15 Operational Underwater Noise from Offshore Wind Farms

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Contents

Abstract

Underwater noise was measured at 25 German offshore wind farms (OWFs) under standardized conditions. The measurements included different turbine types up to 8 megawatt rated power and different foundation types. Water depths ranged from 18 m to 40 m. The two main measurement positions were 100 m from a pre-selected offshore wind turbine (OWT) and in the center of the OWF. Underwater sound was recorded for up to 6 weeks to cover different wind and turbine conditions. The aim was to identify the most relevant influencing parameters of noise radiated by operating OWTs.

The cross-project analysis, based on broadband levels as well as third octave spectra and data, was divided into three wind classes that covered the range from OWT idleness to rated power. Noise from OWTs with gear boxes was slightly higher compared to those with direct drives. No significant differences were found for different foundation types. A trend analysis shows that an increase of radiated noise with increasing turbine size (characterized by its rated power) statistically does not exist. Noise from wind farm-associated vessel traffic was estimated for an exemplary OWF with 87 turbines and was found to be approx. 11 dB lower than the noise radiated by the OWTs.

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Introduction

The number of offshore wind turbines (OWTs) has strongly increased over the last decade and will increase worldwide significantly over the next decade due to the expansion of renewable energy. Meanwhile, the effect of OWT construction noise (impact pile driving) on marine mammals is well reputed; see, for example, Dähne et al. (2017) and Lucke et al. (2009). The ecological impact of underwater noise from operating OWTs and associated vessel traffic, however, is not yet fully investigated. Several studies indicate that the noise origin are mechanical oscillations of components like the gear box or the generator, which propagate through the foundation structure into the water, and this noise input can dominate the ambient noise measured in the vicinity (Betke et al. 2005; Madsen et al. 2006, Norro and Degraer 2016; Yang et al. 2018). Based on the few available underwater noise studies for operational OWT, Tougaard et al. (2020) and Stöber and Thomsen (2021) tried to extend the current knowledge in order to be able to model future soundscapes. Tougaard et al. (2020) used a general linear model, whereas Stöber and Thomsen (2021) used linear regressions to assess correlations between sound pressure level, measurement distance, turbine size, and wind speed. Both studies used data from smaller and older OWTs, which were gathered in various distances to the turbine and at different wind speeds. Driven by the demand for renewable energy, turbine size has increased significantly over the last 15 years. Upcoming projects will have turbine sizes above 10 megawatt (MW) nominal power. Furthermore, new turbine installation includes direct-driven (gearless) generators. In the North and Baltic Sea, monopile turbines, up to 10 meter (m) diameter, were installed in the latest OWF projects. Therefore, it is uncertain whether the noise from smaller and older OWTs can be extrapolated to the newest generation of OWTs.

In Germany, part of the approval process includes underwater noise measurements prior to construction (background or ambient noise) and during operation, according to a standard procedure developed by the Federal Maritime and Hydrographic Agency (Müller and Zerbs 2011). Currently, about 30 OWFs are in operation, and operational noise measurements were performed in a standardized manner on 25 of them. Post-processed data were uploaded in the MarinEARS database of BSH.

Technical properties of the measured OWTs are diverging: beside different brands with possible subtle design differences, they are erected on different foundation types like monopiles or jacket constructions (Fig. 1), and they have either gear boxes or gearless drives; see Table 1. Although the database of 25 measured OWTs is not extensive, differences in sound radiation that are caused by different turbine parameters should appear in the measurement results. The turbine size has also increased significantly over the years; recent plannings state power ratings of up to 15 MW.

Fig. 1 Monopile, jacket, and tripod turbine foundations (from left to right). (Photos: itap)

Table 1 Some details of the 25 tested wind turbine types. Jacket #14 is mounted on so-called suction buckets rather than on piles driven into the ground

Wind farm no.	Turbine type	Power, MW	Gear box?	Foundation
1, 4	Siemens SWT 7.0-154	7.0	No	Monopile
2	MHI Vestas V164-8.0 MW	8.0	Yes	Monopile
3	MHI Vestas V164-8.4 MW	8.4	Yes	Monopile
5	GE Haliade 150-6	6.0	No	Monopile
6, 16	Adwen AD 5-116	5.0	Yes	Tripod
7	Senvion 6.3M152	6.3	Yes	Monopile
8, 9, 10, 18	Siemens SWT 6.0-154	6.0	No	Monopile
11	Senvion 6.2M126	6.2	Yes	Monopile
12	Adwen AD5-135	5.0	Yes	Jacket
13	Siemens SWT 4.0-120	4.0	No	Monopile
14	Siemens SWT 4.0-120	4.0	No	Jacket
15, 19, 23, 24	Siemens SWT 3.6-120	3.6	No	Monopile
20	Siemens SWT 3.6-120	3.6	No	Jacket
22	Senvion 6.2M126	6.2	Yes	Jacket
16	Adwen AD5-116	5.0	Yes	Tripod
17	Siemens SWT 4.0-130	4.0	No	Monopile
25	Bard 5.0	5.0	Yes	Tripod

OWTs from 3 to 8 MW are analyzed; hence, some evidence is expected whether larger turbines radiate more noise than smaller ones.

From earlier investigations (Betke 2014; Tougaard et al. 2020), it is known that OWT operational noise occurs mainly at frequencies below 1 kHz, or even below 100, and the acoustical energy is concentrated in a few narrow spectral lines. The strongest of these tones have typically rms levels of 120 dB re 1 μPa at 100 m distance. Mostly, these narrowband sounds recorded underwater are caused by the tooth mesh frequencies of the gear box and by periodically alternating forces in the generator. In areas with high shipping density (e.g., along main shipping lanes, like most parts of the German Bight of the North and Baltic Sea), operational OWT noise does occur much above the ambient noise level. One important question is if the noise caused by operating OWTs is the only possible impact or if the vessel traffic related to the operation of an OWF will also have an influence on the overall level within as well as in the vicinity of an OWF? Therefore, in some of the German OWF projects measured in 2019 till 2021, the vessel noise caused by the operating OWFs was partly determined, and the underwater noise was also investigated.

Methods

All operational noise measurements per OWF were conducted within the first years of their operation (new OWTs). The measurements were conducted in the period from 2013 to 2021. The water depth at the measurement locations varied from 18 m to 40 m. The typical setup used throughout the measurements is shown in Fig. 2. The hydrophone was decoupled from the marker buoys; its height above the sea floor was approximately 2 m. The complete setup was designed to minimize self-noise. The devices stayed at their position for 4 to 6 weeks. In general, there were four positions per OWF: (i) 100 m from a pre-selected OWT, preferably one that was located at a corner of the OWF, (ii) in the OWF center, and (iii) 1 km and (iv) 5 km outside the

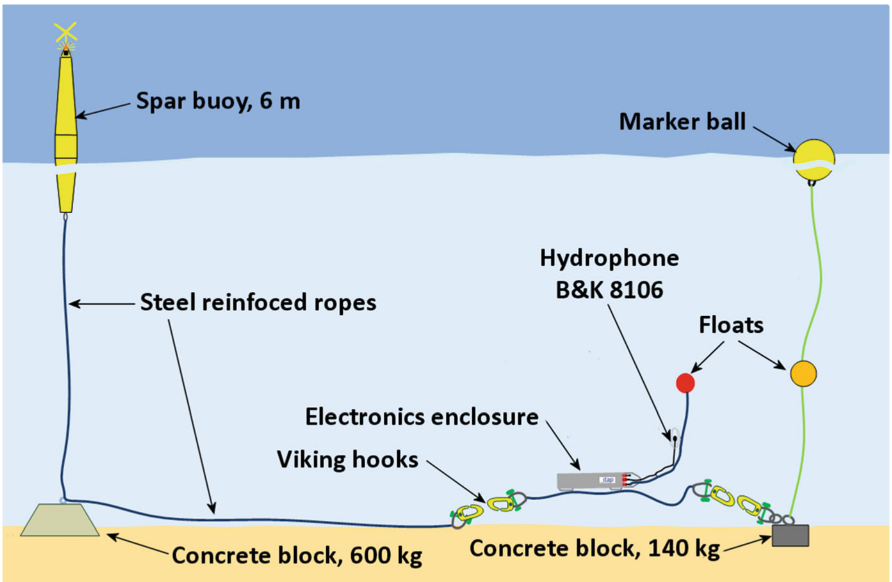

Fig. 2 Measurement setup with mooring details for operational noise measurements within German OWFs

Table 2 Definition of wind classes

Wind class	Wind speed at hub height	Turbine state
Low	<3.5 m/s	Off or very low power
Medium	7.5–11 m/s	30–75% rated power
High	>11 m/s	>75% rated power

OWF boundary. For the current evaluation, only the 100 m position was selected, since they promised the highest signal-to-noise ratios between operational noise of the OWTs and the ambient noise.

Sound was recorded intermittently for 10 min every 2 h in an uncompressed data format (wave, 24-bit; f_s 44.1 kHz) due to the fact that the weather conditions, mostly wind and therefore the power generation of OWTs, will mostly change on larger time scales. This scheme proved to provide enough data for the later analysis for different wind conditions. Before deployment and after recovery of the instruments, hydrophones were calibrated with a Brüel and Kjær 4229 calibrator. The actual sound pressure within the calibrator cavity was monitored with a GRAS 46AG condenser microphone; the value went into the calibration. This calibration process is in accordance with ISO 17025 (2022) and given best practice (HELCOM 2021).

The raw data (uncompressed wav files) were evaluated with a validated software package developed at itap (IONIS). In a first step, the equivalent continuous sound pressure level (L_{eq}; this quantity equals the rms level) in accordance with the German measurement guideline (Müller and Zerbs 2011) was determined in intervals of 5 s. Based on the 5 s values, the L_{eq} and the exceedance levels L_{05}, L_{50} (median), and L_{90} were calculated for both broadband and third octave bands according to the German measurement guideline (Müller and Zerbs 2011). In some cases, and in order to identify tonal noise components radiated by the OWTs, narrowband spectra with 1 or 2 Hz resolution were computed as well. The results were then arranged by three wind classes "low," "medium," and "high"; see Table 2. The wind farm operating companies supplied power and wind versus time data for the relevant OWTs in 10 min steps (mean values). The values in Table 1 were derived from a number of such datasets. The German measurement guideline (Müller and Zerbs 2011) requires at least 3 h of usable sound data per wind class. Despite the intermittent recordings, this was significantly exceeded in all measurements (raw data per wind class ranged from 8 h to more than 50 h).

Measurement Results

A typical narrowband spectrum of a 6 MW OWT is shown in Fig. 3. The peak at 73 Hz also determines the overall or boradband sound presure (SPL). The spectrum has 1 Hz resolution and 5 minutes averaging time. Most OWTs had only a single prominent spectral peak; there were all found in the frequency range 50 to 200 Hz; however with differing amplitudes.

Figure 4 displays the broadband sound pressure levels of all measured OWTs build-up on different foundation types for the wind class "low" (OWTs off) and

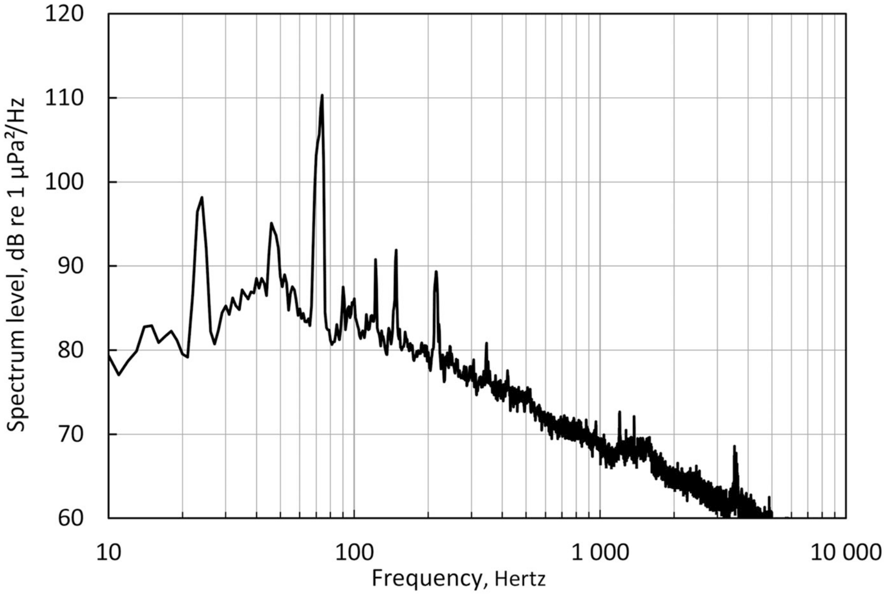

Fig. 3 Typical narrowband spectrum of the operational noise of a 6 MW measured in a distance of 100 m for the wind condition high (full power)

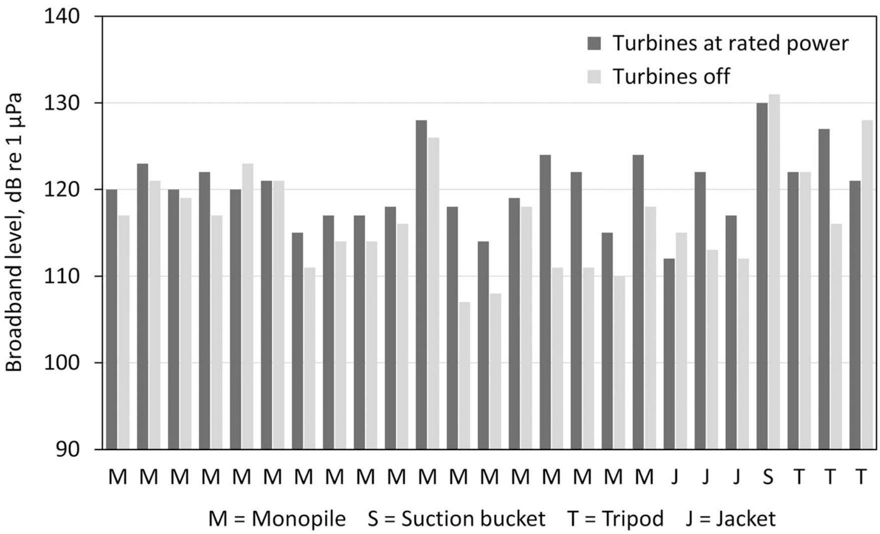

Fig. 4 Broadband sound pressure levels measured in 100 m distance to the offshore turbines at maximum power and wind class high for different foundation types

“high” (OWTs >75% rated power). In this figure and the following ones, the L_{50} (median value) is shown, which was computed from the whole observation period of 4 to 6 weeks per wind class based on 5-s L_{eq} values. Eighteen of the 25 foundations were monopiles; the remaining were four-legged jackets and other foundation types. It can be seen that in 22 out of 25 measurements, the sound pressure levels at 100 m distance to the foundation are, as expected, higher in wind class "high" compared to "low" except for the suction bucket, one monopile, and one tripod foundation. The increase between OWTs off ("low") and at rated power ("high") seems to be also depending on the ambient noise. In the case of high ambient noise levels in the vicinity of the OWT, the increase of the broadband level of operating OWTs is limited. Apparently, there is no systematic-level difference between wind classes "low" and "high" for the two foundation groups monopiles and non-monopiles; the actual levels are given in Table 3. Additionally, the differences between wind classes "low" and "high" might be influenced by other parameters like OWT type or gear-/gearless-driven OWTs.

Figure 5 compares broadband averaged sound pressure levels (L_{50}) of OWTs with gear box to gearless or direct-driven ones with capacities between 2 and 8 MW. Again, no obvious difference was detected, but Table 3 suggests that gearless OWTs might

Table 3 Average (median) sound pressure levels measured in 100 m distance from different OWT types operating under full power (ranged between 2 and 8 MW) for the two different foundation types, monopiles and non-monopiles (based on Fig. 4), and separated into with and without gear box (based on Fig. 5)

Parameter	Average broadband SPL from Fig. 4 and Fig. 5, dB re 1 μPa
Monopile foundations	121.5
Other foundations	122.0
Drive with gear box	122.3
Gearless (direct) drive	120.0

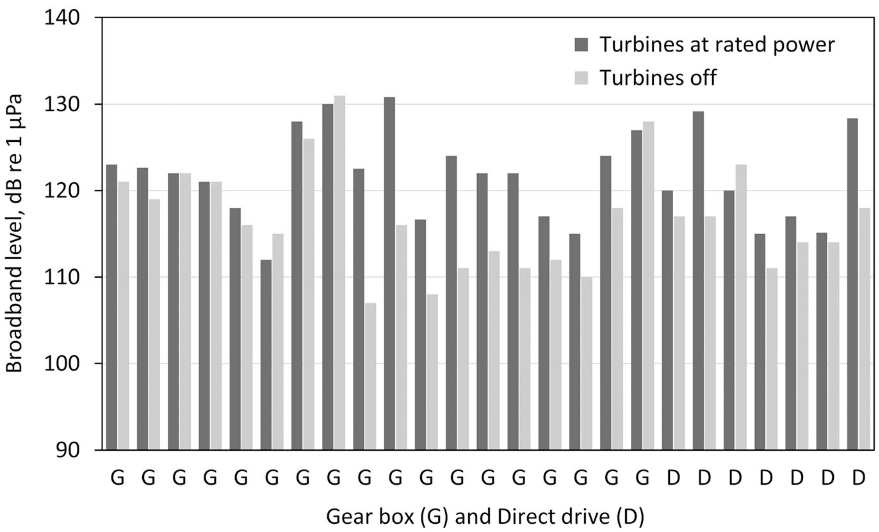

Fig. 5 Broadband sound pressure levels for turbines with maximum power (ranged between 2 and 8 MW) with gear box and with direct drive measured in 100 m distance

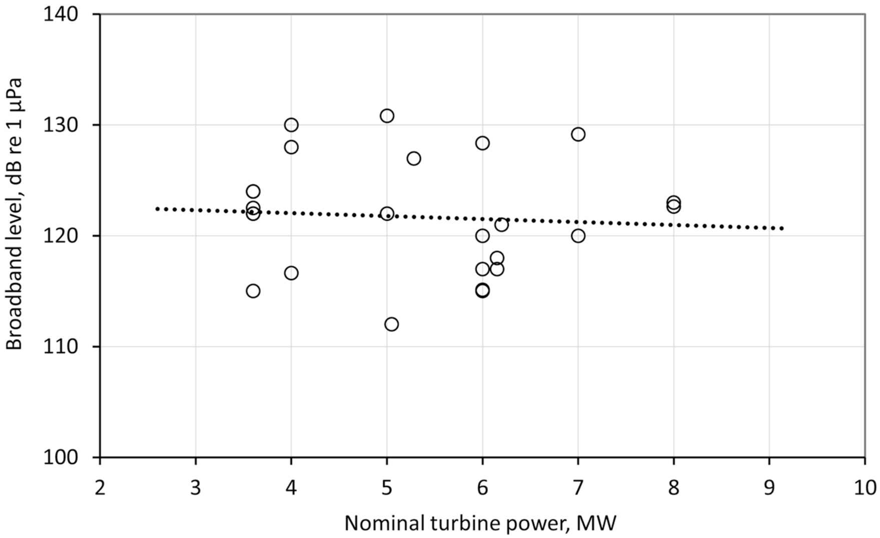

Fig. 6 Broadband sound pressure level (SPL) measured in 100 m distance versus rated turbine power. The dotted line is a linear regression fit with L = −0.27 P + 123 dB, where P is the rated power and L is the broadband SPL

have 2 dB lower levels in average in the vicinity of the foundation. However, this difference should be treated with caution because of the small sample size, the various combinations of foundation designs and OWT types, as well as the differences in ambient noise levels. Averaged sound pressure levels did not increase with turbine size or turbine power, respectively. In fact, a small negative linear correlation between turbine power and measured sound pressure levels was determined (Fig. 6). With increasing OWT size or increasing power rating, the diameter of the monopile foundation increases significantly as well. Thus, the OWT size is not an independent parameter.

Wind Farm-Related Shipping Noise

Based on the results in Figs. 4 and 5, the ambient noise levels in the vicinity of OWTs ranged between 107 and 131 dB in wind class low (OWTs off). The only reason for such a high difference in the measured ambient noise can be shipping noise or other anthropogenic sources, like noise from surrounding OWFs in operation. The operational noise measurements in Germany for OWFs grouped in a “cluster” were usually performed in parallel for all OWFs in the cluster. The idea behind this approach was to investigate if operational noise from surrounding OWFs will influence the ambient noise in one specific OWF. These combined measurements point out that in wind class “low,” the OWTs are off in all OWFs of the cluster. Therefore, observed differences in ambient noise are probably caused by ship movements related to the OWF maintenance/operation or by public shipping outside the OWF.

A typical situation for an OWF far away from shore is that an offshore service vessel stays in the OWF for 2 to 4 weeks before it returns to the base port for bunkering or crew changes. Exceptions are OWFs which are close to the coast so that service teams can make a round trip within a working day during daylight. Typically, inside the OWF, the service vessel moves between OWTs from time to time to deboard the service teams. Occasionally, crew transfer vessels may be active in the area as well. However, most of the time, the service vessel will be in standby position within the OWF or in the surrounding.

Figure 7 depicts the AIS (automatic identification system; a system by which ships communicate their position and other voyage-related information) track of the offshore service vessel "Bibby WM Horizon" as an example over a period of 52 days in 2021 during the operational noise measurements. The vessel was active in the 2 interlinked OWFs "EnBW Hohe See" and "EnBW Albatros" with 87 turbines of the 7 MW class. During this time interval, the vessel left the area southward toward the coast for its base port only three times for several days (crew changes and bunkering). For about 70 h, the ship was driving inside the OWF with a speed >2 knots (kn); maximum speed inside the OWF was 10 kn. The AIS track points are spaced approx. 30 min; shorter intervals were not available from the Sat-AIS provider.

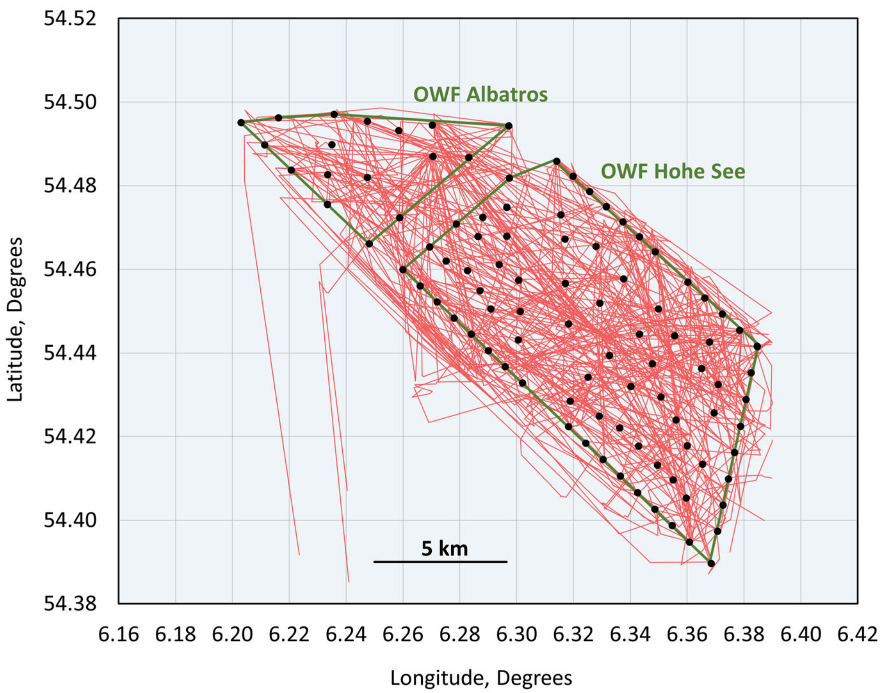

Fig. 7 Movement of a typical offshore service vessel in and close to an OWF, recorded over a period of 52 days during operational noise measurements

Table 4 Comparison of the sound energy produced by the OWF and a typical offshore service vessel during stay inside the OWF

Sound source	Average sound power		Sound energy emitted into the sea in 50 days	
1 service vessel during transits in OWF (2 to 10 kn)	0.8 W	118.8 dB re 1 μW	3.3 MJ	125.1 dB re 1 J
87 wind turbines	10.9 W	130.4 dB re 1 μW	47.2 MJ	136.7 dB re 1 J

For an estimate of the overall sound energy emitted into the water by both sound sources, (i) OWTs and (ii) service vessel, several assumptions must be made to get a first approximation. First, the service vessel's source level is required. For this specific service vessel, no valid source-level measurement is available, but a similar vessel of this class from itap's measurement archives has a source level of L = 170 dB re 1 μPa @ 1 m. For the noise of a single OWT, a permanent value of L = 120 dB re 1 μPa @ 100 m, based on the measurements of this study, is assumed. Sound propagation was approximated with a 15 $\log_{10}$ (distance ratio) law over the first kilometers. The actual results are listed in Table 4.

With the above assumptions, the OWT cluster emits about 11.5 dB more sound energy within a given time interval than the service vessel in the OWF. The sound pressure level cannot be derived straight from this result since the SPL depends on the location and also on time, because the service vessel is moving. For a long average and at large distances from the OWF, the difference between sound levels caused by all OWTs and the service vessel is 11.5 dB. However, this is a theoretical value, since several kilometers outside the OWF, its noise emission is normally not measurable.

The 11.5 dB difference is mainly caused by the small operation time compared to that of the OWF, which is assumed operational 24 h/day. Additional noise sources like crew transfer vessels or the service vessels' dynamic positioning system might make this difference smaller.

Discussion

In Holme et al. (2023), a subsample of the measurements of this study (only OWFs Gode Wind 01, Gode Wind 02, and Borkum Riffgrund 02) was used in distances between 63 m from pre-selected OWTs and 5.000 m from the OWF to investigate the influence of turbine size (6.3 and 8.5 MW), wind speed, and foundation types (only monopile and suction bucket) on operational noise. Holme et al. (2023) did not find a correlation between the measured broadband sound pressure level and turbine size or foundation type. They also found out that the noise from OWTs had no significant influence on the broadband ambient noise level at distances of 1 km and more from the OWF boundary. The ambient noise levels inside and outside the observed three OWFs varied without OWTs off (wind class "low") by up to 5 dB, which is a hint that the influence of vessel activities will significantly dominate the ambient noise inside but also outside the OWFs. In the case of operating OWTs in these OWFs, the overall broadband sound pressure level shows partly an increasing, decreasing, or constant broadband level as function of distance. This finding is in accordance with the findings of this study that the ambient noise outside the OWFs mostly is dominated by other noise sources, most likely noise from OWT service vessels and from commercial ship traffic. For this study, time periods where vessels will be in the vicinity of the measurement positions (<1 km) were excluded to avoid any unwanted effect of crossing vessels. In the study of Holme et al. (2023), the same finding will be reported that nearby crossing vessel showed a fast increase of measured SPL and a fast decrease over several minutes, which is a strong hint that any vessel activity in the vicinity of any OWTs masks or exceeds significantly the overall broadband level generated by an operating OWTs for the short period of crossing nearby.

The measurements indicate that the overall noise emitted into the sea by an OWF (noise from the OWTs plus noise from service vessels) is dominated by OWTs and not by the vessels, since the period of vessel activities within OWFs is limited. Furthermore, based on the rare transits between OWF and base port, the noise from service vessels outside OWFs is limited, and an intermixture with other vessel noise is given. However, the impact of underwater noise from OWFs will also depend on the ambient noise, which is mostly dominated by public shipping noise, especially close to shipping lanes with high vessel traffic.

This study, as well as others (Holme et al. 2023), shows that the most relevant influencing parameters of operating OWTs are currently not identified or well understood.

Within this study, only OWTs during the first years of operation were monitored, but based on experiences from onshore wind farms, a change in the radiated noise from wind turbines running over a long period cannot be excluded. This suggests that modelling the soundscapes of future OWF scenarios might not be possible by interpolating existing measurements from smaller OWT size. In Holme et al. (2023), it was demonstrated that the modelling based on interpolations by Tougaard et al. (2020) will overestimate the noise from OWFs, like Gode Wind 01, Gode Wind 02, and Borkum Riffgrund 01, by up to 8 dB. However, to get statistically valid soundscapes for continuous noise in the water, the often dominating factor shipping noise must be taken into account.

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