Final Report

Experience report on operational noise:

Cross-project evaluation and assessment of underwater noise measurements from the operational phase of offshore wind farms

Acronym: OWF NOISE

Version 2

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Disclaimer: The information in chapter 4.1 describes the procedure of the approval authority for offshore projects in the German EEZ of the North- and Baltic Sea and was summarized by the Federal Maritime and Hydrographic Agency (BSH).

List of changes

Version	Datum	Bemerkung
Version 1	14.07.2023	First version
Version 2	28.05.2024	Update of Chapter 6.1: Comparison of the underwater noise measurement data at a direct distance (i) as measured (distance varied between 100 and 400 m) and (ii) normalized to exactly 100 m by using geometric propagation attenuation: 15*log10(distance)). In addition, an incorrect data set was corrected. All additions/changes to version 1 are marked in italics. Table 5 and 6 supplemented with the normalized values Figures 14, 18, 19, 20, 21 and 23 were supplemented with the normalized values. Figure 22 is newly created. Normalized values were added to the summary

* The latest version of the report completely replaces all previous versions.

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List of abbreviations

AIS	Automatic Identification System
EEZ	Exclusive Economic Zone
BfN	Federal Agency for Nature Conservation (Bundesamt für Naturschutz)
BMU	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit)
BNatSchG	Federal Nature Conservation Act (Bundes-Naturschutzgesetz)
BSH	Federal Maritime and Hydrographic Agency (Bundesamt für Seeschifffahrt und Hydrographie)
c	Sound velocity
CTV	Crew Transfer Vessels
dB	Decibel
DP	Dynamic Positioning
et al.	(lat.) inter alia (i. a.) / among other things
R&D	Research & Development
ADP	Area Development Plan
FKZ	Support code (Förderungskennzeichen)
HELCOM	Baltic Marine Environment Protection Commission – Helsinki Commission
Hz	Hertz
ISO	International Organization for Standardization
itap (GmbH)	Institut für technische und angewandte Physik GmbH (Institute for Technical and Applied Physics)
kHz	Kilo-Hertz
kn	Knots
L_E / SEL	Sound Exposure Level
LNG	Liquid Natural Gas
LOBE	Level of Onset of Biologically adverse Effects
$L_{p,pk}$	Zero-to-peak Sound Pressure Level
p	Sound pressure
PTS	Permanent Threshold Shift
MarinEARS	Marine Explorer and Registry of Sound (Marine research and national noise register for reporting impulsive noise events in the German EEZ of the North- and Baltic Sea to the EU in accordance with the MSFD)
MSFD	Marine Strategy Framework Directive (Meeresstrategie Rahmenrichtlinie)
OSPAR	Oslo Paris Convention (OSPAR-Agreement for the Protection of the Marine Environment of the North Atlantic)
OWTG	Offshore Wind Turbine Generator
OWF	Offshore Wind Farm
ρ	Density of a medium
SL	Sensation Level (hearing level resp. acoustic waves)
SPL	Sound Pressure Level
SNR	Signal-to-Noise Ratio
TL	Transmission Loss
TTS	Temporal Threshold Shift
v	Particle velocity
TSA	Traffic Separation Area
Z	(Noise-) characteristic impedance

1. Summary

The industrial use of the oceans has increased rapidly in the last decade, especially through the use of renewable energy sources at sea in the form of offshore wind farms (OWFs). This trend will continue over the next years and decades. The operation of OWFs not only introduces noise into the water from the operating offshore wind turbines (OWTGs), but also operational shipping traffic for maintenance- and repair purposes (OWF-related service traffic) represents another source of underwater noise. The lifetime of wind farms is about 25 years, so it can be assumed, that this will further introduce noise (continuous noise) into the water in the coming years, which could potentially cause avoidance- and disturbance effects for marine fauna. For the long-term environmentally compatible use of renewable energy sources at sea, this noise input into the water must therefore also be measured, evaluated and assessed in terms of its ecological impact.

At the European level, the basic concept for threshold values[1] with regard to impulsive and continuous underwater noise (impulse and continuous noise; criterion D11C1/2) has been defined by the EU working group *TG-NOISE*; however, the development and coordination of threshold values at the national and regional level has not yet been completed. Thus, there are currently no binding guideline- or limit values for the ecological assessment of operational noise.

In the period from 2011 to 2022, 22 offshore wind farms were built and put into operation in the German Exclusive Economic Zone (EEZ) of the North- and Baltic Sea as well as three windfarms within the 12-nautical-miles-zone. Thus, more than 1,500 offshore wind turbines (OWTGs) with a total capacity of more than 8 GW is in operation in 2023. Over the next few years, however, this number will increase significantly due to the expansion targets for renewable energy sources (expansion target for 2030 is 30 GW). In accordance with the precautionary principle and based on the first measurement experiences from wind farms in operation (e. g. Betke, 2003; 2004), the Federal Maritime and Hydrographic Agency (BSH), the licensing and approval authority, enabled extensive underwater noise measurements to evaluate this noise input into the water. Underwater noise measurements were carried out in a standardized procedure both before construction (background noise) and during operation

[1] The threshold value refers to a LOBE (Level of Onset of Biologically adverse Effects), i. e. the beginning of a harmful, biological effect on a corresponding indicator species. Further information: https://environment.ec.europa.eu/news/zero-pollution-and-biodiversity-first-ever-eu-wide-limits-underwater-noise-2022-11-29_en.

(operational noise) of the wind farms in accordance with the measurement guideline for underwater noise (BSH, 2011), evaluated and integrated into the national noise register MarinEARS[2], including extensive accompanying information from the wind farms, such as turbine type, power- and weather data, etc.

Within the scope of the R&D-project OWF Noise, all available operational- and background noise measurement data of all German offshore wind farms from MarinEARS were summarized for the first time in a cross-project study. Until now, it is neither comprehensively known, what causes the background- and operational noise, nor what ecological impacts result from these continuous noise inputs in the short, medium and long-term. Thus, neither the current status of the wind farms in operation can be assessed, nor environmentally compatible planning for the future expansion of renewable energy sources at sea can be guaranteed.

Hosting a total of 27 operational- and 12 background noise measurements in 24 wind farms with 16 different OWTG-types from seven different manufacturers and nominal power between 2.3 and *8.4* MW, founded on five different foundation structures, three measurement positions per wind farm, each with three defined operating states of the turbines, the measurement database from MarinEARS currently represents the largest database of its kind worldwide.

Based on the cross-project evaluation of the background- and operational noise measurements, the following results and findings were obtained:

General

- Based on the standardized sound measurements, evaluation and documentation in MarinEARS, a direct, systematic comparison between different wind farms can be carried out, in order to identify and quantify possible project- and site-specific parameters influencing operational noise. A comparison of noise conditions before the construction of wind farms with noise conditions during operation is also possible due to the standardized measurement-, evaluation- and documentation concept.
- The evaluation of noise conditions during the operation of offshore wind farms inside and outside wind farms is extremely complex, as noise input from wind turbines in operation and from OWF-related service traffic do not differ significantly in time or

[2] MarinEARS - Marine Explorer and Registry of Sound; specialist information system for underwater noise and national noise registry for noise events (continuous and impulse noise) in the German EEZ of the North- and Baltic Sea to the EU in accordance with the MSFD (https://marinears.bsh.de).

space from background noise already present in the surroundings. A cumulative examination of all continuous noise inputs is therefore necessary.

- This cross-project study was able to summarize the current state of knowledge regarding operational- and background noise and identify existing knowledge gaps with respect to a cumulative evaluation of the ecological effects of operational noise.

Project- and site-specific factors influencing operational noise

- Noise input from operating offshore wind turbines is basically characterized by low frequencies. In most cases, tonal components resulting from the characteristic ratios of the gearbox, the generator and the rotational speed of the rotors (natural or eigenfrequency of the rotor-drive system) are emitted into the water with frequencies in the range of 25 and 160 Hz. In some cases, a few harmonics, i. e. integer multiples of the natural frequency (natural harmonics), can also be measured in the spectrum up to a few hundred Hertz.
- These low-frequency noise inputs into the water are only dominating the broadband Sound Pressure Level in the immediate vicinity of the turbines (~ 100 m) and when the turbines are operating close to their nominal power. The mean (broadband) total Sound Pressure Level (SPL_{50} or L_{50}) at nominal power of the turbines varies between 112 and 131 dB (median and mean value 120 dB, *normalized to 100 m 122 dB*). The mean Sound Pressure Level (L_{50}) from the 1/3-octave-band with the dominant component of the natural frequency of the system varies between 102 and 126 dB, *or 130 dB for values normalized to 100 m* (median and mean value 114 dB, *116 dB if normalized to 100 m*).
- Level statistics of the Sound Pressure Level ($L_{90,\ 50,\ 05}$) are mandatory for an assessment of the noise inputs caused by the turbine in operation with nominal power in the wind class "high", since the prevailing weather conditions also change the surrounding background noise caused by vessel noise and weather-related noise inputs, and there is a partial mixing of these noise inputs.
- The natural frequencies of the turbines tend to be lower-frequency (≤ 80 Hz) for direct-drive resp. gearless turbines and are also "quieter" than turbines with gearboxes, although the gearless turbines had on average 1.4 MW larger nominal outputs (median value 2.3 dB and mean value 1.5 dB).

- A significant correlation between the noise inputs into the water by the turbines and their foundation structure (monopile, tripod, tri-pile, jacket with different pile diameters up to 8.1 m) could not be determined. Large monopiles tend to be a bit "quieter" than the other foundation structures, such as jackets, with several skirt-piles with smaller pile diameters (on average 2.0 dB). A further detailed evaluation according to the different non-monopile foundation structures was not followed due to the small sample size.

- A strong correlation between the noise inputs and the nominal power of the turbines (between 2.3 and 8.4 MW) could not be found either. There is a tendency for turbines with a high nominal power to be slightly "quieter" than turbines with a low nominal power (on average ≤ 5 MW *122.5 dB*, > 5 MW *119.0 dB*). However, this may also be due to the change from gearbox to direct drive, which has mostly taken place. Moreover, the latest generation of turbines also seems to be tendentially "quieter" than older turbines.

- No evaluation-relevant differences of the operational noise based on different water depths (20 to 40 m) or North- resp. Baltic Sea can be identified either.

- The broadband difference in the mean Sound Pressure Level (L_{50}) between turbines in operation with nominal power (wind class "high") and at standstill (wind class "low") varies between 0 dB and 13 dB (mean value *3.8 dB*, median value 3.0 dB). *In three cases, the broadband Sound Pressure Level for the wind class "low" (turbines at standstill) is up to 3 dB louder than in the wind class "high" (turbines with nominal power).* These three cases are wind farms with smaller and older wind turbines. The reason could possibly be caused by higher shipping traffic inside and outside the wind farms. Measurement data under the same weather conditions (wind class "high") between the operating states "turbine in operation with nominal power" and "turbine at standstill" are not available.

- The tonal, low-frequency components of the turbines in operation can usually still be measured outside the wind farms up to distances of a few kilometers, but with increasing distance, they mix with the general background noise level, so that the emitted noise is no longer dominating the broadband Sound Pressure Level (signal-to-noise-ratio < 6 dB). The background noise level outside OWFs is mostly dominated by non-OWF-related shipping traffic outside the wind farms and varies strongly in different directions to a wind farm resp. between different sea areas.

- The permanent Sound Pressure Level (L_{50}) in the wind farm with turbines at standstill (wind class "low") varies between 107 dB (*normalized to 100m 110 dB*) and 132 dB (median- and mean value 117 dB, *normalized to 100m 118 dB*). Such level differences in good weather with no or weak wind is most likely caused primarily by vessel noise.
- It can be seen that there is a high correlation between vessel density incl. distance to the measuring position and the permanently present noise level: the more vessels, the larger and faster the vessels and the closer they pass the measuring positions, the louder the background noise level. This fundamental relationship between vessel density and continuous noise has also been clearly demonstrated by modelling and measurements in the North- and Baltic Sea by the BIAS and JOMOPANS research-projects.

Operational shipping traffic (OWF-related service traffic)

- The operational shipping traffic within the restricted wind farm areas is initially negligible in terms of energy, compared to the permanent, non-OWF-related shipping traffic outside the wind farms and the emitted operational noise of the turbines in operation. This is due to the fact that usually only one service vessel plus occasional small crew transfer vessels and other support vessels move in and around the wind farm during the day. In the wind farms themselves, service vessels mostly only travel at reduced speed (< 8 knots). The majority of the time, the service vessels are at anchor in or around the wind farm. During the night, there is usually no vessel movement. This shows that the service vessels for wind farms situated close to the coast enter the harbour in the evening and that accommodation facilities have been available offshore for wind farms situated far from the coast. This is consistent with the environmental report to the site development plan (SDP) (BSH, 2023).
- The noise input of service traffic outside the wind farms is limited to only a few arrivals and departures per day for wind farms close to the coast resp. per week for more distant wind farms. For an evaluation of these noise inputs into the water, this must be put in relation to the additional shipping traffic. Furthermore, the OWF-related and non-OWF-related shipping traffic is completely mixed on the fixed routes. Based on the environmental report to the SDP 2023 (BSH,2023), non-OWF-related shipping traffic accounts for 70% in summer and 80% in winter, so that the share of OWF-related service traffic on the total Sound Pressure Level outside wind farms can be classified as low to negligible.

Possible ecological effects of operational noise

- The broadband total noise level does not exceed a Sound Pressure Level of 130 dB at any time in any of the 27 wind farms considered due to the wind turbines in operation, including all background noise caused by wind and waves as well as vessel noise.
- Based on existing audiogram studies for marine mammals, in particular for the key species harbour porpoise, a physical damage in the form of a temporal or permanent threshold shift (TTS or PTS) can be excluded (e. g. Kastelein et al., 2017). Due to the tonal and very low-frequency noise input from the turbines (≤ 160 Hz), it can generally be assumed that these noise components cannot be perceived by harbour porpoises even at distances of 100 m from the turbine. Other animal species, such as harbour seals, are certainly able to perceive these low-frequency noise inputs.
- Temporally and spatially limited, increased noise inputs from service vessels cannot be excluded within the wind farms. However, the operational traffic moves at speeds of up to 8 knots at only a fraction of the time.
- Existing modelling approaches (e. g. Tougaard et al., 2020; Stöber & Thomsen, 2021) for operational noise are mostly based on only a few and partly smaller turbine types (often with gearbox), so that predictions of the noise conditions of existing German OWFs of the latest generation (e. g. Holme et al., 2023) lead to considerable overestimations of the actually measured operational noise of turbines of up to 8 dB. Also, the interference radii calculated in Stöber & Thomsen (2021) for a 10 MW turbine of 6.3 km with gearbox and 1.4 km for gearless turbines could not be validated with this cross-project study. Thus, the tonal components (natural harmonics) could partially be detected by measurement up to distances of 5 km but were not dominating the broadband Sound Pressure Level. Moreover, the low-frequency noise input from the wind turbine is no longer audible to individual marine mammals, such as harbour porpoises, at distances of 100 m from the turbine.
- The impact assessment of operational noise must always be carried out cumulatively in the context of all continuous noise components, consisting of noise inputs from the wind turbines, OWF-related and non-OWF-related shipping traffic, as well as abiotic noise inputs from e. g. wind and wave action. Only by considering the entire continuous noise in and around the wind farms, a spatially and temporally cumulative evaluation of the possible, ecological impacts of operating wind farms can be scientifically backed. From a physiological point of view, a species-specific and audibly suitable processing of the noise inputs is recommended for a further evaluation of operational noise resp. continuous noise.

2. Introduction and aim of this study

The use of offshore renewable energy sources is growing rapidly in Europe, also in Germany, pushed by the renewable energy process after 2011 (Fukushima). However, the demand for renewable energy must go hand in hand with an awareness of sustainability issues, especially the protection of nature and marine ecosystems. The construction and subsequent operation of offshore wind farms leads to very different inputs of sound energy into the sea. The Marine Strategy Framework Directive (MSFD, 2008) basically distinguishes noise inputs into the water into two descriptors: 11.1 impulsive noise, such as impulse pile-driving or detonation noise, and 11.2 continuous noise, such as vessel noise or operating noise from offshore wind turbines (OWTGs).

Within the scope of the threshold value development for impulse- and continuous noise for all European waters by the EU working group *TG-NOISE*, the basic concept for the threshold values with regard to continuous underwater noise (continuous noise; criterion D11C2) was defined as follows: "In no month of the assessment year may more than 20% (≤ 20%) of the habitat of the selected species have underwater noise inputs, that exceed the threshold value". The development and coordination of these threshold values are important determining processes and will take place both nationally and regionally, in order to be able to use them in a target-oriented manner. However, this means, that currently, there are neither nationally, nor internationally binding guideline- or limit values for an ecological assessment of operational noise (continuous noise).

For underwater orientation, search for food and communication, the harbour porpoise uses an echolocation system and therefore reacts sensitively to noise in the seas. For these reasons, this species is considered a key species in the German North- and Baltic Sea in the context of the assessment of anthropogenic noise inputs into the water.

In the first years of these observations, the main focus was increasingly on construction noise, as in most cases the construction work of the foundation structures is carried out by means of impact pile-driving. This well-established installation method causes particularly loud, impulsive underwater noise, which can cause physical damage to the auditory system of harbour porpoises in the form of temporal or permanent threshold shifts (e. g. Lucke et al., 2009; Kastelein et al., 2015; Southall et al., 2019). Furthermore, avoidance behavior has been observed to occur temporally and spatially over several kilometers with this installation method (Brandt et al., 2016; Rose et al., 2019). Through the intensive efforts of the industry and public funding, a standard of technology for noise mitigation measures has been developed within a few years, which led to a considerable reduction and thus to compliance with the German noise mitigation values[3] for impulsive noise input (Bellmann et al., 2020).

In contrast, the ecological impacts of underwater noise input from the operation of offshore wind turbines (OWTGs) have been less systematically studied up to now. Several studies indicate that the mechanical vibrations of components, caused by the conversion of the rotation of the turbine via the gearbox to the generator, are radiated into the water via the foundation structure (tower incl. foundation). Through measurements in offshore wind farms in other countries, the approximate nature of this noise was already known early (e. g. Betke et al., 2003, 2004). It was assumed, that this noise input can dominate the ambient noise measured in the immediate vicinity resp. permanently present background noise (e. g. Betke, et al., 2005; Madsen et al., 2006; Norro & Degraer, 2016; Yang, et al., 2018). According to the environmental report on the site development plan (SDP) 2023 (BSH, 2023), however, no injury of marine mammals (the key species in German waters is the harbour porpoise) within the scope of the Federal Nature Conservation Act (BNatSchG) is to be assumed as a result of operational noise.

In the first German offshore wind farm *alpha ventus*, similar noise inputs into the water were measured in 2011 (Betke, 2014). However, at that time the operational noise was only superficially investigated. Thus, it was not known whether and to what extent the operating noise depends on the size or the nominal power of a wind turbine as well as its type of construction (direct drive or gearbox). Another influencing parameter on the noise radiation could be the type of foundation; thus, a difference between monopile and jacket foundations should also be considered. Furthermore, site-specific parameters, such as bathymetry or wind speed, may also have an effect on the soundscape.

Driven by the demand for renewable energy and the available experience, turbine size and thus their (nominal) power have increased considerably over the last decade. Currently, OWTGs in the 8 to 9 MW class are being erected; upcoming offshore projects will have nominal out-

[3] German dual noise mitigation (value) criterion for the avoidance of temporary hearing threshold shifts in harbour porpoises due to impulsive noise input into the water: 5% exceedance level of the Sound Exposure Level (SEL_{05}) ≤ 160 dB and zero-to-peak Peak Level ($L_{p,pk}$) ≤ 190 dB to be observed at a distance of 750 m from the source.

puts of well over 10 MW. A first prototype of a 15 MW OWTG has already gone into test operation onshore (renewable energies, 2023[4]); 18 MW OWTGs are also being planned. In addition, the trend is increasingly towards gearless turbines (direct drive).

In contrast to the monitoring and efficiency control of foundation set-ups (construction phase) by means of the impact pile-driving method, it was not possible to systematically investigate the possible project- and site-specific factors of OWTGs in operation, either in Germany or internationally, using a large, empirical data base. This might have been due to lack of existing and freely accessible operational noise measurement data. Moreover, in most cases, no standardized measurement and evaluation concepts were applied for operational noise measurements, so that a comparison of the existing measurement data of different, international wind farms turned out to be difficult or only possible to a limited extent. Some studies have summarized the freely available, empirical data sets of operational noise measurements and generated models for the noise radiation and -propagation of turbines in operation based on these (e. g. Tougaard et al., 2020; Stöber & Thompson, 2021). However, no study is known that has considered the cumulative effects of all permanent noise inputs in the water, as in and around wind farms, there are noise inputs from the turbines themselves, OWF-related service traffic, non-OWF-related shipping traffic and abiotic effects, such as wind and wave action.

The aim of the OWF Noise R&D-project is, firstly, to identify and quantify the main parameters influencing the noise input into the water from OWTGs in operation. On the other hand, the cumulative effect of the operating noise of the turbines, the operational OWF-related shipping traffic and the permanent background noise in and around the wind farms will be systematically investigated. For this purpose, the operating noise measurements of 27 wind turbines selected out of 24 wind farms were analyzed for the first time in the present study.

The operational noise measurements used in the present study were carried out for single wind farms with at least three measurement positions at distances between 100 m from a selected turbine, in the center of the wind farm center and up to 5 km outside the wind farm in three defined operating states of the turbines (turbine standstill, turbines running at nominal power and turbines are between the previously mentioned operating states) in parallel over several weeks. Moreover, for the assessment of operational noise, 12 so called background noise measurements were also carried out in and around selected wind farms, mostly

4 https://www.erneuerbareenergien.de/technologie/offshore-wind/offshore-windturbinen-v236-co-vestas-nimmt-rekord-windenergieanlage-betrieb

at the same measurement positions as the operational noise measurements before construction of the wind farms.

All data sets for operational- and background noise measurements are available in the national noise register MarinEARS for continuous noise and include wind farms from the German EEZ of the North- and Baltic Sea. Comparable to the noise register impulse noise in MarinEARS, all so called continuous noise measurements were recorded and quality evaluated in a standardized form and well documented. Thus, the database for continuous noise contains not only the raw data and processed measurement datasets, but also essential accompanying information for operational- and background noise, such as wind conditions, OWTG type including performance data, measurement reports, etc. Following the precautionary principle extensive measurements were ordered during the Preconstruction, construction and operational phase in the approval procedures in Germany. In that way one of the largest databases for operational- and background noise worldwide has been established. The BSH, in cooperation with acousticians from *Müller-BBM GmbH* and *itap GmbH*, developed the "Measurement Guidelines for Underwater Noise Measurements" (BSH, 2011), which contains specifications for this type of continuous noise measurement and its subsequent evaluation according to the state of knowledge at that time. The main focus of the measurement specification was and is on the recording of the noise input of OWTGs in operation and not on the recording of the operational service traffic.

The standardized data sets in MarinEARS for background- and operational noise make the measurement data and their accompanying documents manageable for a cross-project analysis. Based on this database, the goal of this R&D-project is to conduct a cross-project analysis to identify the site- and operation-related influence parameters of the noise input into the water by operating wind turbines; see chapter 6.1 and 6.2.

Vessel noise, which can be attributed to the operation of the wind farm (OWF-related service traffic) and is therefore actually part of the operational noise of a wind farm, has hardly been investigated nationally or internationally so far. Only in the years from 2019 onwards, isolated measurements of operational shipping traffic have been carried out in and around wind farms in German waters. A further question of this research project is therefore whether and which influence can be attributed to the additional service traffic of offshore wind farms. With the available, empirical measurement data and analyses of already completed operational noise measurements, a first estimation of the operational vessel noise is presented; see chapter 0.

The recording of the background noise prior to the construction of the wind farm is also mandatory, since operational noise must be considered in the context of permanent background noise, in order to analyze and evaluate the cumulative effects of all permanent noise inputs into the water; see chapter 6.3 and 7.2. In the two funded research projects BIAS[5] for the Baltic Sea and JOMOPANS[6] for the North Sea, large-scale underwater noise measurements of the permanently present background noise were recorded from the years 2014. Basically, it turned out, that the permanent background noise is significantly dependent on the type and number of vessels and vessel speed; the larger, faster and the more vessels (vessel density) are in operation, the greater the noise input into the water. But abiotic noise inputs, such as wind and waves, can also influence the background noise, at least in certain frequency ranges. Noise maps from the two research projects show a high correlation between the measured underwater noise and the existing vessel routes (traffic separation areas - TSA) in the North- and Baltic Sea.

The measured noise from offshore wind turbines is also compared in this report with the hearing ability of harbour porpoises, which in Germany are considered the key species for the ecological impact assessment of noise inputs into the water. With this, a further contribution to the more extensive, impact assessment of the possible disturbance and avoidance effects of operational noise shall be provided; chapter 7.3. Finally, chapter 7.4 discusses the possible, cumulative effects of operational noise.

[5] Baltic Sea Information on the Acoustic Soundscapes – BIAS: EU life plus project. https://biasproject.wordpress.com/

[6] Joint Monitoring Program for Ambient Noise North Sea – JOMOPANS: EU intereg project. https://northsearegion.eu/jomopans/

3. Underwater noise: metrics and definitions

Basically, natural noise inputs into the water can be due to abiotic sources, such as wind and waves, but also biotic sources, such as animal sounds for echolocation or communication among themselves. Besides these natural sounds, there are anthropogenic sound sources, such as ship traffic, or construction activities, such as pile-driving and operational activities to be considered. The Marine Strategy Framework Directive (2008) divides all noise inputs (descriptor 11: energy input into the water / underwater noise) into impulsive noise input and continuous noise input. Operating noise from wind turbines and background noise are classified as continuous noise. In the following, the most important, acoustic parameters for continuous noise are briefly described. The terminology used in this report for underwater noise is based on ISO 18405 (2017) as well as the measurement specification for underwater noise (BSH, 2011).

3.1 Sound pressure and Sound Pressure Level (SPL)

Sound in general consists of pressure fluctuations in a medium, such as water or air. Typically, sound is described by two physical quantities, the sound pressure *p* (in Pascal *Pa*), which characterizes the pressure variation, and the particle velocity *v* (in mm/s), which characterizes the speed, at which the medium is deflected. The particle velocity should not be confused with the sound velocity c_{water}, i. e. the speed of propagation of sound in a medium, which in the case of water is usually in the range of c_{water} = 1.480 m/s. The particle velocity *v* is significantly lower than the sound velocity *c*.

Sound pressure p and particle velocity v are related in the acoustic characteristic impedance Z (in Ns/m^3 resp. kg/m^{2}s; outdated: Rayl), which characterizes the wave impedance of the medium, in the following way:

$$Z = \frac{p}{v} = \rho \cdot \mathrm{c}$$ *Equation 1*

with

ρ – density of the medium (in kg/m^3),

c – sound velocity (in m/s).

Sound can basically be understood as a rapid fluctuation of the ambient- or static pressure; Figure 1. The physical quantity *sound pressure* thus adds to the constant ambient pressure.

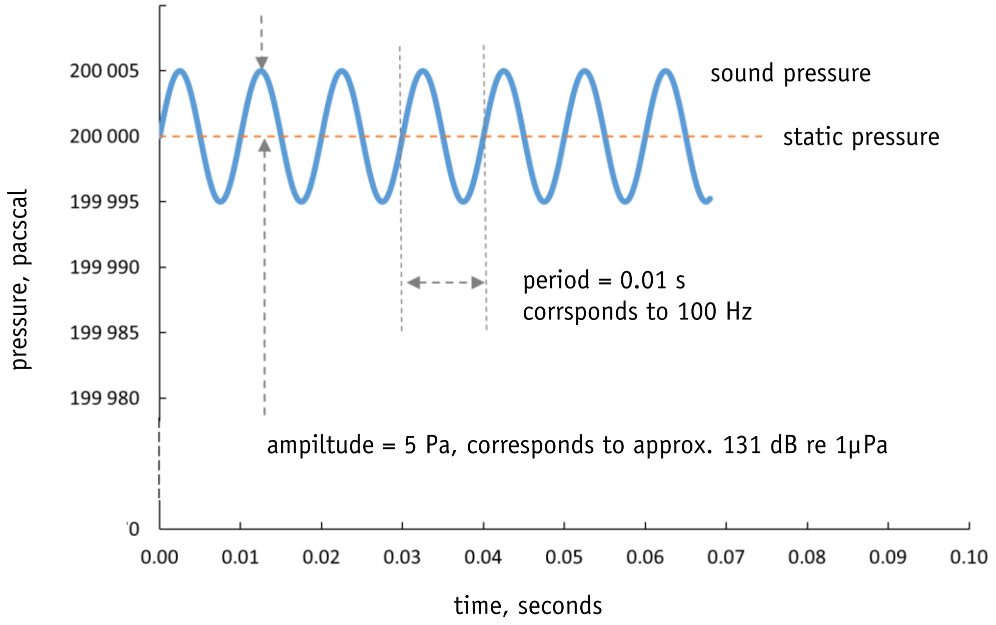


Figure 1: *Schematic representation of sound pressure and static water pressure using the example of a single tone with a frequency of 100 Hz. The static pressure of 200 kPa in this example corresponds to a water depth of about 10 m.*

Definition

As in other areas of the communication engineering, when the values to be represented span a wide range of values, sound is not characterized by the physically measurable sound pressure, but by the sound level or more precisely Sound Pressure Level. Measuring instruments resp. sensors for underwater noise (hydrophones) initially provide linear values of the sound pressure, but not a logarithmic level (in dB). This must therefore be converted into the desired level quantity. Generally, this is done with

$$L^{7} = 10 \log_{10}(\langle p^2 \rangle / p_0^2) \quad (\textit{Equation 2})$$

with

$\langle p^2 \rangle$ - squared and time-averaged sound pressure p (in Pa),

p_0 - internationally standardized reference sound pressure 1 µPa (ISO 18405, 2017).

[7] Sound Pressure Level = SPL in the ISO 18405 (2015); in Germany mostly L will be used.

The averaging time, which does not explicitly occur in Equation 2, can be freely selected according to the task. In this investigation, it is 5 s, which corresponds to the BSH measurement regulation (BSH, 2011), section 6. The level *L* in Equation 1 can also be written as "energy-equivalent continuous sound level" L_{eq} as follows:

$$L_{eq} = 20 * log_{10} \frac{1/_T \int_0^T p(t)^2 \, dt}{p_0} \qquad \textit{(Equation 3)}$$

with

p(t) – pressure varying over time (in Pa),

T - averaging time (in s); in this study 5 s.

The result *p* is the sound pressure in Pa (mostly the average sound pressure, since the level L is practically always an average level).

Statistics - Exceedance level

Statistical representations can be formed on the basis of the Sound Pressure Level, averaged over time intervals of 5 seconds. These are occasionally also incorrectly referred to as "percentile levels" (e. g. in DIN 1320, 2009). When analyzing operational sound, the L_{05}, L_{50} and L_{90} are preferably used as meaningful quantities.

The L_{90}, for example, is exceeded in 90% of the measurement time and thus by 90% of the measured values and acts as a measure for quiet periods resp. mostly characterizes the permanent background noise level. The L_{90} is mostly influenced by noise from distant vessels and wind- and wave noise, but also includes the OWTG operating noise from neighboring wind farms, if present.

The L_{05} is exceeded by 5% of all measured values of the analysis period and serves as a measure for the "loudest" levels of the averaging periods. It is statistically more robust than the absolute maximum value, which can attain a very high value due to a single loud disturbance or noise input. However, with strong winds, the L_{05} can also be disturbingly affected by ambient noise, e. g. single wave action or chain clanking of the measuring device anchorage.

The L_{50}, also known as the median, is a mean value that is robust against outliers in both directions and is suitable as a data basis for qualitative statements in comparisons.

For the evaluation of stationary plant noise, it is therefore necessary to take a close look at L_{05}, L_{50} and L_{90} instead of the L_{eq} averaged over the entire measurement period. In the following, the L_{50} is also used for the identification of possible influencing parameters on operating noise.

The calculation of the statistical level quantities L_{05}, L_{50} and L_{90} is based on $L_{eq,5s}$ (Equation 3), i. e. the equivalent continuous sound level determined in 5 second steps.

Example: *Assumed, that within a wind class, a total of 3,000 evaluable 5 second intervals were recorded, i. e. about 4.2 hours. These 3,000 discrete values of the $L_{eq,5s}$ are sorted by size in ascending order. The L_{50} is now the level value no. 1,500, the L_{05} is the level no. 2,850 and the L_{90} is the level no. 300.*

Frequency spectra

Levels can be specified both broadband, i. e. in the form of a single number for the entire frequency range under consideration, e. g. from 10 Hz to 20,000 Hz, and for individual frequency bands; see Figure 2. In the standardized 1/3 octave-spectrum (also called third octave band spectrum), the frequency resolution is always three values per frequency doubling resp. octave; Figure 2 (left). For the narrowband spectrum (Figure 2, right), the frequency resolution and other parameters, such as windowing and time averaging, can be freely selected according to the analysis.

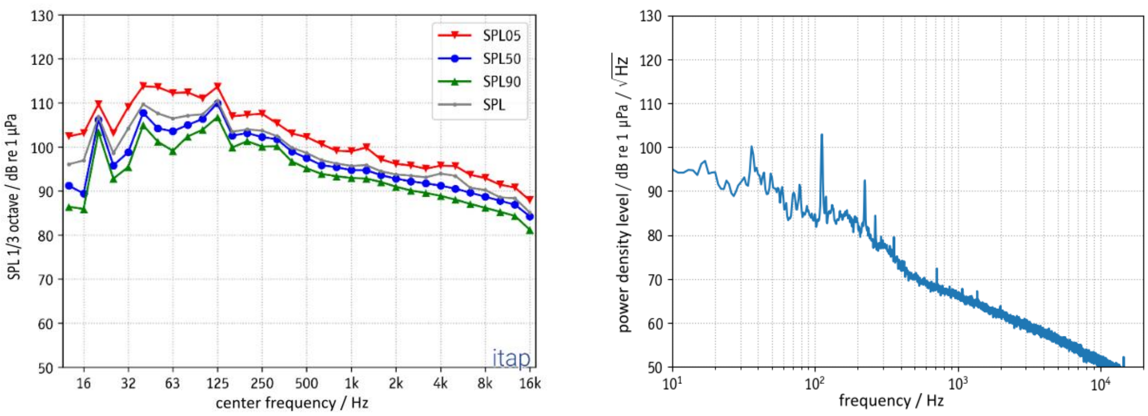


Figure 2: *Left: averaged 1/3-octave-spectrum of an operational noise measurement in approx. 100 m distance to a plant and the associated 5, 50 and 90% exceedance levels, right: narrowband-spectrum with 1 Hz resolution. The broadband L_{50} (total level of the blue curve in the left image) is about 118 dB re 1 µPa.*

3.2 Typical sound sources in the sea

Generally, sound sources in the sea, that affect the underwater acoustic environment, are divided into two categories: natural (biotic or abiotic) and anthropogenic (man-made) sound sources.

Natural sound sources in the sea are primarily weather-related effects. These can generally be caused by wind, waves, rainfall and storms/bad weather. Depending on the strength and type of weather effects, the characteristic frequency range will vary. Additionally, sounds from marine life, as well as seismically evoked sounds, are also considered natural sound sources. In the following, some known sound sources are summarized:

Wind and waves: Wind-induced underwater noise has a very flat maximum in the spectrum at 500 Hz and is detectable up to above 10 kHz. The sound level increases by about 5 dB for each doubling of the wind speed in the range 1.5 m/s to 20 m/s (Carey & Evans, 2011).

Rainfall: Rain, hail and also snow cause noise in the range of several kHz up to several 10 kHz. Small raindrops around 1 mm produce a pronounced maximum at 13 to 16 kHz (Bjørnø, 1994).

Other abiotic sound sources: Other abiotic sounds are thunderstorms, ice movements and seismic sounds. Massive rainfall, such as hail or heavy rain, usually produces relatively high-frequency noise input into the water and is dominating the broadband Sound Pressure Level depending on the water depth.

Biotic sounds: Animals can also transmit sound into the water for echolocation, hunting or communication; among others, the click sounds of the key species harbour porpoise in the North- and Baltic Sea. These are in the frequency range around 130 kHz; at such high frequencies, the absorption of the water is quite strong, which is why the clicks only have a range of up to one kilometer (Clausen *et al.*, 2010).

Technical note: *Basically, the operational noise measurements in the period from March to October showed, that neither heavy rain, hail, nor natural sounds of harbour porpoises were level-determining factors in the operational noise measurements in and around wind farms.*

3.3 Anthropogenic underwater noise input from the operation of offshore wind farms

Basically, noise emissions resulting from the operation of a wind farm can be classified into operational vessel noise (service traffic) and noise emissions from operating offshore wind turbines (OWTGs). Both noise inputs are briefly described in the following.

3.3.1 Noise emissions from offshore wind turbines

Noise inputs into the water that can be observed during the operation of an offshore wind turbine, largely originate from rotating machine parts, such as the rotor blade, the gearbox and the generator. These cause structural vibrations of the gondola and the tower and propagate to below the waterline, where they are radiated as underwater noise (Figure 3).

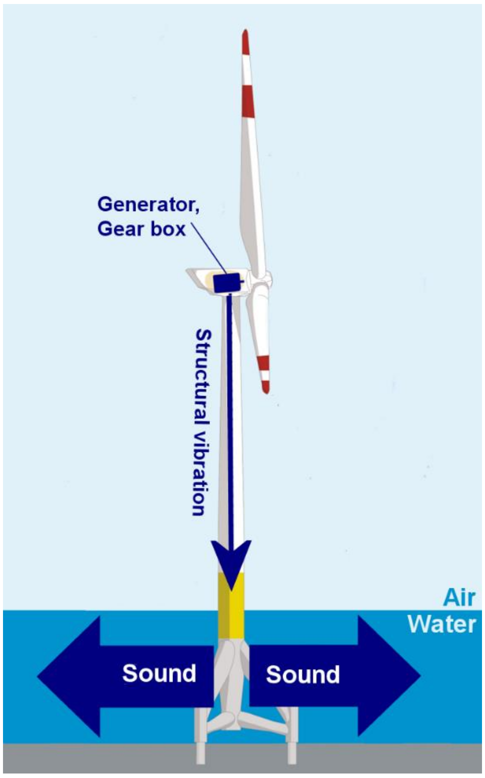


Figure 3: Schematic representation of the input of machine noise into the water.

If, for example, 100 cogs per second come into mechanical contact in a gear stage, a sound with a basic frequency of 100 Hz is to be expected, possibly also integer multiples of the basic frequency, called natural harmonics. The frequencies of this narrow-band noise produced by the system (rotor-drive system natural frequency) are predominantly well below 1,000 Hz (e. g. Betke and Matuschek 2012, Betke 2014). In the frequency spectrum, this noise appears as narrowband level peaks. In Figure 4, the noise inputs of operating wind turbines with nominal outputs between 1.5 and 5 MW are summarized as narrowband spectra from published measurements (Betke and Matuschek, 2012). Such typical narrowband spectra can also be found in other recent publications (e. g., Tougaard et al., 2020; Stöber and Thompson, 2021).

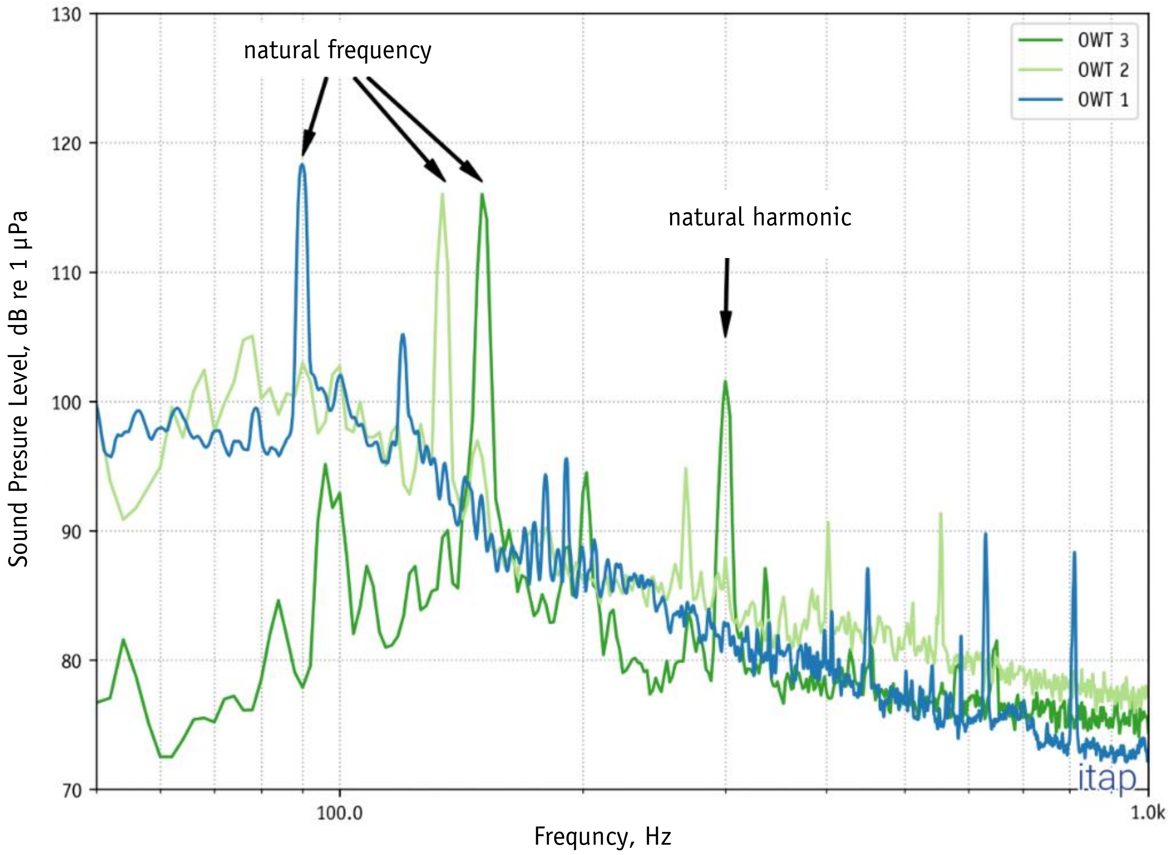


Figure 4: Underwater noise from three different OWTGs, each at a distance of about 100 m. OWT1: 5 MW turbine installed on a tripod-foundation, OWT2 and OWT3 each 2 MW turbines installed on monopiles with different diameters (Betke and Matuschek, 2012).

For gearless turbines, in which the rotor directly drives the generator (direct drive), the mechanism of noise generation described in the previous section does not apply. The generator is usually driven by permanent magnets. The number of slots of the generator in relation to the rotor speed determines its natural frequency and natural harmonics respectively. A basic frequency of 20 to 50 Hz is often assumed, depending on the type of direct drive and the number of permanent magnets. Thus, noticeable tonal noise components have also been detected in such wind turbines in some cases.

Aerodynamic noise from the rotor blades, which dominates the airborne noise of wind turbines in the immediate vicinity, does not play any role in underwater noise, since the airborne noise practically does not enter the water due to the significantly different noise impedances of air and water. Moreover, vibrations from the rotor blades are generally not transmitted via the generators, so that this type of noise input into the water is also not significant.

3.3.2 Noise emissions due to shipping traffic

The noise input from vessels depends on the size resp. length of the vessels, the sailing speed and the propulsion method. In the MSFD and in the recommendations of HELCOM and OSPAR, the 1/3-octave-bands around 63 and 125 Hz are indicators for conventional vessel noise of larger vessel units. This could also be clearly demonstrated in part by measurements within the projects BIAS (BIAS, 2016) and JOMOPANS and by several other long-term measurements (NRC, 2003).

In the case of the usually small vessels resp. boats, which are often used for recreational activities, the spectrum of noise radiation is mostly much higher-frequency and has a maximum in the range of 1 to 10 kHz (Kipple & Gabriele, 2003). For other types of drive, such as the electric drive on some of the ferries of the Fehmarn Belt crossing, there are sometimes maxima in the spectrum between 400 and 500 Hz (*itap GmbH*'s own measurements).

It should be noted at this point, that an environmentally compatible conversion is also gradually making its way into shipbuilding. This so-called Blue Technology is currently increasingly relying on liquid natural gas (LNG) drive. It is not yet possible to estimate the influence of these new types of drive, some of which are supported by turbines, on the spectral distribution and level of noise emissions into the water.

3.4 Hearing ability of harbour porpoises

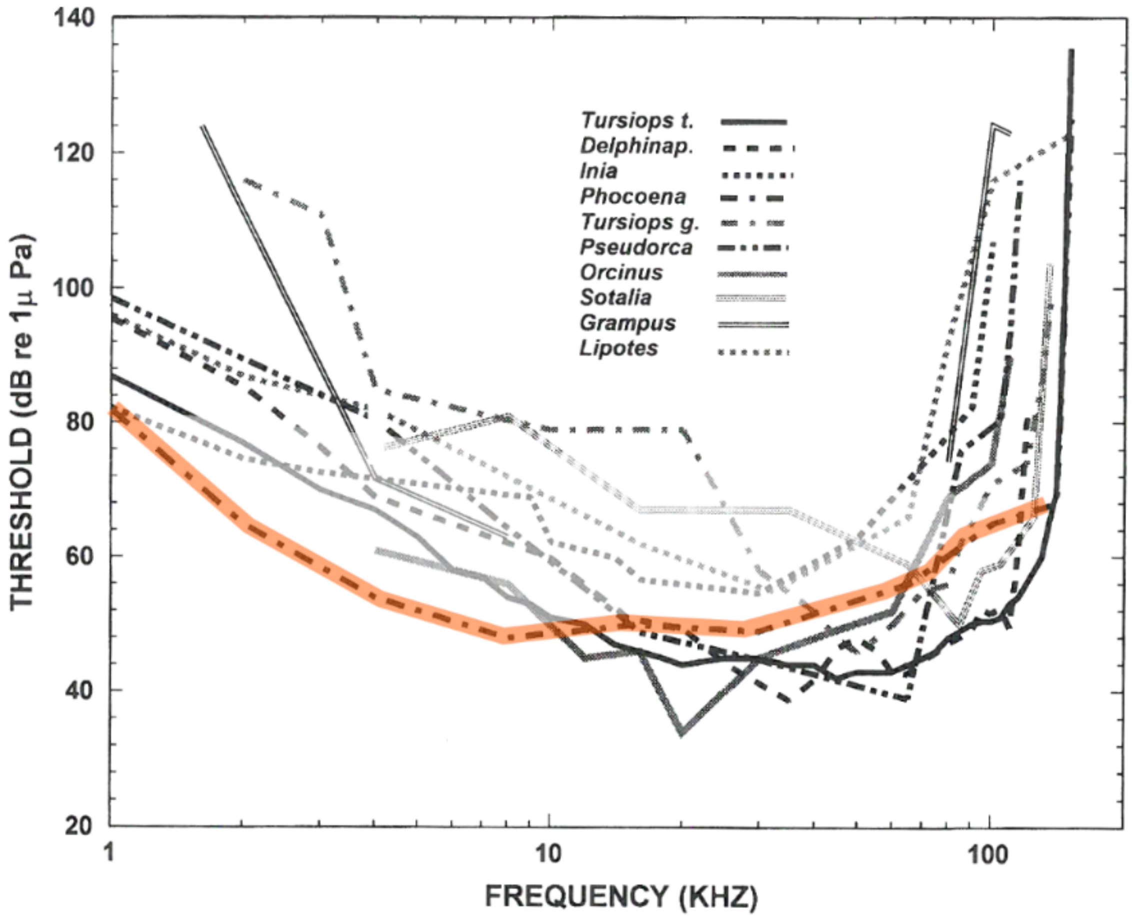
The (resting) hearing threshold is the most important audiological parameter for assessing the hearing ability of animals. It indicates the noise level, that a tone of a certain frequency (single tone resp. sinusoidal signal; sometimes a sinus sweep is also used) must have, in order to be perceived by the animal (Figure 5). As in humans, the hearing threshold of animals is also strongly frequency-dependent, e. g. Zwicker and Fastl (1999). Moreover, there are significant differences among individuals. In about half of the individuals, the hearing threshold lies within a range of ± 5 dB around the median value. At the edges of the hearing range,

i. e. at particularly low and high frequencies, the dispersion is greater, as expected (e. g. Betke, 1991). These frequency dependencies and individual capabilities are also known for land mammals and birds (Hefner & Hefner, 1992; Beason, 2004).

The narrow maxima (tonal components of the rotor-drive-system eigen-frequency) in the underwater noise spectrum caused by the OWTGs in Figure 4 can be compared directly with measured hearing thresholds; the comparability is favored by the fact, that the critical bandwidth, which is important in the auditory system for loudness perception, has roughly the same width as the measured 1/3-octave-bands in many cetacean species, such as the harbour porpoise (Au and Hastings, 2008).

For frequency range below 500 Hz, however, there are only few reliable (absolute) hearing threshold data from different harbour porpoise individuals. Thus, little is known about the significance of variability among individuals, i. e. the differences in auditory perception between different animals of the same species. As in other animals (and in humans), another difficulty in the assessment is, that the mere audibility of a sound (= level is above the hearing threshold) does not necessarily mean a disturbance- or avoidance effect (e. g. Zwicker and Fastl, 1999).

Generally, the hearing range in harbour porpoises extends from approximately 125 Hz to 140 kHz (Kastelein et al., 2015). The range of "good" hearing was determined between 13 and 140 kHz and is defined with a level increase of up to 10 dB above the lowest hearing threshold at 125 kHz. Clicking sounds emitted by harbour porpoises for echolocation and used for orientation resp. hunting are in the range 100 to 140 kHz.



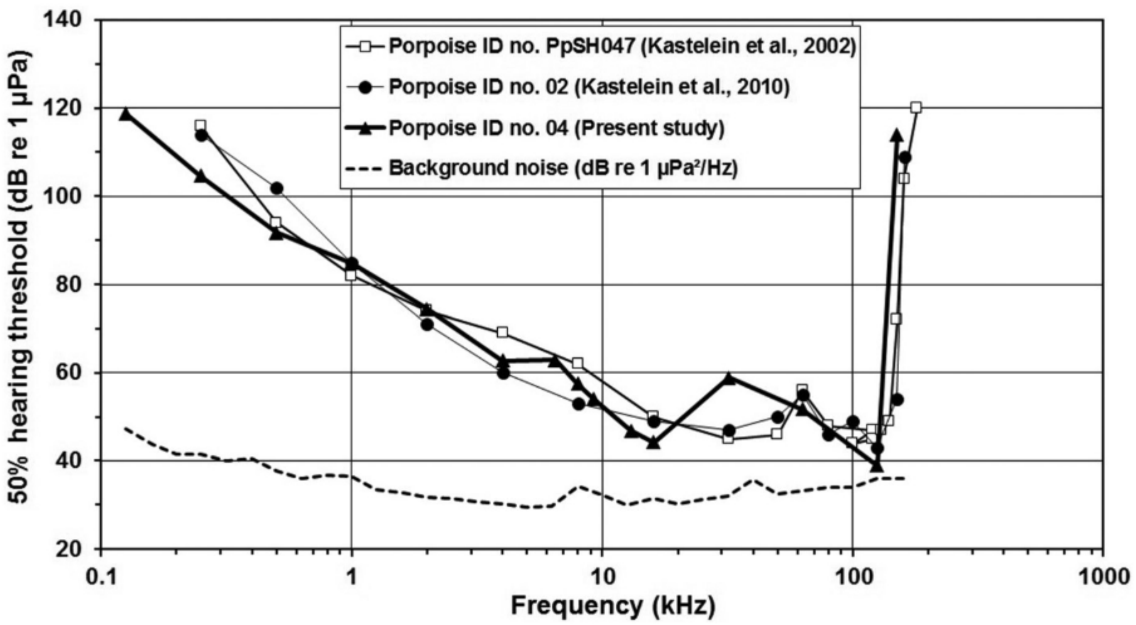


Figure 5: *Top: Hearing thresholds of various toothed whales; the hearing threshold of a harbour porpoise is highlighted in color (Au and Hastings, 2008). Bottom: Auditory hearing thresholds of different harbour porpoise individuals (Kastelein et al., 2015).*

4. Measurement requirements and implementation

The requirements for the measurement systems and the measurement procedure are summarized in the "Standard: Investigation of the effects of offshore wind turbines on the marine environment (StUK4)" (BSH, 2013) and the measurement regulation for underwater noise measurements (BSH, 2011) and have been ordered in German wind farms in the regulation- and implementation process since 2011.

4.1 Current implementation practice for the performance of operational noise measurements in offshore wind farms

As part of the monitoring of the operational phase, underwater noise must be investigated in a standardized manner in and around offshore wind farms in accordance with the measurement guideline for underwater noise of offshore wind farms (BSH, 2011).

The aim of the investigation of underwater noise in the operational phase of the offshore wind farms is to assess the potential impact on the marine environment, in particular on the key species harbour porpoise. The assessment shall be carried out for individual offshore wind farms and at the same time create the basis for assessing cumulative effects of underwater noise in the operational phase across all projects. This also requires a comparison with the noise situation before the construction of the wind farm (so called background noise situation).

Based on the ongoing experience gained, additional requirements for operational noise measurements have emerged, that are applied in the approval practice in the form of specifications. These are summarized below:

In the case of offshore wind farms located in close proximity to each other, the investigations of operational noise shall preferably be carried out in a uniform, temporal and spatial design and shall be coordinated in time with the BSH.

Spatially, the measurements of underwater noise will be combined, as far as possible, with the acoustic recording of the harbour porpoise. Considering the respective habitat use of the area by harbour porpoises, the period of the six-week surveys is selected, in order to be able to assess possible impacts in connection with the biological surveys. In the immediate vicinity of nature conservation areas, the effects of underwater noise on this sensitive area must also be ensured with a suitable survey concept.

On top of the requirements from the BSH measurement guideline for underwater noise (2011) mentioned in chapter 4.2, increasing attention is being paid to ensuring, that, besides the noise input from the turbines, the noise input from OWF-related service traffic is also recorded, at least in outline, by means of a suitable survey concept.

Monitoring concept

A measurement- and evaluation concept agreed with the authorities must be submitted by the offshore wind farm operator and the measuring institute before the measurements are carried out. Thereby, the following aspects must be considered:

- Description of the number, marking and location of the measurement positions in and around the investigation area.
- If possible, the duration of the measurements should not be less than six weeks, in order to record different wind classes and operating conditions of the turbines.
- The measurements shall preferably be carried out in the months with the highest porpoise appearance in the area of the investigation site.
- The data recording must be carried out bindingly uncompressed in WAV format.
- The measurement devices shall be calibrated in advance and corresponding evidence shall be submitted to the BSH.
- Qualified personnel shall be used for the deployment and recovery of the equipment/devices.
- The offshore wind turbines must run in normal operation during the operational noise measurements; no noise-intensive maintenance- or repair work is carried out in the wind farm.
- For a comparison of the noise situation before and during the operation of an offshore wind farm, background noise measurements must also be carried out at comparable measuring positions preferably shortly before the start of construction of the foundation installations.

Evaluation and reporting

- The data must be evaluated for the entire measurement period. The following aspects must be considered in the evaluation.
- Information about all OWF-related vessel movements via AIS data recording in and around the wind farms.
- Weather data (wind speed at hub height) from the monitoring of the nearest wind turbines.
- Electrical power of the nearest turbines for the entire measurement period; the temporal resolution shall not be less than 10 min.
- Characteristic (operating-) conditions must be defined and presented in the report (wind classes, power of the turbines, distance of the measuring station).
- If possible, a comparison of the noise situation from the background- and operational noise measurements should be carried out.
- Six months after completion of the measurements, the final report shall be submitted to the responsible authority.

Data transmission

- The raw data from all measuring stations for the entire measurement period shall be submitted to the approval- and monitoring authority BSH no later than six months after completion of the measurements.
- The processed data ($L_{eq,5s}$, statistics, frequency analysis) for all measuring stations and for the entire period shall also be uploaded to the national noise register MarinEARS no later than six months after completion of the measurements.

Blocking of the raw data from underwater noise measurements

All underwater noise measurement data in Germany are generally subject to approval and must be classified as sensitive information worth protecting that is not intended for the public. The passing on of the raw data to third parties is strictly prohibited.

The following precautions also apply:

- During military exercises and manoeuvres, underwater noise measurements shall not be carried out outside the safety zone. The spatial and temporal limitation is the responsibility of the navy command.
- The raw data shall be handed over to the BSH for archiving immediately after evaluation.
- The operator of the offshore wind farm and the commissioned measuring facility shall store exclusively processed, reduced data (processed data sets) for their own purposes. The processing of the data shall be coordinated with the BSH and shall ensure, that vessel signatures are no longer identifiable.
- Online transmission of the raw data and data transfer via the internet must be avoided.
- Any further use of the data must be agreed in advance with the BSH.

4.2 (Noise measurement) data to be recorded according to the BSH measurement regulation

The underwater noise measurement shall randomly be collected from individual wind turbines in the area of the wind farm, whereby the measurements shall be carried out at a distance of approx. 100 m from one pre-selected turbine and in the centre of the wind farm. Thereby, turbines in the periphery of a wind farm should be selected, which are preloaded by as few other disturbing noise inputs as possible, e. g. other turbines or high vessel traffic densities, in order to be able to measure only the noise emitted by this turbine into the water. Thus, these selected turbines should not be located near e.g. the substation, a converter platform or a traffic separation area (TSA). In addition, the operators must ensure, that this turbine and the immediately neighbouring turbines are in normal operation during the underwater noise measurements, i. e., that no maintenance work or repairs are being carried out.

Additionally, measurements shall be carried out at a distance of 1 km to the wind farm and in the nearest NATURA 2000 / special area of conservation (SAC), provided that this is not further than 5 km from the wind farm (BSH, 2011). If there are no SAC in the vicinity, a representative noise measurement position at a distance of approx. 5 km from the respective wind farm shall be carried out as an alternative. All measurement positions must be coordinated with the BSH, in order to e. g. not affect the safety of navigation. When selecting the measuring positions, other practical aspects must also be considered; for example, measuring positions in the immediate vicinity resp. in the safety zone of pipelines, cables, substations, uncleared ammunition areas, known wrecks, etc. must be avoided. This also applies to cabling within wind farms.

All measurements shall be recorded in a lossless (uncompressed) format (wave, 24-bit) with a sampling rate of at least 44.1 kHz (BSH, 2011). This also corresponds to the standard format of the ISO 18406 (2017) for underwater noise measurements of impulsive noise such as pile-driving. A lossless recording format with 16-bit has also proven itself for continuous noise measurements in the projects JOMOPANS and BIAS. The use of compressed data formats should be excluded as far as possible, as this usually entails quality losses.

First, the $L_{eq,5s}$ is determined, i. e. the (energy-) equivalent continuous Sound Pressure Level with an averaging time of 5 seconds and frequency-resolved in 1/3-octave-bands. From this, the $L_{05,50}$ or $L_{90,5s}$ with an averaging time of 5 seconds (which is exceeded in 5, 50 or 90% of the total 5 second intervals) are calculated for each selected wind class. Moreover, the energy-equivalent continuous noise level is calculated over the entire measurement period of an operating mode. Representative equivalent continuous noise levels $L_{eq,5s}$ shall also be presented frequency-resolved in at least 1/3-octave-bands.

Narrowband spectra with a resolution of 1 to 2 Hz can also be created for certain time periods. However, it must be ensured, that no vessel signatures are recognizable from such high-resolution representations (especially from military vessels). It should also be noted that the height of the maxima in narrowband spectra depends on several parameters, such as the spectral resolution, the averaging time, etc., so that level values can only be inaccurately taken from these spectra.

<u>*Technical note:*</u> *Time intervals, that are obviously influenced by disturbing noises, such as heavy rain or vessels passing by the respective measuring positions at a distance of approx. 1 km or less, should be excluded from the above-mentioned evaluation, if possible.*

4.3 Operating data of the offshore wind turbines

The expectation is that the noise radiation of a wind turbine depends on its operating condition; the generated Sound Pressure Level should generally increase as expected with the wind speed or the power output. The wind data from the gondola anemometers and the power data of the OWTGs were provided by the respective wind farm operators in the form of 10- to 15-minute-averages for all available operating underwater noise measurements. For each wind farm, two sets of data were requested from the operators, one for pre-selected OWTGs, in whose immediate vicinity a measurement position (100 m distance) was located, and the other from the measurement position "centrally in the wind farm", i. e. from one of the directly neighbouring OWTGs.

To illustrate the wind conditions, Figure 6 exemplarily shows measured values from two selected OWTGs in the North Sea for a period of six weeks. Figure 7 shows examples of typical wind- and power values of two different OWTG-types as a function of the measured wind speed. The turbines usually run at wind speeds of 3 to 4 m/s and normally supply electrical energy from this wind speed. The nominal power is usually reached at wind speeds of 11 to 12 m/s. The height of the turbine has only a minor effect on the wind speed at sea. Due to the logarithmic wind profile (Gasch, 1993), the wind increases by less than 0.5% with an increase in height from 80 to 120 m. Figure 6 and Figure 7 are based on 10-minute-values over a period of 6 weeks (approx. 6,000 values per OWTG).

According to the BSH measurement guideline (BSH, 2011), three power ranges, operating modes resp. wind classes must be recorded: "low", "medium" and "high". For each of the three wind classes, the evaluable measurement time should be at least three hours. The wind classes are not specified in detail, nor was it possible to specify the form, in which the wind data must be collected, when the BSH measuring guideline was created.

For the operational noise measurements of *itap GmbH*, the following procedure was followed: First of all, the wind classes were determined on the basis of representations, such as those in Figure 7. In all the operating noise measurements carried out so far, it turned out, that the measured OWTGs of different nominal power and different manufacturers for different turbine types use very similar gradations for the achieved power of their turbines with regard to wind strength; see Table 1.

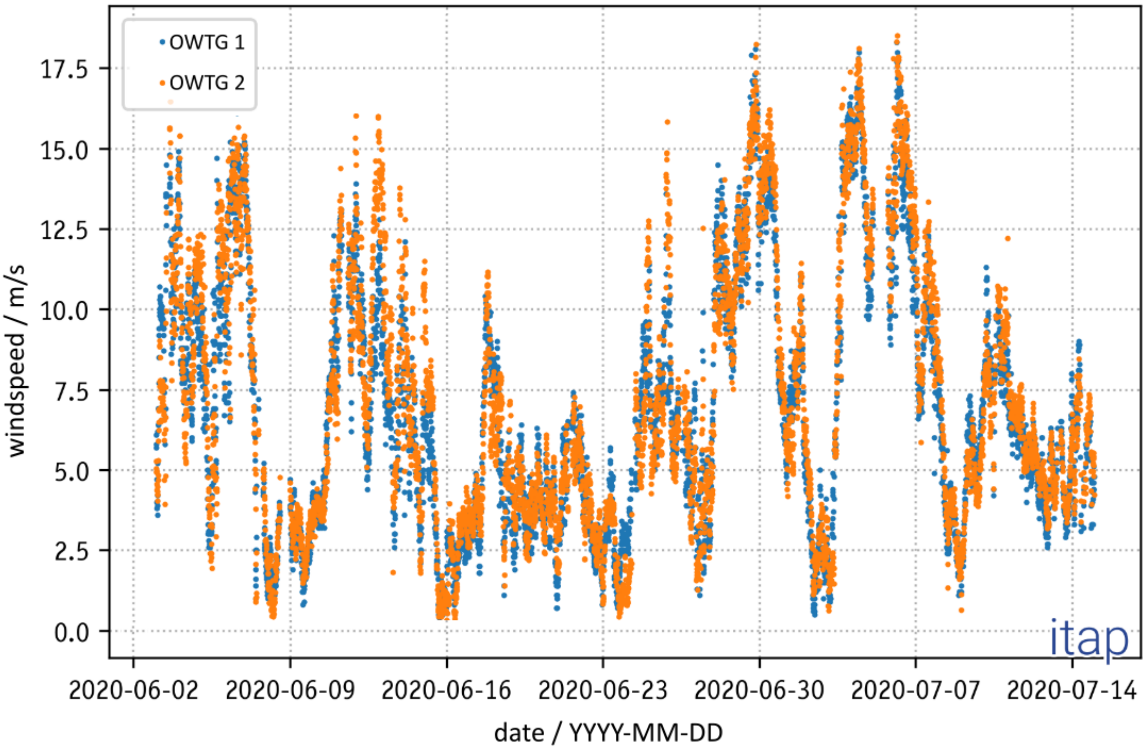


Figure 6: *Measured wind speeds in two wind farms in the north-western zone 1 of the North Sea over a measurement period of approx. 6 weeks during operational noise measurements between March and September.*

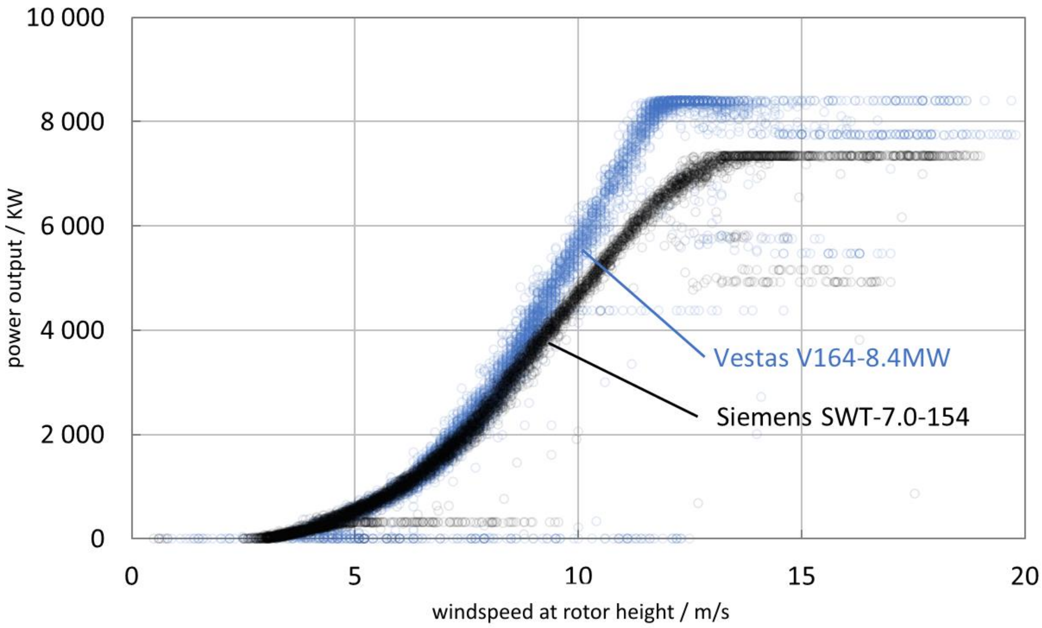


Figure 7: *Electrical power as a function of the wind speed for two different OWTGs from different manufacturers with 7 MW (black, gearless) and 8.4 MW (blue, with gearbox) nominal power (Betke and Bellmann, 2022).*

Wind class	Wind at hub height	OWTG condition, output/power
low	0 to 3,5 m/s	standstill or almost standstill
medium	7 to 10 m/s	30% to 75% nominal power
high	from 11 m/s	over 90% nominal power

Table 1: Definition of the itap GmbH of the wind classes for the following evaluation according to the measurement regulation of the BSH (2011).

Technical note: *In order to meet the requirement of at least 3 hours of measurement data per wind measurement position and wind class, measurement durations of 5 to 6 weeks were mostly performed. Due to the choice of location for offshore wind farms, the wind class "low", i. e. OWTGs at standstill, is usually the most critical wind class. Thus, there are usually at least 600,000 5 second intervals per measuring position per wind farm for the evaluation. Moreover, the measurement period from October to March with the traditional autumn- and winter storms turned out not to be optimal for recording all three wind classes, so that the operational- and background noise measurements were mainly carried out in spring and summer.*

4.4 Measuring devices and anchoring

The requirements on the underwater noise measuring systems are specified in chapter 3 of the measurement guideline of the BSH (BSH, 2011) and generally comply with the ISO 18406 (2017). Among other things, the hydrophones must be calibrated at least every 24 months. Since 2019, *itap GmbH* has been calibrating the hydrophones used itself by means of a standard-compliant calibration process (ISO 17025); Figure 8. A standardized calibration via the manufacturer of the measuring instruments or the hydrophone is also possible. This test is carried out at a frequency of 250 Hz and with air as test medium. The reference element is a GRAS 46AG condenser measuring microphone, which is regularly calibrated by a DAkkS-accredited DKD test centre (currently Norsonic-Tippkemper GmbH, 59302 Oelde-Stromberg).

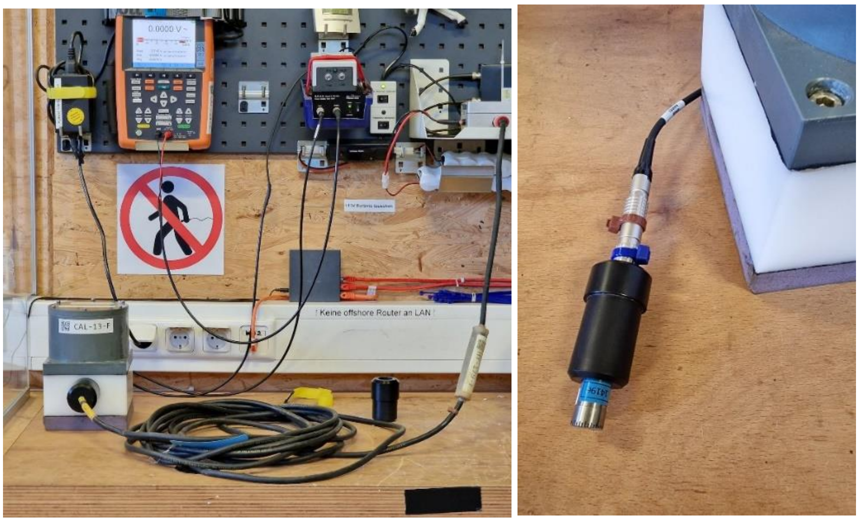


Figure 8: *Calibration station for hydrophones. The white cuboid at the bottom left encloses the test volume, in which different test sound pressures can be generated with a loudspeaker (in the cylindrical top unit); a value around 150 dB re 1 µPa is used for operating noise measurements. The actual sound pressure in the test volume is determined with the reference microphone (right picture). Together with the output voltage of the hydrophone, its calibration factor is calculated from this.*

The moorings should not generate any disturbing inherent noise, such as chain rattling (self-noise). Furthermore, the moorings must not affect the safety and effortlessness of navigation for ships as defined by the Maritime Facilities Act (SeeAnlV) (BSH, 2017). Each mooring must have a surface marking, the integrity of which must be determined at least every 14 days by means of a visual inspection.

Figure 9 shows a sketch of the standard measuring arrangement with two surface markers, a spar buoy with flashing light (on the left) and a yellow marker ball about 50 m away. The marking with a spar at least 6 m long is part of the BSH requirements for measuring points in the EEZ (BSH, 2017).

Figure 10 shows the components for sound recording. The hydrophone of e. g. type Brüel & Kjær 8106 is held by a net float at about 2 m above the seabed. The steel tube lying on the seabed contains the recording electronics, dry batteries for power supply and a timer control. This is programmed to record sound every 2 hours for a duration of 10 minutes. This intermittent recording procedure provides sufficient data for an observation period of several weeks as defined by the BSH measurement regulations (at least 3 hours per wind class).

During the last few years, in agreement with the BSH, continuous data recording has often been used instead, as measurement technology including data storage has steadily improved in recent years.

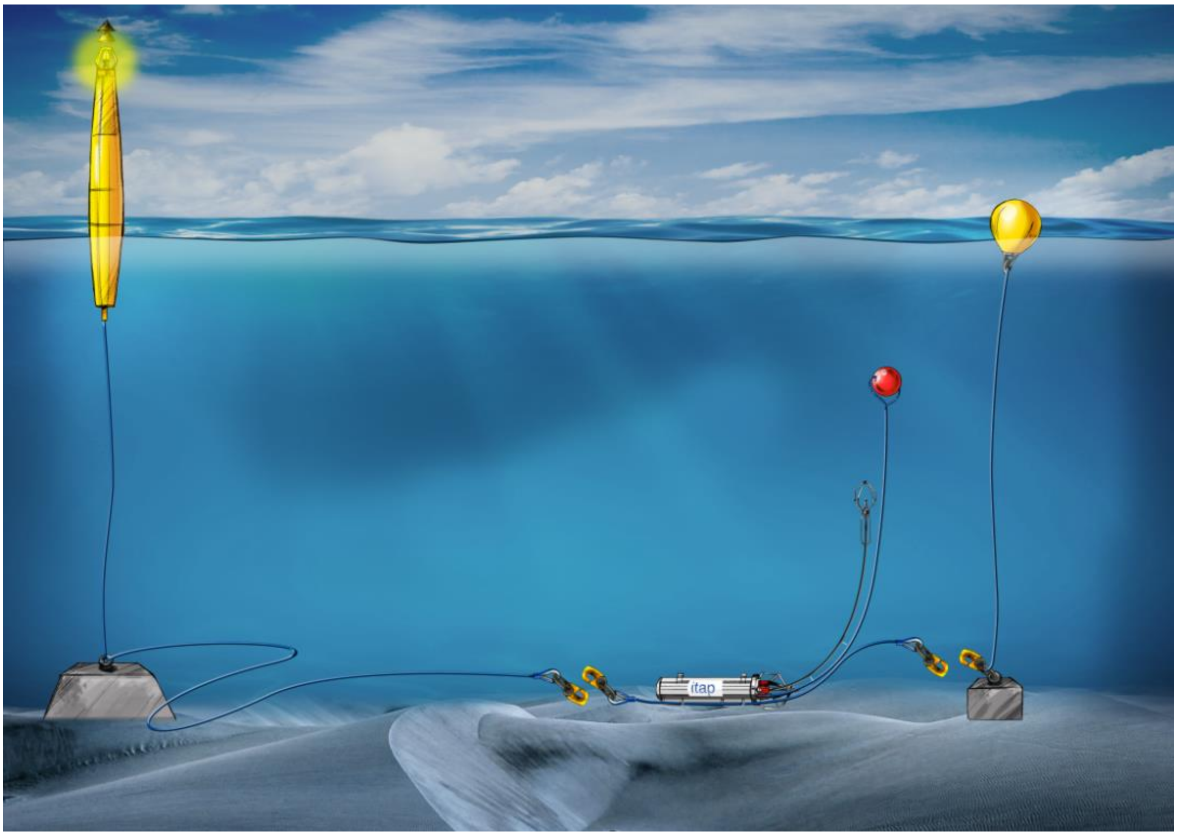


Figure 9: Sketch of the measuring arrangement used as standard.

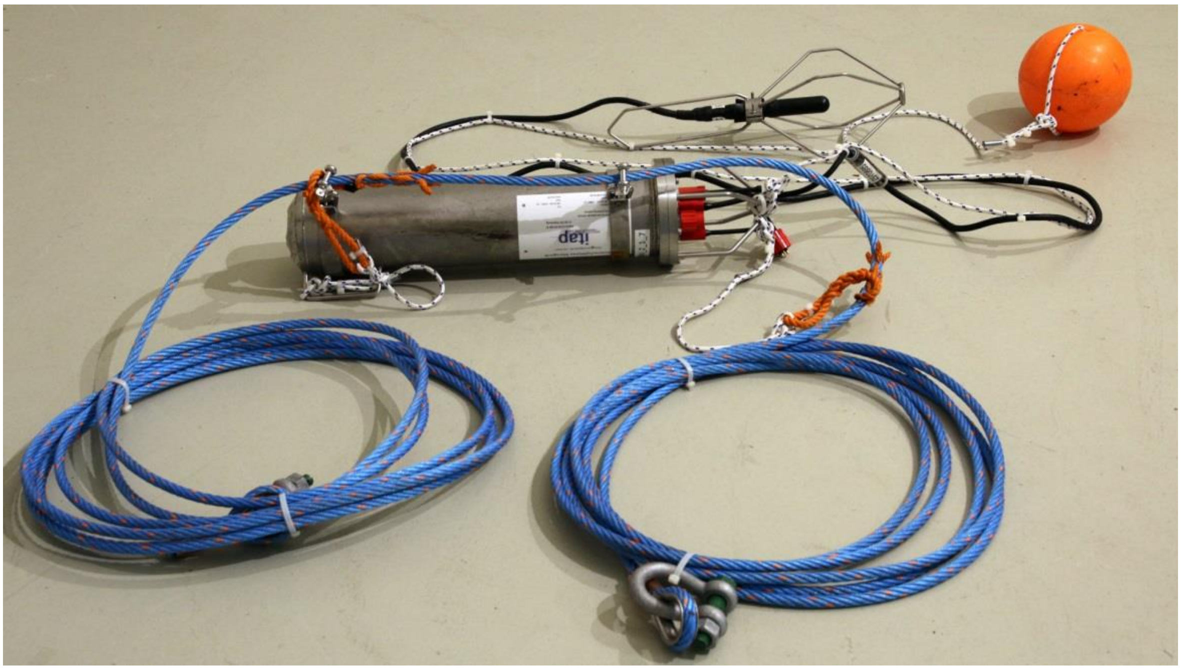


Figure 10: Underwater noise measurement device of the itap GmbH; at the very back, the hydrophone with floatation body.

Since 2022, measuring devices of the type SoundTrap 600 from the company *Oceans Instruments* have also been used on a trial basis. These measuring devices have the advantage of a very long runtime of several months in uncompressed 16-bit file format. The disadvantage of these measuring devices are the limiting dynamic range and the rigid connection between hydrophone and measuring device housing for the power supply and the data recording. However, these measuring systems were also applied for continuous measurements of the background noise level in the JOMOPANS research project and thus offer possibilities for comparison with existing measurement data.

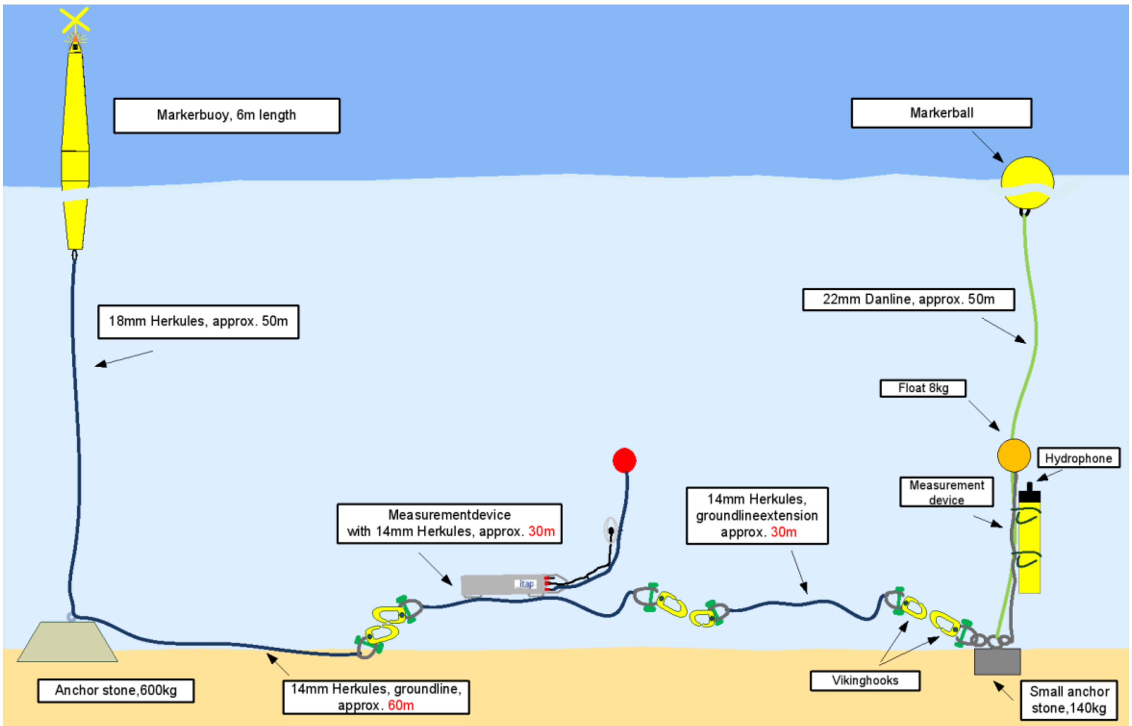


Figure 11: Schematic representation of the anchoring concept with additional measuring device (e. g. Wildlife Acoustics SM2M or SoundTrap, yellow tube on the far right).

A third, very similar configuration resulted from the fact, that at some wind farms and measuring positions, the noise measuring devices and the porpoise detectors (PODs) of the participating, biological survey offices shared a common anchorage. The POD was attached to the anchor rope of the marker ball and did not interfere with the noise measurement.

All measuring devices and moorings applied comply with the requirements of the measuring regulation for underwater noise (BSH, 2011).

4.5 Acoustic evaluation

For the evaluation of the recordings according to the criteria mentioned in chapter 4.2, software developed by *itap GmbH* was used (IONIS, version 0.6.5), a variant of which is also used for the evaluation of impulsive noise inputs according to ISO 18406 (2017), e. g. offshore construction noise, impact piling noise or detonation noise during UXO clearance activities. For the statistical quantities, in addition to the Sound Pressure Level L_{05}, the L_{50} and L_{90} were calculated in accordance with the measurement guideline for underwater noise measurements (BSH, 2011), both broadband and frequency-resolved in 1/3-octave-bands.

This evaluation software was also compared resp. evaluated by comparisons with the assessments of the software for continuous noise measurements developed within the BIAS research project.

4.6 Performance of the measurements

In the case of geographically neighbouring wind farms, the operational noise measurements were usually carried out for all two or three wind farms of the "cluster" at the same time. This procedure reduces the organizational effort and lowers the costs for the deployment and the recovery of the measuring instruments. In individual cases, one or two measuring stations could be saved by neighbouring wind farms sharing the 1-km or 5-km measuring position.

The main advantage, however, is, that the background noise level, which is approximately given by the level in the wind class "low" (all OWTGs off), can directly be compared for several wind farms. This makes it possible, for example, to narrow down, whether an unusually high background level represents a local anomaly, caused by e. g. service vessels in the wind farm or is determined by the constantly present noise from distant shipping traffic.

Another advantage of a cluster measurement is, that the operating conditions of neighbouring wind farms are also documented, so that e. g. unusual, acoustic situations in wind farm A, such as repairs at existing OWTGs, can be excluded, when evaluating the operating noise in wind farm B.

5. Offshore wind farms included in analyses

Table 2 lists the combinations of installed wind turbines and foundation structures from offshore wind farms in the German EEZ, for which the underwater operating noise has been measured so far according to the BSH specifications; Table 3 summarizes some project- and site-specific parameters. Overall, the data set for this study includes

- 27 operational noise measurements carried out in 24 wind farms,
- 16 different OWTG-types from seven different manufacturers,
- nominal power/capacity between 2.3 and 8.4 MW,
- founded on five different foundation structures,
- water depths between 15 and 40 m,
- in at least three measuring positions per wind farm and
- in three defined operating states of the plants.

Figure 13 shows examples of the foundations or foundation structures mentioned in Table 2. The "suction bucket jacket" used in two wind farms is not shown. It is a 3-legged jacket-structure that was fixed to the seabed with "suction buckets" instead of piles; a schematic representation of a suction bucket can be found in the literature (Koschinski & Lüdemann, 2019). The difference is not readily apparent above the waterline.

The OWF NOISE project does not include:

- The newer wind farms or those still under construction with erection dates from 2022.
- Only one of the two wind farms within the 12-nautical-miles-zone of the German North Sea has been included, since water depths of significantly less than 10 m occur in one of these wind farms.
- OWF *alpha ventus*: At the first German offshore wind farm, operational noise measurements were carried out in 2011 as part of the RAVE (Research at Alpha Ventus) research network (Betke and Matuschek, 2012). Experiences from this investigation have been incorporated into the BSH measurement guideline (BSH, 2011).

In the BSH North Sea site development plan (BSH, 2020), the EEZ was divided into 5 zones, within which areas for the potential use of offshore wind were defined. Due to the small areas for the use of offshore wind in the German EEZ of the Baltic Sea, no zones, but only areas were defined. The areas are marked with an “N” for the North Sea and an “O” for the Baltic Sea; in addition, the areas are numbered consecutively; Figure 12. In the following evaluations, the respective zones, in which certain measurement data were collected for a defined wind farm, are named.

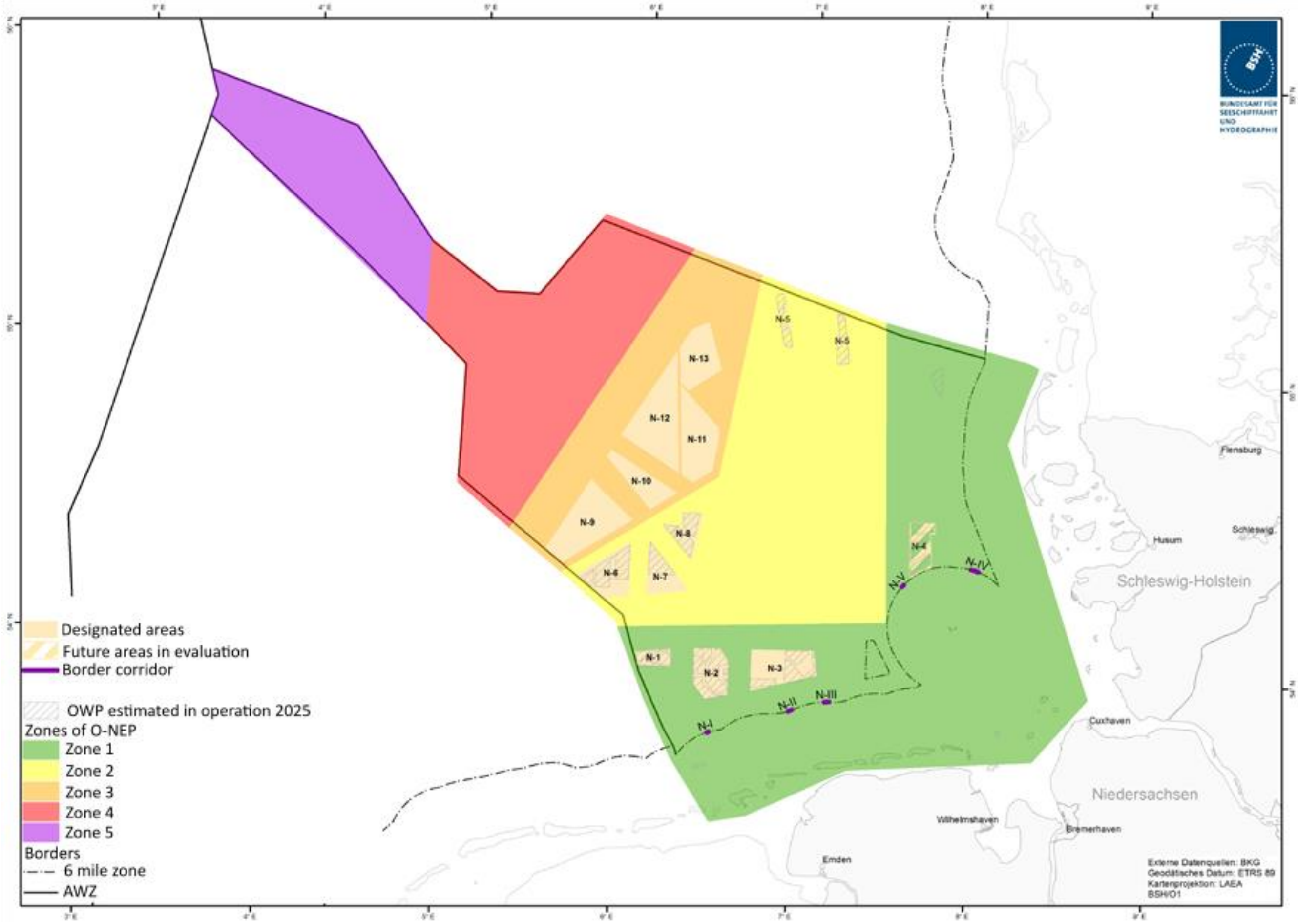


Figure 12: Determination of zones and areas for the use of offshore wind of the German EEZ of the North Sea (source: site development plan of the BSH 2020).

No.	Foundation	Location of the OWFs	OWTG type	WD [m]	Nominal power [MW]	Gearbox
1	Monopile	North Sea zone 1 O	Siemens SWT-3.6-120	21	3.6	yes
2	Monopile	North Sea zone 2 NW	Siemens SWT 7.0-154	40	7	no
3	Monopile	Baltic Sea	Siemens SWT-6.0-154	27	6	no
4	Tripile	North Sea zone 2 NW	Bard 5.0	39	5	yes
5	Monopile	North Sea zone 1 NW	Siemens SWT-4.0-120	25	4	yes
6	SB Jacket			25		
7	Monopile	North Sea zone 1 NW	Vestas V-164-8.0	28	8	yes
8	SB Jacket			28		
9	Monopile	North Sea zone 1 NO	Siemens SWT-3.6-120	18	3.6	yes
10	Monopile	North Sea zone 2 NO	Siemens SWT-3.6-120	30	3.6	yes
11	Monopile	North Sea zone 2 NW	MHI-Vestas V164-8.4	38	8.4	yes
12	Jacket	Baltic Sea	Siemens SWT-3.6-120	35	3.6	yes
13	Monopile	Baltic Sea	Siemens SWT-2.3-93	17	2.3	yes
14	Monopile	North Sea zone 2 NW	Siemens SWT 7.0-154	39	7	no
15	Tripod	North Sea zone 2 NW	Areva Multibrid M5000	39	5	yes
16	Monopile	North Sea zone 1 NW	Siemens SWT-6.0-154	30	6	no
17	Monopile	North Sea zone 1 NW	Siemens SWT-6.0-154	33	6	no
18	Monopile	North Sea zone 1 O	Siemens SWT-3.6-120	25	3.6	yes
19	Monopile	North Sea zone 1 NW	GE Haliade 150-6	28	6	no
20	Monopile	North Sea zone 1 NW	Senvion 6.2M126	28	6.2	yes
21	Jacket	North Sea zone 1 O	Senvion 6.2M126	24	6.2	yes
22	Monopile	North Sea zone 1 SW	Siemens SWT-3.6-120	20	3.6	yes
23	Monopile	North Sea zone 2 SO	Siemens SWT-4.0-130	27	4	no
24	Tripod	North Sea zone 1 NW	Adwen AD 5-116	28	5	yes
25	Monopile		Senvion 6.3M126	28	6.3	yes
26	Monopile	North Sea zone 2 W	Siemens SWT-6.0-154	39	6	no
27	Jacket	Baltic Sea	Adwen AD 5-135	37	5.1	yes

Table 2: Combinations of wind energy turbines and foundation structures from OWFs in the German EEZ of the North- and Baltic Sea, at which operational noise measurements were carried out. For the North Sea, the zones and the location of the wind farms in the zones from the FEP 2020 are also shown. Abbreviations used: SB = suction bucket, WD = water depth, N – north, S – south, E – east, W – west.

Parameter(s)	Range or value	Number of OWTGs	Comments
nominal power	2.1 – 4 MW	10	
	4.1 – 6 MW	9	
	6.1 – 8,4 MW	8	
foundation	Monopile	19	
	Jacket	5	Also includes 2 suction bucket jackets.
	Tripod	3	Special design „tri-pile“ from Bard is included here.
Gearbox	yes	20	
	no	7	Of these, six are from the manufacturer Siemens and one from GE-Wind; other gearless OWTGs are not yet represented in the German EEZ.
Water depth	> 15 to 20 m	3	
	21 to 30 m	15	
	31 to 40 m	9	

Table 3: Summary of some site- and project-specific parameters of the surveyed plants.

Figure 13: Foundations of OWTGs. From left: Monopile, Jacket, 4-legged Tripod, Tri-pile (photo far right: Martina Nolte, CC BY-SA 3.0 de, all others: itap GmbH).

6. Results

In a first step, the results of the measurement position at a distance of approx. 100 m from the respective, pre-selected wind turbine are presented; chapter 6.1. Thereby, both, the broadband (chapter 6.1.1) and the spectral characteristics (chapter 6.1.2) are presented. One of the main objectives of this research project was to determine, whether the Sound Pressure Level generated or radiated by the wind turbines underwater correlate with certain characteristics of the turbines or the site. From a physical point of view, above all, the electrical (nominal) power and the type of drive (gearbox or direct drive or gearless) are to be mentioned here. Moreover, the influence of the foundation design and the water depth were investigated; see chapter 0. Site-specific influencing parameters were also investigated; see chapter 6.1.4.

The evaluation of the measurement data at the other measurement positions inside and outside the wind farms has turned out to be much more complicated, since there is often a mixing with the permanently present background noise level; chapter 6.2.

A comparison between the operational- and background noise measurements carried out to evaluate the noise situation before construction and during operation of the wind farm is the subject of chapter 6.3. Initially, only the noise input from the wind turbines in operation is considered.

Based on the few, specific measurements from the past three years, noise inputs from operational shipping traffic (service traffic) have been investigated in chapter 0.

6.1 Measurements in approx. 100 m distance to wind turbines

The evaluations of all operational noise measurements have shown that the identification of possible influencing parameters on the radiated noise of turbines is possible by the L_{50}-value; this is especially evident in the 1/3-octave spectra. Compared to the L_{50}-value, the L_{05}-value shows broadband level increases that can hardly be assigned to a wind turbine in a technically plausible way. Presumably, these are caused by close vessel passages or a noise input by wind and wave impact. The tonal components, which can clearly be attributed to the rotor-drive-system eigen-frequency, are mostly not fully apparent, when using the L_{05}-value or partly overlap with the tonal components of other turbines. The L_{05}-value would thus overestimate the noise input from the turbines. The L_{90} represents rather the permanent (background) noise around the OWTG. When using this level value, a significant underestimation of the possible radiated noise input of an OWTG can be assumed.

For these reasons, unless otherwise described, the following evaluations are based on the L_{50}-value per wind class, i. e. the median of all 5-s evaluation intervals of this measurement series over a measurement period of at least five weeks.

6.1.1 Frequency-independent characteristics

The main measurement results of the noise input from the wind turbines operating at nominal power (i. e. at wind class "high") at a distance of approx. 100 m are summarized in Table 4, presented as broadband L_{50} and 1/3-octave band with the highest level (eigen-frequency of the rotor-drive-system) and as L_{50} in this "dominant" 1/3-octave band.

Marked are the cases, in which, according to the measurement guideline (BSH, 2011), it was necessary to deviate significantly from the distance d = 100 m. The background were safety-related concerns during the deployment and recovery of measurement devices in the safety zone of the OWTGs. Due to the known, geometric transmission loss $15*\log_{10}(d/100\ m)$ dB, theoretically possible corrections for deviations in distance could be made. However, it turned out, that this rough procedure for level distance correction between 750 m and 10 km (e. g. Bellmann et al., 2020), which has been proven from the pile-driving noise range, led to extremely high Sound Pressure Levels at a distance of 100 m from the turbines, which must be classified as partly unrealistic from an acoustic point of view. One possible reason could be the very small distance between the measurement position and the source, which is located in the acoustic-near field of the radiating source, and thus the acoustic energy resp. power cannot adequately be measured by sound pressure measurements alone.

This would lead to a significant overestimation, when using the transmission loss for a level distance correction. Therefore, level corrections were not applied in the following; all levels shown are thus the (Sound Pressure Level) values delivered by the hydrophones at the respective measurement position. *As an example, the values normalized to 100 m ($15*\log_{10}$(distance)) are also shown in the following tables (in brackets) and highlighted in colour in the following figures.*

Table 5 summarizes the level statistics of the broadband measurement data contained in Table 4.

No.	Founda-tion	Nominal power, MW	Gearbox	L_{50} broadband, dB re 1 µPa	1/3-octave band with highest level, Hz	Highest 1/3-octave-level L_{50}, dB re 1 µPa	Deviating measurement distance, m
1	Monopile	3.6	yes	124	160	123,7	
2	Monopile	7	no	120	80	116	
3	Monopile	6	no	115	25	108	
4	Tripile	5	yes	121 (127)	160	121	250
5	Monopile	4	yes	128	160	117	
6	SB Jacket			131	160	121	
7	Monopile	8	yes	119	80	110	
8	SB Jacket			123	40	113	
9	Monopile	3.6	yes	115	50	102	
10	Monopile	3.6	yes	118 *(123)*	160	117	*200*
11	Monopile	8.4	yes	120	125	113	
12	Jacket	3.6	yes	122	160	120	
13	Monopile	2.3	yes	123	63	115	
14	Monopile	7	no	122 (129)	80	120	300
15	Tripod	5	yes	127 (131)	80	127	180
16	Monopile	6	no	117	25	110	
17	Monopile	6	no	117	80	112	
18	Monopile	3.6	yes	122	160	121	
19	Monopile	6	no	120	80	110	
20	Monopile	6.2	yes	118	125	109	
21	Jacket	6.2	yes	117	160	115	
22	Monopile	3.6	yes	124	160	124	
23	Monopile	4	no	114 (120)	160	111	250
24	Tripod	5	yes	122	80	115	
25	Monopile	6.3	yes	121	80	110	
26	Monopile	6	no	119 (128)	80	109	400
27	Jacket	5.1	yes	112	80	102	

*Table 4: Essential measurement results for the measurement position "100 m away from a selected OWTG" in the wind class "high" incl. the foundation type and the nominal power of the OWTG. For some OWTGs, it was necessary to deviate significantly from the 100 meters, see column on the far right. The distance-corrected values by means of transmission loss (15*log_{10}(distance)) are shown in parentheses. The numbering corresponds to that from Table 2.*

	broadband Sound Pressure Level L_{50} dB re 1µPa	highest 1/3-octave level L_{50} dB re 1 µPa
Maximum	131	126
Average value	120 *(122)*	114
Median	120 *(122)*	114
Minimum	112	102

*Table 5: Broadband Sound Pressure Level ($L_{50, 5s}$) and Sound Pressure Level in the highest 1/3-octave band (rotor-drive-system eigen-frequency), measured at a distance of approx. 100 m from all measured and operating OWTGs under nominal power (wind class „high“) from Table 4. The level statistics with the distance-normalized values (using propagation attenuation 15*log10(distance)) are shown in brackets.*

In the appendix in chapters 9.1 to 9.3, all broadband measurement data (Sound Pressure Level L_{50}) in approx. 100 m distance are compared independently of all other project- and site-specific parameters for the wind classes „low“, „medium“ and „high“, ergo wind turbines at standstill to below nominal power, for the level quantities L_5, L_{50} and L_{90}.

In Figure 14, the measured broadband $L_{50, 5s}$–values from Table 4, together with the names of the OWFs, are shown graphically and in the operating states OWTG at standstill and under nominal power.

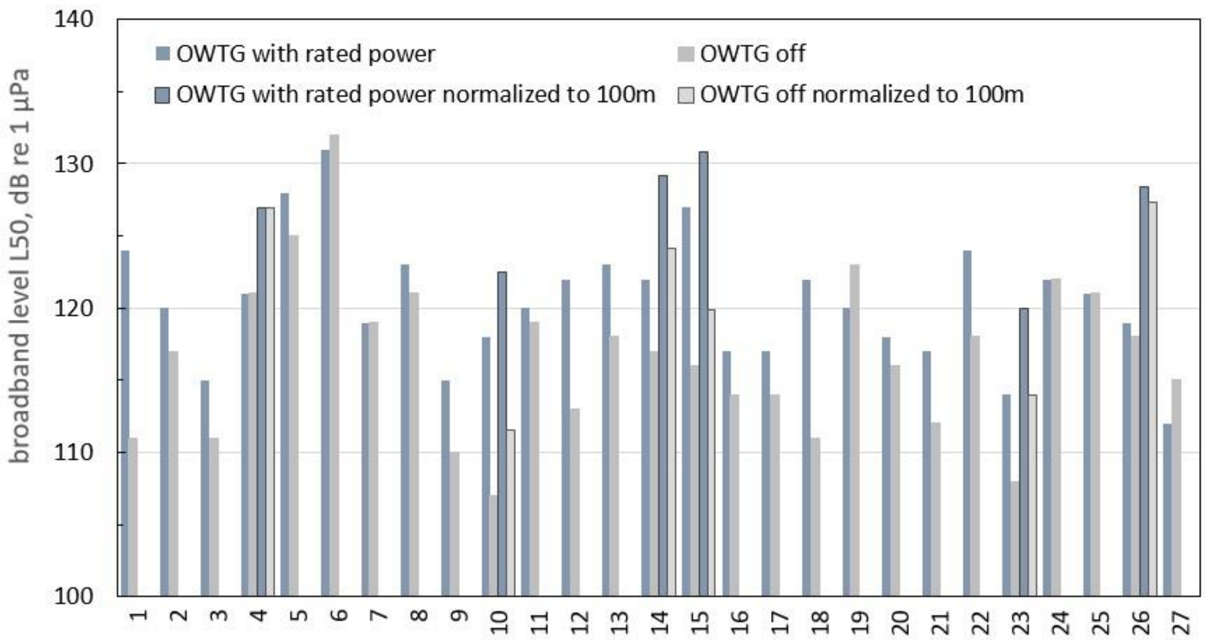


Figure 14: Broadband Sound Pressure Levels L_{50} (averaging time 5 s) at a distance of 100 m from selected operating OWTGs from Table 4. In this and the following figures, "OWTG off" refers to the measurement at wind class "low". The OWTGs run at nominal power in the wind class "high".

6.1.2 Spectral characteristics

Figure 15 summarizes the number and the eigen-frequency of the rotor drive system (1/3-octave band) of the level-determining, tonal components of the turbines in operation with nominal power (wind class "high") at a measurement distance of approx. 100 m. The number and the eigen-frequency of the rotor-drive-system (1/3-octave band) are shown in Table 4.

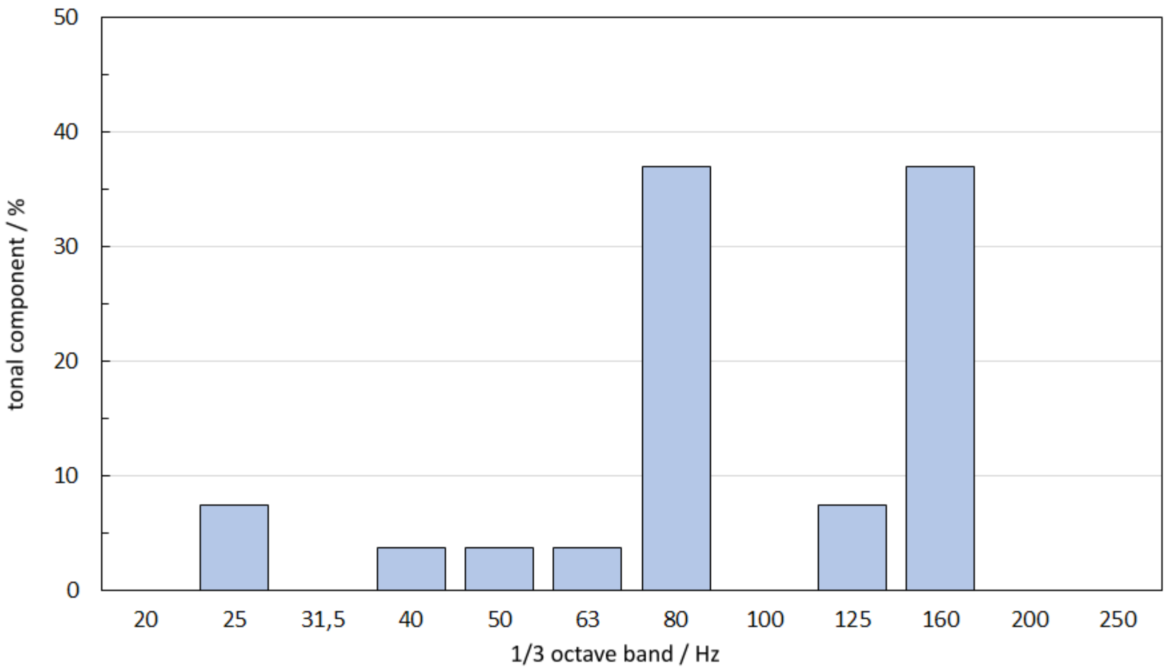


Figure 15: Distribution of the spectral maxima and percentage number of wind turbines, for which a single 1/3-octave band dominating the broadband Sound Pressure Level was detected (Table 4).

It is shown, that more than 75% of all wind turbines investigated in this study introduce a single 1/3-octave band between 80 and 160 Hz which dominating the broadband Sound Pressure Level (Table 4). In two cases, a tonal component is found in the 25 Hz 1/3-octave band. These two systems are gearless systems of recent construction. However, there were also five other gearless turbines, that emitted level-determining noise inputs into the water in the 1/3-octave band around 80 Hz. Three turbines with gearboxes had eigen-frequencies between 40 and 63 Hz. Interestingly, in two wind farms in the north-western zone 1 of the North Sea, turbines of the same type were installed on a monopile and a suction bucket jacket. In one wind farm, the turbines of the same type had the same eigen-frequencies, in the other wind farm, the natural frequency was 80 Hz for the monopile and 40 Hz for the suction bucket Jacket foundation. These differences may well result from different angular settings of the rotor blades, the number of rotations of the rotor blades and/or the averaged performance data over several minutes.

Figure 16 shows an example of the 1/3-octave spectrum for a selected turbine with and without gearbox from the same manufacturer - Siemens SWT-3.6-120 with gearbox and Siemens SWT-6.0-154 gearless - in operation with nominal power in the wind class "high" (Matuschek et al., 2018; Gerlach & Betke, 2021).

The 1/3-octave spectra show that the160 Hz 1/3-octave band (rotor-drive system natural frequency) incl. the 1st harmonic for the turbine with gearbox and the 25 Hz 1/3-octave band for the gearless turbine at the measurement position approx. 100 m away which dominating the broadband Sound Pressure Level, when the wind turbine is operated at nominal power (full load).

In order to prove, whether the increased levels occurring in the 1/3-octave spectra in a 1/3-octave band are stochastic or tonal (sinusoidal) noises, a narrowband analysis using FFT (Fast Fourier Transform) was carried out for the two OWFs as an example; see Figure 16. The narrowband spectra for the wind class "high" (OWTG running below nominal power) and for the wind class "low" (OWTG standing still or almost still) were compared.

These are sinusoidal components for the turbines in operation below nominal power. As soon as the turbines are at standstill resp. almost at standstill (wind class "low", Figure 17), these tonal components are no longer present. Thus, this low-frequency, tonal component can clearly be assigned to the wind turbines in operation. These tonal components can also be calculated by specifying the rotor speed and the gearbox setting resp. -ratio and the generator configuration (rotor-drive-system eigen-frequency).

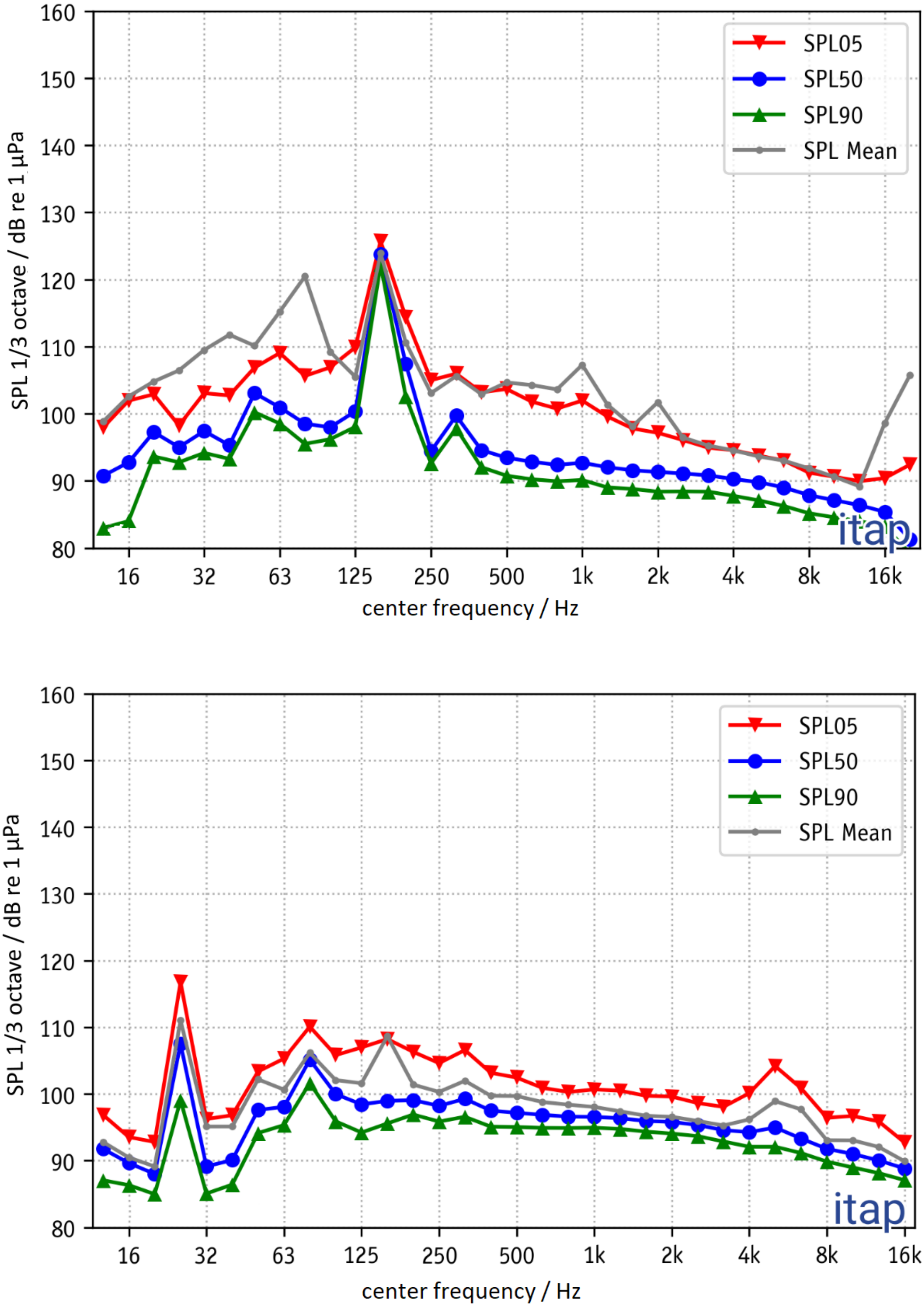
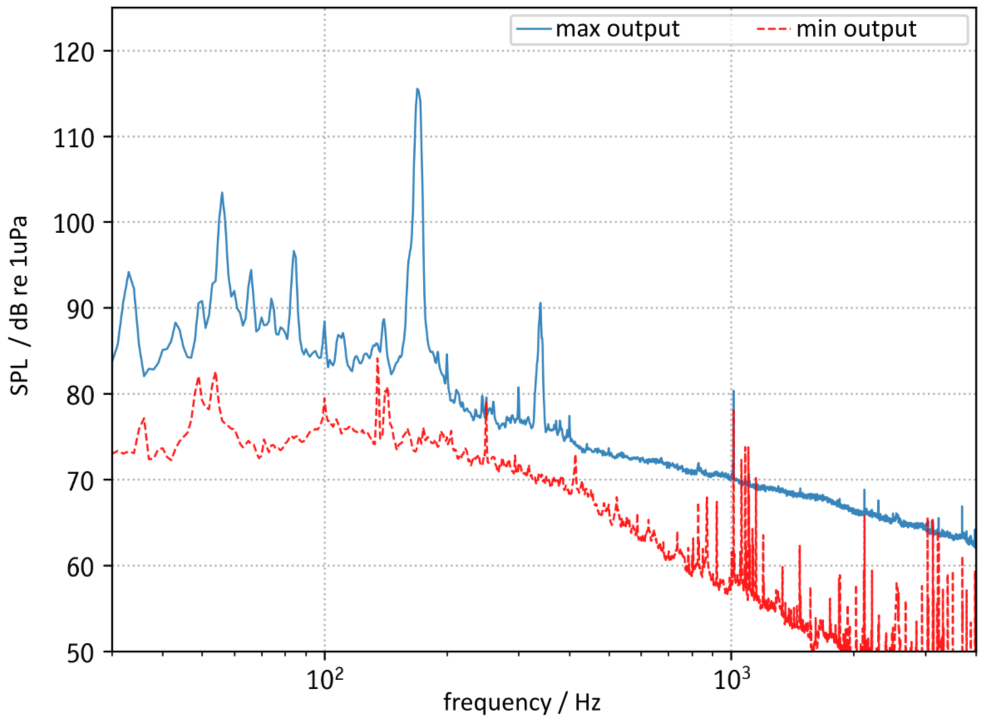


Figure 16: *Exemplary 1/3-octave spectra for turbines of the same manufacturer with gearbox (top; Siemens SWT-3.6-120) and without gearbox (bottom; OWEA Siemens SWT-6.0-154).*



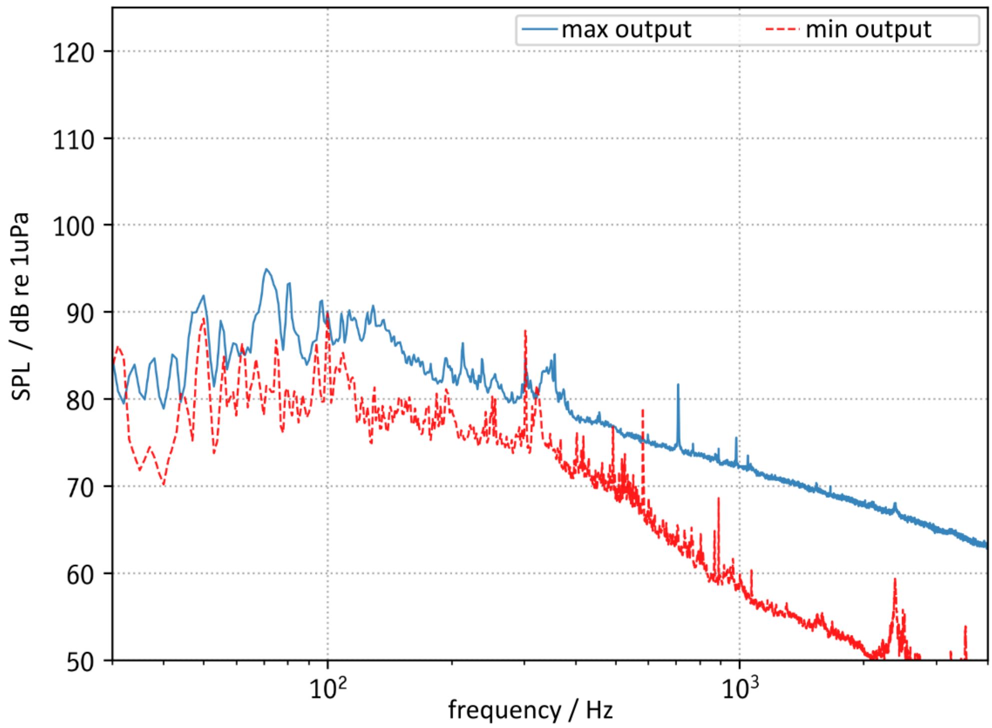


Figure 17: Exemplary comparison of the narrowband-FFT-spectra for a selected wind turbine with and without gearbox from Figure 16 in the wind class "low" (turbines at standstill) and wind class "high" (turbines below nominal power).

6.1.3 Project-specific variables

In a cross-project, multifactorial variance analysis, an attempt was made to identify possible variables on the radiated, tonal components of the wind turbines in operation. The following correlations were found:

Foundation structure: Figure 18 shows the L_{50} for the different foundation structures. On average, the values for monopiles tend to be *2.0* dB lower than those of the other (structurally resolved) foundation types, such as jackets or tripods. Whether and to what extent the design of the foundation structure, the pile diameter, the foundation mass or other parameters have an influence (frequency resp. amplitude) on the noise input radiated into the water by turbines in operation cannot be taken from this analysis. The number of measurements, especially of turbines with foundations other than monopiles, is too small to be able to prove systematic and statistically valid level differences.

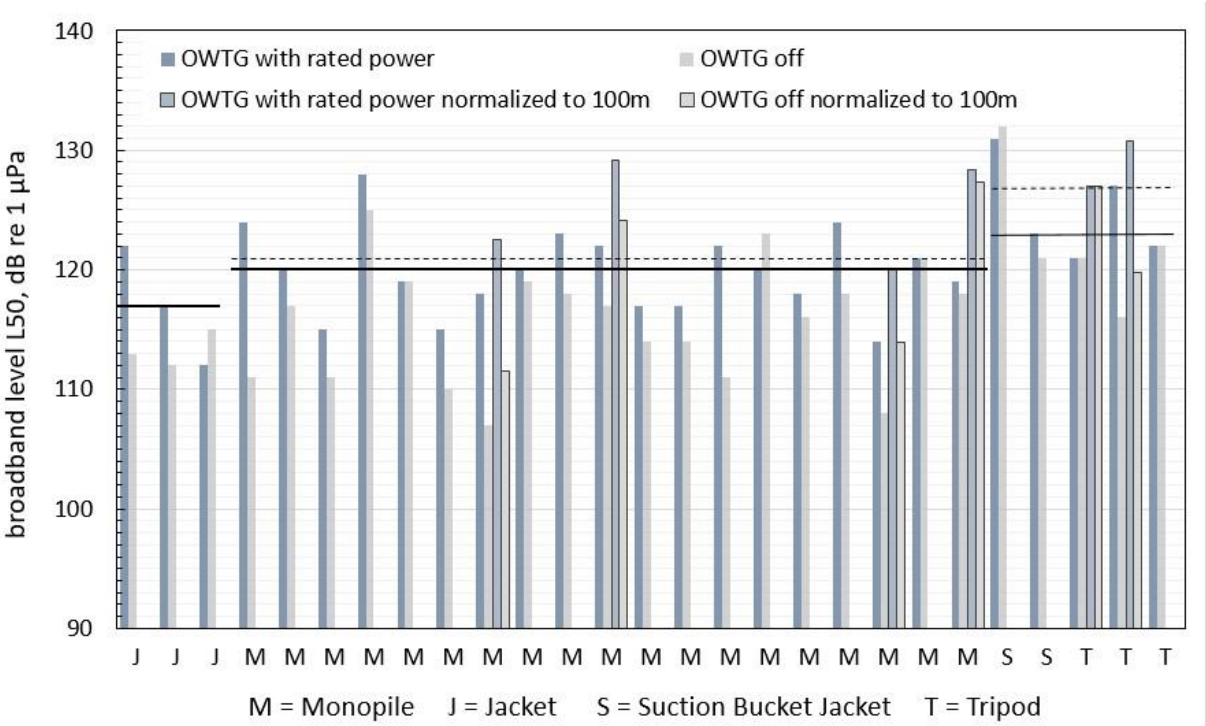


Figure 18: Broadband Sound Pressure Levels L_{50} in 100 m distance from the OWTGs depending on the foundation types. The horizontal lines represent the median of the respective foundation type, solid lines represent the measured values, dashed lines represent normalized values.

Gearbox type: Figure 19 shows the levels (L_{50}) sorted by gearbox and direct drive (gearless). This shows a weak indication, that the average (median) level for gearless systems is about 2.5 dB lower than for systems with gearboxes.

Table 6 shows the statistics for the two possible, project-specific variables foundation structure and gearbox type.

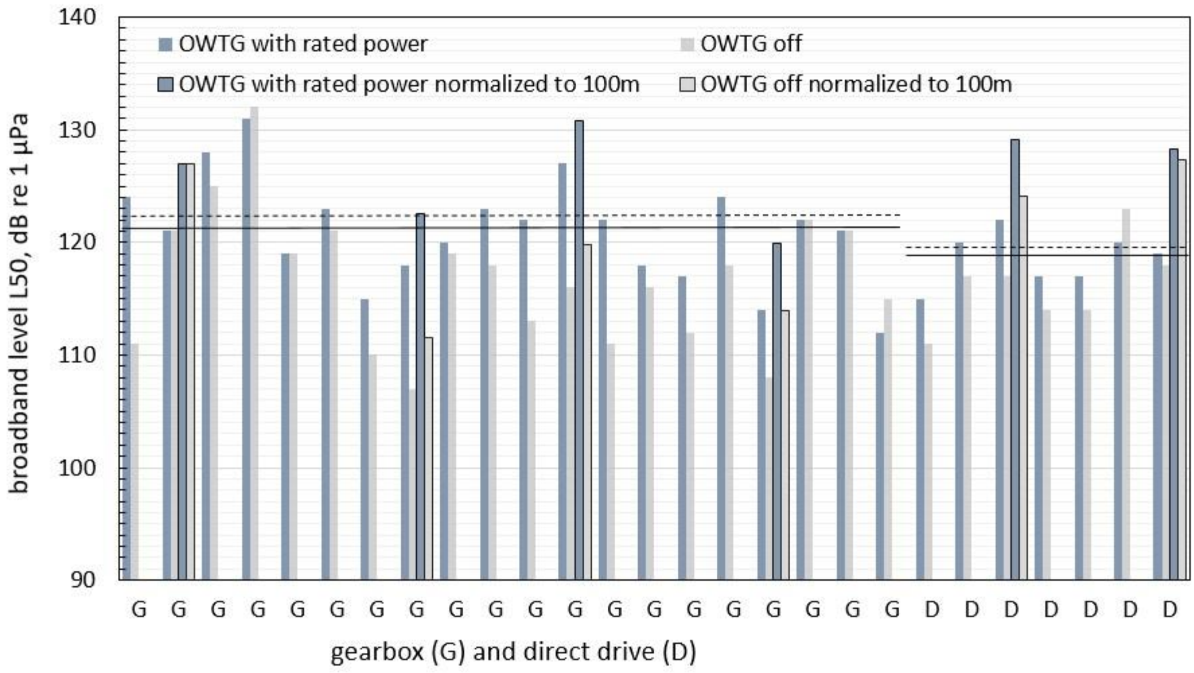
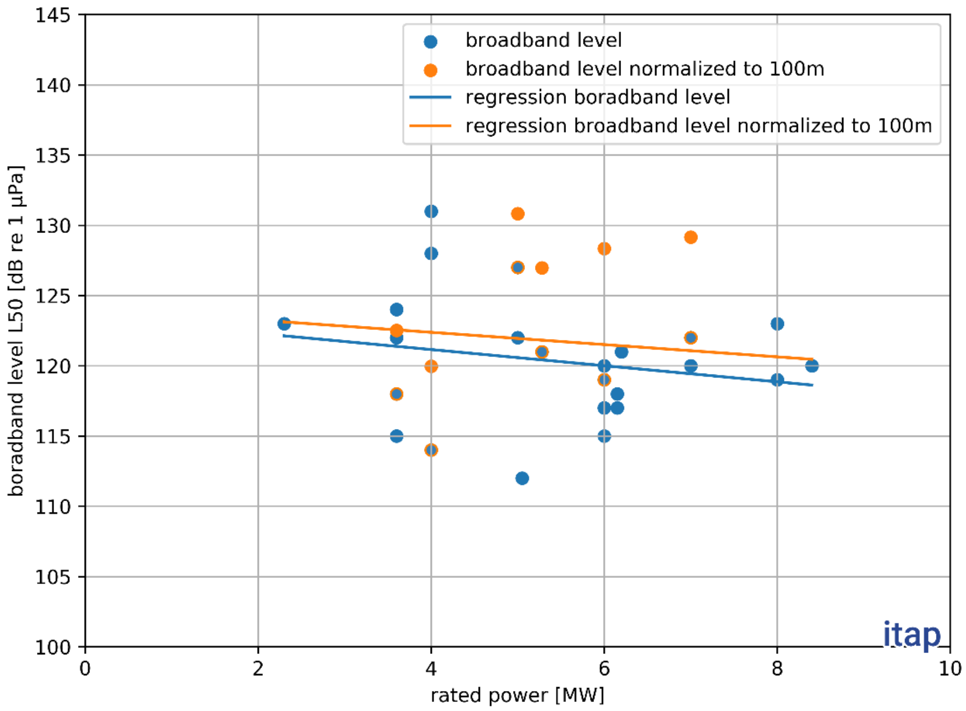


Figure 19: *Broadband Sound Pressure Levels L_{50} at a distance of 100 m from the OWTGs sorted by drive-system (G - gearbox; D - direct drive resp. gearless). The horizontal lines represent the median of the respective drive type, solid lines represent the measured values, dashed lines represent normalized values.*

Parameter	Sound Pressure Level L_{50} dB re 1µPa from Figure 18 and Figure 19		
	Average value	**Standard deviation**	**Median**
monopile	*119,8 (121,3)*	*3,5 (4,2)*	*120,0 (121,0)*
other foundation structure	*122,0 (122,5)*	*6,1 (6,1)*	*121,5 (123,1)*
with gearbox	*121,1 (122,2)*	*4,6 (4,7)*	*121,5 (122,3)*
without gearbox	*118,6 (120,7)*	*2,2 (5,4)*	*119,0 (120,0)*

Table 6: *Statistical values (?) of the Sound Pressure Level L_{50}, measured on operating OWTGs of different types and foundation structures at a measurement distance of approx. 100 m. The values normalized to 100 m are shown in brackets.*

Nominal power: Figure 20 shows the measured broadband Sound Pressure Levels L_{50} and Figure 21 the level of the dominant 1/3-octave band level L_{50} as a function of the nominal power of the turbines.



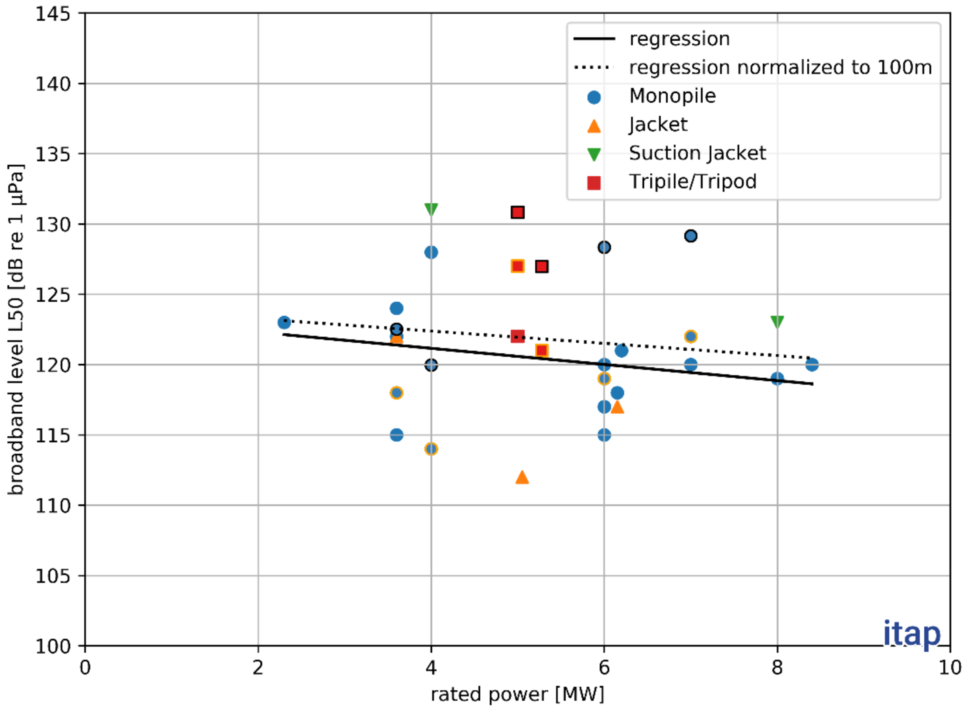


Figure 20 indicates, that the measured total broadband level at a distance of approx. 100 m from turbines operating at nominal power decreases with increasing nominal power. The total broadband level may be significantly influenced by other factors, such as the background sound level; see below. If only the 1/3-octave band which is dominating the broadband Sound Pressure Level is taken, however, there is also a decrease in level with increasing nominal power; see Figure 21.

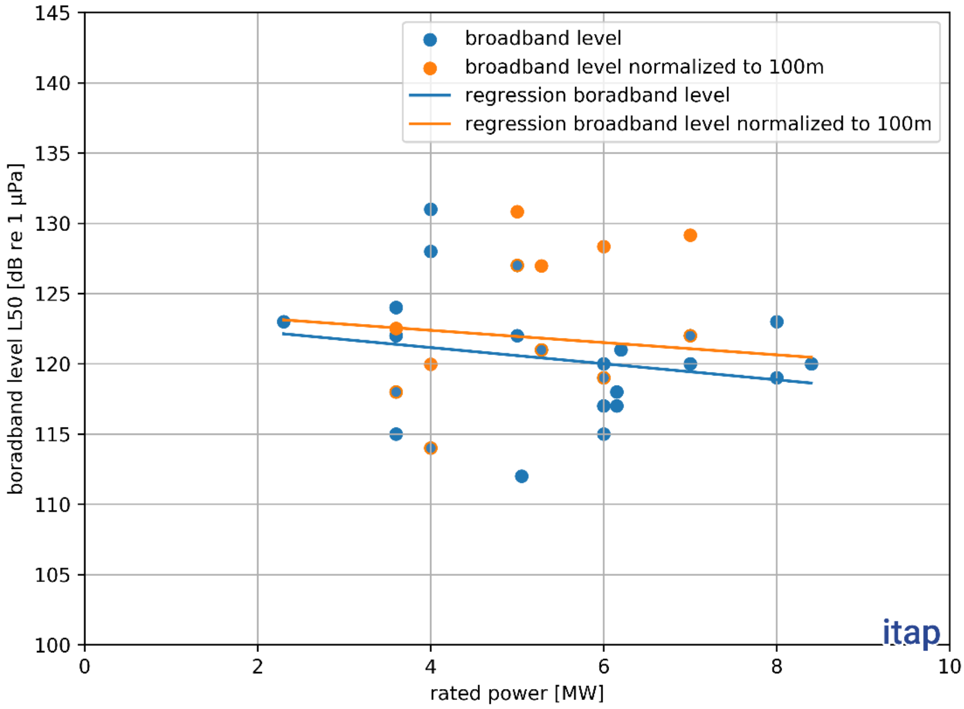
Thus, a constant to decreasing Sound Pressure Level can be assumed for more modern OWTGs with higher nominal power.

Existing background noise level: Figure 22 shows the measured differences between the broadband Sound Pressure Level L_{50} with nominal power (wind class "high") and switched-off OWTGs (wind class "low").

Figure 22 shows, that there is a large variance in the measured broadband Sound Pressure Levels between the operating states "units running at nominal power" and "units switched off". In most cases, the broadband Sound Pressure Levels L_{50} are, as expected, greater for units, that are in operation than for units, that are switched off. The level difference tends to decrease with increasing nominal power resp. newer construction year. In most cases, the Sound Pressure Level in the wind class "medium" is between the levels of the wind classes "high" and "low"; only in isolated cases, the level in the wind class "medium" is greater than in the wind class "high".

Vice versa, it could also be concluded, that the "newer" the turbines, the less Sound Pressure Level L_{50} increases between the operating states "turbines in operation at nominal power" and "turbines are off" at a distance of up to 100 m from the turbine.

However, four cases have also been measured, in which the broadband Sound Pressure Level in the wind class "high" (turbines in operation with nominal powers) are quieter than in the wind class "low" (turbines producing no output/power).



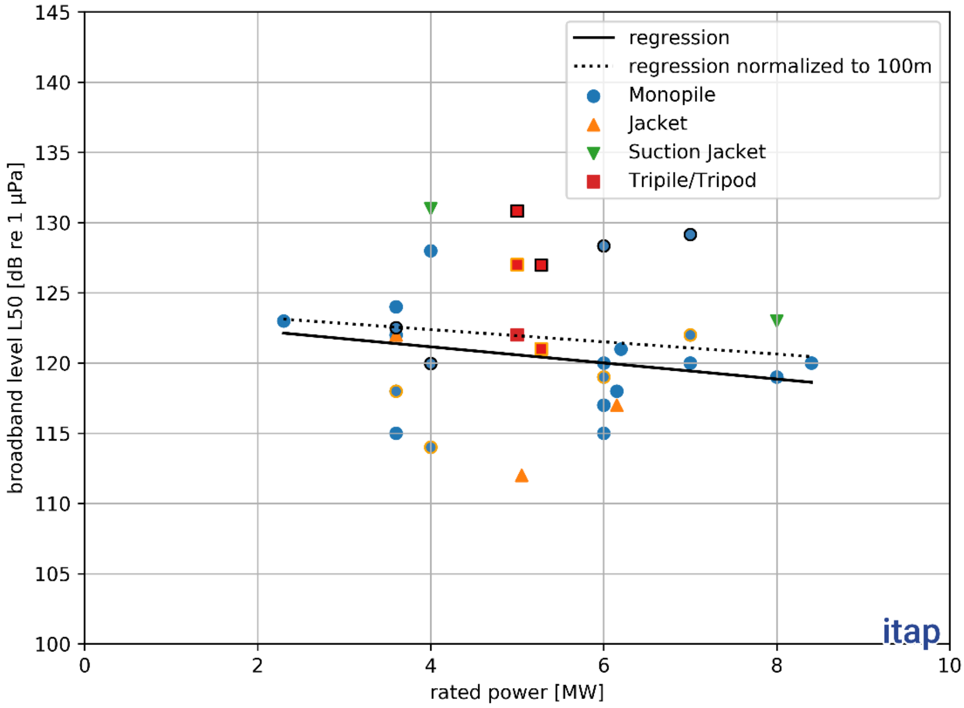
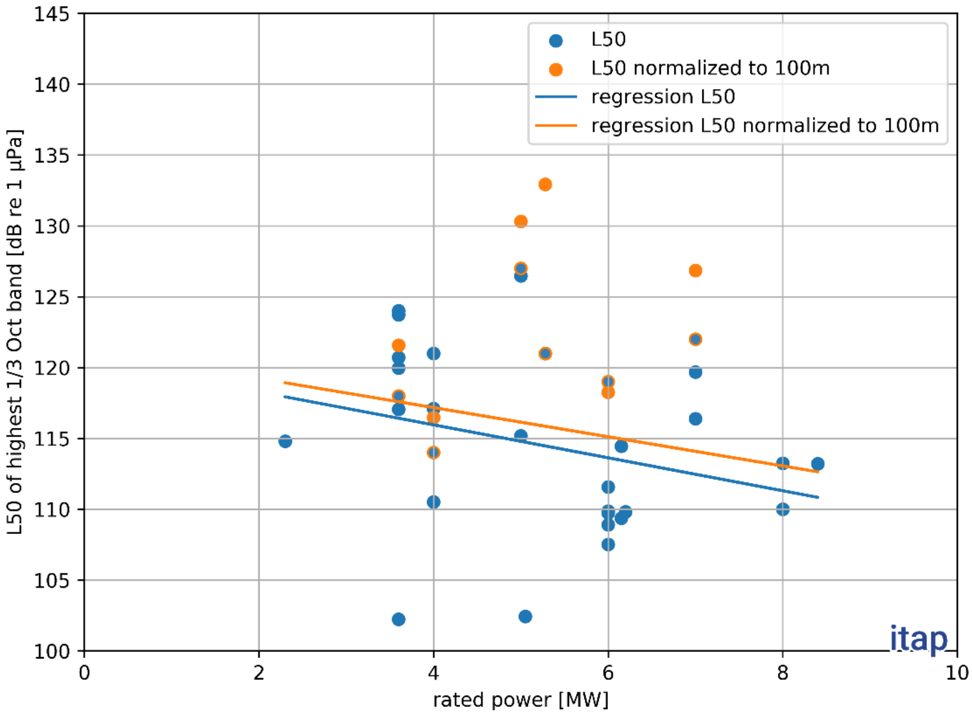


Figure 20: *Broadband L_{50} in 100 m distance from the OWTGs as function of the nominal power. Top: independent of foundation structure; below: broken down by foundation type. The values standardized to 100 m are outlined in black, outlined in orange are the values which are not standardized.*



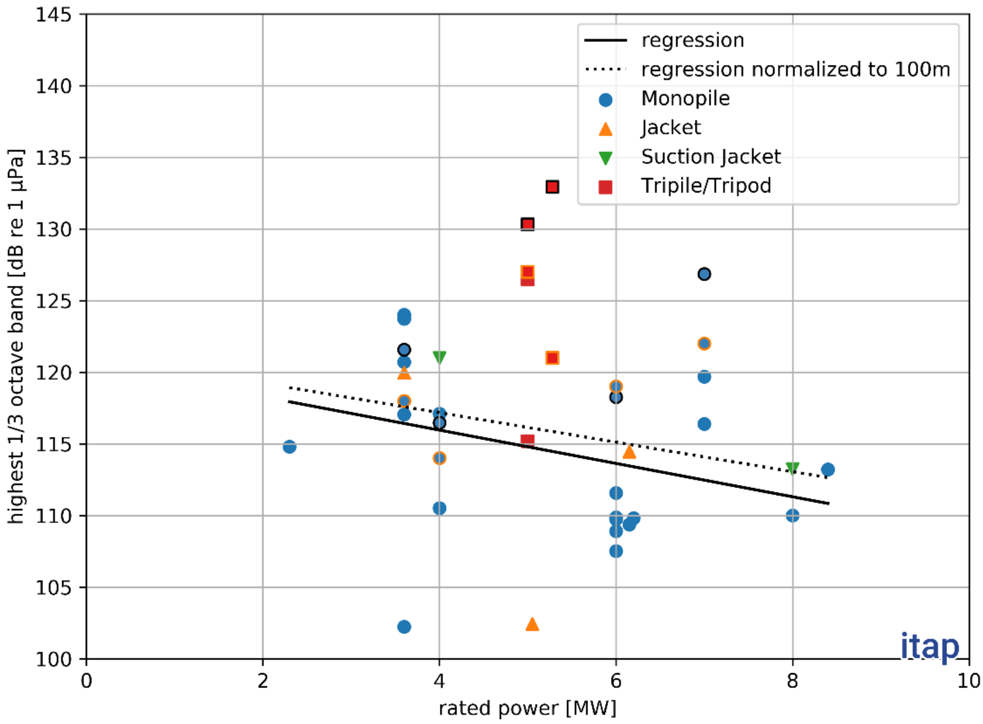


Figure 21: *L_{50} of the 1/3-octave band with the highest level in 100 m distance from the OWTG as function of their nominal power. Top: independent of foundation structure; below: broken down by foundation type. The values standardized to 100 m are outlined in black, outlined in orange are the values which are not standardized.*

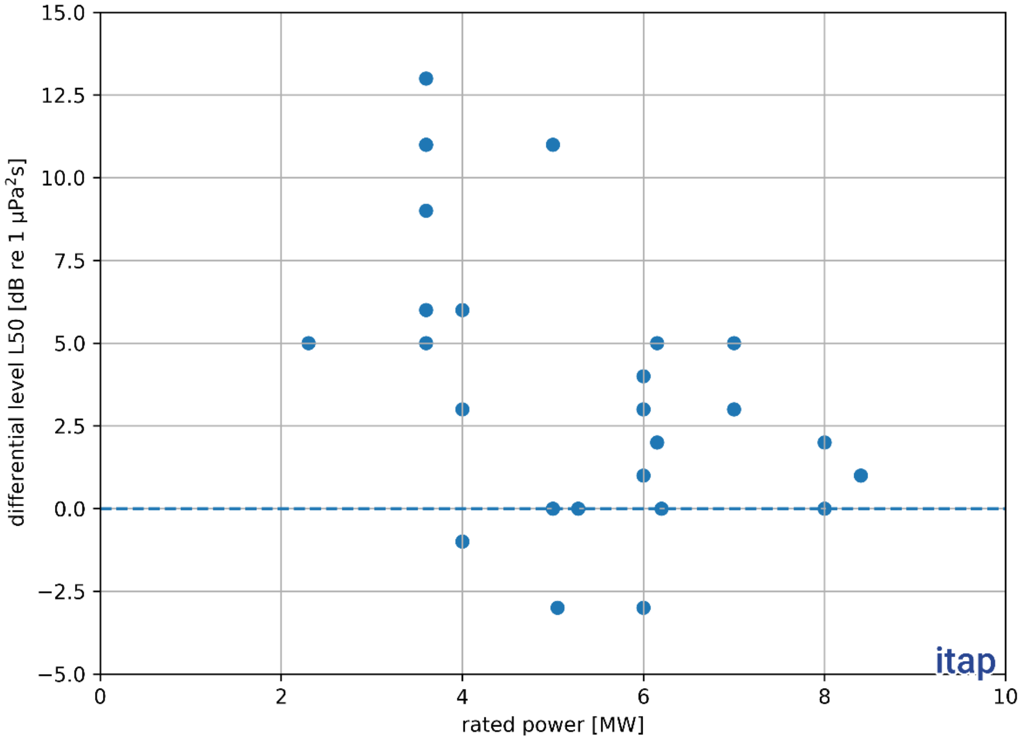


Figure 22: Difference level between the broadband Sound Pressure Level L_{50} with operating OWTGs with nominal power (wind class "high") and switched-off OWTGs (wind class "low") as a function of the turbine size.

6.1.4 Site-specific variables

Water depth: In Figure 23, the measured levels are plotted as a function of the water depth. A statistically valid correlation does not seem to exist; the level tendentially seems to decrease slightly with increasing water depth. *In contrast, the values normalized to 100 m increase slightly.*

Theoretically, the water depth cannot have a major influence on the available data sets, as it only covers a range of about 1:2 for all measured OWTGs (about 20 m to 40 m).

Assuming, that the sound radiation from the water surface to the seabed is the same, this would mean a difference of 3 dB under otherwise identical conditions. However, measurements at a monopile have shown, that the vibration amplitude and thus the sound radiation decreases towards the seabed (Betke et al., 2003). This is probably due to the increasing bending stiffness of the "pre-tensioned" pile in the seabed. In addition, if the same vibration energy is introduced from the gondola into the tower at both 20 m and 40 m water depth

(i. e. the same turbine is installed in both cases), no higher sound level is to be expected either or at most a slight change due to subtle changes in sound radiation.

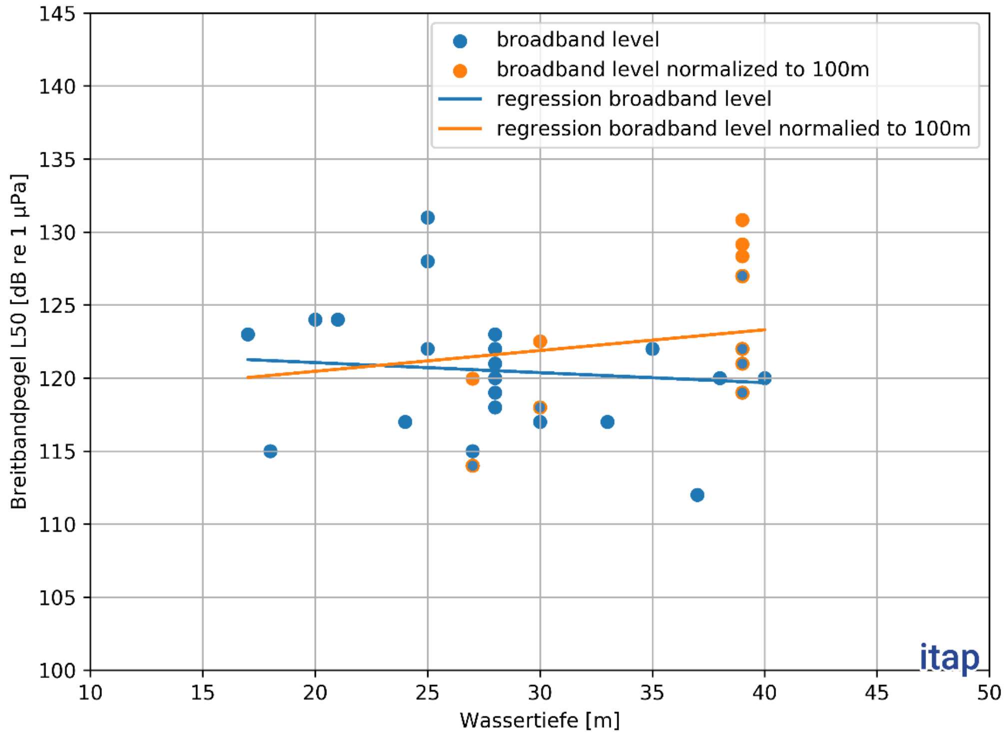


Figure 23: *Broadband levels L_{50} in 100 m distance from the OWTGs in operation (nominal power) as function of the water depth. Outlined in orange are the values which are not standardized.*

Further site-specific parameters were not carried out due to the low variance in the investigated wind farms. Most wind farms in the German North Sea were installed in predominantly sandy soils, while in contrast only a few wind farms were installed in the Baltic Sea, some with very complex soil stratification.

6.2 Measurements in and around offshore windfarms

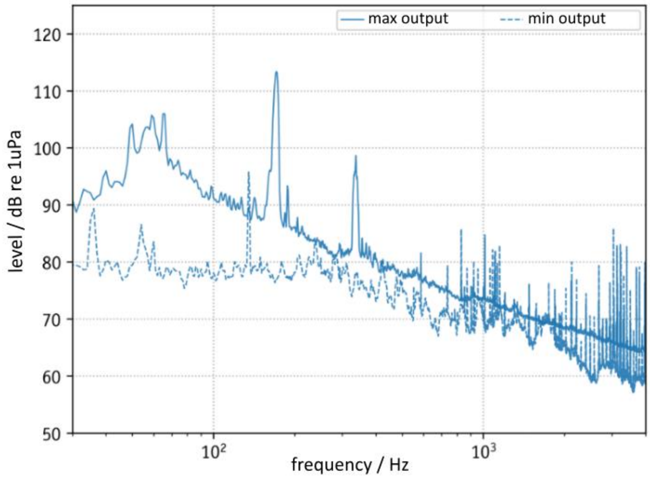
Figure 24 shows an example of the narrowband-FFT-spectra measured at a selected system in the eastern Zone 1 of the North Sea (; OWTG: Siemens SWT-3.6-120 with gearbox) for the measurement positions approx. 100 m from the OWTG, compared at approx. 1 km and approx. 5 km outside the OWF for the wind classes "high" (nominal power) and "low".

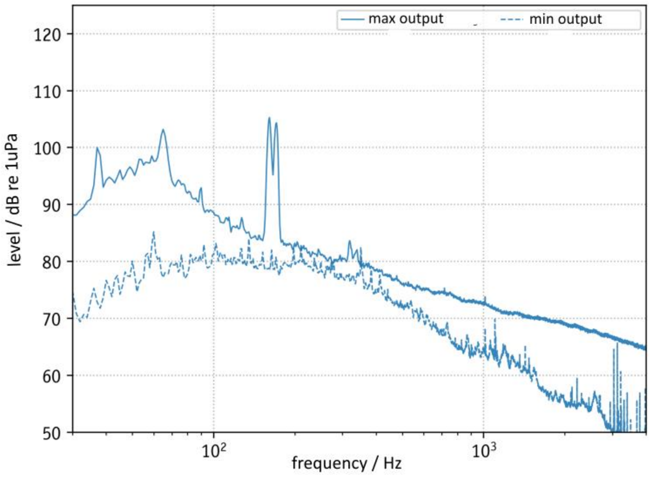
The amplitude of the characteristic frequency (here 160 Hz) at nominal power decreases steadily with increasing distance from the respective system or wind farm. Independently, all measurement positions outside the wind farm show, that the spectrum around the narrow-band, tonal component around 160 Hz slightly widens. It can be assumed, that this spectral extension is caused by the presence of two or more wind turbines, which may have slightly different eigen-frequencies due to the rotor speed or the pitch angle. A further possibility can also be based on the fact, that only 10-minute mean values of the respective wind turbine generator were available for all evaluations and therefore this said installation showed variations in the rotor speed or the like.

In the case of a representation in the spectral width of 1/3-octaves, however, this slight spectral extension is not relevant. It is also shown, that at a distance of approx. 100 m, harmonics of 160 Hz can still be measured and detected in the water, i. e. natural harmonics of 160 Hz; however, these higher narrowband components are no longer dominating the broadband Sound Pressure Level s. They are also no longer present in the measured spectra as the distance from the wind farm increases.

It can also be seen that the broadband level usually drops significantly between the wind class "high" and "low". In the low-frequency range, this is primarily due to natural sound sources (wind, waves, etc.). It is worth mentioning, that partly in both wind classes, vessel noise can be measured and heard from a greater distance of a TSA, which also contributes to a broadband level increase. In isolated cases, there are higher levels in the wind class "low", which usually are due to the noise input from smaller vessels, that no longer operate in or around the wind farm in bad weather (wind class "high").

Table 7 exemplarily summarizes all broadband Sound Pressure Levels at all measurement positions from Figure 24 inside and outside the OWF.





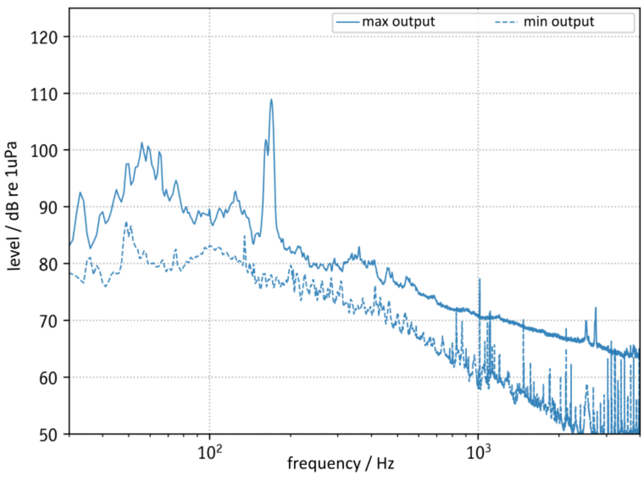


Figure 24: Typical narrowband FFT-spectra at a selected turbine in the eastern zone 1 of the North Sea (Siemens SWT-3.6-120 with gearbox) at a distance of 100 m (top), 1 km (middle) and 5 km (bottom), each at nominal power (wind class "high ") and standstill (wind class "low").

Measurement position	Wind class	Sound Pressure Level in dB re 1µ Pa			
		L_{90}	L_{50}	L_{eq}	L_5
100 m from OWTG	high	120	122	123	127
	medium	117	123	125	130
	low	106	111	117	124
center of OWF	high	110	115	116	121
	medium	109	114	120	127
	low	103	109	112	118
1 km from OWF	high	108	115	116	119
	medium	107	114	116	121
	low	101	108	116	122
5 km from OWF	high	114	116	118	122
	medium	112	117	119	123
	low	106	112	117	124

Table 7: Measured, broadband Sound Pressure Levels according to measurement positions and wind class sorted for a selected wind farm in the eastern zone 1 of the North Sea north of Helgoland.

Table 7 shows, that the Sound Pressure Level within the wind farm tends to increase with the wind class or the increasing operation of the wind turbines. Outside the wind farm, however, there are usually no or no significant level increases with regard to the continuous Sound Pressure Level L_{eq} and the percentile value L_{05}. Only for the L_{90} and L_{50} values at the measuring positions "centre of OWF" and "1 km from OWF", the level rises with increasing wind class. A special feature of this relatively "old" and "small" OWTG (3.6 MW) is, that the Sound Pressure Level for the wind class "medium" is higher than for the wind class "high", at least within the wind farm. There can be many reasons for this, such as regulatory mechanisms of the respective turbine, and cannot be further analysed on the existing data basis of averaged performance data.

It was also shown that the level values 5 km away from the wind farm are higher than at a distance of 1 km. This indicates that the Sound Pressure Level outside the wind farm is not dominated by the operation of the turbines or the wind farm, but by the surrounding back-ground noise level (mainly shipping traffic).

6.3 Comparison of background- and operating noise

As part of the approval process for a wind farm, a background noise measurement before the start of construction of a wind farm and an operating noise measurement in accordance with the measurement regulations for underwater noise (BSH, 2011) are ordered. From the comparison of these two measurements, it should be evaluated, whether and if so, which effects the operation of this wind farm has on the overall ambient noise in and around it.

A total of 12 background noise measurements were carried out in zones 1 and 2 of the North Sea.

The direct comparison of background- and operational noise measurements has proved to be more complicated in recent years. The comparisons do not show any clear results; for example, there could be an increase or decrease in background noise due to the construction of individual wind farms resp. clusters of wind farms. Some examples are presented in more detail here.

As an example, measurements from the western zone 2 of the North Sea near the Netherlands, the determined background- and operational noise is compared in Table 8.

Wind class	Background noise, 2018	Operational noise, 2021	Operational noise, 2021
low	116	119	119
high	116	121	120

Table 8: Broadband Sound Pressure Levels L_{50} (background noise) measured prior to the construction of a planned wind farm in the western zone 2 of the North Sea in comparison with values from two neighbouring measurement positions during the operational noise measurement (all values in dB re 1 µPa).

Table 8 shows, that no that the Sound Pressure Level only increase by 1 or 2 dB between the wind classes low and high. However, the present evaluation of the operational traffic in and around this wind farm also cannot fully explain an increase in background noise of 3 dB for the wind class "low" and up to 5 dB for the wind class "high" between the background- and operational noise measurements. It could possibly be, that the ambient noise in the wind class “high”, such as wave impact, has increased due to the now installed foundation structures. However, it also cannot be excluded, that the non-OWF-related shipping traffic around this wind farm has increased within the three years between the operational- and background noise measurements, at least for the wind class “low”. However, the available data from the underwater noise measurements and the AIS-data are not sufficient to make a quantitative statement on this.

Two further examples of neighbouring wind farms (OWTG: Siemens SWT 7.0-154, gearless) from background- and operational noise measurements carried out in the north-western zone 2 of the North Sea are shown in Table 9 and Table 10. There is an increase of 4 dB in the wind class “high” between the background- and operational noise measurements. This increase is clearly due to the operation of the turbines of both wind farms, as there are low-frequency noise inputs into the water. However, experience shows, that this tonal component decreases significantly with distance from the respective turbine and increasingly mixes with the background noise level. Moreover, another wind farm and a converter platform already exist in this area, so there is OWF-related service traffic in varying densities around this area.

Wind class	Background noise, 2018	Operational noise, 2021
low	117	117
high	116	120

Table 9: Broadband Sound Pressure Levels L_{50} (background noise) measured prior to the construction of a planned wind farm in the western zone 2 of the North Sea compared to values from an adjacent measurement position during the operational noise measurement (all values in dB re 1 µPa).

Wind class	Background noise, 2018	Operational noise, 2021
low	118	117
high	118	122

Table 10: Broadband Sound Pressure Level L_{50} (background noise) measured prior to the construction of another planned wind farm in the western zone 2 of the North Sea in comparison with values of the operational noise measurement (all values in dB re 1 µPa).

The comparison of the measurements from 2018 and 2021 with regard to the wind class "low" (turbines are at standstill) shows no statistically significant changes for both wind farms or measurement position, respectively. The effect of the service traffic of these three examples on the overall noise level is further investigated in Chapter 0.

6.4 Vessel noise in connection with wind farms in operation

6.4.1 Service traffic in and around a wind farm

The measured broadband Sound Pressure Levels (L_{50}) over all wind farms listed here in the wind class "low", i. e. with the wind turbine switched off, lie between 107 and 132 dB re 1 µPa; this covers a level range > 20 dB, which is equivalent to a factor > 10 of the physical metric sound pressure (Pa). The only possible reason for such a large level range is vessel noise or possibly other anthropogenic noise, since the prevailing wind conditions ("low") exclude high Sound Pressure Levels caused by e. g. wind and wave impact. It is not yet clear, to what extent the service traffic associated with the operation of a wind farm plays a role resp. whether these levels influence the overall Sound Pressure Level (ambient noise).

Until 2020, the noise input of wind turbines in operation was the focus of any investigation of operational noise measurements in Germany. The evaluations carried out up to that point showed, that the noise input of the turbines could only be recorded and assessed properly, if no vessels were present in the immediate vicinity of the turbine and the underwater noise measuring device. As a pragmatic solution, the measurement periods, in which operational traffic was present within a radius of < 1 km from all measurement positions within the wind farm, were excluded for the evaluation, if possible. It turned out, that a vessel passing close by, regardless of size or speed, completely dominates the overall noise level at the measuring device within the wind farm for a short period of time. From 2020 onwards, the first attempts were made to quantify and investigate the vessel noise caused by vessel movements in and around the wind farm under investigation using AIS-recordings. AIS stands for Automatic Identification System; a system, with which vessels regularly communicate their position and other information about their journey. So far, this open question has only been addressed at isolated wind farm areas through a targeted selection of measurement positions and the use of vessel movements.

A typical scenario for a wind farm at a greater distance from the coast is, that a service vessel remains in the wind farm for two to four weeks, i. e. including overnight accommodation for the maintenance personnel, before returning to the base port to change personnel and pick up operating supplies. In the wind farm, the service vessel moves between the turbines from time to time to drop off service teams for maintenance work. Occasionally, smaller CTVs (Crew Transfer Vessels) may also be active in the area for transport trips. These trips are usually limited to daylight and "good weather", i. e. the service intervals are usually longer in summer than in winter. For the longest time, the service vessel is parked in the wind farm or in the surrounding area. Furthermore, there are maintenance trips by other, smaller vessels for ecological operational monitoring for e. g. visual observations and POD-maintenance trips; such trips take place every few weeks (usually every six to eight weeks) for a few days in and around the wind farm, also only in good weather.

In the case of wind farms near the coast, the service vessels and CTVs usually sail daily from the base port to the wind farms and back. The maintenance work there is also mostly limited to the daytime period (BSH 2023).

Figure 25 shows the AIS-track of the offshore service vessel at a wind farm in the western zone 2 over a period of 52 days. Another example of the AIS-track of a service vessel from the western zone 2 of the German EEZ in the North Sea is shown in Figure 26. Both examples are located in the central western part of the German EEZ in the North Sea.

The points in the AIS-tracks have an interval of about 30 minutes. Shorter intervals were not available from the commercial AIS-provider (Fleetmon; JAKOTA Cruise Systems GmbH, Rostock). This is partly because the distance of the considered wind farms from the coast makes normal reception of AIS-data transmitted on VHF (very high frequency) unreliable and it was necessary to switch to relatively expensive satellite-AIS.

The movement of the OWF-related service vessel in the western zone 2 of the German EEZ in the North Sea from Figure 25 was examined in more detail: During the mentioned period of 52 days, the company-owned service vessel left the wind farm three times for a few days to enter the base port. In the wind farm, it travelled for a total of about 4 hours, whereby a speed of 2 knots was selected as threshold value for the "travelling" condition. The highest speed inside the considered wind farm was 10 kn; outside, up to 12 kn were recorded (Figure 27). For the said service vessel, a maximum speed of 13 kn is mentioned.

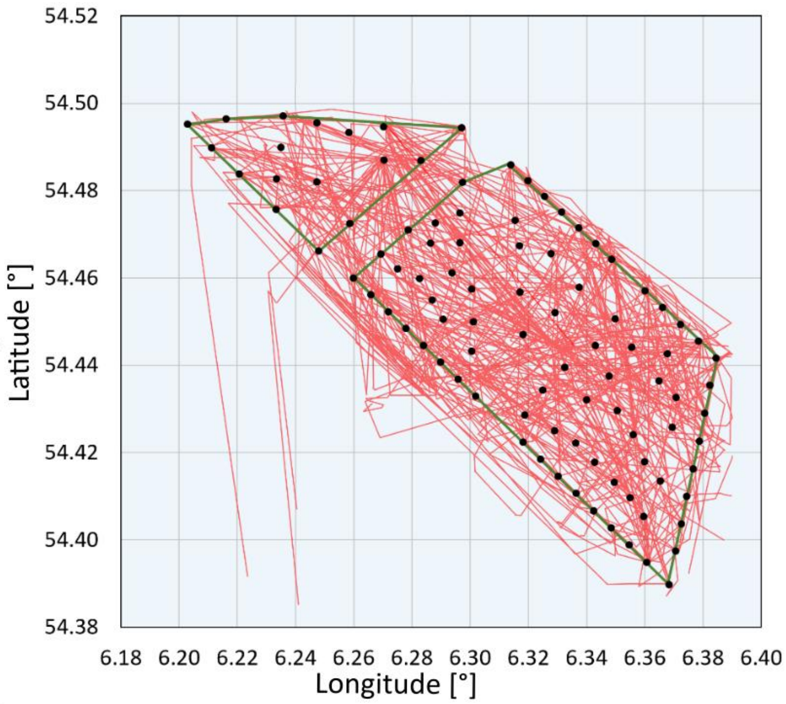


Figure 25: Movements of the company's own offshore service vessel in the western zone 2 of the North Sea over a period of 52 days in the summer of 2021 during several weeks of operational noise measurements. The vessel movements were reconstructed using AIS-recordings.

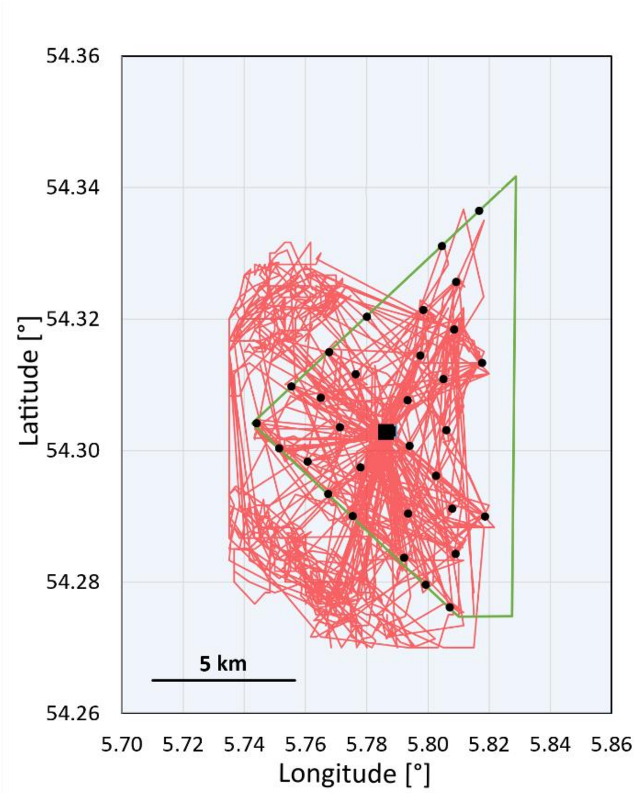


Figure 26: Movements of the company's own offshore service vessel in the western zone 2 of the North Sea over a period of 56 days in the summer of 2021 during several weeks of operational noise measurements. The vessel movements were reconstructed using AIS-recordings. The black square in the centre of the wind farm marks the substation.

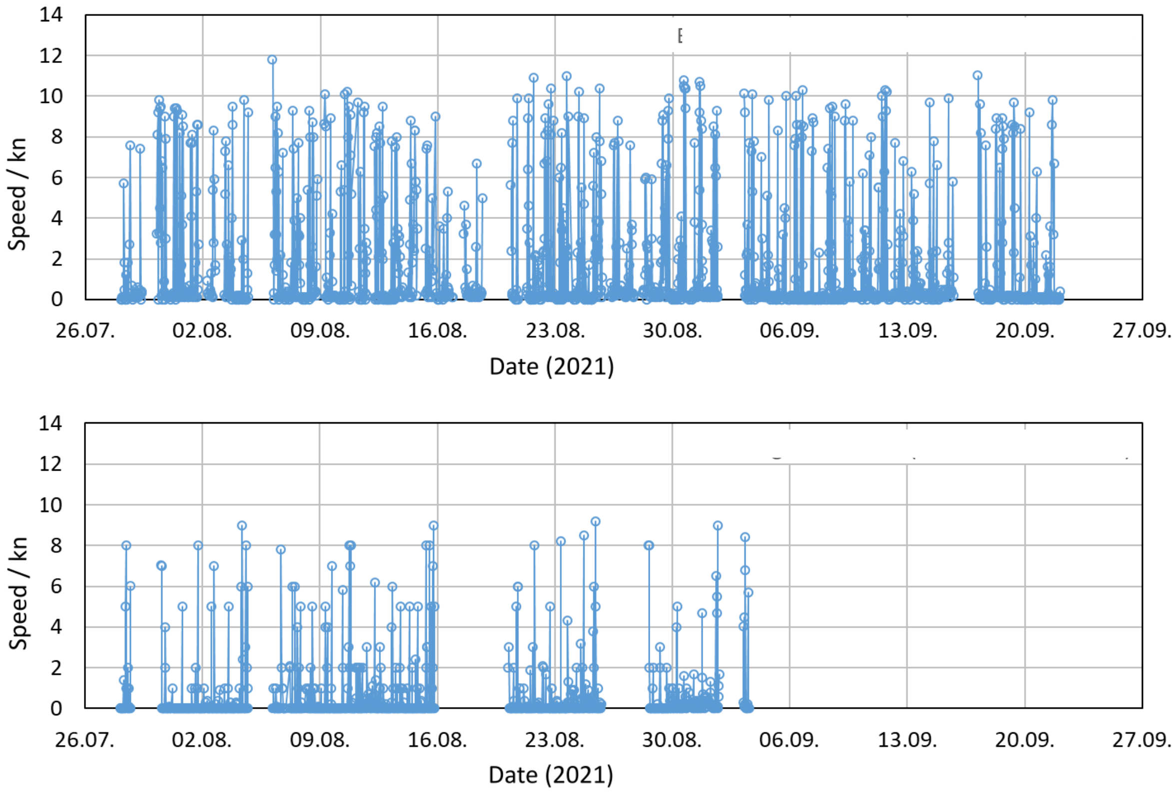


Figure 27: Using AIS-data, the speeds of the service vessels were determined from Figure 26 and Figure 27. For the majority of the time, the vessels were not in motion.

In the following, for the purposes of the Marine Strategy Framework Directive (2008), the energy shall be estimated, that is transmitted

(i) from the OWTGs of a wind farm and

(ii) by the service vessels operating there

into the sea in the form of noise.

First of all, the source level of the service vessel is required. No empirical source level value was available for the above-mentioned service vessels, but according to the measurement archives of *itap GmbH*, vessels similar in design have source levels around L = 170 dB re 1 µPa @ 1 m, when in motion. For individual OWTGs, a constant value of L = 120 dB re 1 µPa @ 100 m is assumed, based on measurement data from this report. For the noise propagation, a level decrease of $15*\log10(r_2/r_1)$, based on the geometric transmission loss in shallow water, is assumed for simplification, if the distance to the sound source is increased from r_1 to r_2. From these values, sound power- and energy values can now roughly be calculated (Table 11).

Sound source	Average acoustical power	Sound energy radiated into the sea within 50 days
Service vessel during trips in the OWF from Figure 25; in total 4 h.	119 dB re 1 µW (= 0.8 W)	114 dB re 1 J (= 0,22 MJ)
87 OWTG	130,4 dB re 1 µW (= 11 W)	137 dB re 1 J (= 47 MJ)

Table 11: Estimation of the acoustical energy radiated by the company's own service vessel and the OWTGs, using an example in the western zone 2 of the North Sea with 87 OWTGs, each with a nominal power of 7 MW.

The noise levels in Table 11 mean, that the moving service vessel has introduced about 200 times less (sound-) energy into the water during the observation period of 52 days than all OWTGs of this wind farm together. A sound level at a specific location cannot easily be determined from this, as the sound source service vessel is constantly changing its position. Only at a great distance from the wind farm, a vessel can be regarded as a stationary source, but the noise input and transmission in the water can usually no longer be separated from the general ambient noise over great distances due to the poor signal-to-noise-ratio.

It should be noted at this point, however, that noise can also be introduced from vessels in standby modus. Although there is no propeller noise, except when correcting the position, the vessel's engines run continuously for the power supply and also emit noise via the vessel's hull. However, based on our own measurements and literature data, this is usually significantly less than the noise input of a moving vessel. Independently of this, it is known from the literature, that vessel noise generally also increases with increasing speed (chapter 0). A special feature are vessels in the dynamic positioning mode (DP-mode), which can hold themselves in position by means of variable thrusters. In this case, the noise input into the water usually increases with the prevailing current, when the vessel is in standby. Service vessels for wind farms are mostly equipped with such a DP-drive.

In a second step, all clearly assignable vessels for these 52 days were searched for the said wind farms and an attempt was made to determine the proportion of mooring times and travel operations; see Figure 28.

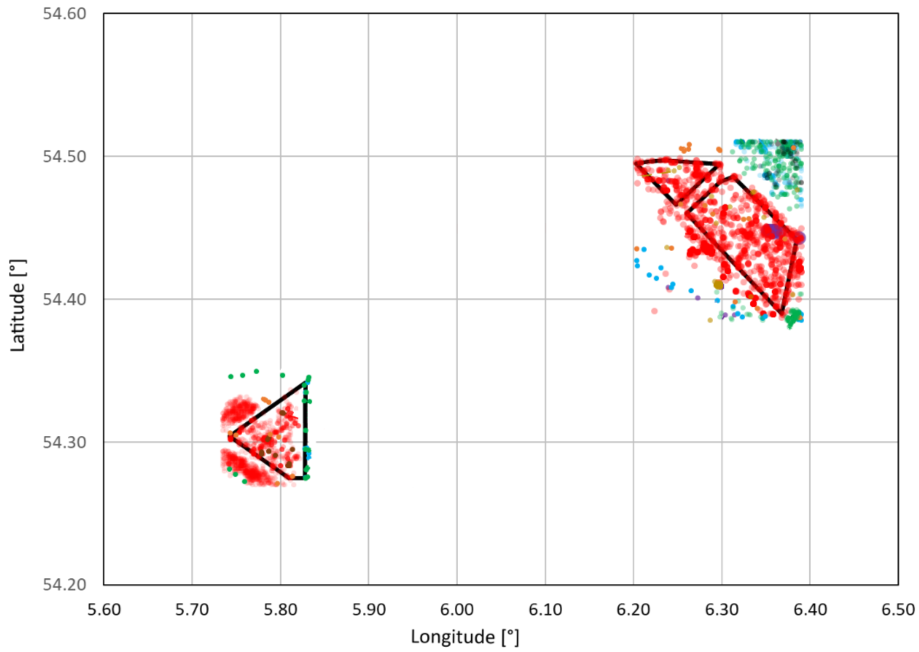


Figure 28: *Vessels in the area of selected offshore wind farms in the western zone 2 of the North Sea (bottom left and top right) during the measurement period for operational noise from July to September 2021. Each OWF-related vessel is marked with a different colour.*

Figure 28 confirms the information provided by the OWF-operators, that different vessels were in operation in and around the wind farms for different short-term operations on a daily basis. Moreover, it can be seen, that, depending on the wind farm and the adjacent wind farms, some of the vessels also carried out their lay times or standby outside the wind farm boundaries.

For the selected wind farm in the western zone 2 of the German EEZ in the North Sea, other wind farms border to the east, so that mooring places to the northwest or southwest outside the wind farm were often visited. The cluster of vessels to the north-east of the selected wind farm can be attributed to another wind farm in operation and a converter platform.

It can therefore be assumed that, in a purely energetic consideration of the broadband noise input (SPL) into the water, the roughly considered difference between the OWTG and the vessel is less than 23 dB.

6.4.2 Service traffic outside the wind farms

The influence of (OWF-related) operational service traffic outside the inaccessible OWF-areas on the general (total) Sound Pressure Level usually depends very strongly on further non-OWF-related shipping traffic. For example, Figure 29 shows a map of the shipping density generated from AIS-data for the entire year 2017 (averaged) for the eastern North Sea north of the offshore/deep-sea island of Heligoland, consisting of three OWFs within zone 1 at that time (www.marinetraffic.com). These three wind farms were activated in 2013 and 2014.

Clearly visible in Figure 29 is the shipping route from the Elbe (Hamburg, Cuxhaven) first north-west and then north, in some distance west along the cluster "Nördlich Helgoland". This is the travel route taken by all large ships, that cannot pass through the North Sea-Baltic Sea Canal to get to the Baltic Sea through the Skagerrak. The red line directly west of the southern wind farm is probably due to the operational shipping traffic of the neighbouring OWF to the north. Before the three offshore wind farms were erected, this shipping route probably ran east through the current wind farm area.

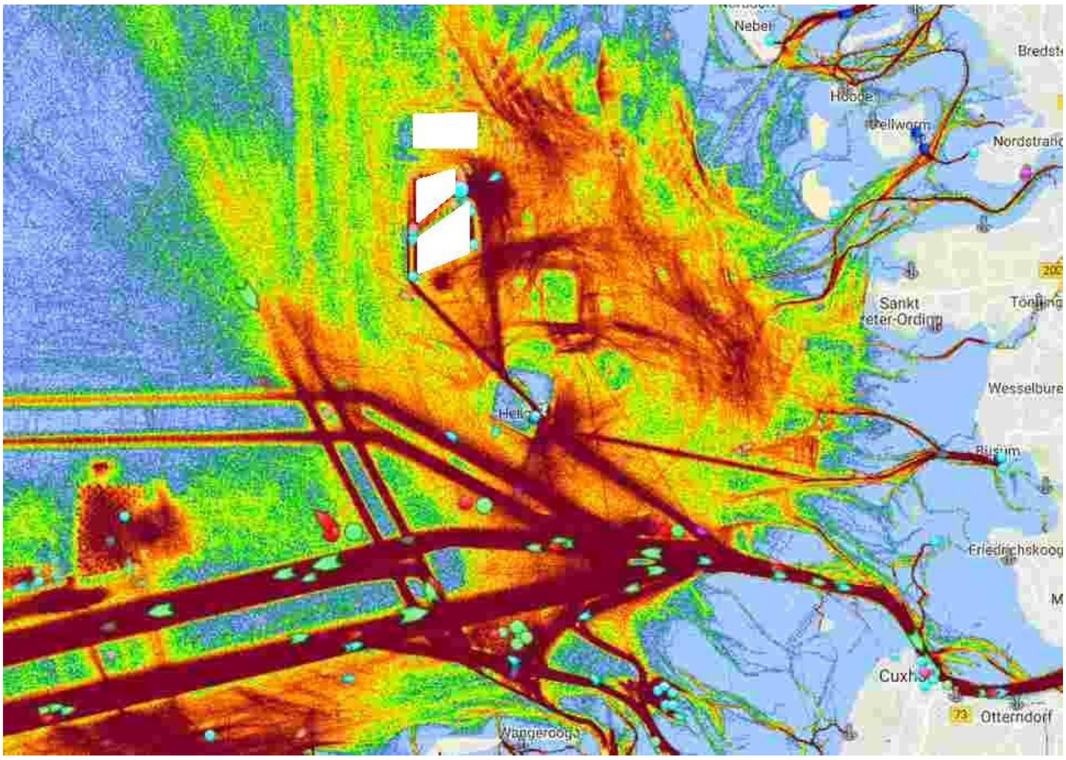


Figure 29: Color-coded traffic density from AIS-data for the East Central EEZ of the North Sea. North of the offshore island of Heligoland, three wind farms were in operation in 2017, which are marked in white (source: www.marine-traffic.com, 03.12.2017).

The high vessel density east of the "Nördlich Helgoland" cluster is probably due to the operational shipping traffic of the three OWFs and the two converter platforms operated there. However, there is also a high density of vessel traffic to the east and north-east of the northern wind farm, which is clearly not due to the supply vessels of the wind farms and converter platforms.

The apparent thinning out of shipping density west and north of the "Nördlich Helgoland" cluster is due to the limited range of the AIS-radio telegrams. The nearest AIS-receiving station of the marine-traffic.com measuring network is near St. Peter Ording, approx. 84 km away from the northwestern AIS-transponder of the northern, marked wind farm. The maximum coverage of the AIS-receiver is approx. 78 km, whereby the range is heavily dependent on the weather. Thus, vessels west of this wind farm are sometimes out of the range of the AIS. The AIS-receiving station in Cuxhaven is also too far away to adequately register vessel movements west and north-west of the three OWFs.

Another AIS-receiving station is located on Sylt, the range of which does not cover the three wind farms either. This gives the impression that vessel traffic density is significantly reduced west of the three wind farms but increases significantly further north near Sylt. These apparent fluctuations in traffic density are due to the fact, that the AIS-reception network does not cover the entire area.

Merging the AIS-data from marine-traffic.com with the Danish Maritime Authority (www.dma.dk) data sets available from Denmark is shown in Figure 30 and confirms this assumption.

Figure 30 also clearly shows the contours of further German wind farms in the eastern zones 1 and 2 of the North Sea west of the island of Sylt. The reddish colouring of the access roads to the wind farms and the trips within the wind farms is deceptive, since the vessel density is shown as an average over a complete year. A daily or weekly vessel movement to the areas is also shown as a solid line.

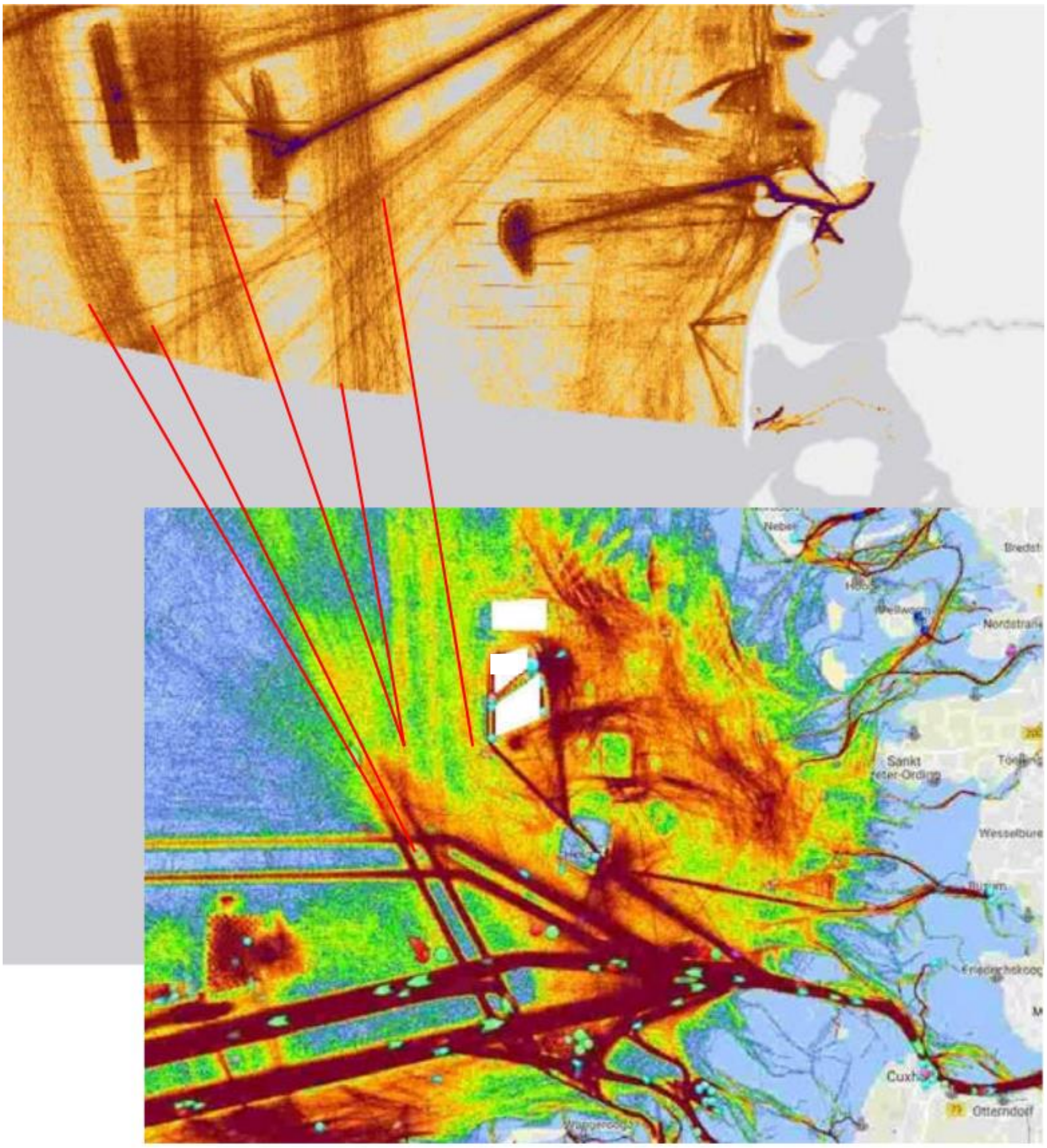


Figure 30: Overlay of the AIS-charts from www.marine-traffic.com with the AIS-data available from Denmark from the Danish Maritime Authority (www.dma.dk). The shipping routes were graphically interpolated to the west of the wind farms.

7. Discussion

7.1 Variables that possibly affect operational noise

As part of this study, 27 available operating noise measurements from 24 offshore wind farms in the German EEZ of the in the North- and Baltic Sea were combined in a cross-project study for the first time. The data used for analysis are stored in the national noise register MarinEARS for continuous noise. An overview::

- 16 different OWTG-types from seven different manufacturers,
- nominal powers between 2.3 and 8.0 MW,
- five different foundation structures (monopiles, tripods, tri-piles, jackets with driven piles and suction bucket jackets) with pile diameters between 2.42 and 8.1 m,
- in two wind farms, turbines of the same type were installed on two different foundation structures,
- water depths between 20 and 40 m,
- simultaneous underwater noise measurements at not less than three measurement positions per wind farm at distances between 100 m from a selected turbine and 5 km from the OWF and
- three defined operating states of the systems (OWTG at a standstill, nominal power and $\leq$ 90% power of the systems),
- 12 background noise measurements prior to the construction of selected wind farms,
- all processed measurement data sets are available in a standardized form, quality assured and stored with essential accompanying information, such as the performance data of the respective selected wind turbines, weather data and sometimes also vessel movements inside and outside the wind farms.

Based on this large database, an attempt was made in chapter 6.1 to identify and quantify possible project- and site-specific variables by means of a cross-project analysis of the existing data. However, it turned out, that the variations of the above-mentioned variables, such as the combination of a specific foundation structure with a selected wind turbine and the given water depth, has turned out to be so large, that possible influencing parameters could be identified, but due to the small sample size of the most diverse parameter combinations, a valid quantification of these variables is not easily possible.

Moreover, it turned out, that only the underwater noise measurements at a distance of a few hundred meters from a pre-selected turbine within the wind farm can be used to identify possible variables affecting operational noise, since otherwise, there was overlapping of the underwater noise caused by the wind turbines with the permanent ambient noise.

In the following chapters, the results of this study are compared and discussed with studies already known from the literature.

7.1.1 Foundation type and nominal power

The noise radiated into the water by offshore wind turbines in operation is characterized by a tonal component (natural frequency of the rotor drive system) which dominating the broadband Sound Pressure Level, that is in the frequency range < 160 Hz and whose amplitude can vary greatly.

There are indications that the average noise radiation from monopile foundations can potentially be a little quieter than from other foundation structures (chapter 0). This assumption is supported by two wind farms, where an identical turbine type was installed on a driven monopile and a suction bucket jacket as well. The two turbines on driven monopiles were 2- and 4-dB quieter than the systems of the same type and nominal power on the suction bucket jackets. When comparing the operating states "OWTG with nominal power" with "OWTG at a standstill", the Sound Pressure Level increases by 0 to 3 dB in three of the four measured OWTGs. In one case, the Sound Pressure Level was 2 dB louder with the systems switched off.

However, further comparative measurements are necessary to validate this fact due to the partially limited data situation concerning turbine type and foundation structures that are not monopiles. Moreover, pile diameters and embedment depths of the skirt-piles differ significantly, so that a statistically valid quantification of the different foundation structures and pile diameters is not possible on the available data basis.

A direct comparison under same conditions in terms of weather and ambient noise between a wind turbine operating at nominal power and a wind turbine standing still in the same wind class, as for onshore operational noise measurements according to the FGW-directive, has not yet been carried out. The technical, administrative and financial efforts for a total or at least a partial wind farm shutdown during the wind class "high" (OWTG running with nominal power) are too high so far. Therefore, only the two wind classes "low" (OWTG mostly at a standstill) and "high" (OWTG running with nominal power) can be compared. However, this comparison is subject to some uncertainties since the ambient noise differs due to the significantly different wind conditions in the selected wind classes "low" (up to 3.5 m/s) and "high" (from 11 m/s). Usually, limited abiotic noise is introduced by wind and waves in the wind class "low"; simultaneously a higher number of vessels operate in and around the wind farms, so that the anthropogenic noise input from vessels often clearly dominates the ambient noise level. In the wind class "high", when larger cargo vessels dominate the traffic routes with small vessels and operational OWF-related service traffic being suspended due to weather conditions, increased abiotic noise input from wind and waves can be assumed. Therefore, it is not possible to quantify if abiotic noise caused by waves breaking on the foundation structures influences the overall noise level measured in a wind farm.

No statistically valid correlation between prevailing water depth (20 to 40 m) resp. nominal power of the turbines and underwater noise emissions were found. Slightly decreasing noise emissions with increasing nominal power, newer types of systems and gearless implementation of the systems were observed. It is assumed that turbine type (geared or gearless), turbine generation (new vs. old), and rated power result in decreasing sound pressure levels during wind turbine operation.

Holme et al. (2023) used a collection of measurements from this study (three wind farms from the northwestern zone 2 of the German EEZ in the North Sea) at distances between 63 m from specific wind turbines and 5,000 m from the respective wind farm to determine the influence of turbine size resp. nominal power (Siemens SWT 6.0 -154 6.3 MW and Vestas V 164-8.0 8.5 MW), wind speed and foundation type (driven monopile and suction bucket jacket) on operating noise. In underwater noise data, measured inside and outside of the wind farm, Holme et al. (2023) did not find any statistically significant relation between measured broadband Sound Pressure Level and nominal power nor foundation type.

Based on the few available underwater noise studies of operating wind turbines, e. g. Tougaard et al. (2020) and Stöber & Thomsen (2021) tried to expand the current knowledge and to identify possible variables, in order to model an estimate for wind turbines growing in size. Tougaard et al. (2020) used a general linear model, whereas Stöber & Thomsen (2021) applied linear regressions to assess correlations between measured Sound Pressure Level, measurement distance, nominal power and wind speed. Both studies mainly concentrated on data from “smaller” and “older” OWTGs up to 6 MW with gearboxes, collected at different distances from the turbine and at different wind speeds. Furthermore, the measurement data are based on different measurement- and evaluation concepts, so that a direct data comparison was limited. These studies assume, that noise emissions from operating wind turbines increase significantly with respective nominal power, what contrasts with this study. Broadband level as well as level-determining, tonal and low-frequency components of systems (natural frequency of the rotor-drive system) resulted in decreasing Sound Pressure Levels in this study.

This discrepancy probably results from the constructive developments towards gearless and more modern systems (generators) as well as the increasing size and therefore weight of the systems including foundation structures, so that fewer vibration amplitudes are transmitted due to the larger masses. Moreover, system developers gained experience from at least a decade that led to development of larger, more efficient and low-maintenance systems. To keep wear and tear as low as possible, the minimization of (structural) vibrations resp. load changes on the plant and the coupling of rotor-drive system and transmission to the tower is a main objective of every turbine manufacturer. There are control techniques in development, in order to omit frequency excitation in the range of the natural frequency of the turbines resp. the tower and foundation by means of speed windows.

In contrast to Figure 22, Figure 31 also shows the differences in the Sound Pressure Levels $L_{05\ \&\ 90}$ between the operating states "turbines in operation at nominal power" (wind class "high") and "systems at a standstill" (wind class "low") of all operational noise measurements. The measurement data were sorted in ascending order according to the nominal power of the systems.

A difference > 0 dB shown in Figure 31 relates to an increase in the level with operation of the turbine with nominal power (wind class "high") compared to standstill of the system (wind class "low"). The differences for all SPL values ($L_{05,\ 50,\ 90}$) shown that become smaller with increasing nominal power of the systems are striking . Figure 31 also indicates that the Sound Pressure Levels in the operating state "turbines are at a standstill" are higher than in the "turbines operating at nominal power" state (negative differences) for some operational noise measurements. This may be related to significantly higher vessel activity in and around the wind farm in the wind class "low".

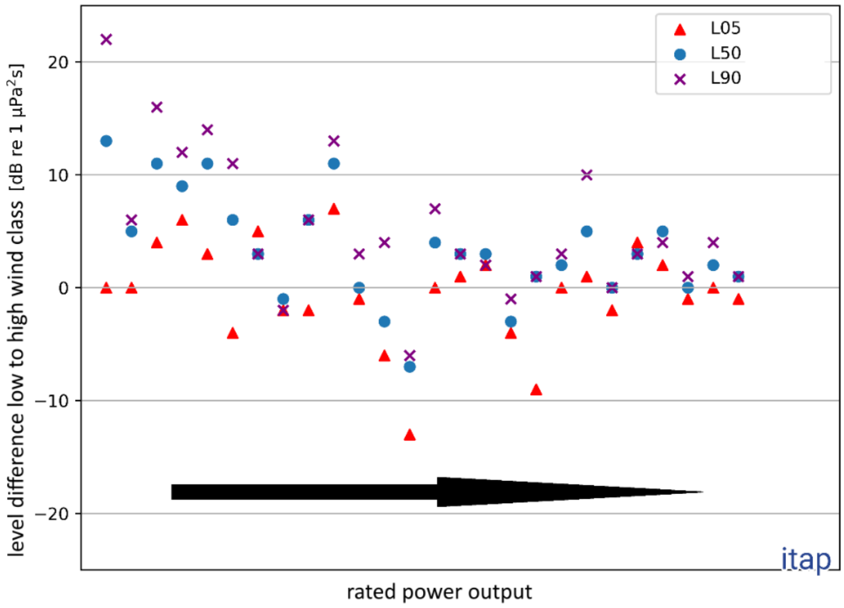


Figure 31: *differences in the Sound Pressure Levels ($L_{05,\ 50,\ 90}$) between the operating states "turbines in operation at nominal power" (wind class "high") and "systems at a standstill" (wind class "low") for all operational noise measurements. The measurement data were sorted in ascending order with increasing nominal power of the systems.*

Holme et al. (2023) demonstrated that the noise emissions modelled by Tougaard et al. (2020) on interpolations of identified and quantified influencing parameters on operational noise, overestimate the measured noise emissions of the three existing OWFs from the north-western zone 1 of the North Sea with turbines of the newer generation and nominal powers up to 6 MW broadband by up to 8 dB.

A validation of the influencing factors for a further modelling of existing and future wind farms derived from studies by Tougaard et al. (2020) and Stöber & Thomsen (2021) could not be performed either by this study or by the study by Holme et al. (2023).

In this report, only wind farms in the first years of operation were examined metrologically. However, experience with onshore wind farms shows that the noise emitted by a wind turbine in operation can change over longer operational periods of time. The reason for this is probably signs of wear and tear, especially in the translation of the gearbox from the rotor to the generator. Whether such signs of wear and tear also occur with direct drives (gearless systems) and how this influence emitted underwater noise, cannot currently be stated quantitatively or qualitatively neither from the available data nor from literature studies.

7.1.2 Noise outside the wind farm

This study shows that as expected, the tonal and low-frequency noise emissions from the OWTGs in operation decrease in amplitude with distance to the source. While these tonal components can still determine the level at a distance of approx. 100 m from the turbine, already in the centre of the wind farm and around the wind farm at distances of up to 1 km, a complete mixing with the permanently present ambient noise takes place, i. e. the signal-to-noise-ratio between the tonal components and the background noise is < 10 dB (usually even < 6 dB). At a measuring distance of 5 km, the tonal components can usually no longer be clearly measured, depending on the prevailing ambient noise.

Holme et al. (2023) also found that the noise input from wind turbines at a distance of 1 km and more from the wind farm boundary has no significant impact on the broadband Sound Pressure Level. The Sound Pressure Level inside and outside of the three wind farms considered in their study varied by up to 5 dB without the influence of the turbines (wind class "low", i. e. turbines are at a standstill), which indicates that the impact of vessel activities significantly dominates the ambient noise both inside and outside the wind farms. In the operation of the wind turbines in these three wind farms, the broadband Sound Pressure Level partly shows an increasing, falling or constant broadband level depending on distance. This result is consistent with the results of this study that the background noise outside the wind farms is largely dominated by other sound sources, most likely shipping noise. Thus, depending on the shipping traffic density around the wind farm, there can be an increasing, constant or decreasing broadband level resp. background noise level; see Figure 30.

7.1.3 Operational OWF-related service traffic

Periods, in which vessels were near the measurement positions (< 1 km), were excluded from the analysis for this study, in order to avoid unwanted effects from vessel noise. The study by Holme et al. (2023) reports the finding that a cruising vessel near a measurement position shows a rapid increase in the measured, broadband Sound Pressure Level and a rapid decrease over several minutes. This has also been documented in several other studies on shipping noise, especially in sea areas, where shipping traffic density is very low (e. g. Bellmann et al., 2017).

In the environmental report of the site development plan 2023 (BSH, 2023), vessel traffic in and around existing and planned wind farms was examined on the basis of traffic densities using AIS-recordings in 19 selected areas in the German EEZ of the German North Sea. For this purpose, AIS-recordings from June and December 2019 were examined with regard to the general vessel density and in particular the proportion of service traffic for wind farms. It became apparent that the average, non-OWF-related vessel traffic makes up 70% in summer and 80% in winter of the total vessel traffic in the considered areas of the North Sea (BSH, 2023). For individual sub-areas, in some cases, there may be significant fluctuations with regard to the above-mentioned averaged values. Basically, the higher the non-OWF-related vessel traffic, the less important the OWF-related service traffic is. The proportion of OWF-related service traffic in and around the existing wind farms is relevant in terms of the number of vessel movements (traffic density), but in all other cases, e. g. in TSA, the non-OWF-related vessel traffic predominates. It was also shown that the total number of service traffic per wind farm or converter platform, in contrast to e. g. the construction of the wind farm, is comparatively small and mostly smaller service vessels are used in and around the wind farms. There is also a strong seasonal effect; significantly more movements of the service vessels can be measured in summer than in winter. This coincides with the statements of this study (chapter 0), that the OWF-related service traffic is mostly focused on good weather and on the daytime. The Environmental Report (BSH, 2023) also documents the trend based on AIS-evaluations, that OWFs close to the coast are mostly designed for daily trips from the base port to the OWF, while OWFs off the coast tend to rely on residential units in and around the wind farms, so that the service traffic to coasts can be assessed as very low. Furthermore, the service vessels take a fixed route between the OWFs and the base ports. These statements are confirmed by the detailed investigations of two wind farms listed in Chapter 0.

A quantification of the influence of the service traffic on the total noise in and around the wind farms cannot be made on the basis of (averaged) vessel densities. For this, the noise input of each vessel type would have to be modelled, based on its size and travel speed, in order to be able to separate the sound components of the non-OWF-related and the OWF-related service traffic in a second step. The OWF-related service traffic consists of comparatively smaller vessels and travels at reduced speeds (< 8 knots) in the wind farms. Moreover, these service vessels are anchored at roadstead in and around the wind farms for the majority of the time, as already described in chapter 0. Therefore, a rather small contribution to the total noise from the OWF-related service traffic is to be expected.

In chapter 6.3, a first, rough attempt was made to quantify the theoretical influence of OWF-related service traffic within the wind farms. It turned out, that the noise input of the service traffic is considerably lower than that of the wind turbines in operation. Furthermore, the OWF-related service traffic is distributed over a very large area. Thus, it is possible to identify temporally and spatially limited areas, in which service traffic could dominate the background noise level, but large-scale and permanent noise pollution cannot be assumed.

For the above reasons, it can be expected that the share of OWF-related service vessels in the total noise is low to negligible, at least in the vicinity of traffic separation areas or other highly frequented shipping routes.

7.2 Background noise

Due to limited measurement experiences with the recording of permanent background noise, in the early days, background noise measurements were carried out in the project area up to two years before the start of construction. Because of changes in the external framework conditions, these measurements often show considerable differences to the later operational noise measurements, so that a direct comparison is not possible resp. not trivial. For example, in some cases, background noise measurements were carried out in or around the planned wind farm before the area was closed to non-OWF-related shipping traffic. A few years later the background level (wind turbines are at standstill) of the operational noise measurements was significantly quieter in this area in isolated cases than level values previously collected from background noise measurements. Moreover, background- and operational noise measurements were partly carried out in the same sea area, but not at identical resp. comparable measurement positions. This partly led to the fact that the impact of non-OWF-related vessel noise from e. g. nearby traffic separation areas in the vicinity of the measurement position showed a considerable difference.

Additionally, in past measurements, the focus was initially only on the direct noise input of the wind turbines, so that the influence of e. g. vessel noise often was not considered, and this sometimes leads to poor comparability of the different measurements.

Another difficulty with former background noise measurements is due to the fact that other wind farms in the immediate vicinity were already in operation and therefore the influence of these neighbouring turbines had to be evaluated as background noise for the new project. By considering each individual construction project in isolation, no information was available whether and, if so, which unusual noise inputs from the neighbouring wind farms were present during the measurements, e. g. due to repair work, short-term campaigns with increased OWF-related vessel deployment or, if applicable, also partial shutdowns of individual wind turbines.

All these experiences led to the fact that background (ambient) and operational noise measurements were often carried out as cluster investigations in the following years. This could, for example, be a combination of simultaneous operational noise measurements in wind farm A and background noise measurements in wind farm B, but also a combination of operational noise measurements in several neighbouring wind farms. The advantage of such cluster-investigations is, that the operating conditions during the measurements of all neighbouring wind farms were available for the evaluation of the underwater noise measurements.

Moreover, with the construction of a wind farm in the north-western zone 1 of the German EEZ in the North Sea in 2016, the performance of background noise measurements was optimized by conducting measurements only maximum 2 weeks before the start of construction (impact pile-driving) until approx. 4 weeks after the start of construction. This approach has two advantages:

(i) the project area is already closed or restricted to non-OWF-related shipping traffic and

(ii) an additional evaluation of the noise input of the construction vessels used prior to and directly at the start of construction can be carried out.

It emerges from this analysis that the vessel density and also the measured background (ambient) noise within the wind farm increased considerably in some cases due to the construction activities within the construction area, as can also be seen in the environmental report of the area development plan 2023 (BSH, 2023).

The measurement concept was also optimized by using identical resp. comparable measurement positions background- and operational noise measurements. Where possible, this is ensured by using fixed POD-stations for long-term monitoring in and around the project areas.

A further aspect i, that especially for sea areas in the vicinity of larger traffic separation areas, the time intervals between the background- and operational noise measurements should be as short as possible, since the vessel density on these traffic routes can change dynamically due to the economic situation, so that a reliable comparison may only be possible to a limited extent. This often applies in particular to measurement position(s) outside the (planned) wind farm.

Modifications in the implementation of the background noise measurements with a measurement period shortly before the start of construction in the shut-off wind farm, at comparable measurement positions and over a period of at least six weeks have proven successful in recent years.

7.3 Biological effects of operational noise

Based on the results of this study and also data from literature (e. g. BSH, 2023; Tougaard et al., 2020; Stöber & Thomsen, 2021), the risk of killing or injuring marine mammals due to temporal or permanent threshold shifts (TTS and PTS) (Southall et al., 2019) caused by underwater noise inputs from operating OWTGs can be excluded.

The BMU noise mitigation concept (2013) indicates a possible avoidance- or disturbance effect on harbour porpoises starting at a broadband total noise level of impulsive noise inputs, such as pile-driving noise, of approx. 140 dB. This value was determined by underwater noise measurement data from impact pile-driving in combination with measurements of behavioural reactions in harbour porpoises. Slightly higher-sound level values eliciting a behavioural response were determined by further studies in subsequent years (Brandt et al., 2016; Rose et al., 2019). Even within the considered wind farms at a distance of 100 m from individual OWTGs, sound pressure levels of only up to 130 dB were measured. Moreover, the noise inputs from operating wind turbines were in the very low frequency range (< 160 Hz). Threshold values (Level of Onset of Biologically adverse Effects - "LOBE") for certain species and waters are still subject to discussion in the EC working group TG Noise. On a national and regional level coordination is still needed with regard to specific sound thresholds to be applied for continuous noise. Therefore, further comparison with threshold- or noise mitigation values cannot yet be made at this point.

Figure 32 shows exemplary measured 1/3-octave spectra at a distance of three selected wind turbines in operation (turbines with nominal power of 6.0 resp. 6.15 MW from two different manufacturers with and without gearbox; from the northwestern zone of the North Sea at approx. 30 m water depth) in comparison to measured (resting) hearing thresholds of various harbour porpoise individuals (Kastelein et al., 2010 & 2017). The wind farms are located in area N2 and N3 of the North Sea at water depths between 25 and 35 m. North and south of the wind farms are the TSAs GBWA and Terschelling. Thus, the pre-exposure due to non-OWF-related vessel noise is relatively high.

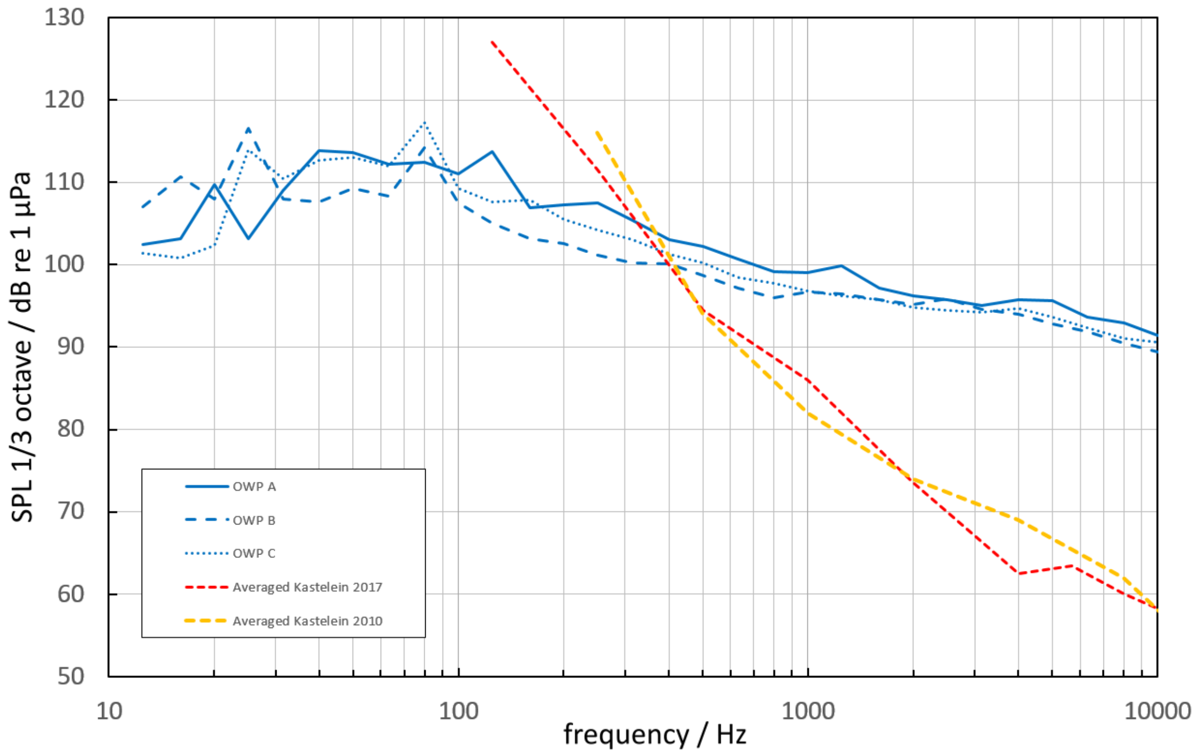


Figure 32: *Measured hearing thresholds of harbour porpoises (Kastelein et al., 2010 & 2017) compared to operational noise, measured at 100 m distance from three selected wind turbines (turbines with nominal power of 6.0 resp. 6.15 MW from two different manufacturers with and without gearbox, wind class „high" from the northwestern zone of the North Sea with water depths around 30 m).*

The hearing thresholds shown in Figure 32 are based on single individuals of harbour porpoises and show an interindividual variance in hearing ability. It is also known that the choice of measurement method and the type of stimuli can have an influence on the determination of hearing thresholds (e. g. Betke, 1991). A direct comparison of measured operating noise in 1/3-octave bands with the measured absolute thresholds of hearing (narrow-band sine sweeps) is not possible in terms of energy. However, Figure 32 illustrates the frequency-dependent hearing ability of harbour porpoises in general. Accordingly, the tonal and low-frequency components (< 160 Hz) of modern wind turbines with and without gearboxes in operation at a measurement distance of approx. 100 m are in the range of or even significantly below the hearing ability of harbour porpoises.

From a psychoacoustic point of view, it can be assumed, that these low-frequency and tonal components probably cannot be perceived by harbour porpoises. In the present example, from a frequency of approx. 500 Hz, the measured Sound Pressure Level is above the absolute hearing threshold of harbour porpoises. In this frequency range, however, no resp. hardly any noise is introduced into the water by operating OWTGs; see chapter 6.1.2. This Sound Pressure Level is generally to be equated with the broadband ambient noise typical for such weather conditions (wind class "high"), which is mostly caused by abiotic noise inputs, such as wind and wave action, and by anthropogenic vessel noise from neighbouring traffic separation areas.

In contrast, other species, such as seals, harbour seals and various fish species, can partly perceive low-frequency sounds (Terhune, 1988, Popper et al., 2019). As an example, the resting hearing thresholds of harbour seals from literature (Kastelein et al., 2009, Reichmuth & Holt, 2013) are compared with the operational noise levels in Figure 33.

Here, too, the hearing thresholds are based on only a few individuals and different measurement methods resp. stimuli, which could explain the interindividual differences. An energetic direct comparison with the operational noise data is also not possible here; however, the noise inputs of the wind turbines are clearly above the hearing thresholds shown, so that a general audibility can be assumed.

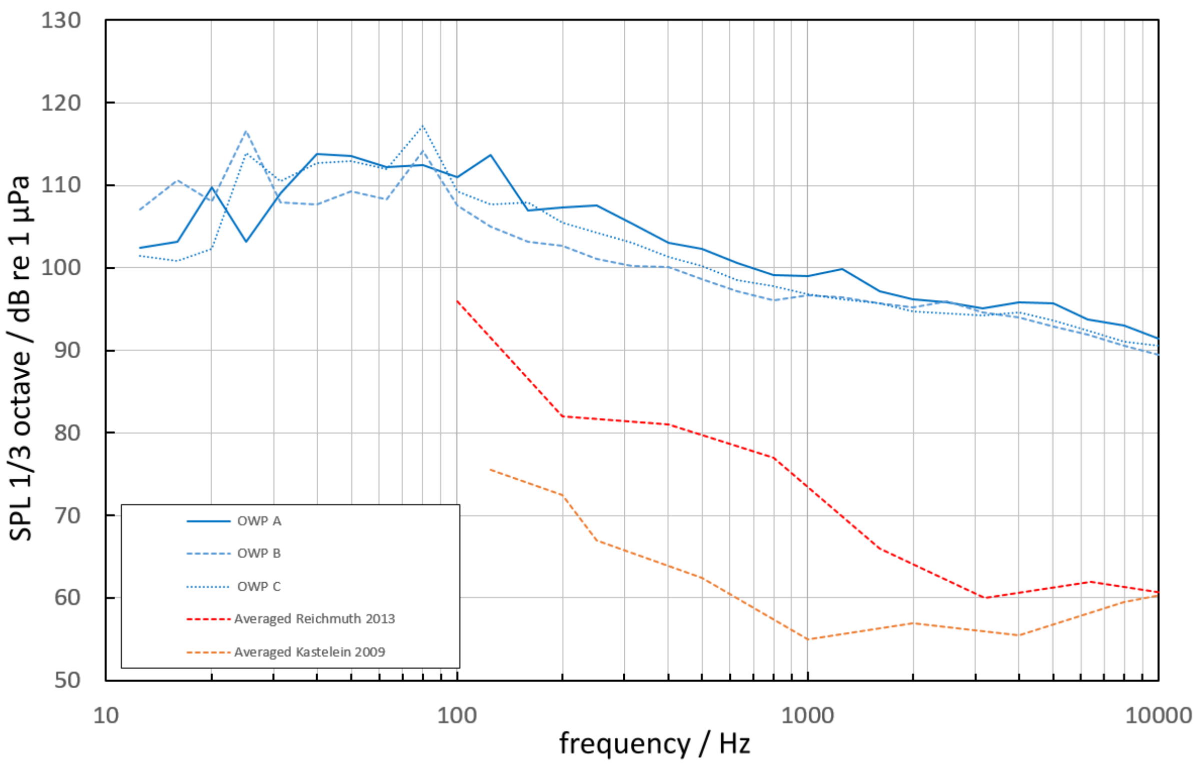


Figure 33: Measured absolute hearing thresholds of harbour seals and grey seals from the literature in comparison to the operating noise, measured at a distance of 100 m from selected wind turbines (turbines with nominal power of 6.0 resp. 6.15 MW from two different manufacturers with and without gearbox, wind class "high).

Stöber and Thomsen (2021) predict a disturbance effect on marine mammals up to a distance of 6.3 km for a single 10 MW OWTG not yet in operation. This distance is reduced to 1.4 km, if the wind turbine is designed as a gearless turbine. These disturbance radii were predicted by interpolating existing measurement data from wind turbines up to 6 MW. To what extent this benchmark can be confirmed by the present study based on Figure 32 and Figure 33 as well as the identified influencing parameters on operational noise (chapter 6.1) remains open and requires further investigation. Moreover, this study, Table 6, shows, that gearless turbines of the latest generation currently tend to generate a lower-frequency, tonal component (natural frequencies ≤ 80 Hz) with lower amplitudes than OWTGs with gearboxes. Based on Figure 32, the probability of audibility by harbour porpoises is thus further significantly reduced due to the lower tonal component and the lower amplitude.

From a psychoacoustic point of view, a disturbance or avoidance effect by noise below the hearing threshold can generally be excluded in humans and land mammals. For birds and terrestrial mammals in particular, it has been scientifically investigated that even audible or noise which might cause TTS does not necessarily lead to avoidance of an area, if this results in an advantage, such as increased food intake or higher reproductive success (Reck, 2001). Such cumulative effects have not yet been extensively studied for marine mammals.

7.4 Cumulative effects of operating noise

For a comprehensive evaluation of possible ecological impacts of operational noise (status quo or even future wind farm scenarios), a modelling of the continuous noise of operational noise and also ambient noise (mainly vessel noise and abiotic noise input from wind and waves) is indispensable. Based on the results of this study, the main parameters influencing operational noise can though be determined qualitatively, but a statistically valid quantification is still subject to high uncertainties. From this cross-project evaluation, at least a tendency can be deduced that the noise emissions from operating OWTGs are only of a low-frequency nature (a maximum of a few hundred hertz) and only determine the level in the respective wind farm at very short distances from the respective wind turbines. Furthermore, an increase in noise emissions into the water due to higher nominal power of the OWTGs is not to be expected.

Another influencing parameter in the impact assessment of operational noise, which has received little attention so far, is the already existing ambient background noise. Measurements from offshore wind farms in the German EEZ of the North and Baltic Sea show that there is often an overlapping of low-frequency operating noise caused by wind turbines and the permanent ambient noise at a distance of 1 to 5 km from wind farms, depending on the density of non-OWF-related shipping traffic. Through the existing research projects BIAS and JOMOPANS, at least the vessel-based ambient noise can be estimated for the entire North Sea and Baltic Sea on the basis of existing vessel densities including travel speeds and vessel sizes through modelling.

For the impact assessment of operational noise, on the one hand, a cumulative consideration of noise inputs from wind turbines, OWF-related service traffic and non-OWF-related shipping traffic, as well as noise inputs from abiotic effects, such as wind and wave action, at least at high wind speeds, must be carried out. On the other hand, the hearing ability of the observed species must also be considered, e. g. by determining sensation level values suitable for hearing by means of frequency weighting (e. g. Southall et al., 2019; Kastelein et al., 2015), since disturbance- and avoidance effects due to underwater noise are involved.

The rough energetic (broadband) estimation of noise inputs from OWF-related service traffic and wind turbines presented in chapter 6.3 is therefore not suitable for the ecological impact of operational noise. Moreover, also other aspects, such as food availability, reproductive success, water quality, etc. may have to be considered for a comprehensive assessment.

It can be assumed that in areas with high, non-OWF-related vessel densities, a complete overlapping with the permanent ambient noise will already take place at short distances from the wind farms. However, in sea areas with very low vessel densities, the noise input from operating wind turbines can certainly be measured also outside wind farms and may have a significant contribution to the broadband Sound Pressure Level.

One example is a wind farm in the protected special area of conservation "Sylter Außenriff" (eastern zone 1 of the North Sea). Measurements of background noise from 2012 indicate this sea area as a "very quiet" one for the German EEZ of the North Sea. The averaged Sound Pressure Level L_{eq} over several weeks is 101 dB for the wind class "low" and 108 dB for the other two wind classes. The L_{05}-value of all 5 second intervals vary between 114 and 120 dB, regardless of the wind class, and in most cases is due to one of the few vessel passes in the immediate vicinity of the underwater noise measurement position. The ambient noise measurements were carried out before the wind farm was closed to non-OWF-related shipping traffic. The operational noise measurements from 2016 show an increase of the L_{eq} of 10 to 13 dB in the wind class "high". However, this level increase is not clearly attributable to low-frequency noise inputs from the OWTGs but shows a general increase in the low-frequency range below approx. 200 Hz. Even at a distance of 5 km, 5 to 7 dB higher Sound Pressure Levels were measured. However, the reason for these significant level increases could not yet be clearly identified due to the lack of AIS-recordings during the background- and operational noise measurements; thus, its increase due to OWF related service traffic in and around the wind farm cannot be excluded. However, it also cannot be excluded that the natural, low-frequency noise components caused by wind and waves have increased due to the existing foundation structures.

This example from the special area of conservation "Sylter Außenriff" shows that a possible increase in Sound Pressure Level cannot be excluded though due to the operation of a wind farm in a very quiet sea area, but this level increase only takes place in the low-frequency range up to a few hundred hertz, so that an audibility for some species cannot be assumed. Therefore, an impact assessment not only has to consider the cumulative noise inputs, but also the hearing ability of the species.

One issue, that has not yet been considered, is the frequency range of the existing underwater noise measurements. So far, underwater noise measurements have been carried out up to 20 kHz. The noise input from wind turbines and also vessel movements generally decrease significantly with increasing frequency from several kilohertz. However, existing underwater sensors, such as sonar systems or sonars on vessels, also carry sound energy into the water in the range of 40 to 120 kHz, directed towards the seabed. Sound propagation in the horizontal direction cannot be completely excluded. Harbour porpoises, for example, are particularly sensitive in this frequency range and a part of their echolocation and communication also takes place in this frequency range. Due to the lack of underwater noise measurements in this high-frequency range, this very high-frequency noise input into the water by vessels has not yet been considered with regard to this issue. It can be assumed that the spectrally very narrowband and pulsed inputs by these technical devices will not lead to an increase in the (overall) Sound Pressure Level, but due to the hearing ability of porpoises, among others, these frequencies are particularly perceived by animals and could trigger a disturbance- or avoidance effect. Thus, from a psychoacoustic point of view, it is recommended to carry out measurements up to the upper cut-off frequency of harbour porpoises (< 200 kHz) in and around the wind farms. Thus, in several studies on construction noise (impulsive pile-driving noise), an avoidance effect around the construction site was observed several hours before the actual deterrence measure using acoustic devices, such as pingers and seal scarers (e. g. Brandt et al., 2016; Rose et al., 2019). It is known, that prior to the actual pile-driving of foundation structures, vessel movements around the construction site increase considerably,

e. g. in order to deploy the Big Bubble Curtain noise abatement system on the seabed, including measuring the position of the nozzle hoses on the seabed using side-scan sonars or similar, and to deploy the measurement sensors required for the efficiency control.

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9. Annex: Levels at the 100 m positions of all OWTGs

9.1 Sound Pressure Level L_{05}

No.	Foundation	Nominal power, MW	gearbox	L_{5}, „WC low“ *1 broadband, dB re 1 µPa	L_{5}, “WC high“ *1 broadband, dB re 1 µPa	Differ-ence, dB re 1 µPa	Measuring distance, m
1	Monopile	3.6	yes	126	126	0	
2	Monopile	7	no	121	125	4	
3	Monopile	6	no	121	121	0	
4	Tripile	5	yes	142 *(148)*	129 *(135)*	-13	250
5	Monopile	4	yes	132	137	5	
6	SB Jacket			135	133	-2	
7	Monopile	8	yes	125	124	-1	
8	SB Jacket			127	127	0	
9	Monopile	3.6	yes	121	121	0	
10	Monopile	3.6	yes	116 *(121)*	120 *(125)*	4	*200*
11	Monopile	8.4	yes	124	123	-1	
12	Jacket	3.6	yes	122	128	6	
13	Monopile	2.3	yes				
14	Monopile	7	no	123 *(130)*	125 *(132)*	2	300
15	Tripod	5	yes	123 *(127)*	130 *(134)*	7	180
16	Monopile	6	no	120	121	1	
17	Monopile	6	no	120	122	2	
18	Monopile	3.6	yes	124	127	3	
19	Monopile	6	no	131	127	-4	
20	Monopile	6.2	yes	122	122	0	
21	Jacket	6.2	yes	121	122	1	
i22	Monopile	3.6	yes	132	128	-4	
23	Monopile	4	no	119 *(125)*	117 *(123)*	-2	250
24	Tripod	5	yes	130	129	-1	
25	Monopile	6.3	yes	128	126	-2	
26	Monopile	6	no	131 *(140)*	122 *(131)*	-9	400
27	Jacket	5.1	yes	124	118	-6	

*1 WC low/WC high – indicates the wind classes low (turbines in standstill) and high (turbines in operation at nominal power)

9.2 Sound Pressure Level L_{50}

No.	Founda-tion	Nominal power, MW	gearbox	$L_{5,\text{ „WC low“}}$ [*1] broadband, dB re 1 µPa	$L_{5,\text{“WC high“}}$ [*1] broadband, dB re 1 µPa	Difference	Measuring distance, m
1	Monopile	3.6	yes	111	124	13	
2	Monopile	7	no	117	120	3	
3	Monopile	6	no	111	115	4	
4	Tripile	5	yes	*121 (127)*	121 *(127)*	*0*	250
5	Monopile	4	yes	125	128	3	
6	SB Jacket			132	131	-1	
7	Monopile	8	yes	119	119	0	
8	SB Jacket			121	123	2	
9	Monopile	3.6	yes	110	115	5	
10	Monopile	3.6	yes	107 *(112)*	118 *(123)*	11	*200*
11	Monopile	8.4	yes	119	120	1	
12	Jacket	3.6	yes	113	122	9	
13	Monopile	2.3	yes				
14	Monopile	7	no	117 *(124)*	122 *(129)*	5	*300*
15	Tripod	5	yes	116 *(120)*	127 *(131)*	11	*180*
16	Monopile	6	no	114	117	3	
17	Monopile	6	no	114	117	3	
18	Monopile	3.6	yes	111	122	11	
19	Monopile	6	no	123	120	-3	
20	Monopile	6.2	yes	116	118	2	
21	Jacket	6.2	yes	112	117	5	
22	Monopile	3.6	yes	118	124	6	
23	Monopile	4	no	108 *(114)*	114 *(120)*	6	250
24	Tripod	5	yes	122	122	0	
25	Monopile	6.3	yes	121	121	0	
26	Monopile	6	no	118 *(127)*	119 *(128)*	1	400
27	Jacket	5.1	yes	115	112	-3	

[*1] WC low/WC high – indicates the wind classes low (turbines in standstill) and high (turbines in operation at nominal power)

9.3 Sound Pressure Level L_{90}

No.	Founda-tion	Nominal power, MW	gearbox	$L_{5,\ „WC\ low"}$ *1 broadband, dB re 1 µPa	$L_{5,\ "WC\ high"}$ *1 broadband, dB re 1 µPa	Difference	Measuring distance, m
1	Monopile	3.6	yes	101	123	22	
2	Monopile	7	no	115	118	3	
3	Monopile	6	no	105	112	7	
4	Tripile	5	yes	123 *(129)*	117 *(123)*	-6	250
5	Monopile	4	yes	122	125	3	
6	SB Jacket			127	125	-2	
7	Monopile	8	yes	116	117	1	
8	SB Jacket			117	121	4	
9	Monopile	3.6	yes	97	103	6	
10	Monopile	3.6	yes	101 *(106)*	117 *(122)*	16	*200*
11	Monopile	8.4	yes	117	118	1	
12	Jacket	3.6	yes	108	120	12	
13	Monopile	2.3	yes				
14	Monopile	7	no	114 *(121)*	118 *(125)*	4	*300*
15	Tripod	5	yes	112 *(116)*	125 *(129)*	13	*180*
16	Monopile	6	no	110	113	3	
17	Monopile	6	no	110	112	2	
18	Monopile	3.6	yes	106	120	14	
19	Monopile	6	no	118	117	-1	
20	Monopile	6.2	yes	113	116	3	
21	Jacket	6.2	yes	105	115	10	
22	Monopile	3.6	yes	111	122	11	
23	Monopile	4	no	103 *(109)*	109 *(115)*	6	250
24	Tripod	5	yes	116	119	3	
25	Monopile	6.3	yes	116	116	0	
26	Monopile	6	no	115 *(124)*	116 *(125)*	1	400
27	Jacket	5.1	yes	105	109	4	

*1 WC low/WC high – indicates the wind classes low (turbines in standstill) and high (turbines in operation at nominal power)

10. List of figures

11. List of tables