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## VESTERHAV SYD OFFSHORE WIND FARM

EIA – Technical report  
Underwater noise modelling

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**PROJECT**

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Vesterhav Syd Offshore Wind Farm  
EIA - Technical report  
Energinet.dk

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## 1 SUMMARY

On behalf of Energinet.dk, NIRAS A/S has undertaken underwater noise modelling for pile driving operations during the construction of wind turbines at the Vesterhav Syd offshore Wind Farm, located in the North Sea, 4 - 10 km west off the coast of Hvide Sande, Jutland.

The construction of offshore wind farms include activities that produce noise levels harmful to nearby marine mammals and fish. The most significant noise levels result from driving monopile foundations into the seabed.

Underwater noise modelling for the pile driving operations was performed for the worst case scenario using the largest proposed monopile diameter of 10 m. Modelling is based on one foundation being installed within any 24 hour period.

The modelling scenarios sought to determine all necessary sound levels to allow for accurate impact assessment of the piling activities. The modelling included determining peak-levels and sound exposure levels. Furthermore, species specific modelling was carried out, with the results reflecting the actual hearing of relevant species groups.

This report does not include impact assessments due to noise. This is treated in the reports for the respective ATR's for marine mammals and fish.

### **Dansk resumé**

På vegne af Energinet.dk, har NIRAS A/S foretaget beregning af undervandsstøj for støjende aktiviteter i forbindelse med opførelse af Vesterhav Syd offshore vindmøllepark, beliggende 4 – 10 km fra kysten vest for Hvide Sande.

Opførelse af offshore vindmølleparker inkluderer aktiviteter, der producerer skadelige støjniveauer for marine pattedyr og fisk. De mest signifikante støjniveauer fremkommer når fundamentene til vindmøllerne skal bankes ned i havbunden.

Undervandsstøjberegningerne for pælenedramning blev udført for worst case scenariet, hvor der antages brug af monopæle med en diameter på 10 m. Beregningerne er baseret på, at der kun nedrammes et fundament indenfor enhver 24 timers periode.

Beregningerne har til formål at bestemme lydniveauerne således, at der kan laves præcise vurderinger af hvilken virkning på marine pattedyr og fisk, opførelsen af vindmølleparken vil få. Beregningerne inkluderer maks-niveauer og lyddosis (SEL), samt art-specifikke parametre der reflekterer forskellige marine pattedyrs hørelse.

Der er i rapporten ikke foretaget miljøvurderinger på fisk og marine pattedyr. Disse vurderinger foretages i behandling af de respektive emner i andre baggrundsrapporter.

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## 2 INTRODUCTION

On March 22<sup>nd</sup> 2012 a broad political majority of the Danish Parliament agreed on the energy policy for the period 2012-2020. Establishment of 450 MW near-shore wind farms will ensure fulfillment of part of the agreement and conversion to a green energy supply in Denmark by 2020. On November 28<sup>th</sup> 2012 the Danish government pointed out six sites around Denmark, which are to be subject for pre-investigations prior to the development and production of a total of 450 MW wind power, including submarine cables and cable landfall. The selected sites are Bornholm, Smålandsfarvandet, Sejerø Bugt, Sæby, Vesterhav Syd and Vesterhav Nord. The Danish Energy Agency is responsible for the procurement of the 450 MW wind power for the six nearshore wind farm areas.

With injunction from the Danish Energy Agency (DEA) dated January 29<sup>th</sup> 2013 Energinet.dk is designated to manage and contract the preparation of technical reports, appropriate assessment as well as environmental impact assessment (EIA) reports, including appurtenant plan documents and proposal for environmental report for the selected six sites. The work will include assessments of the structures and the installation of these, both at sea and on land.

The planned Vesterhav Syd Offshore Wind Farm is located approximately 4 - 10 km off the coast of Jutland (Denmark) west of Hvide Sande. The turbine manufacturer and size has not yet been chosen, however the wind turbine sizes will be in the range from 3 MW to 10 MW. The water depth at Vesterhav Syd is between 10 m and 35 m.

The purpose of this report is to perform underwater noise modelling to investigate and document the underwater noise levels resulting from construction of the wind farm, to allow for an environmental impact assessment of the effect of underwater noise on marine mammals and fish.

### 2.1 Objectives

The objective of this report is:

To use available knowledge about underwater sound propagation to determine the worst case sound exposure in the North Sea as a result of pile driving operations during the construction of the Vesterhav Syd Offshore Wind Farm. Modelling will extend to ranges where significant impact on marine mammals can occur.

### 3 PROJECT DESCRIPTION

Vesterhav Syd Offshore Wind Farm comprises the establishment of a nearshore wind farm, inter-array and export cables as well as cable landfall facilities including cable termination station (and additional substations) for connection to the power grid on land.

The entire installation phase is assumed to last for a time period of approx. 3½ years, from mid 2016 to the end of 2019. The offshore wind farm is expected to be in commission by 2020 with an anticipated operation time of 30 years.

The entire survey area is shown in Figure 1.



Figure 1: Survey area of the wind farm Vesterhav Syd Offshore Wind Farm.

### 3.1 Installations offshore

Vesterhav Syd Offshore Wind Farm will be located within an approx. 60 km<sup>2</sup> survey area, which covers an area, situated 4 – 10 km off the coast northwest of Hvide Sande. Water depths in the area vary between 15 and 25 m. The offshore wind farm will possibly be established with a maximum capacity of 200 MW and will possibly take up an area of 44 km<sup>2</sup> within the survey area.

#### Facts about the project offshore

##### Capacity

Max. 200 MW

##### Turbine sizes

The size of the turbines may vary between 3 and 10 MW. Impact assessments are applied to the turbine size that is most critical regarding individual environmental factors.

Turbine capacity	Rotor diameter	Total height	Hub height	Max. number
3 MW	112 m	137 m	81 m	66 stk.
10 MW	190 m	220 m	125 m	20 stk.

The export cables from the wind farm to the mainland may be installed in two 500 m broad corridors, running from the northern part of the wind farm to the coast near Klegod and Tyvmose, both sites located north of Hvide Sande.

A description of the project and construction methods for the installation offshore is presented in a separate report (Energinet.dk, 2015).

The wind farm turbines are placed on foundations secured in the seabed. Different foundation types exist, as briefly discussed below.

#### 3.1.1 Foundation considerations

The foundation types possible for the Wind Farm include jacket, gravity and monopile foundations. The worst case scenario is in this project assumed to be the one that causes the highest underwater noise levels.

Gravity foundations consist of a heavy concrete base that is lowered onto the seabed and due to its great weight will remain stable. The installation of these foundations cause very low noise levels and as such are considered irrelevant in a worst case consideration with regards to noise exposure.

Jacket foundations consist of a number (typically 4) piles attached to a metal frame. These piles are positioned like the legs on a chair in each corner of the metal frame, and using impact hammers each pile is driven into the seabed for

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stability. This action creates very high noise levels as the energy from the hammer makes each pile vibrate and thus create sound waves.

Monopile foundations consist of a single very large diameter steel or concrete pile that is driven into the seabed by an impact hammer. Monopile diameter is considerably larger than for a jacket foundation for the same wind turbine size. The noise level of sound emanating from the vibrating pile is higher than for jacket foundations. The larger the diameter of the monopile, the more force required to drive it into the seabed and thus the higher the source level from the hammer blows.

### 3.1.2 *Pile driving source level considerations*

Based on the above, it was chosen only to model monopile foundations using an impact hammer, as this is assumed to represent the worst-case scenario.

As mentioned earlier, the wind turbine size has yet to be decided, however will be between 3 MW and 10 MW. In order to model the worst case scenario, it was chosen to model the largest turbine size of 10 MW which requires a monopile with a diameter between 8 m – 10 m dependent on local conditions. The modelling will thus, as the worst case scenario only consider 10 m diameter monopiles.

No existing wind farms have used 10 m diameter monopiles of this size to this date, however source level modelling for a 10 m monopile was performed for Horns Rev 3 offshore wind farm and in agreement with Energinet.dk should also be used for Vesterhav Syd Offshore Wind Farm. Here, the source level was determined to be:  $SPL_{\text{zero-peak}} @ 1 \text{ m distance} = 244.7 \text{ dB re. } 1 \mu\text{Pa}$ , and  $SEL @ 1 \text{ m distance} = 221.6 \text{ dB re. } 1 \mu\text{Pa}$ .

### 3.1.3 *Source modelling method*

In the technical description report it is written that the impact piling operation per pile is expected to take between 4 – 6 hours. This is supported by (Nedwell, Barham, & Mason, 2012) where a worst case duration was chosen to be 5 hours. The chosen duration for underwater noise modelling will be 6 hours according to agreement with Energinet.dk.

The hammer is proposed to strike with a maximum energy of 3,000 kJ, with 20 strikes per minute, and a maximum of 7,000 strikes during the 6 hours it takes to install a single foundation.

In the technical description report it is furthermore described that only one wind turbine foundation will be installed within a 24 hour period.

The National Oceanic and Atmospheric Administration (NOAA) recommends, that for underwater noise modelling that does not include animal fleeing, 1 hour of piling operations at full power should be used for assessing cumulative impact.



It was agreed with Energinet.dk, to use this method, which equates to modelling the source with only 1 hour of operation = 1800 strikes instead of 7000. This corresponds to adding 32,6 dB to the source level when modelling cumulative criteria.

### 3.1.4 Summary – source modelling inputs

The method of modelling the activities as described in this chapter, was chosen in cooperation with Energinet.dk in order to ensure a similar approach to underwater sound propagation modelling in all offshore wind farm projects mentioned in chapter 2.

Table 1 summarizes the chosen source inputs for the underwater noise modelling.

Parameter	Value used in modelling
Wind Turbine size	10 MW
Foundation type	Monopile (d = 10 m)
Hammer force	3,000 kJ
Source Level (SPL <sub>zero-peak</sub> @ 1 m)	244.7 dB re 1 μPa
Source Level (SEL @ 1 m)	221.6 dB re 1 μPa
Cumulative modelling - duration	1 hour at 100% hammer force
Cumulative modelling - number of strikes	1,800
Maximum number of foundations installed within a 24 hour period	1

Table 1: Source modelling parameters

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## 4 BACKGROUND

This chapter introduces the relevant units of measurement used to represent the underwater noise modelling results. The noise modelling criteria used for the impact assessment for fish and marine mammals is then listed.

Following this introduction, the source level is given in the relevant units. Then, underwater sound propagation theory is briefly explored and the methods used by NIRAS' underwater noise propagation software NISIM, are explained.

### 4.1 Method

#### 4.1.1 Units of measurement

Underwater sound levels are measured in dB re. 1  $\mu$ Pa. Different methods of representing the sound level exist to characterize the intensity, exposure level, max levels along with species specific weighted levels. Depending on the intended use of the results, and the type of source, it can be useful to use one sound level representation over another.

For impulsive sound sources, such as impact piling, and thus of interest in this project, the three metrics used are:

- The sound pressure level peak-peak ( $SPL_{pp}$ ) and zero-peak ( $SPL_p$ )
- The sound exposure level (SEL)
- M-weighted SEL ( $M_{hf}$  and  $M_{pw}$ )

A number of threshold levels using these three metrics have been selected, by the subcontractors in charge of performing the impact assessments for fish and marine mammals respectively, and will thus be modelled and presented in this report.

The three metrics are briefly explained in the following, while the thresholds are explained in the respective assessment reports for fish and marine mammals.

#### Sound Pressure Level (SPL)

The  $SPL_p$  is the maximum instantaneous sound pressure level of an impulse  $p(t)$ , given by:

$$SPL_p = 20 \log_{10}(\max|p(t)|)$$

The closely related  $SPL_{pp}$  is the maximum difference in sound pressure level of an impulse  $p(t)$ , given by:

$$SPL_{pp} = 20 \log_{10}(\max(p(t)) + |\min(p(t))|)$$

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Where  $SPL_p$  is usually the instantaneous change in SPL at the occurrence of an impulsive noise from zero dB to the maximum SPL, the  $SPL_{pp}$  represent the differential change from positive maximum to negative minimum as a result of the wave propagation. If the pressure wave maximum and minimum are direct opposites,  $SPL_{pp}$  will simply be twice as high as  $SPL_p$ , that is  $SPL_p + 6$  dB.

### Sound Exposure Level (SEL)

The SEL, also known as the sound exposure level is defined as the time-integral of the square pressure over a time window  $T$  covering the entire pulse duration, and is given by:

$$SEL = 10 \log_{10} \left( \int_T p^2(t) dt \right)$$

In the case of impulsive sources like impact piling, SEL describes the summation of energy for the entire impulse, and can be expanded to represent the summation of energy from multiple pulses. The latter is written  $SEL_C$  denoting that it represents the cumulative sound exposure. The sound exposure level is often used in the assessment of marine mammal and fish behaviour over an extended duration of impulsive sources, or for multiple concurrent sources.

### M-weighted SEL

The M-weighted SEL adapts the SEL modelling to reflect the hearing of a certain species or group of species with similar hearing ability. M-weighting functions can be thought of as the waters counterpart to the A-weighting function which is often used to represent the hearing of humans in air. These weighting functions take into account the nonlinear hearing of the species by a set of correction coefficients at each frequency. Thus, the results represent what the species will actually hear when exposed to a certain noise. The M-weighting functions are therefore very useful when determining the behavioural responses of marine mammals to any noise.

In this project, the two marine mammal groups of interest are: Mid frequency cetaceans and pinnipeds.

$M_{mf}$  is the M-weighting correction for high-frequency cetaceans while  $M_{pw}$  is the M-weighting correction for pinnipeds in water.

## 4.2 Legal basis /legislation

There are currently no rules or regulations for the noise exposure from underwater noise sources in Denmark. It is evaluated on a case by case basis, whether the noise levels, in combination with other impacts following from such activities, whether or not it will be allowed. This subject is treated further in the impact assessment reports for the specific ATR's for marine mammals and fish.

To assess the impact on marine mammals and fish, it was chosen by ITAP and BioApp that the threshold levels in Table 2 should be modelled.

<b>Marine Mammal group</b>	<b>Effect</b>	<b>Peak dB re 1µPa</b>	<b>SEL dB re 1µPa<sup>2</sup>-s</b>	
<b>Pinnipeds</b>	<b>PTS(<math>M_{pw}</math>)</b>	<b>218</b>	<b>186 *</b>	<b>Southall et al. 2007</b>
	<b>TTS(<math>M_{pw}</math>)</b>	<b>212</b>	<b>171 *</b>	<b>Southall et al. 2007</b>
	<b>Behaviour response(<math>M_{pw}</math>)</b>	<b>212</b>	<b>171 *</b>	<b>Southall et al. 2007</b>
<b>Cetaceans Mid frequency</b>	<b>PTS(<math>M_{mfc}</math>)</b>	<b>230</b>	<b>198 *</b>	<b>Southall et al. 2007</b>
	<b>TTS(<math>M_{mfc}</math>)</b>	<b>224</b>	<b>183 *</b>	<b>Southall et al. 2007</b>
	<b>Behaviour response</b>	<b>-</b>	<b>145 (single strike)</b>	<b>Lucke et al. 2009</b>
<b>Harbour Porpoises</b>	<b>PTS</b>	<b>209</b>	<b>179 *</b>	<b>Southall et al. 2007</b>
	<b>TTS</b>	<b>194</b>	<b>164 *</b>	<b>Lucke et al. 2009</b>
	<b>Behaviour response</b>	<b>-</b>	<b>145 (single strike)</b>	<b>Lucke et al. 2009</b>
<b>Fish</b>	<b>Injury</b>	<b>-</b>	<b>213 *</b>	<b>Carlson et. al. 2007</b>
	<b>PTS</b>	<b>-</b>	<b>189 *</b>	<b>Carlson et. al. 2007</b>
	<b>PTS</b>	<b>206</b>	<b>187 *</b>	<b>Woodbury and Stadler 2008</b>
	<b>TTS</b>	<b>206</b>	<b>187 *</b>	<b>Woodbury and Stadler 2008</b>
	<b>TTS</b>	<b>-</b>	<b>185 *</b>	<b>Carlson et. al. 2007</b>
	<b>TTS</b>	<b>-</b>	<b>183 *</b>	<b>Carlson et. al. 2007</b>
	<b>Behaviour response</b>	<b>-</b>	<b>-</b>	

Table 2: Noise modelling criteria. Thresholds for noise levels chosen for modelling by ITAP and BioApp. PTS stands for Permanent Threshold Shift, while TTS means Temporary Threshold Shifts. Thresholds marked with a \*, indicate that this threshold is of interest both for single strike scenario and for the cumulative scenario.

For further explanation of the chosen parameters, the reader is referred to the respective reports for the impact assessment for fish and marine mammals.

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### 4.3 Underwater sound propagation

This section is based on (Jensen, Kuperman, Porter, & Schmidt, 2011) chapter 1 and chapter 3 as well as (Porter M. , 2011), and seeks to provide a brief introduction to sound propagation in oceans. The interested reader is referred to (Jensen, Kuperman, Porter, & Schmidt, 2011) chapter 1, for a more detailed and thorough explanation of underwater sound propagation theory.

In the ocean, the sound pressure level generally decreases with increasing distance from the source. However, many parameters influence the propagation and makes it a complex process.

The speed of sound in the ocean, and thus the sound propagation, is a function of first and foremost pressure, salinity and temperature, all of which are dependent on depth and the climate above the ocean and as such are very location dependent.

The theory behind the sound propagation is not the topic of this report, however it is worth mentioning one aspect of the sound speed profile importance.

Snell's law states that:

$$\frac{\cos(\theta)}{c} = \text{constant}$$

Where  $\theta$  is the ray angle, and  $c$  is the speed of sound [m/s], thus implying that sound bends toward regions of low sound speed (Jensen, Kuperman, Porter, & Schmidt, 2011). The implications for sound in water are, that sound that enters a low velocity layer in the water column can get trapped there. This results in the sound being able to travel far with very low sound transmission loss.

When a low velocity layer occurs near the sea surface, with sound speeds increasing with depth, it is referred to, as an upward refraction. This causes the sound waves to be reflected by sea surface more than by the seabed. As the sea surface is often modelled as a calm water scenario (no waves), it causes little to no transmission loss. This scenario will always be the worst case situation in terms of sound transmission loss.

When a high velocity layer occurs near the sea surface with the sound speed decreasing with depth, it is referred to, as a downward refraction. This causes the sound waves to be angled towards the seabed rather than the sea surface, and it will thus be the absorption and reflection of the seabed that determines the transmission loss.

In any general scenario, the upward refraction scenario will cause the lowest sound transmission loss and thus be considered worst case.

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The physical properties of the sea surface and the seabed further affect the sound propagation by reflecting, absorbing and scattering the sound waves. Roughness, density and media sound speed are among the surface/seabed properties that define how the sound propagation is affected by the boundaries.

The sea surface state is affected mainly by the climate above the water. The bigger the waves, the more rough the sea surface, and in turn, the bigger the transmission loss from sound waves hitting the sea surface. In calm seas, the sea surface acts as a very reflective medium with very low sound absorption. In rough seas, the sound waves will to a higher degree be reflected backwards toward the source location, and thus result in an increased transmission loss.

Another parameter that has influence on especially the high frequency transmission loss over distance is the volume attenuation, defined as an absorption coefficient reliant on chemical conditions of the water column. This parameter has been approximated by:

$$\alpha' \cong 3.3 \times 10^{-3} + \frac{0.11f^2}{1 + f^2} + \frac{44f^2}{4100 + f^2} + 3.0 \times 10^{-4}f^2 \quad (dB/km)$$

Where  $f$  is the frequency of the wave in kHz (Jensen, Kuperman, Porter, & Schmidt, 2011).

#### **4.4 Underwater noise modelling software – NISIM**

NIRAS uses the underwater noise modelling software: NISIM, developed by Heat, Light and Sound Research Inc., by Michael Porter and Laurel Henderson.

NISIM has been developed to model the sound propagation of especially but not limited to impulsive sound sources such as impact piling and seismic surveys.

It uses a fully range-dependent and modified implementation of a ray theory method; “Bellhop” (Bucker & Porter, 1986), (Bucker & Porter, 1987), (Porter & Liu, 1994) and is suited for both shallow and deep water modelling. The implementation was modified to overcome inherited shortcomings of the original Bellhop when it comes to low frequency modelling in shallow water scenarios.

NISIM is able to provide all relevant outputs, including the units of measurement presented in chapter 4.1.1. Results are presented in table form as the range from source position to any desired noise level threshold, and in color-coded maps that show the noise levels at any position within a set radius of the source. NISIM uses the acoustic time-series of the actual noise source as input, and thus contains and models the full frequency content of the noise source. NISIM also allows the use of moving sources, as well as stationary sources with a set duration.

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NISIM uses a variety of databases to extract the necessary location specific data, such as sound speed profiles, bathymetry, sea state profiles and sediment properties, and will always select the database with the most precise data for the area in question. For this project, it was chosen to define the sediment properties manually as a seabed survey was performed prior to the environmental assessment for the wind farm.

#### **4.5 Worst case and assumptions**

A number of assumptions have been made for the underwater noise modelling. These include:

The sound source level was derived from an extrapolation of known source level data for smaller pile diameters, as no data is yet available for piles of 10 m diameter.

Assumption that the water surface is completely flat (calm waters). This provides the maximum sound propagation as it becomes a completely forward reflecting boundary.

The sound propagation has only been modelled for one sound speed profile (SSP), chosen to be the annual average. Depending on what time of year the Wind Farm construction will occur along with the weather conditions at that time, the SSP may differ from the one used in this modelling, and therefore also influence the sound propagation and noise levels.

No background noise is included in the modelling as it is considered irrelevant due to the extremely loud noise levels caused by the impact piling.

Other minor sound sources related to the construction have been omitted from the model as well, as they are considered vastly inferior to the noise caused by impact piling.

#### **4.6 0-alternative**

In order to apply an impact assessment a common base for comparison is necessary. The impact assessment has to be compared with the 0-alternative, that is defined as the case where the wind farm is not established.

If the project is not executed, there will be no environmental impacts. The off-shore area will remain unaffected.

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## 5 EXISTING CONDITIONS

This chapter describes the baseline conditions at Vesterhav Syd offshore wind farm site, relevant to the underwater noise modelling. This includes seabed sediment type, bathymetry and sound speed profile.

### 5.1 Bathymetry

NISIM allows the use of either ETOPO-1 by the National Geophysical Data Center under the American NOAA (Amante & Eakins, 2009), or through manual input.

ETOPO-1 is a 1 arc-minute model and consist of data from a number of regional and global data sets. NISIM uses ETOPO-1 by default.

For this project, a finer resolution of 30 arc-seconds was extracted from NOAA's seabed sampling (NGDC, 2013).

### 5.2 Sound Speed Profile (SSP)

NISIM allows the use of either sound speed profiles from the World Ocean Atlas from 2009 (WOA09), (Locarnini, Mishonov, Antonov, Boyer, & Garcia, 2010), (Antonov, Seidov, Boyer, Locarnini, Mishonov, & Garcia, 2010), or through manual input. WOA09 is an objectively analysed 1° resolution database including more than 20 parameters, the relevant ones being temperature, pressure and salinity, all given in annual, seasonal and monthly averages, based on historical data. Since the sound speed profile is a function of temperature, pressure and salinity, this database can be used to calculate the sound speed profile.

This database was used for the calculations due to the availability of all relevant parameters for calculating the sound speed profile, and due to being a widely used and maintained database.

It has not been specified at what time of year the construction phase will take place, and it was therefore chosen to use an annual average sound speed profile for modelling.

### 5.3 Sea surface state

NISIM allows for various sea state modelling techniques, to reflect either calm or any degree of rough seas. As explained in chapter 3.1.2, the worst case scenario is calm seas, as it is the most reflective scenario with the lowest transmission loss, and it was therefore the choice of sea surface for this modelling.

### 5.4 Seabed layers

The seabed usually consist of different layers of material, the combination and thickness of which has great influence on the sound propagation. This holds true especially for shallow water scenarios as the waves bounce between sea surface and seabed. By default, NISIM uses dbSEABED database by Institute for Arctic and Alpine Research, University of Colorado at Boulder (Halpern & et.,



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2008). There is however also the option to use a more detailed seabed profile by manually entering it into the model.

As site specific seabed sampling was available prior to the project, the different layer thickness and types are known, and it was therefore chosen to use these in the model.

An example of the seabed layers at the wind farm site, is a 1 m sand/gravel/silt layer on top of 9 m of gravel/sand, with a 80 m layer of clay/sand/boulder below.

## 5.5 Background noise

There will be several sources of noise not included in the underwater sound propagation modelling. These are:

Any biological sources, such as marine mammals.

Noise from ships, as these are expected to produce underwater noise levels inferior to those of the impact piling.

## 5.6 Summary – chosen site specific inputs

Input parameter	Value used in modelling
Sound Speed Profile	Annual average (WOA09)
Bathymetry	30 arc-second extract from NOAA
Sea surface state	Calm waters
Seabed layers, southwestern part of wind farm site	1 m sand/gravel/silt on 9 m gravel/sand on clay/sand/boulder
Seabed layers, northern part of wind farm site	1 m sand/gravel/silt on 4 m sand on clay/sand/boulder
Modelling tool	NISIM
Modelling distance, $R_{\max}$	100 km

Table 3 Site specific inputs

## 6 INSTALLATION PHASE

This chapter provides an overview of the proposed layout of Vesterhav Syd Wind Farm (10 MW turbines), and selects a number of representative locations from where the noise exposure is modelled. Tables provide the modelling results by the minimum distances each species must be from the piling operations at the onset of piling, in order to receive a total  $SEL_C$  below the given thresholds.

### 6.1 Modelling scenario

The offshore wind farm site is shown in Figure 2, with the wind turbine locations selected for noise modelling marked by yellow circles. The marked locations were chosen due to being the most western and eastern point respectively.

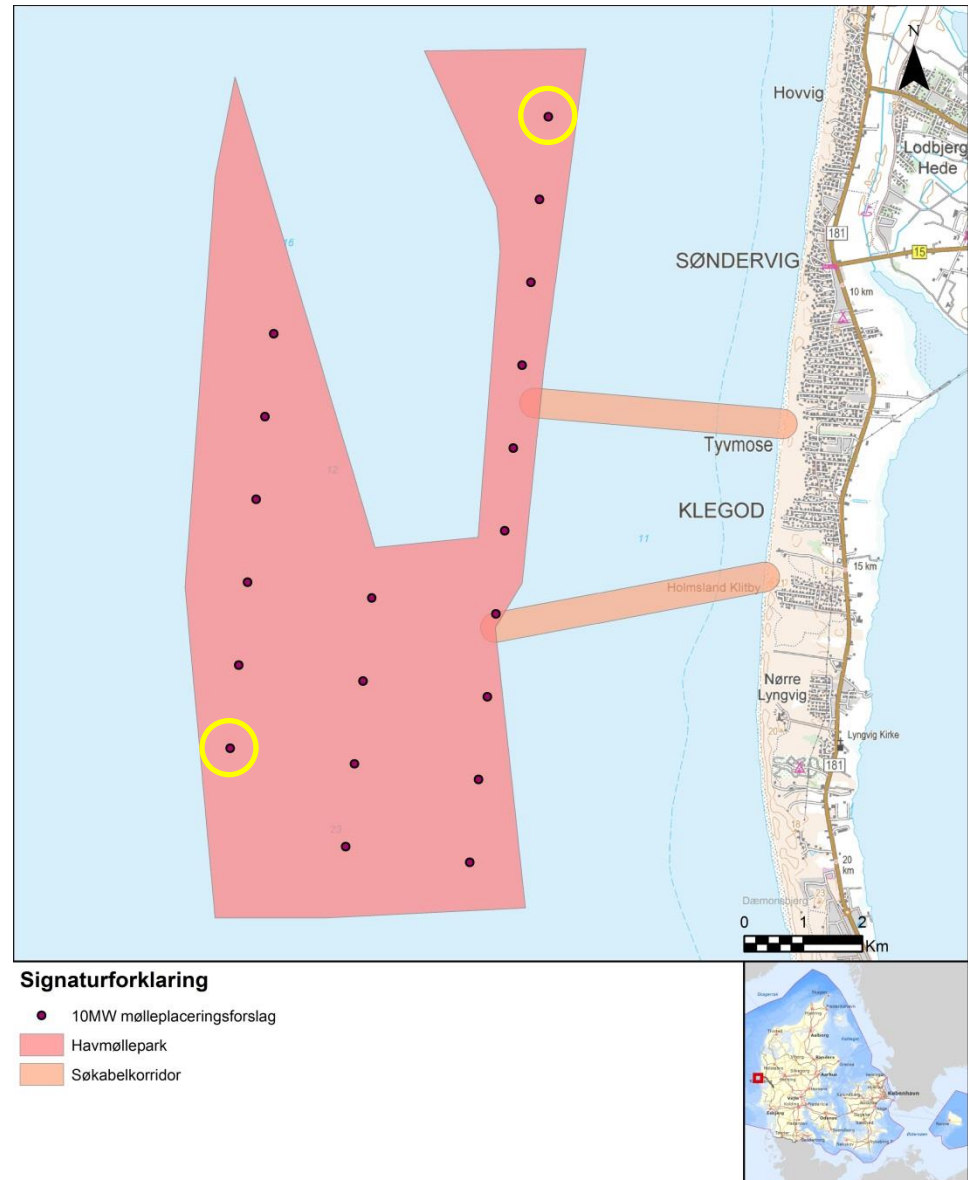


Figure 2: Vesterhav Syd 10 MW wind turbine layout. The black dots indicate wind turbine locations and the two yellow circles mark the chosen modelling locations: Location 1 (West) and Location 2 (East).

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## 6.2 Modelling results

Results from the underwater noise modelling, are given in a combination of tables and sound level maps. Distances in the tables are given in meters from source location.  $R_{\max}$  indicates the maximum distance at which the sound level can be present in any direction from the source.  $R_{\text{mean}}$  indicates the average distance from source at which the sound level can be present.

For thresholds where single or multiple transects reach the coast before the threshold value is met, the  $R_{\text{mean}}$  distance does not include these transects, as they would give a wrong impression of the general mean distance in the offshore direction.

If  $R_{\max}$  for e.g.  $\text{SPL}_p = 220 \text{ dB re. } 1 \mu\text{Pa}$  is 25 m, it means that sound levels of 220 dB and above will only occur within 25 m of the source, and that beyond that distance, noise levels will be below 220 dB.

Sound level maps for  $\text{SPL}_p$ , SEL and M-weighted SEL are presented in appendices to this report.

### 6.2.1 Single pile strike results

Single strike SPL and SEL modelling results are given in Table 4, for the two chosen locations.

Distance to thresholds, single strike				
Threshold	Location 1: West		Location 2: East	
	$R_{\max}$ (m)	$R_{\text{mean}}$ (m)	$R_{\max}$ (m)	$R_{\text{mean}}$ (m)
<b>Peak Sound Pressure Level - SPLp [dB re. 1 <math>\mu\text{Pa}</math>]</b>				
230 dB	< 10 m	< 10 m	< 10 m	< 10 m
224 dB	30 m	25 m	30 m	25 m
218 dB	90 m	80 m	90 m	80 m
212 dB	210 m	170 m	220 m	180 m
209 dB	260 m	240 m	320 m	280 m
206 dB	450 m	400 m	510 m	440 m
194 dB	2 500 m	1 600 m	2 600 m	1 700 m
<b>M-weighted Sound Exposure Level - SEL(<math>M_{\text{mf}}</math>) [dB re. 1 <math>\mu\text{Pa}^2 \cdot \text{s}</math>]</b>				
198 dB	< 10 m	< 10 m	< 10 m	< 10 m
183 dB	100 m	90 m	130 m	90 m
145 dB	11 000 m	9 000 m	11 000 m	9 200 m
<b>M-weighted Sound Exposure Level - SEL(<math>M_{\text{pw}}</math>) [dB re. 1 <math>\mu\text{Pa}^2 \cdot \text{s}</math>]</b>				
186 dB	140 m	130 m	200 m	170 m
171 dB	1 500 m	1 400 m	1 700 m	1 500 m
<b>Unweighted Sound Exposure Level - SEL [dB re. 1 <math>\mu\text{Pa}^2 \cdot \text{s}</math>]</b>				
213 dB	< 10 m	< 10 m	< 10 m	< 10 m
189 dB	180 m	160 m	230 m	180 m
187 dB	300 m	250 m	330 m	280 m
185 dB	420 m	380 m	430 m	380 m
183 dB	530 m	480 m	520 m	480 m
179 dB	1 000 m	920 m	900 m	800 m
164 dB	5 600 m	3 600 m	5 200 m	3 500 m
145 dB	22 000 m	19 500 m	21 000 m	19 200 m

Table 4 Single pile strike results

### 6.2.2 Cumulative pile strikes results

Cumulative strike SPL and SEL modelling results for the piling duration of 1 hour at full power and 1800 strikes are given in Table 5, for the two chosen locations.

Distance to thresholds, 1800 strikes				
Threshold	Location 1: West		Location 2: East	
	R <sub>max</sub> (m)	R <sub>mean</sub> (m)	R <sub>max</sub> (m)	R <sub>mean</sub> (m)
<b>M-weighted Sound Exposure Level - SEL(M<sub>mf</sub>) [dB re. 1 µPa<sup>2</sup> · s]</b>				
198 dB	1 300 m	1 150 m	1 600 m	1 000 m
183 dB	5 500 m	3 800 m	5 000 m	4 200 m
<b>M-weighted Sound Exposure Level - SEL(M<sub>pw</sub>) [dB re. 1 µPa<sup>2</sup> · s]</b>				
186 dB	6 000 m	5 100 m	7 200 m	5 400 m
171 dB	27 000 m	23 000 m	26 500 m	24 000 m
<b>Unweighted Sound Exposure Level - SEL [dB re. 1 µPa<sup>2</sup> · s]</b>				
213 dB	1 000 m	700 m	1 250 m	750 m
189 dB	8 200 m	6 000 m	10 000 m	7 500 m
187 dB	9 000 m	7 000 m	12 000 m	10 000 m
185 dB	12 000 m	8 500 m	13 000 m	11 000 m
183 dB	14 000 m	9 500 m	15 000 m	12 500 m
179 dB	20 000 m	15 300 m	19 000 m	16 200 m
164 dB	45 000 m	40 000 m	43 000 m	40 000 m

Table 5 Cumulative pile strikes results

### 6.2.3 Comparison of results to previous findings

The found results are here compared to results found in previous relevant projects in the North Sea. The only project in the Danish part of the North Sea with a comparable scenario was the Horns Rev III offshore wind farm (Mason, 2013).

The Horns Rev III underwater noise modelling used a different approach to calculating the cumulative results compared to this project, so only the single strike threshold distances are comparable. It is important to note however, that site specific conditions such as bathymetry and sediment layers have an impact on the results and that completely equal results are very unlikely to occur.

The following thresholds were calculated in both this project and in the Horns Rev III project, and are given in Table 6.

Comparison of found threshold distances				
Threshold	Vesterhav Syd		Horns Rev III	
	R <sub>max</sub> (m)	R <sub>mean</sub> (m)	R <sub>max</sub> (m)	R <sub>mean</sub> (m)
Peak Sound Pressure Level - SPL <sub>p</sub> [dB re. 1 µPa]				
206 dB	510 m	420 m	250 m	235 m
M-weighted Sound Exposure Level - SEL(M <sub>pw</sub> ) [dB re. 1 µPa <sup>2</sup> · s]				
171 dB	1 700 m	1 450 m	2 000 m	1 600 m
Unweighted Sound Exposure Level - SEL [dB re. 1 µPa <sup>2</sup> · s]				
145 dB	22 000 m	19 350 m	28 800 m	22 000 m

Table 6: Comparison of results from Horns Rev III offshore wind farm and Vesterhav Syd offshore wind farm

Comparing the results, it is noticed that distances for sound exposure level results for Vesterhav Syd are in general very similar to those of Horns Rev III, which could indicate similar environmental conditions at the two wind farm sites. The differences between the Horns Rev III and Vesterhav Syd results correspond to approximately 0.6 – 0.8 dB.

The longer distances for Vesterhav Syd for the peak sound pressure level can be due to differences in SPL<sub>peak</sub> propagation modelling method in the near-field. The differences between the Horns Rev III and Vesterhav Syd results correspond to approximately 3.5 dB.

Prior to the Kystnære Havvindmøller projects by Niras and Rambøll respectively, a test case scenario was modelled by both companies. Comparison of the results from this scenario showed an approximate 3 dB difference in SPL<sub>peak</sub> results, with Niras' results being on average 3 dB higher.

The above presented differences in sound exposure levels are considered reasonable and reflect minor site specific differences.

The difference in SPL<sub>peak</sub> results are considered caused by the SPL<sub>peak</sub> modelling method, as similar differences were found in the comparative modelling performed prior to the project in cooperation with Rambøll.

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## **7 OPERATION PHASE**

Noise sources in the operation phase is limited to the noise from the operational turbines. This noise can radiate through the foundation and into the water.

Previous assessments for Rødsand Offshore Wind Farm (Tougaard & Teilmann, 2007), Anholt Offshore Wind Farm (DHI, Energinet.dk, 2009) and Sprogø Offshore Wind Farm (Sveegaard, et al., 2008) indicate that operational noise under the water surface from wind turbines will be limited. All reports indicate operational source noise levels 10 – 20 dB above background noise levels in the area, and well below any thresholds for disturbance to occur.

Noise from the operation phase was not modelled in this report as no significant noise is expected. This topic is however further elaborated on in the respective assessments for fish and marine mammals.

## **8 IMPACT ASSESSMENT DURING DECOMMISSION**

It is unclear how any decommissioning would take place in case the wind farm should be demolished in the future. It is however expected that any noisy activities in the case of decommissioning will not exceed those of the construction phase.

Due to the uncertainties of which activities and methods might occur during a possible decommissioning phase, it was not deemed possible nor relevant to model the noise.

## **9 CUMULATIVE EFFECTS**

Several activities during the construction phase will have source levels above the background noise in the North Sea. The primary noise source will be the impact piling activity, whereas activities such as ship traffic and cable installation are expected to introduce significantly lower levels of noise.

There is a risk of multiple wind farms being constructed simultaneously in the North Sea, of which Vesterhav North and Horns Rev 3 offshore wind farm are possible options. Based on the distance to these other wind farms, it is assessed that the cumulative effect, is negligible in terms of noise exposure.

The cumulative effects from ships and cable installation have not been part of the noise modelling documented in this report.

## **10 MITIGATION MEASURES**

For this project it was chosen not to include any mitigation measures in the underwater noise modelling. However should results show that such measures would be required, this chapter lists a number of mitigation methods used in previous projects.

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In a number of previous projects, the attenuation level provided by source level mitigation measures have been: (Reinhall & Dahl, 2011) (Tobias Verfuß, 2012)

Temporary noise attenuation pile (TNAP): reduction  $\approx 10$  dB

Big bubble curtain at FINO-3: reduction  $\approx 12$  dB

Big bubble curtain at OWF Borkum West II: reduction  $\approx 5 - 13$  dB

Small bubble curtain at OWF alpha ventus: reduction  $\approx 2 - 13$  dB

Cofferdam at Aarhus Bay test setup  $\approx 22$  dB

## **11 POTENTIAL INSUFICIENT INFORMATION**

The input data used for the modelling is largely based on historical measurements for the region. This will always introduce a level of uncertainty, as deviations from year to year can occur. In the modelling however, the chosen inputs are for the most part worst-case scenario data, and it is therefore expected, that if any deviation from the modelled results, it will show lower overall sound levels than modelled. Only the sound speed profile was chosen to be an annual average.



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