Offshore Wind Farms
Prediction of Underwater Sound

Minimum Requirements on Documentation
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The authors assume responsibility for the content of this publication.
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1 Preliminary remarks

The BSH is responsible for the approval of offshore wind farms in the German Exclusive Economic Zone (EEZ) in accordance with the Marine Facilities Ordinance. As part of approval procedures for offshore wind turbines, the extent to which sound effects caused by the construction, operation and decommissioning of installations represent a possible threat to the marine environment is to be investigated.

According to the Environmental Impact Assessment Act, there is an obligation to carry out an Environmental Impact Assessment (EIA) for offshore wind farms. As part of this application, an Environmental Impact Assessment (EIA) is prepared by the applicant for this purpose in which, inter alia, the potential effects of the noise input on the marine environment are described and evaluated.

Incidental provision number 14 of the BSH approvals regularly schedules measures for the detection and reduction of the underwater noise. Thus, forecasts are to be created as part of the baseline survey and measurements of underwater noise are to be carried out and documented during sound-intensive work at predetermined distances. Damage-preventing and noise reduction measures are to be assessed via forecasts and investigated during implementation to check their efficiency by means of measurements. The measurements are to be documented and the results of the approval authority reported.

Currently however, there is a worldwide lack of validated experience with regard to underwater noise recording from the construction and operation of offshore wind farms. This is not least due to the lack of standardised measurement methods and validated distribution models.

The temporal and spatial extent of the sound investigations is described in the Standard “Investigation of the Impacts of Offshore Wind Turbines on the Marine Environment” (StUK4, BSH 2013). Prior to the construction phase, forecasts and measurements are to be carried out for this purpose and carried out during the construction phase and in the operational phase of underwater noise measurements. The first findings from the sound tests in the test site “alpha ventus” (itap 2011) and noise measurements in offshore research platforms and masts provided the basis to revise the existing measurement methods in accordance with StUK and to summarise it in a detailed measuring instruction. The measurement instruction is part of the StUK.

The following specification describes the general procedure for the documentation of the forecasts of underwater sound associated with the construction and operation of offshore wind farms. The studies listed here below cover all four phases of the approval together with the requested technical reviews and enforcement procedures of offshore wind farms in the German EEZ:

This specification describes the minimum requirements on documentation for forecasts. Measuring-specific investigations are to be carried out in the four project phases

a) Baseline survey - pre-investigation
b) Construction phase
c) Operation phase
d) Decommissioning phase.

The water noise immissions expected in the water by the construction and operation of offshore wind farms are to be determined by calculated, and, where applicable, contrasted with the guidelines.
This document describes the minimum documentation of forecasts. Reasonable project-specific deviations to the procedure described below can be agreed upon with the approval authority.

2 Definitions and symbols

2.1 Terms

The physical sizes used in this measuring specification are listed in table 1 together with their symbol and SI unit.

Table 1. Overview of the sizes and symbols used.

<table>
<thead>
<tr>
<th>Size</th>
<th>Symbol</th>
<th>SI unit</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sound pressure</td>
<td>(p)</td>
<td>Pa</td>
<td></td>
</tr>
<tr>
<td>Sound velocity</td>
<td>(c)</td>
<td>m/s</td>
<td></td>
</tr>
<tr>
<td>Sound power</td>
<td>(P)</td>
<td>W</td>
<td></td>
</tr>
<tr>
<td>Sound intensity</td>
<td>(I)</td>
<td>W/m²</td>
<td></td>
</tr>
<tr>
<td>Sound pressure level</td>
<td>(L_p)</td>
<td></td>
<td>specified in dB</td>
</tr>
<tr>
<td>Sound power level</td>
<td>(L_P), (L_W)</td>
<td></td>
<td>specified in dB</td>
</tr>
</tbody>
</table>

A comprehensive overview of additional levels including their definition is described in section 2.2.

2.1.1 Individual sound events

A sound event is a physical process which is determined by acoustic parameters (sound field sizes). The term indicates the physical side of the origin of the sound. The perception of sound is normally denoted by the term auditory event.

Individual sound events can be found in the construction phase of offshore wind farms, in particular when using impact hammers of interest.

2.2 Levels

The following defined levels apply for this measuring specification:

- Equivalent continuous sound level \(L_{eq}\) for continuous sound signals,
- Individual event level \(L_E\) for impulsive sound signals,
- Peak sound pressure levels \(L_{peak}\) for impulsive sound signals,

whereby the first is relevant for the operating phase and the others for the construction phase.

The levels used are based on the definitions of ISO 1996-1 (2003), but are not identical to them. In this way, the definition of \(L_{eq}\) is made without frequency evaluation. In accordance with ISO 1996-1, the determination of the peak sound pressure level should be carried out in line with IEC 61 672, the definition in this measuring specification is based on signal amplitude.
The application of these levels was investigated in a study by Elmer et al. (2007). No frequency or time assessments are predetermined for stationary and impulsive signals at this time.

**Equivalent continuous sound level** \( L_{eq} \) **(or average sound level)** is defined by

\[
L_{eq} = 10 \log_{10} \left( \frac{1}{T} \int_0^T p(t)^2 \, dt \right),
\]

whereby \( p(t) \) represents sound pressure, \( p_0 \) reference sound pressure 1 \( \mu \)Pa and \( T \) the average time\(^1\).

**Individual event level (also: sound exposure level, SEL)**

The individual event level \( L_E \)\(^2\) is used for the characterisation of impulsive sounds:

\[
L_E = 10 \log_{10} \frac{E}{E_0}
\]

with sound exposure \( E \)

\[
E = \int_0^T p(t)^2 \, dt
\]

and reference size

\[
E_0 = p_0^2 \cdot T_0
\]

whereby \( p_0 \) represents the reference sound pressure 1 \( \mu \)Pa, \( T_0 \) the reference time duration 1s, and \( T \) the average time. The average time corresponds to the duration \( T_E \) of the event when evaluating individual events.

**Peak sound pressure levels** \( L_{peak} \)

This size is a mass for sound pressure levels without time or frequency assessment or averaging

\[
L_{peak} = 20 \cdot \log_{10} \left( \frac{\rho_{peak}}{p_0} \right),
\]

whereby \( p_0 \) represents the reference sound pressure 1 \( \mu \)Pa and \( \rho_{peak} \) represents the maximum established positive or negative sound pressure \( p_{peak} \)

\[
p_{peak} = \max (|p(t)|).
\]

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\(^1\) In accordance with ISO 1996-1, the equivalent continuous sound level is also denoted by the index \( T L_{eqT} \).

\(^2\) It is also common to name the individual event level \( L_E \) SEL (sound exposure level).
2.3 Forecast terms

2.3.1 Source Level SL

The source level SL symbolises the sound power of a source of sound. It is often designated as sound pressure level in literature which is ideally "measured" at 1 m distance from an isotropic radiator.

Remarks:

This value is a virtual size which cannot be metrologically determined at 1 m distance. There are, in essence, three reasons for this. First, a source is spatially extended and cannot be accepted as a point source at 1 m distance, secondly, at 1 m distance the near-field is not separable from the radiating capable far field, thirdly, a spatially extended source usually exhibits directional characteristics, and thus a sound intensity would have to be considered as a basis or the surface of the sphere site-related sound levels would have to be assigned.

2.3.2 Transmission Loss TL

Transition loss consists of the geometrical acceptance, i.e. the distribution of sound energy on a large enveloping surface, a dissipative contribution (internal friction, relaxation properties, sea state-caused damping, edaphic damping etc.) and so-called anomalies due to reflections and the dispersion of soil and surface together.

2.3.3 Sound pressure level at the place of immission – Received Level RL

Sound pressure which is recorded at a measuring place. This can be composed of several sources or contributions from various reflections.

2.3.4 Shallow water sound distribution

Shallow water areas are areas with a water depth of < 200 m. Thus, the areas of the North and Baltic Sea with water depths of about 50 m can be described as shallow water areas. Sound distribution is characterised by frequent reflections on the soil and surface, depending on the source.

2.4 Other accompanying parameters

It develops a so-called sound channel whose distribution conditions are essentially described by the boundary conditions (limitation of surface and soil, soil properties) and thus impedances on interfaces (impedance discontinuities at edge surfaces and bubbles in the water). Stratification effects and thus a clear gradient of the sound velocity profile can also lead to a significant change in the sound distribution.

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3 Conceptualisation from Urban (2002), also see Ulrick (1996).
3 General information on forecasts in each project phase

3.1 Description of the forecast model and the input data
The forecast quality essentially depends on the accuracy of the input data and of the model used. It is therefore essential to describe the origin and quality of source data and of the distribution model. A few points are named below.

3.1.1 Source level
The following questions must be answered:
- How is the source level defined?
- How was the source level determined?
- Was experimental data used? In which frequency range is this representative (measurement environment)?
- Did data have to be scaled, e.g. with pile driving operations due to the altered geometry of the driving pile, condition of the soil etc.? How was this carried out? Grounds for the procedure.
- Discussion of the acceptances under consideration of near-field, far-field, and boundary conditions, for example.

3.1.2 Drift/dispersion model
To calculate the distribution of sound, different models need to be considered, including ray tracing models, fashion theoretical models, and empirical models.
In the report, the following issues and questions need to be described and clarified.
- Which distribution model was used? Discussion of acceptances.
- How was the bathymetric data used? The impact must be assessed or evaluated if necessary.
- Which material parameters were used for the forecast?
- Was experimental data used, e.g. for the determination of the loss of distribution with empirical models? In which frequency range is this representative (measurement environment)?
- In numerical models, the validity ranges and the input data used should be identified. Furthermore, the average transmission loss from the place of emission to the place of immission is to be identified for example, a distance of 750 m. In numerical models (2D/3D, 3D), the averaging provision shall indicate the water level.

3.2 General parameters

3.2.1 Places of immission
For forecasts, we must consider that there should be comparability with measurements which are carried out at a later time. The following applies:
- In set distances, see 4.3 and 5.3, immissions levels are to be determined.
The values of the entire water column are to be taken into consideration (basis of assessment).

When compared with measuring data it must be taken into account that, for logistical reasons, hydrophones are to be positioned 2 to 3 m above the seabed with measurements.

3.2.2 Forecast levels and investigation parameters

Acoustic forecast levels:

- Sound pressure level as well as individual event level.

The following accompanying parameters are to be considered or discussed as part of the forecast:

- Influence of wind, wave height, breaking waves, current
- Influence of water depth
- Influence of bathymetry
- Influence of sound velocity profile
- Influence of acoustic soil properties.

3.2.3 Frequency range investigated

- In third-octave bands from 10 Hz to 20 kHz.

Remarks:
The frequency range can be reduced upon consultation.

4 Construction phase

4.1 Scope of forecast

- Forecasts on the sound pressure level in the environment in the vicinity of the site are to be carried out for all noise-intensive construction works (e.g. pile driving operations).
- Every type of foundation as well as every method of construction which are used in a wind farm have to be assessed. Should various soil conditions be present, they are also to be assessed.
- The forecast can assume a fictitious centre of the wind farm. This is assuming that only the same types of foundations are built and the environmental parameters are homogeneous.
- If the wind farm lies in the immediate vicinity of a nature conservation site, the forecast for installations at different distances to the protected area is to be carried out.
- If plans are made for two or more pile driving locations to operate in parallel within one farm, this is to be taken into consideration in the forecast.
- If additional farms are situated within 30 km of the surrounding area, these are to be taken into consideration.
• The efficiency of all measures used to reduce noise emissions (e.g. bubble curtain, hydro sound damper, cofferdam) is to be presented in the forecast. The efficiency of the measures is to be described with experimental or theoretical justification.

• The results from the sound measurements in the construction phase of adjacent wind farms already constructed are to be considered in the forecast.

4.2 Accompanying parameters
The influence of the following project-specific parameters is to be described in the forecast.

• Pile driving energy
• Number of driving impacts
• Frequency of impacts.

Remarks:
Pile driving energy is a parameter which drives the noise power of a source, for example. The number of driving impacts and the frequency of impacts are not necessary at this time, as the individual impact is assessed as decisive. Should future cumulative assessments on noise immissions be implemented, they are to be taken into consideration in the forecast.

4.3 In the forecast of places of immission to be considered
The places of immission are set at distances of 750 m and 5,000 m from the foundation structure and in the closest nature conservation site, provided this is distanced further than 5 km from the project site.

4.4 Evaluation and presentation
The evaluation should be carried out for pile driving operations with and without noise mitigation measures under consideration of the parameters in section 3.2.

The results for $L_E$ are to be presented in third-octaves at set places of immission. The total level $L_E$ at the places of immission is to be contrasted with the limit values required (see section 4.5). In addition, the distribution of sound is to be presented in graph form up to 110 dB (SEL), depending on distance, for example, by isophones in 10 dB inclines.

4.5 Assessment
The approvals of the BSH for offshore wind farms have introduced standard values since 2003 and limiting values since 2008 in terms of noise input by pile driving operations.

The valid threshold values are found, for example, in the "Borkum West II offshore wind farm approval", incidental provision 14, page 15:

"With the creation and installation of the installations, the state-of-the-art operational method is to be used which is as quiet as possible in line with the circumstances encountered. A suitable noise protection concept must therefore ensure that the noise emission (sound exposure pressure SEL) does not exceed the value of 160 dB (re 1 μPa) at a distance of 750 m."

Exceeding the assessment level is not permitted.
Approximate statements concerning peak levels should also be made. For example, comparable impulsive sources of noise can be disputed based on experience.

5 Forecasts for the operation of the entire wind farm

5.1 Scope of forecast
- As a minimum, three power ranges, "low", "medium" and "rated output" should forecast the sound pressure level.
- The exact setting of the power range is carried out in agreement with the approval authority.
- The sound forecast should also consider current measurement results from wind farms already in operation, such as the "alpha ventus" test field.

5.2 Accompanying parameters
The influence of the following project-specific parameters is to be described in the forecast.
- Type: gears, generators, ventilators, etc.
- Performance and load data of the installations.

5.3 Places of immission
In consideration of the operation of the wind farms, all installations should be considered cumulatively:
- The places of immission are to be determined at a distance of about 100 m from the source of sound, i.e. at the edge of the wind farm.
- In addition, forecasts are to be carried out outside the wind farm at a distance of 1,000 m and for the nearest nature conservation site, provided this is not distanced more than 5 km from the project area. Alternatively, should there be no nature conservation sites in the vicinity, a forecast is to be carried out at a distance of 5 km from the wind farm.
- The exact places of immission are to be agreed upon specific to each project and installation with the approval authority.

5.4 Evaluation and presentation
The source of wind turbine noise at representative places of immission are to be contrasted with the environmental noise measured of the baseline survey. Cumulative effects should be assessed.

The evaluation should be carried out in a frequency-resolved manner of 1/3 octave bands from 10 Hz to 20 kHz.

The presentation must describe the specified wind turbine power points.
- Spectral components should be identified which correspond to the subsequent identification of characteristic spectral lines in the operation of wind turbine installations. The operator of the installations must pass on these characteristics.
6 Creation of reports

6.1 Formal information in reports

6.1.1 Title page

The title page should at least contain the following information:

- Title (with name of the project)
- Report number
- Name of the company
- Date of the report, with revision status if necessary
- Name and address of the client
- Place, sea area
- Name of employees
- Information on the total number of pages in the report, including annex
- The number of pages in the annex should also be given on the title page if the annex contains its own numbering of pages.

6.1.2 Invariable information on subsequent pages

All subsequent pages must contain the following information:

- Name of the company
- Report number
- Date
- Page numbering.

It is not necessary to provide information on the total number of pages on the following pages.

6.1.3 Signatures

As a rule, the report is signed by the author.

6.2 Content of reports

6.2.1 Subdivision of contents

The report should include the following structures:

- Data on the execution of investigations
- Data on results
- Assessments.

6.2.2 Requirement for the description of the forecasts

At least the following information must be contained in the text:
• Name and description of the forecast.
• Description of the investigation object such as foundation types, pile driving procedures, pile driving energy and expected duration.
• List of relevant sources of noise.
• Description of the forecast procedures used and discussion of acceptances, also see 3.1.
• Description of source definition and modelling
• Discussion of the validity of acceptances.
• If it is checked "based" on a norm, then the place where the test procedure deviates from the norm is to be described (No norms are currently available, neither for measurements nor for forecasts).
• Data on the forecasts carried out as well as the results derived from them. These data are generally complemented with tables, graphs and sketches.
• It is important to document in particular the extent to which parameters such as bathymetry, condition of the soil etc. influence results.
• Information about the software (name, manufacturer, model, revision/change status).
• In order to trace the effects of forecasts subsequently found to be faulty on test results, the version number or the revision number of calculation programmes must be specified.
• Data regarding forecast uncertainty.

6.2.3 Requirement for the presentation of results
The following information is to be named on the diagrams:
• Investigation object, place of immission, sea area
• Reference sizes
• Analysis information, third/narrow band with details of bandwidth
• Information on relevant parameters such as winter/summer conditions (stratification, etc.)
• With forecasts on the construction phase, for example pile driving energy or comparable
• With forecasts on the operation of the wind farm, and additionally speeds, performance, etc.
• Reference sizes (display of levels)
• A standardised format is to be used with frequency displays: 10 dB = 20 mm; 1 octave = 15 mm.
7 Documents and normative references


[9] DIN 13320: Spectra and frequency curves, concepts, representation

[10] IEC 60263: Scales and sizes for plotting frequency characteristics and polar diagrams.


8 Contributions

The following people have contributed to the creation of this measuring specification:

- Dr. Betke (ITAP)
- Ms Blasche (BSH)
- Dr. Boethling (BSH)
- Ms Eickmeier (BSH)
- Mr Matuschek (ITAP)
- Dr. Gerdes (FWG)
- Dr. Nejedl (FWG)
- Mr Verfuß (PtJ)
- amongst others.

9 Updating

This measuring specification is a component of the Standard “Investigations of the Impacts of Offshore Wind Turbines on the Marine Environment (StUK) and is, when required - but not later than after two years - compared and possibly updated on the basis of experiences and insights gained and that have arisen in the application.

Dr. Andreas Müller

Dr. Carsten Zerbs