Sound Source Characterization for the World's Largest Floating Offshore Wind Farm Hywind Tampen

Hannah Joy Kriesell, Ana Sofia Aniceto, Robin D. J. Burns,
Kari Mette Murvoll, Jürgen Weissenberger, and Samuel J. Welch

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Abstract

Floating offshore wind farms represent a major advancement in renewable energy, enabling deployment in deepwater regions with stronger wind speeds. By 2035, they could account for up to one-third of offshore wind energy production. Hywind Tampen, in 2025 the world's largest floating offshore wind farm, consists of 11 turbines with 94.6 MW total capacity, supporting the decarbonization of offshore oil and gas operations and serving as a platform for environmental research.

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H. J. Kriesell (✉) · A. S. Aniceto · K. M. Murvoll · J. Weissenberger
Equinor ASA, Environmental Technology, Trondheim, Norway
e-mail: hjkr@equinor.com; aanic@equinor.com; kmmu@equinor.com; jweiss@broadpark.no

R. D. J. Burns · S. J. Welch
JASCO Applied Sciences, Droxford, Hampshire, UK
e-mail: robin.burns@jasco.com; sam.welch@jasco.com

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This work synthesizes findings from a sound source characterization study of operational turbines and assesses potential impacts on marine life. Using a directional hydrophone array within the wind farm and two omnidirectional hydrophones outside, the study identified narrowband sound emissions below 200 Hz, with prominent tones at ~25 and ~75 Hz. Median broadband source levels ranged from 156.5 to 163.8 dB re 1 μPa^{2}m^2, approximately 3 dB lower than levels recorded in a previous study for smaller turbines at the wind farm in Hywind Scotland, indicating a nonlinear relationship between turbine size and sound levels. Transient, impulsive sounds from the mooring system, previously reported at Hywind Scotland, were absent. Noise modeling showed no risk of injury to fish or marine mammals, with temporary threshold shifts occurring only within 150 m.

Keywords

Offshore wind · Floating wind park · Sound characterization · Environmental impact · Noise modeling · Hearing thresholds · Marine mammals · Tonal noise

Introduction

Floating offshore wind farms represent a transformative advancement in renewable energy, offering solutions for deepwater regions where traditional fixed-bottom turbines are unfeasible, potentially providing one-third of total offshore wind energy production by 2035 (Beiter et al. 2022). Hywind Tampen is located 140 km northwest of Bergen in Norway and currently stands out as the largest floating offshore wind farm globally, with 11 turbines and a total system capacity of 94.6 MW. Hywind Tampen not only contributes to decarbonizing offshore oil and gas operations by providing power to the oil and gas fields Snorre and Gullfaks but also serves as a platform for multidisciplinary environmental research.

Understanding the underwater acoustic emissions of floating wind farms is essential for assessing potential impacts on marine life and informing mitigation strategies. Anthropogenic noise in marine environments can affect a wide range of aquatic species, particularly those reliant on acoustic cues for communication, navigation, and foraging. Two sound source characterization studies, for which Equinor ASA contracted JASCO Applied Sciences (JASCO), were conducted previously on Hywind DEMO (a single wind turbine, 2.3 MW capacity, 8.3 m diameter substructure) off the coast of Stavanger, Norway (Martin et al. 2011) and Hywind Scotland (5 turbines, 6 MW capacity, 14.4 m diameter substructure) off the coast of Peterhead, Scotland (Burns et al. 2022). In these studies, the main sounds attributed to the turbines were tones related to power generation and transient sounds from the mooring system. This chapter synthesizes findings from the sound source characterization study at Hywind Tampen performed in 2024 (the respective report by JASCO can be found here: Welch et al. 2025, https://cdn.equinor.com/files/h61q9gi9/global/2e10e1b78ec449e6c62959e12362b8d302e1acd8.pdf?hywind-tampen-fowf-ssc.pdf).

There were three main objectives of the Hywind Tampen study: (1) establishing an operational noise profile for a single turbine so that a source spectrum can be extracted through back-propagation, (2) evaluate whether mooring or other operational noises were still present at Hywind Tampen, and (3) conduct a noise impact assessment for fish and marine mammals to better understand potential influences of noise emissions from an operational floating wind farm on marine life. The possible effect of different mooring systems and materials of the substructures of Hywind Scotland and Hywind Tampen is discussed, and suggestions are provided to aid in effectively reducing noise emissions in future floating offshore wind farms.

Methods and Materials

Study Site

Hywind Tampen is located in the North Sea, approx. 140 km northwest of Bergen, Norway, in water depths between 270 and 300 m (Fig. 1). It consists of 11 turbines (Siemens Gamesa SG 8.0-167) with floating concrete spar foundations (maximum diameter 18 m and height 91 m) that are connected via a shared mooring system made of 19 suction anchors of 16 m length each in a honeycomb formation (Fig. 1).

Acoustic Recordings

To record underwater sound emissions at Hywind Tampen, M36-V35-900 omnidirectional hydrophones from GeoSpectrum Technologies Inc. (GTI) were fitted on JASCO's Autonomous Multichannel Acoustic Recorders (AMARs) and deployed from the DOF *Skandi Iceman* using a Triton XLS remotely operated vehicle.

Fig. 1 Location of Hywind Tampen in the North Sea and the producing oil and gas fields "Snorre" and "Gullfaks" that Hywind Tampen powers (left). (©with permission from Equinor ASA). Red dots onshore indicate Norwegian cities. Right: deployment location of JASCO's Autonomous Multichannel Recorders (AMARs) at Hywind Tampen, showing relative positions to wind generator turbines (WTG) and the mooring system. Red rectangle: equipment retrieved after 3 months; blue oval: equipment retrieved after 13 months and not part of this study, but details can be found in Welch et al. 2025

Table 1 Deployment details for the different recording stations

Station	Deployment duration (months)	Distance to wind park (km)	Water depth (m)	Directionality
1	3	0	284	Directional
2	13	4	288	Directional
3	3	2	291	Omnidirectional
4	3	10	273	Omnidirectional

The setup included two four-channel directional arrays, where one array was located within the turbine park and one outside its perimeter, and two single-channel omnidirectional hydrophones which were deployed externally to capture ambient and tonal signals (Fig. 1 and Table 1). This configuration allowed for spatially resolved acoustic measurements and helped the identification of tonal sources, transient events, and potential mooring-related noise (Table 1).

The hydrophones in station 1, 3, and 4 recorded continuously without a duty cycle at a sampling frequency of 64 kHz. The recording channels had 24-bit resolution with a spectral noise floor of 20 dB re 1 $\mu Pa^2/Hz$ and a nominal ceiling of 165 dB re 1 μPa. Each AMAR was calibrated prior to deployment and after retrieval. Station 2 was retrieved during the preparation of this chapter and is therefore not included in the analysis.

Sound Propagation Modeling for Assessment of Noise Impact on Marine Species

To assess potential noise impact on marine mammals and fish, the underwater noise propagation and visualization software dBSea (version 2.4.17) from Irvin Carr Consulting was used. A map covering approximately 225 km^2 of the Hywind Tampen area and its surroundings with a spatial resolution of 100 m containing bathymetry information was retrieved from the European Marine Observation and Data Network (EMODnet) Map Viewer (available at: https://emodnet.ec.europa.eu/geoviewer/, accessed April 2025). Environmental parameters (salinity, sound speed, and temperature) for the area were taken from the World Ocean Database (WOD, by the National Oceanic and Atmospheric Administration, or NOAA, Boyer et al. 2016). The sound speed is a function of temperature, salinity, and water depth. The WOD presents sound speed profiles based on in situ measurements. To simulate optimal sound propagation, models were run using the sound speed profile (SSP) data for each of the 12 months. The SSP that resulted in the best sound propagation was then selected.

To determine the solvers, the following factors were considered: the Hywind Tampen noise profile is not impulsive but a continuous sound source and operates in a relatively shallow water environment of approximately 260 m with the sound source frequencies ranging from 10 to 25 kHz. In this study, dBSea was set to normal mode solver for center frequencies up to 500 Hz and a ray tracer solver was used for center frequencies including and above 630 Hz. The normal mode solver is well-suited for low-frequency sound waves in shallow or short-range scenarios, which tend to have longer wavelengths and can propagate over large distances with less attenuation. At higher frequencies, sound waves tend to behave more like rays, with less diffraction and more direct paths (see, for example, Jensen et al. 2011). The model incorporated four different seafloor layers from 0 to 200 m in four increments (0–20 m, 20–50 m, 50–100 m, and 100–200 m), each with specific densities, acoustic velocities, and attenuation characteristics (see Welch et al. 2025, Table 7, p. 54). The source level results from the field study by JASCO were used to simulate noise propagation in different wind speed conditions (20, 25, 30, 35, and 40 knots, corresponding to, respectively, 10.3 m/s, 12.9 m/s, 15.5 m/s, 18 m/s, and 20.6 m/s). A point source was assumed, which is appropriate for far-field noise propagation modeling, as the difference between a point source and a distributed source becomes negligible at greater distances from the source. The source depth was set to 50 m, which is approximately half of the length of the submerged substructure.

Threshold values for temporary threshold shift (TTS) and permanent threshold shift (PTS) in marine mammals exposed to non-impulsive noise were sourced from Southall et al. (2019). The sound level results were frequency-weighted based on the hearing groups defined in the same study. For fish, the following equation from Lucke et al. (2024) was used to calculate the filter function, where f_2 is the roll-off frequency, and b is the equation order depending on the hearing group of fish:

$$W_{\text{fish}}(f) = 10\log_{10}\left\{\frac{1}{\left[1+(f/f_2)^2\right]^b}\right\}\text{dB}.$$

For threshold values concerning fish, the study by Popper et al. (2014) served as a reference. This chapter provides values specifically for fish with swim bladders that play a role in hearing, primarily for pressure detection. Consequently, only results for this species group, corresponding to the groups P1, P2, and P3 in Lucke et al. (2024) were reported. The root mean square (rms) sound pressure level thresholds are 170 dB re 1 μPa^2 over 48 hours for recoverable injury and 158 dB re 1 μPa^2 over 12 hours for TTS. Recoverable injury is defined by Popper et al. (2014) as injuries that are not likely to result in mortality such as hair cell damage and minor internal or external hematoma. TTS for fish is defined as any change in hearing sensitivity of 6 dB or more, leading to short-term or long-term changes in hearing ability that may, or may not, impact the individual's fitness.

Results

Sound Source Characterization

The primary sound emissions from the Hywind Tampen turbines consisted of narrowband tones, predominantly below 200 Hz, with two significant tones at 25 Hz and 75 Hz as the main contributors to the recorded sound spectra (Fig. 2).

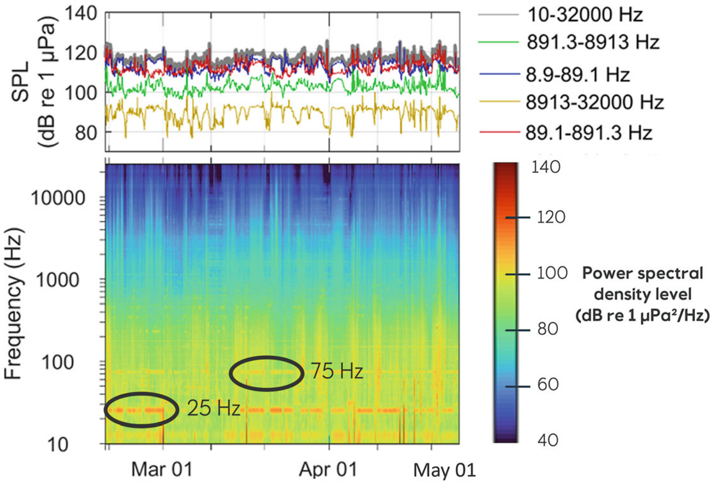

Fig. 2 Top panel: sound pressure level (SPL) for five different frequency bands at station 1. Lower panel: long-term acoustic summary. Black circles indicate the 75 and 2 Hz tones. The color indicates power spectral density levels as a function of time (x-axis) and frequency (y-axis)

Station 1 was chosen as an example as the spectra for all stations were very similar for all recorders.

Power spectral density levels are shown in Fig. 3, and all three stations show peaks in the spectra at 25 and 75 Hz.

Directional acoustic analysis allowed to determine the direction of sound sources. Figure 4 shows overlapping generator sounds from three wind turbine generators at 25 and 75 Hz. The prevalence of the light blue color indicates that the 75 Hz tone from turbine HY06 is dominant in these recordings from station 1.

Additionally, other less intense and sporadically occurring sounds were also identified. A fundamental tone at 15 Hz which was considerably quieter than the primary generator-related tones, with median spectral levels at 15 Hz being 3.2 dB and 4.5 dB lower than the tones at 25 Hz and 75 Hz, respectively. It is faintly visible in Figs. 2 and 4. Other detected tones were at 900 Hz, which was continuous, and another at 1118 Hz, which exhibited very abrupt start and stop times. No broadband noise sources were detected, and the dominant sound emissions from the Hywind Tampen turbines are narrowband tones, principally below 200 Hz, with the two notable tones at around 25 and 75 Hz being the primary contributors to the recorded sound spectra.

Source Level Calculations

The back-propagated decidecade band source levels for a single turbine are summarized for the four highest wind speeds (25–40 knots) in Table 2. The broadband source levels for all wind speeds can be found in Welch et al. (2025, Table 8, p. 58),

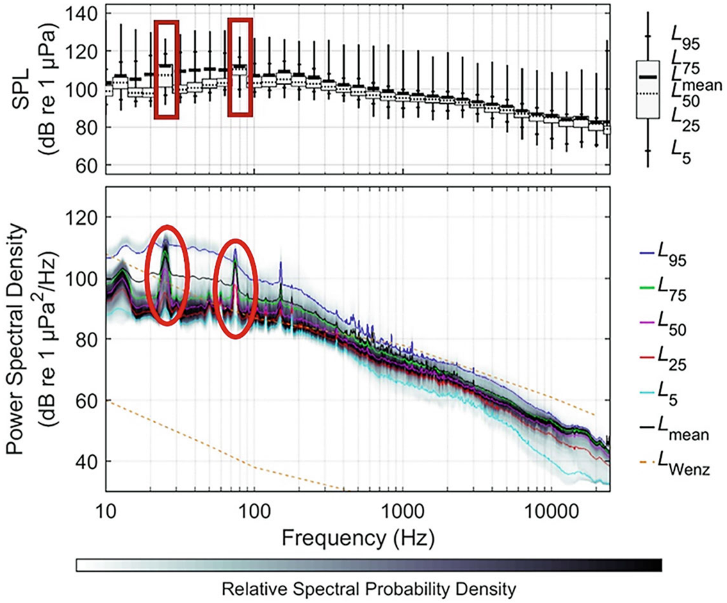

Fig. 3 Top panel: decidecade box and whisker plots for station 1. The whiskers indicate the maximum and minimum sound levels within each band, while the boxes show the interquartile ranges, spanning from the 25th percentile (L_{25}) to the 75th percentile (L_{75}). Additionally, the median (50th percentile, L_{50}) and mean (L_{mean}) sound levels are shown as, respectively, dotted and solid horizontal lines on the plots. Bottom panel: power spectral density plot with 1 Hz resolution in logarithmic scale. The plots display lines representing different statistical sound levels in 1 Hz frequency bins, which can be directly compared to the Wenz curves (Wenz, 1962). The shaded areas indicate the spectral probability density, helping to identify whether the distribution is multimodal. This density reflects the empirical probability of sound levels within each 1 Hz frequency bin, providing insight into how the spectra are distributed over the recorded period. Both representations indicate the main energy of the sound below 100 Hz, and red squares (top) and red circles (bottom) highlight the dominating tonal sounds at 25 and 75 Hz, respectively

and the back-propagated decidecade band source levels for a single turbine operating at all the different wind speeds can be found in Appendix H.1. to H.8.

Broadband source levels ranged from 153.6 to 161.0 dB re 1 $\mu Pa^2 m^2$ (5th percentile), 156.5–163.8 dB re 1 $\mu Pa^2 m^2$ (median), and 159.1–168.7 dB re 1 $\mu Pa^2 m^2$ (95th percentile). Source levels were notably lower at wind speeds below 20 knots, when the generator was idle or producing minimal power, compared to speeds of 20 knots or higher, where rotor RPM was maximized, and significant power was generated.

Noise Impact Assessment for Marine Mammals and Fish

Marine mammal vocalizations were also identified in the Hywind Tampen dataset, including sperm whale (*Physeter macrocephalus*) clicks and killer whale (*Orcinus*

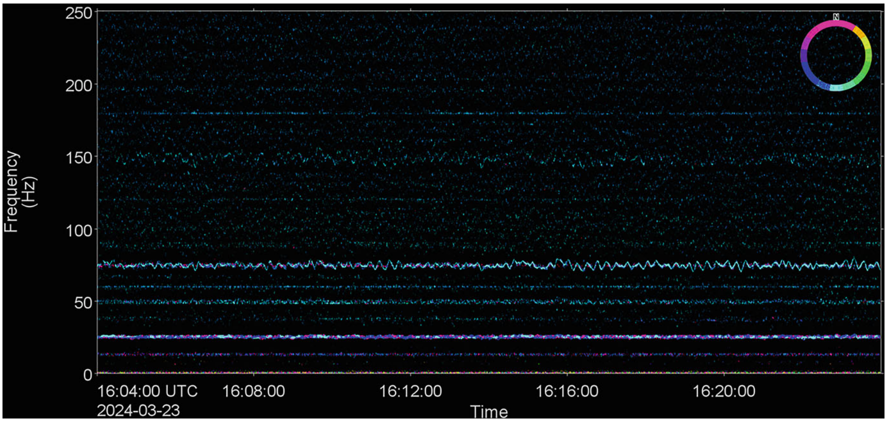

Fig. 4 Directogram from station 1 displaying the varying sound emissions from three wind generator turbines, HY05, HY06, and HY07. The color indicates the direction of the source of all sounds recorded according to the color wheel in the top right corner, which is conventionally oriented with north at the top

orca) clicks and whistles, highlighting the importance of evaluating the turbines' noise impact on marine mammals. The modeled scenarios were likely conservative due to the choice of the sound speed profile with the best propagation characteristics, which was the month of July, as well as choosing the 95th percentiles decidecade band source levels of those wind speeds with the highest source levels. The resulting noise levels were frequency-weighted for each of the marine mammal hearing groups and are presented as sound exposure levels over 24 hours (SELc) according to Southall et al. (2019). The results for fish were frequency-weighted according to Lucke et al. (2024) and are expressed in SPL over 48 hours dB re 1 μPa^2 (recoverable injury) and SPL over 12 hours (TTS) dB re 1 μPa^2 according to Popper et al. (2014).

The results showed that even in these conservative model scenarios, there is no risk for permanent injury to marine mammals or fish, while temporary threshold shifts might occur for marine mammals if they stay within 150 m of the wind turbines over a period of 24 hours (Table 3).

The model scenario with the largest distance at which a hearing group could experience TTS was for VHF weighted sound levels resulting in 150 m at 25 knots wind speed. An animal belonging to this hearing group would have to stay within this area for 24 hours to potentially experience TTS. This scenario is illustrated in Fig. 5, and the TTS risk zone is indicated by a white line, exemplary for HY01.

For fish, there was no exceedance for recoverable injury at 170 dB re 1 μPa over 48 hours and results indicated TTS (158 dB re 1 μPa over 12 hours) threshold distances below 20 m only for wind speeds of 25 and 30 knots. The model is likely not accurate at such close ranges, and this limitation should be taken into account when interpreting these distances to thresholds.

Table 2 Median and 95th percentile decidecade band source levels for a single turbine operating at the four highest wind speeds

	Source level (dB re 1 $\mu Pa^2 m^2$)							
	Wind speeds							
	25 knot (12.9 m/s)		30 knot (15.4 m/s)		35 knot (18 m/s)		40 knot (20.6 m/s)	
	Percentiles							
Decidecade band center frequency (Hz)	50th	95th	50th	95th	50th	95th	50th	95th
10	157.4	162.3	136.1	139.9	148.6	152.6	144.6	147.6
12	154	161.1	134.8	140.3	148.7	152.7	146	148.9
15	153.7	159.3	141.3	146	148.1	151.5	142.5	145.2
19	153.1	159.2	137.7	141.2	148.9	152	142.8	145.6
25	155.9	160.4	139.4	146.5	156.1	159.8	143.8	148
31	148.5	152.1	145.8	149.9	148.6	151	144.8	147.5
39	146	148.7	144.7	149.3	145.3	147.5	145.8	149.5
50	144.8	147.8	148.1	152.9	145.5	148.2	144.3	146.1
63	145.5	148.5	150.9	155.1	147.1	150.3	147.6	149.8
79	152.9	156.1	154.6	157	154.2	155.8	158.5	160.4
100	148.3	150.8	154.2	156.3	149.6	152.4	147.4	149
125	148	150.8	153.5	155.5	150.1	152.5	149.6	151.1
158	149.1	151.9	153.6	155.9	151	153.3	150.1	151.9
199	146	149.4	151.4	154.8	153.4	156.3	148.1	150
251	144.8	147.6	149.8	153.1	149.8	153.2	147.2	149.4
316	143.9	147	149.9	152.8	149.1	152.4	147.2	149.2
398	142.8	146.2	149.3	152.7	147.4	151.2	146.4	147.3
501	141.2	144.2	148.7	152.2	144.4	147.9	145.5	147.2
630	140	143.4	147.6	150.1	142.6	144.5	142.4	143.7
794	138.9	141.4	144	148.3	141.7	143.4	141.8	142.7
1000	138.8	141	142.9	146.5	140.9	142.6	141.5	142.2
1250	138.2	140.5	142.7	146.4	140.8	142.4	141.5	142.2
1600	137.8	140	141.9	145.3	140.8	142.2	141.4	142.1
2000	138.3	140.5	142.3	145.7	141.2	142.5	142.1	142.8
2500	137.5	139.7	141.4	144.7	140.1	141.3	141.3	142
3150	136.5	138.5	140.1	143.3	138.7	140	140.6	141.4
4000	135.5	137.7	139.3	142.3	137.9	139.1	139.8	140.8
5000	134.9	137	138.7	141.6	137	138.2	138.1	139.3
6300	133.3	135.4	137.3	140.1	135.2	136.5	135.9	137.5
8000	132.2	134.2	136	138.9	134	135.1	134	135.7
10,000	131.9	133.9	135.7	138.4	133.4	134.6	133.1	134.4
12,500	131	133.1	134.8	137.6	132.5	133.7	131.7	132.6
16,000	132.7	134.8	136.3	139.2	134.1	135.3	132.5	133.3
20,000	131.4	133.5	134.6	137.7	132.6	133.9	130.6	131.5
25,000	130.1	132.1	132.9	136.1	131.1	132.3	128.5	129.5

Table 3 The maximum distances to threshold values represent the maximum distances from a turbine at which an animal from the respective hearing group would need to remain for 24 hours or more to experience temporary threshold shift (TTS) or permanent threshold shift (PTS). The thresholds are indicated as TTS onset and PTS onset according to Southall et al. (2019). *LF* low frequency cetaceans, *HF* high frequency cetaceans, *VHF* very high frequency cetaceans, *PCW* phocid carnivores in water. NA indicates no exceedance of the respective threshold at any distance

Marine mammal auditory group	PTS onset (dB re 1 μPa^{2}s)	PTS onset (dB re 1 μPa^{2}s)	Maximum distance to threshold (m)									
			20 knots		25 knots		30 knots		35 knots		40 knots	
			PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS	PTS	TTS
LF cetaceans	199	179	NA	120	NA	140	NA	100	NA	80	NA	80
HF cetaceans	198	178	NA	NA	NA	NA	NA	50	NA	NA	NA	NA
VHF cetaceans	173	153	NA	140	NA	150	NA	140	NA	140	NA	140
PW	201	181	NA	NA	NA	20	NA	20	NA	20	NA	20

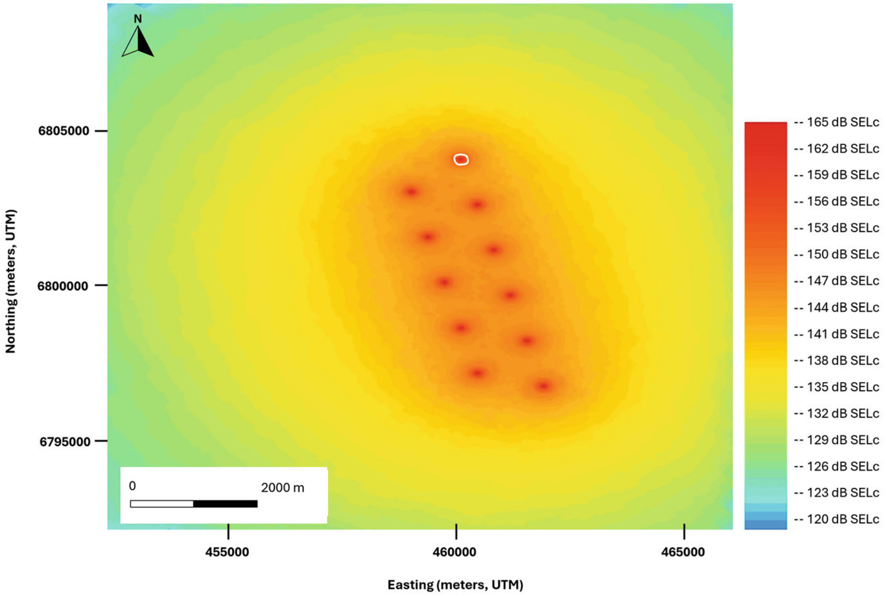

Fig. 5 Sound levels (SELc = cumulative sound exposure level) weighted for VHF cetacean hearing at Hywind Tampen for 25 knots wind speed resulting in the highest broadband source level of 168.7 dB re 1 μPa^2m^2. The threshold of 153 dB is indicated as a white line exemplary for HY01 (top right). A VHF cetacean would have to stay within the area of this line for 24 hours or longer to potentially suffer from TTS

Discussion

The primary sound emissions from the Hywind Tampen turbines consist of narrowband tones below 200 Hz. The two most prominent tones, which define the turbine's acoustic signature, increase in frequency and intensity, peaking at approximately 25 Hz and 75 Hz, typically at wind speeds exceeding ~20 knots. The Hywind Tampen turbines utilize a direct-drive system, which has no gearbox and thus no associated gear noise, which has been found to significantly contribute to lower sound emissions in other offshore wind farms (Stöber and Thomsen 2021). Instead, the fundamental frequency of the generator is determined by the rotational speed of the rotor and the number of pole pairs in the generator. This relationship can be described as: Frequency (Hz) = (Revolutions per minute × Number of pole pairs)/60. Assuming a constant rotational speed of 10.5 revolutions per minute (rpm), this converts to 0.175 revolutions per second. Multiplying this by the number of pole pairs results in a fundamental frequency of approximately 25.2 Hz. The 75 Hz was also directly related to the rotational speed and the number of pole pairs but occurred at three times the fundamental frequency. This relationship highlights the direct influence of the turbine's rotational dynamics on its sound emissions.

The 15 Hz tone could originate from an electrical system operating at a consistent rate, while the tones at 900 Hz could be related to pitch actuation, which is the adjustment mechanism of the turbine blades relative to the wind to optimize the turbine's performance. The 1118 Hz tone might be related to the operation at a fixed rate of a hydraulic pump system. In addition to the advanced sound source characterization enabled by the directional recording system, marine mammal vocalizations were also identified. While the primary focus was not to detect marine mammals, this demonstrates how such recordings can be valuable for determining species presence within a wind farm's operational area. On average, broadband sound levels were 5–6 dB higher above 20 knots, indicating that rotor speed, rather than wind speed, is a stronger predictor of the sound levels and spectrum produced by the Hywind turbine.

The main difference in the noise signatures of Hywind Tampen and Hywind Scotland is the absence of identifiable mooring transients at Hywind Tampen while they were very prominent at the Scotland site. This difference is likely due to two key factors. First, Hywind Scotland uses a fully chain-based mooring system, while over two-thirds of the mooring system at Hywind Tampen have been replaced with steel wires. Second, the substructure materials differ significantly: Hywind Scotland turbines have a steel substructure, whereas substructures at Hywind Tampen are made of concrete. These structural differences are considerable, and Hywind Tampen source levels are about 3 dB lower on average than at Hywind Scotland. This study indicated that the relationship between noise emissions and size of offshore floating wind turbines is likely not linear, and larger turbines do not necessarily produce more noise. Improvements to the mooring system and the use of concrete substructures have resulted in quieter operations. It is important to now shift the focus to tonal noise emissions, and future research should explore potential impacts on marine species associated with these tones.

Noise modeling using the back-propagation source levels from HY06 indicated that there is no risk of hearing injury and only a very low likelihood of TTS, as animals would need to remain within 150 m or less to the turbines for an extended period of time.

The pursuit of improved, more efficient technology and the reduction of environmental impacts is an ongoing process that requires continuous research and understanding. Achieving this goal relies on open dialogue and collaboration between engineers, scientists, and regulators. Hywind Tampen serves as a model for integrating environmental research with technological advancements and the possibility for quieter designs and more sustainable floating offshore wind farms. These findings should inform noise mitigation strategies and guide the development of environmentally responsible offshore wind energy projects.

Competing Interest Declaration The author(s) has no competing interests to declare that are relevant to the content of this manuscript.

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