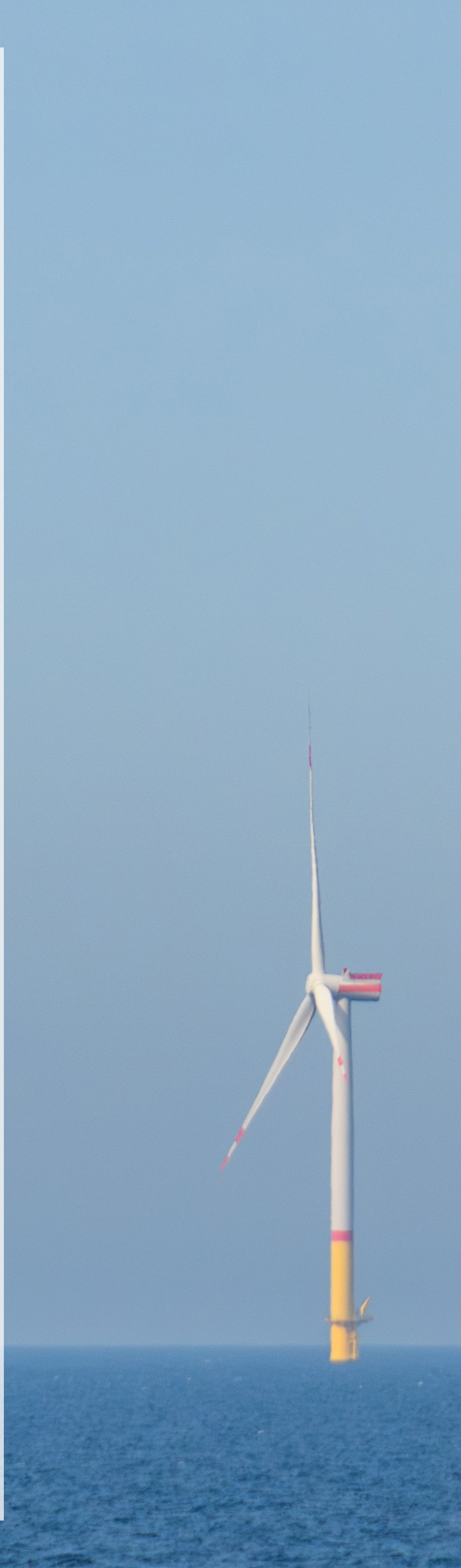
CUMULATIVE EFFECTS OF LARGE-SCALE OFFSHORE WIND DEVELOPMENT ON UNDERWATER NOISE LEVELS IN DANISH WATERS

Current (2023) and projected future (2030) underwater noise conditions were modelled for Danish marine waters, to understand the relative contribution of future offshore wind development on cumulative underwater noise levels. Underwater noise was modelled for three areas surrounding Denmark separately (North Sea, Western Baltic, and Bornholm) in two or three frequency bands centered at 125 Hz, 315 Hz and – for North Sea - 500 Hz. The results showed that expanding offshore wind energy in Danish marine waters is likely to negatively affect the indicators used to assess Good Environmental Status in the framework of the Danish Marine Strategy, thereby making it more difficult to achieve and/or maintain Good Environmental Status. Underwater noise from operation of offshore wind farms should be included in future assessments of new projects and appropriate measures to reduce the radiated noise levels, particularly from services vessels, should be considered. However, the main contributor to the continuous noise indicators is likely to remain commercial shipping.



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