Noise Impact Assessment Hywind Tampen

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Summary

In this study we assessed the possible impact on marine mammals of noise from the Hywind Tampen wind turbines. Measured data from Hywind 1 were used as the basis of the assessment. The sound from Hywind 1 was measured over a period of several month being representative for a variety of weather and operational conditions. The sound was measured at 150m distance from Hywind 1 and at a control station about 10k away with otherwise quite similar conditions. The work at Hywind 1 was analysed and reported by a renowned third-party consultant called JASCO. It was not easy to detect sound from Hywind 1 in the surrounding of other natural and anthropogenic noises, a clear sign that Hywind 1 only created a relatively low sound level. Sound at low frequencies, 25Hz, 50Hz and 125Hz, was detected that was attributed to the revolution of the rotor and the gear. For this study a scaling factor was used to account for the more powerful wind turbines that will be used at Hywind Tampen. Suggestions made in a report assessing the noise input from Hywind Scotland by consultant company Xodus were followed. At Hywind 1 a short transient sound was detected, most probably originating from the mooring system, it was describes as a “snapping” broadband sound that occurred occasionally. This transient sound was clearly detectable at Hywind 1 but is not known if this sound also occurs on other Hywind installations with a modified design. For completeness it has been included in this study.

This study modelled the noise in the environment around Hywind Tampen by using a modelling tool that predicts sound propagation based on distance from source and environmental parameters like water temperature and salinity and sea bottom conditions. The obtained results were related to internationally accepted threshold values for impact on marine mammals. Due to their excellent hearing capabilities, marine mammals have generally lower threshold values for impact from sound than other animal groups like fish and invertebrates, therefore we only considered those for marine mammals.

Two properties of sound were used for the assessment, this is the sound pressure expressed as sound pressure level (SPL) and the accumulated energy of the sound over a longer time period. This is called Sound Energy Level SEL. In this study we used SEL over a 24h time period. Guidelines developed by the National Oceanid and Atmospheric Administration NOAA in US suggest that both metrics are used and suggests respective thresholds for both, SPL and SEL. This is based on the theory that sound can cause damage to the auditory system of marine mammals ether by a short strong sound pulse or by a series of lower sound pulsed where the energy over time adds up until a damage occurs. Damage in this respect is the onset of temporary threshold shift (TTS) or permanent threshold shift (PTS) of the hearing capabilities of the respective animals. The NOAA guidelines are regarded as the most stringent to date. Threshold values for behavioural reactions published in literature were also considered.

None of the threshold values for injury were exceeded in the vicinity of Hywind Tampen. The continuous sound generated by Hywind Tampen has a low sound pressure, far below any threshold values, and the accumulated energy over 24h also stayed below the threshold values exept for the group of low frequency cetaceans where the SEL threshold for TTS onset was exceeded at distances closer than 45m to the shaft of the wind turbine. The probability of an animal to stay for 24 hours within a 45m radius to a wind turbine was however evaluated as zero, so no overall risk was found. The continuous sound created by Hywind Tampen is only audible for marine mammals at a couple of hundred meters at average levels of ambient sound.

The transient (snapping) sound has stronger sound pressure values that could come close to some of the threshold levels for harassment. There are however many uncertainties on the exact source strength of this sound and the assessment can only be an indication. The sound pressure (SPL) from the transient sound was below accepted criteria for injury. The accumulated energy over 24 hours (SEL) did not exceed accepted threshold values for injury.

Overall the risk of a negative impact on marine mammals by sound created form the Hywind Tampen installation was evaluated as non existenent.

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1 Introduction

FT SST ERO has been commissioned to undertake an underwater noise impact assessment for Hywind Tampen.
Hywind Tampen Windfarm is planned to be installed between Snorre and Gullfaks oil field and will consist of 11 x 8.4MW floating wind turbines.

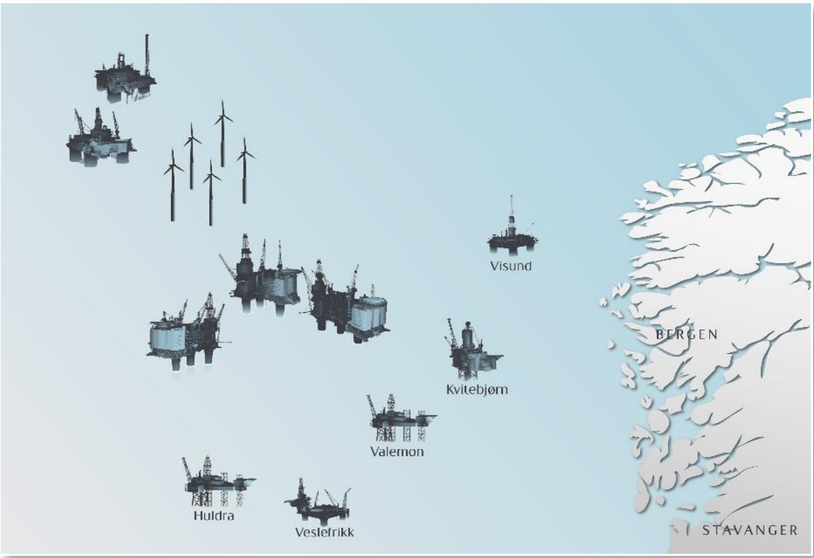

Fig 1. Schematic overview over location of Hywind Tampen Windpark in the Norwegian Sea.

In relation to noise there are several issues to review. This is underwater noise during construction caused by increased activity of ships in the area and by some special activities like installations of anchors and infrastructure, and noise created by the floating windmills during operation. The current report only assesses the noise that originates from the wind mill structure during operations. The noise during construction does not differ substantially from other marine activities typical for offshore industry. Noise created during installation is also much less than for wind farms installations where impact piling is used and the impact statement for Hywind Scotland concluded that this impact is negligible and will therefor not be part of this assessment.
During operation of the wind mills /wind park two kinds of noise is created, continuous noise crated by rotating parts of the windmill that is then propagated from the floating shaft into the water, and transient noise that has been identified at Hywind Pilot. This noise most probably comes from the anchor chains, cables and connections.
At Hywind Pilot, located outside of Stavanger, sound has been measured from end of March 2011 to end to mid of August 2011and reported by JASCO. This data set has been assessed by Xodus for the bigger Hywind windmills at Hywind Scotland. In this report we use information from both reports for assessing the noise impact at Hywind Tampen.

2 Underwater noise

2.1 Acoustic concepts and terminology

Sound travels through the water as vibrations of the fluid particles in a series of pressure waves. The waves comprise a series of alternating compressions (positive pressure variations) and rarefactions (negative pressure fluctuations). Because sound consists of variations in pressure, the unit for measuring sound is usually referenced to a unit of pressure, the Pascal (Pa). The unit usually used to describe sound is the decibel (dB) and, in the case of underwater sound, the reference unit is taken as 1 µPa.

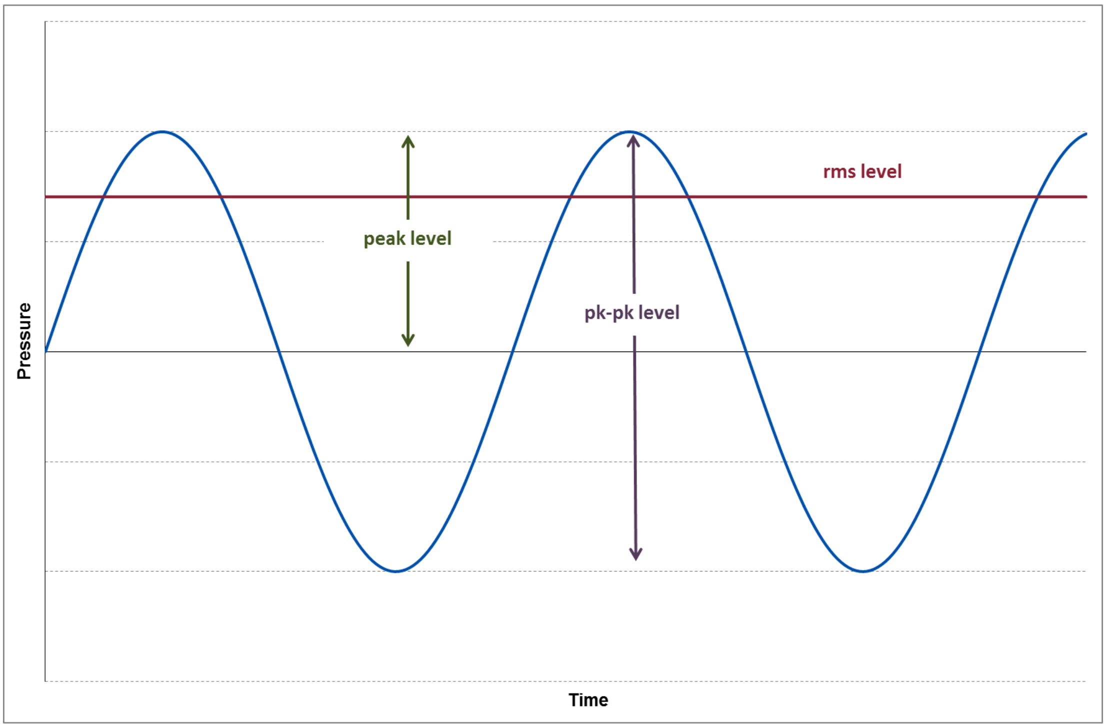

Fig. 2 Graphical representation of acoustic wave descriptors.

There are multiple ways to report sound levels. We will adhere to the ISO standard 18405:2017 and recommendations given by NOAA using the following metrics and units:

SPL Sound Pressure Levels RMS. Applicable to continuous sounds. (dB re 1 µPa)

SPL_{peak}, L_p Sound Pressure Level zero to peak. Applicable to continuous sound exposure (dB re 1 µPa),

SEL_{cum24h} also L_E, Sound Exposure Level cumulated over 24h (dB re 1 μPa^2 s)

dB_{SL} Source Level. This is the sound pressure level of an equivalent point source as measured at one meter distance, can be expressed as SPL, SPL_{peak} or SEL (re 1 µPa m , re 1 μPa^2 s m)

2.2 Baseline noise

Background or “ambient” underwater noise is generated by a number of natural sources, such as rain, breaking waves, wind at the surface, seismic noise, biological noise and thermal noise. Biological sources include marine mammals (which use sound to communicate, build up an image of their environment and detect prey and predators) as well as certain fish and shrimp. Anthropogenic sources also add to the background noise, such as fishing boats, ships, industrial noise, seismic surveys and leisure activities. Generalised ambient noise levels in the oceans has been described by Wenz 1962. spectra attributable to various noise sources (Wenz, 1962) are shown in Figure 3. Brokker et all (2012) describe background noise levesl in UK wates ranging from

92dBre 1 µPa (rms) under low sea state to a maximum of 132 dB re 1 µPa (rms) at sea state 3. Mean values are at 111 to 112 dB re 1 µPa (rms). At the Hywind control site an average ambient noise level of 121.5 dB re 1µPa (rms) was measured. Ambient noise levels for the Tampen area are not know from direct measurements, but the area sees less traffic as the area of the Hywind control side outside Stavanger. Conditions for Tampen area assumed to be in the same range as reported by Brooker for UK waters with a mean value approximately 112 dB re 1 µPa (rms).

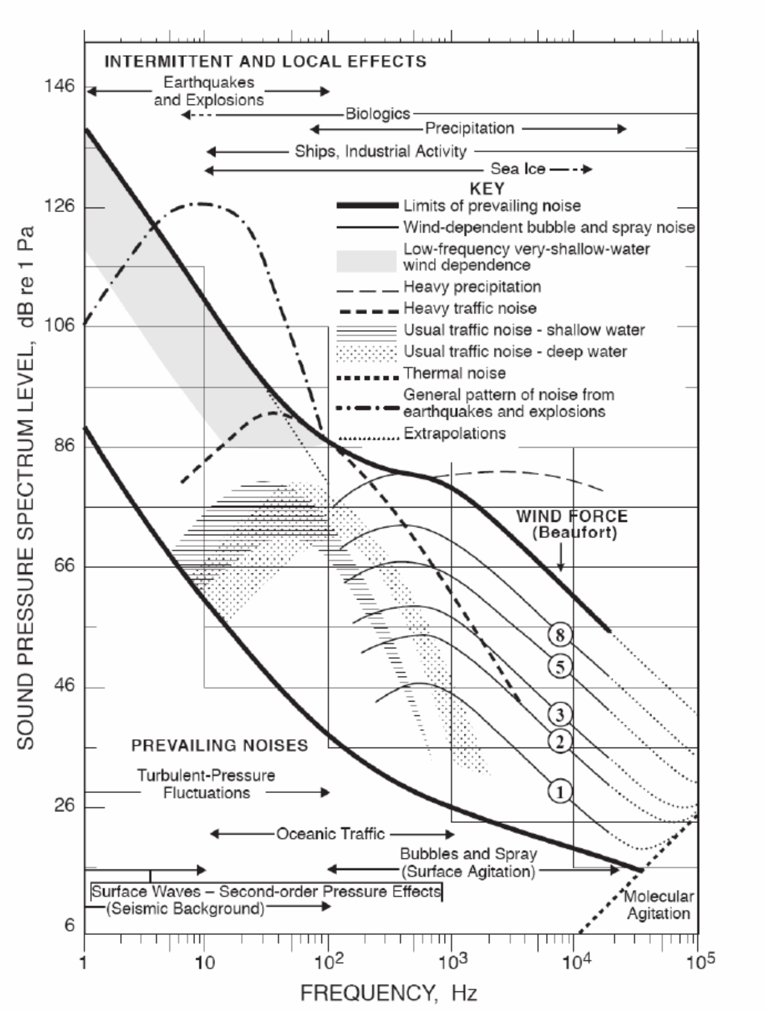

Fig 3. Generalised ambient noise attributable to various natural and anthropogenic noise sources (Wenz 1962)

2.3 Threshold values for assessing impacts

There is no regulatory framework in place on the NCS that gives requests on threshold values to be used when assessing noise impact. It is however expected to use the best available scientific knowledge.

There is internationally accepted literature that defines threshold values for most of the groups of marine organisms. In this report we adhere to internationally accepted literature and guidelines and in particular to the guidelines from NOAA (2018) giving threshold values for onset of PTS (Permanent Threshold Shift) and TTS (Temporary Threshold Shift). PTS is an irreversible reduction in hearing sensitivity, TTS is the reversible reduction in hearing sensitivity with full recovery of hearing after exposure. The NOAA guidelines work with a so called “dual criteria”. This is based on the theory that high sound pressures for impulsive sound can lead to PTS or TTS when over a certain threshold, but also sound of lower strength that is repeated frequently can lead to the same impact. Dual metric thresholds using weighted cumulative sound exposure level (SELcum) and peak sound pressure (PK) metrics for impulsive sounds. As dual metrics, the guidelines considers onset of PTS to have occurred when either one of the two metrics is exceeded. For non-impulsive sounds, thresholds are provided using the weighted SELcum metric where the sound energy is integrated over a 24h period. Additionally, to account for the fact that different species groups use and hear sound differently, marine mammals are sub-divided into five broad hearing groups (i.e., LF, MF, HF, PW, and OW) (Tab1) and thresholds in the weighted SELcum metric incorporate auditory weighting functions.

Hearing Group	Generalized Hearing Range*
Low-frequency (LF) cetaceans (baleen whales)	7 Hz to 35 kHz
Mid-frequency (MF) cetaceans (dolphins, toothed whales, beaked whales, bottlenose whales)	150 Hz to 160 kHz
High-frequency (HF) cetaceans (true porpoises, *Kogia*, river dolphins, cephalorhynchid, *Lagenorhynchus cruciger* & *L. australis*)	275 Hz to 160 kHz
Phocid pinnipeds (PW) (underwater) (true seals)	50 Hz to 86 kHz
Otariid pinnipeds (OW) (underwater) (sea lions and fur seals)	60 Hz to 39 kHz

* Represents the generalized hearing range for the entire group as a composite (i.e., all species within the group), where individual species' hearing ranges are typically not as broad. Generalized hearing range chosen based on ~65 dB threshold from normalized composite audiogram, with the exception for lower limits for LF cetaceans (Southall et al. 2007) and PW pinniped (approximation).

Tab 1: Marine mammal hearing groups (NOAA 2018)

Hearing Group	PTS Onset Thresholds* (Received Level) Impulsive	Non-impulsive
Low-Frequency (LF) Cetaceans	*Cell 1* $L_{p,0\text{-pk,flat}}$: 219 dB $L_{E,p,\text{ LF,24h}}$: 183 dB	*Cell 2* $L_{E,p,\text{ LF,24h}}$: 199 dB
Mid-Frequency (MF) Cetaceans	*Cell 3* $L_{p,0\text{-pk,flat}}$: 230 dB $L_{E,p,\text{ MF,24h}}$: 185 dB	*Cell 4* $L_{E,p,\text{ MF,24h}}$: 198 dB
High-Frequency (HF) Cetaceans	*Cell 5* $L_{p,0\text{-pk,flat}}$: 202 dB $L_{E,p,\text{HF,24h}}$: 155 dB	*Cell 6* $L_{E,p,\text{ HF,24h}}$: 173 dB
Phocid Pinnipeds (PW) (Underwater)	*Cell 7* $L_{p,0\text{-pk.flat}}$: 218 dB $L_{E,p,\text{PW,24h}}$: 185 dB	*Cell 8* $L_{E,p,\text{PW,24h}}$: 201 dB
Otariid Pinnipeds (OW) (Underwater)	*Cell 9* $L_{p,0\text{-pk,flat}}$: 232 dB $L_{E,p,\text{OW,24h}}$: 203 dB	*Cell 10* $L_{E,p,\text{OW,24h}}$: 219 dB

* Dual metric thresholds for impulsive sounds: Use whichever results in the largest isopleth for calculating PTS onset. If a non-impulsive sound has the potential of exceeding the peak sound pressure level thresholds associated with impulsive sounds, these thresholds are recommended for consideration.

Note: Peak sound pressure level ($L_{p,0\text{-pk}}$) has a reference value of 1 µPa, and weighted cumulative sound exposure level ($L_{E,p}$) has a reference value of 1µPa²s. In this Table, thresholds are abbreviated to be more reflective of International Organization for Standardization standards (ISO 2017). The subscript "flat" is being included to indicate peak sound pressure are flat weighted or unweighted within the generalized hearing range of marine mammals (i.e., 7 Hz to 160 kHz). The subscript associated with cumulative sound exposure level thresholds indicates the designated marine mammal auditory weighting function (LF, MF, and HF cetaceans, and PW and OW pinnipeds) and that the recommended accumulation period is 24 hours. The weighted cumulative sound exposure level thresholds could be exceeded in a multitude of ways (i.e., varying exposure levels and durations, duty cycle). When possible, it is valuable for action proponents to indicate the conditions under which these thresholds will be exceeded.

Tab 2 Threshold values for onset of PTS as used in this report (NOAA 2018)

TTS onset thresholds for non-impulsive sounds.

Hearing Group	K (dB)	C (dB)	Weighted TTS onset acoustic threshold (SEL_{cum})
Low-frequency (LF) cetaceans	179	0.13	179 dB
Mid-frequency (MF) cetaceans	177	1.20	178 dB
High-frequency (HF) cetaceans	152	1.36	153 dB
Phocid pinnipeds (underwater)	180	0.75	181 dB
Otariid pinnipeds (underwater)	198	0.64	199 dB

Tab. 3. Threshold values for onset of TTS as used in this report (NOAA 2018)

The threshold criteria used in this report are in some parts more stringent than those used in the underwater noise assessment for Hywind Scotland. (Xodus 2015). This has been done because the NOAA guidelines are more recent and acknowledge the most recent literature in the field and because the NOAA guidelines are geting increasing international attention.

Threshold levels for behavioural reactions are extensively discussed in the Xodus report. In this report the same criteria are proposed (Table 4).

Type of sound / criteria metric	Effect	Marine mammal hearing group	
		All cetaceans	Pinnipeds
Single pulses:			
Peak pressure level, dB re 1 μPa	Potential strong behavioural reaction	224	212
SEL, dB re 1 μPa²s		183	171
Multiple pulses:			
RMS sound pressure level, dB re 1 μPa	Potential strong behavioural reaction	160	
	Low level marine mammal disturbance	140	
Continuous sound:			
RMS sound pressure level, dB re 1 μPa	Potential strong behavioural reaction	120	

Table 4 Suggested marine mammal criteria for onset of disturbance (Xodus 2015).

3 Sound propagation modelling

3.1 Sound propagation modelling software

For sound propagation modelling the software package dBSea V 2.5 from Irwinn Carr consulting was used. The software uses bathymetry, sediment and sound speed input data to build a 3D acoustic model of the environment. This, paired with accurate sound propagation models, such as dBSeaPE, a Parabolic Equation algorithm and dBSeaRay, a Ray Theory algorithm, make for accurate prediction of the sound propagation. Parabolic equation algorithms are known to be the most accurate for modelling low frequencies in shallow water scenarios, while ray theory algorithms deliver the best performance at higher frequencies.

4 Input data sound modelling

4.1 Bathymetry

Bathymetry data were taken from EMODNet Bathymetry database (http://www.emodnet-bathymetry.eu/data-products) that provides bathymetry data for the area with about 100m resolution. The postions of the Hywind stuctures were taken from Hywind Tampen field layout document C219.EQ-XE-00001-01 (Table 5).

Name	WGS84 Latitude	WGS84 Longitude	WGS84 UTMz31 Easting	WGS84 UTMz31 Northing
HY01	61° 21' 59.058" N	2° 15' 6.223" E	459 996.73	6 803 829.59
HY02	61° 21' 12.044" N	2° 15' 31.773" E	460 359.63	6 802 370.63
HY03	61° 20' 25.029" N	2° 15' 57.302" E	460 722.53	6 800 911.67
HY04	61° 19' 38.012" N	2° 16' 22.809" E	461 085.43	6 799 452.72
HY05	61° 18' 50.994" N	2° 16' 48.295" E	461 448.33	6 797 993.76
HY06	61° 18' 3.974" N	2° 17' 13.760" E	461 811.23	6 796 534.80
HY07	61° 18' 16.872" N	2° 15' 36.355" E	460 366.28	6 796 950.00
HY08	61° 19' 3.887" N	2° 15' 10.846" E	460 003.38	6 798 408.96
HY09	61° 19' 50.900" N	2° 14' 45.317" E	459 640.48	6 799 867.92
HY10	61° 20' 37.912" N	2° 14' 19.766" E	459 277.58	6 801 326.87
HY11	61° 21' 24.922" N	2° 13' 54.194" E	458 914.69	6 802 785.83

Table 5. Planned infrastructure coordinates for wind mill positions. Please note that positions are given in WGS84, not in ED50 as in field layout document.

Fig. 4. Hywind tampen placed on the bathymetry map

4.2 Sound velocity profile

Salinity, temperature and pressure (depth) are the most important parameters that influence the speed of sound in water. Salinity and temperature profiles from World Ocean Database (NOAA National Centres for Environmental Information (2005). Those data were used to calculate sound speed (Tollefsen C.D.S. 2013) using the following formula:.

c(T,S, z) = 1449.2+4.6T −0.055T2+0.0029T3
+(1.34−0.01T)(S−35)+0.016z

where T is the temperature in ◦C, S is the dimensionless salinity (frequently quoted as
Practical Salinity Units, or PSU), and z is the depth in m. From Equation 1 it is evident that the sound speed depends most strongly on T, with a weaker dependence on S and z.
For each month a sound speed profile was calculated (Fig 5). Because sound is refracted towards depths of low sound speed sound propagation differ over the seson. In order to simulate sound propagation under most different propagation conditions, the sound speed profile for June and April (Fig. 6).

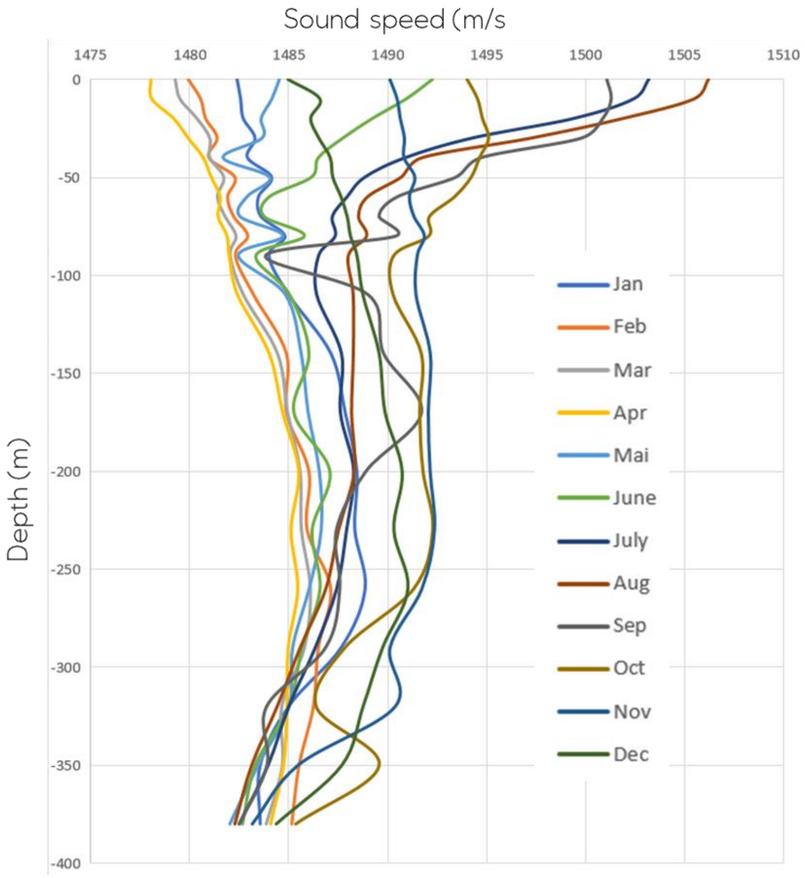

Fig 5. Sound speed profiles representative for the area for each month. For simulations sound speed profilrs form April and June were used.

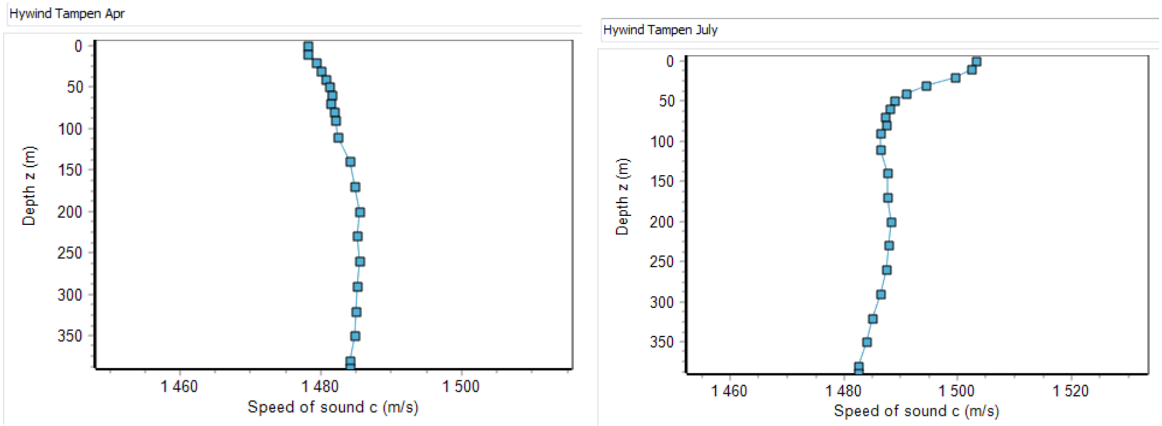

Fig 6. Sound speed prfiles for April (left) and July (right) as used in dBSea

For calculation of sound absorption effects in the water column average values for water temperature and salinity for April (7.07decC; 35.13PSU) and July were used (8.72decC; 35.10PSU.

4.3 Sea bed properties

The acoustic properties of the sea floor have influence of the amount of sound reflected from the sea floor. Bottoms with higher sound speed than the overlying water do reflect more sound back into the water column than bottoms with lower sound speed (Ballard 2017). In this study we used information from the Equinor "Hywind Tampen Substucure and Mooring System Functional requirements" report.
For the model a sandy layer of 1m thickness with a sound velocity of 1650m/s, a density of 1900kg/m and a attenuation of 0.8dB/wavelength as used, and a clay from 1 m to infinite depth with sound velocity of 1500m/s and density of 1500kg/m3 and an attenuttion of 0.2 dB/wavelength was used.

4.4 Sound source properties.

Equinor commissioned Fugro GEOS and Jasco Applied Sciences to undertake underwater noise measurements in the vicinity of Hywind 1 installation at a test site north-west of Stavanger, Norway. The purpose of this exercise was to quantify potential underwater noise emissions form the Hywind turbines during operation in order to inform any impact assessments what will be required for future Hywind projects. Measurements were undertaken at a test location some 150 m from the main structure and the hydrophone was deployed at a depth of 91 m. Additional background noise level readings were undertaken at a remote control site with comparable natural environmental conditions, 10 km from the Hywind test site.
This measurements were used to assess noise impact for the Hywind Scotland project. This study was done by Xodus in 2015. The study by Xodus also includes suggestion on upscaling the produces sound to the somehow bigger turbines to be used for Hywind Scotland. In this study we use information from both reports for the definition of the source strength for the sound at Hywind Tampen.

4.4.1 Operational sound

Sound originating form Hywind was reported in the respective JASCO report as power spectral densities and as 1/3 octave band spectral values (ref Figure 25 and Figure 38 in JASCO Measurement Report). Those data were measured at 150m distance. The Jasco report identified tonal frequencies created by the Hywind at 25Hz and harmonics thereof with frequencies of 50 Hz and 125Hz. Power spectral densities from the Jasco report were converted to approximate sound pressure level data in third octave bins. Same results as in the Xodus report were achieved. In order to get values at source spherical propagation was assumed and 43.5dB were added to the values measured at 150m. A 4 dB upscaling factor was used according to the suggestions made in the Xodus 2015 report. A total SPL source level of 166 dB re 1µPa 1m (rms) was used for each of the Hywwind Tampen wind turbines in the simulations.

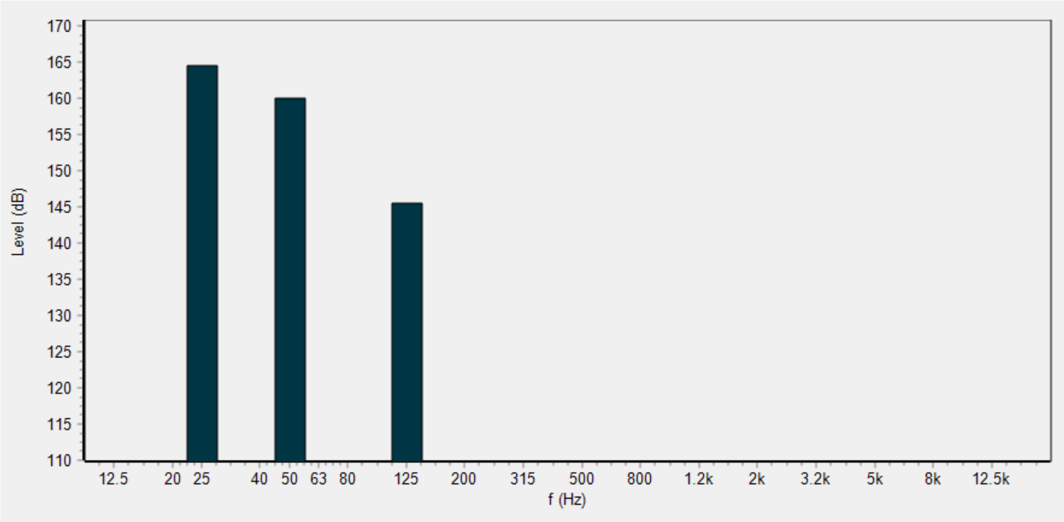

Fig. 7. Spectral content of the operational noise used in the sound simulations. Only those frequency bands that show clear difference to the general ambient sound in the area are shown.

Note: The steps of reading out data from graphs in the Jasco report, doing back calculations to source level and the upscaling to bigger wind turbines is based on some assumptions and results in uncertainty. Especially the scaling factor of 4dB for the bigger and more powerful wind turbines is based on assumptions, field measurement on bigger floating wind turbines are not available.

4.4.2 Impulsive Sound

The Hywind 1 sound study identified a transient sound measurable in the vicinity of Hywind 1. The exact origin of this transient sound has not been identified, it is assumed to be produced by tension realese in the mooring structure. **It is unknown if other Hywind installations also exhibit this transient noise**.

This transient sound was measured above SPL_{peak} 160 dB re 1 µPa at a distance of 150m corresponding to SPL of 120 to 125 dB re 1µPa. The frequency of this sound extends troughout the recorded frequency range of 0-20kHz.

For this study a original sound file from the Hywind I study was used for the sound source characterisation of the snapping sound (as WAF file). This signal was scaled up to the source strength on the place of its assumed place of origin on the shaft of the Hywind structure in 150m distance. Sperical propagation laws were assumed and 43.5 dB was added to the sound level measured at 150 resulting in a SPL_{peak} level at the source for a individual turbine to be 203dB re 1 µPa @ 1m. The snapping sound was reported to occur up to 23 times a day, for calculation of SEL over 24h 23 snapping events per day per wind turbine were used accumulating to 253 snapping events for all the Hywind Tampen wind turbines.

There is a high uncertainty for the source strength of this transient sound mostly attributed to the unknown position of its origin. It could be stronger or weaker, calculations done in this study are only a rough indication.

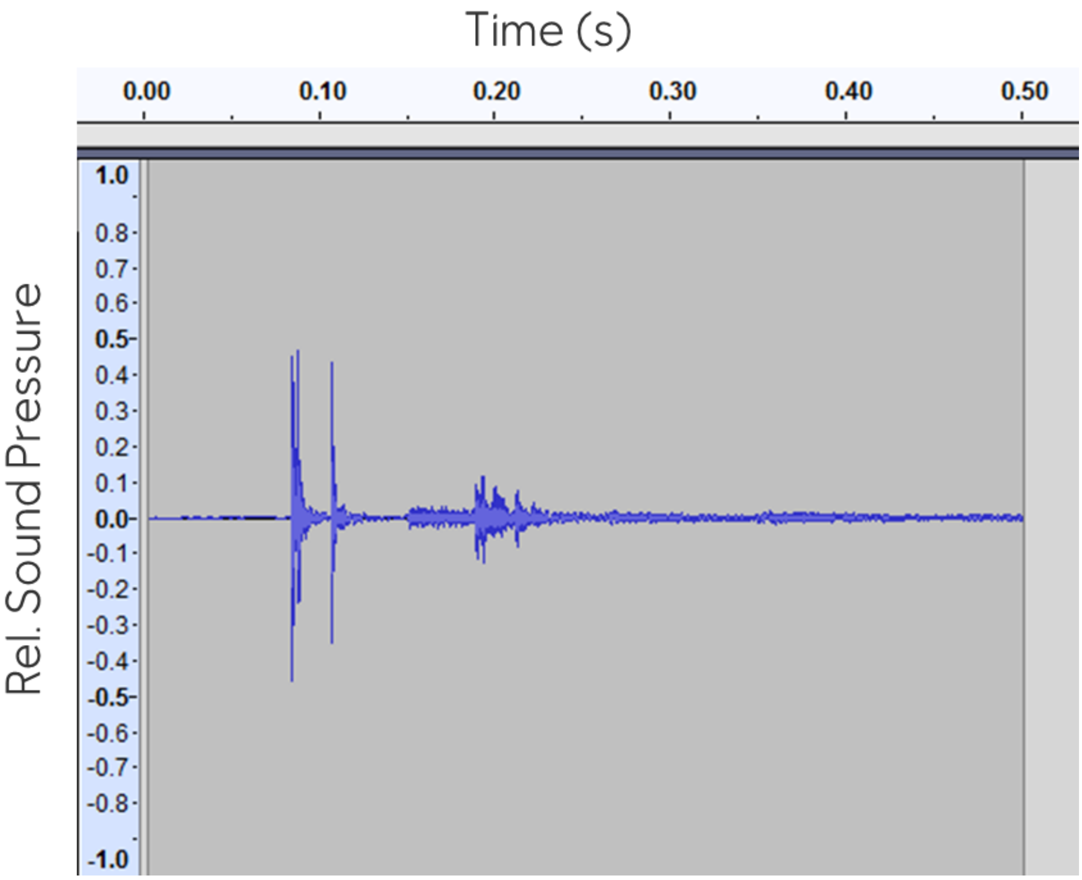

Fig 8.Transient sound from Hywind expressed with relative sound pressure.

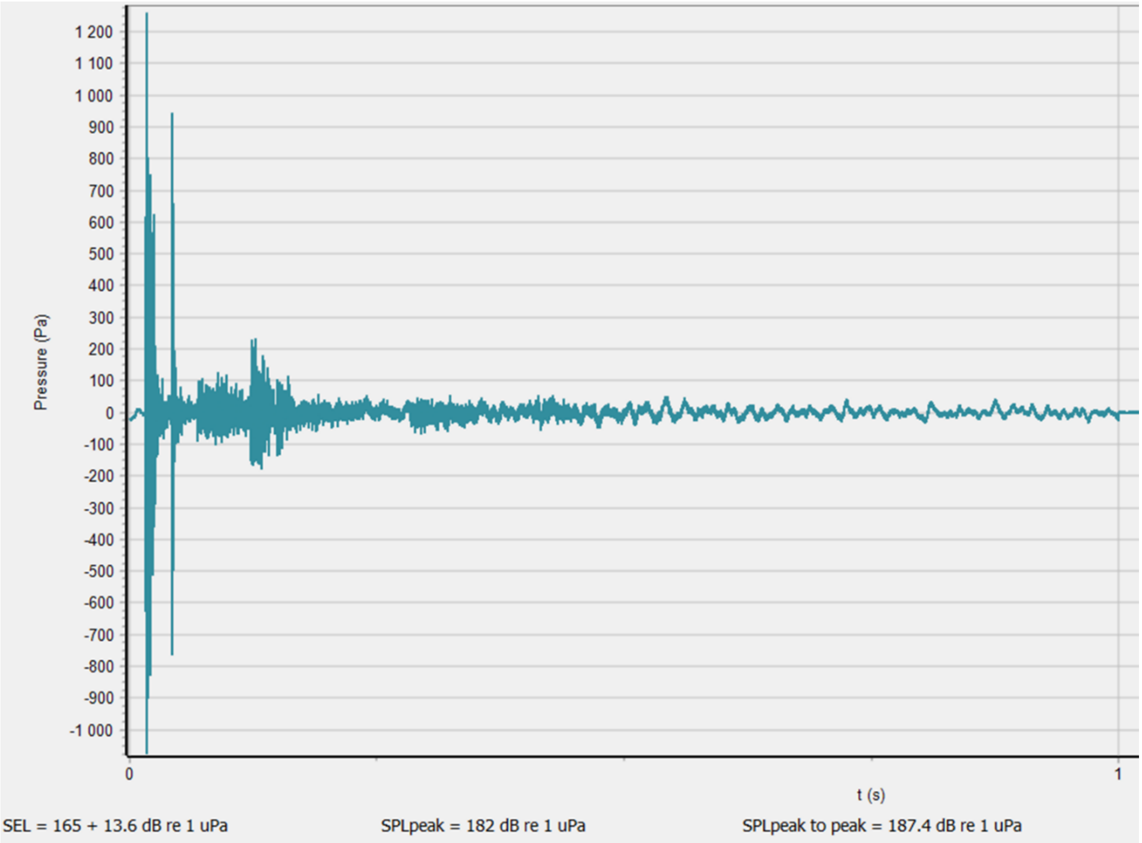

Fig 9. Input data for transient sound used in modelling software.Example for HY01. Original wav file measured at 150m distance upscaled to source level at 1 m from source.

A Fast Fourier Transformation (FFT) of the sound file (Audacity V2.2.2), showed a main frequency content of the signal between 50Hz and 10kHz (Fig 10) . Lower and higher frequencies are about 10dB lower and are not considered in the respective modelling because the contribute less than 1 % to the sound energy.

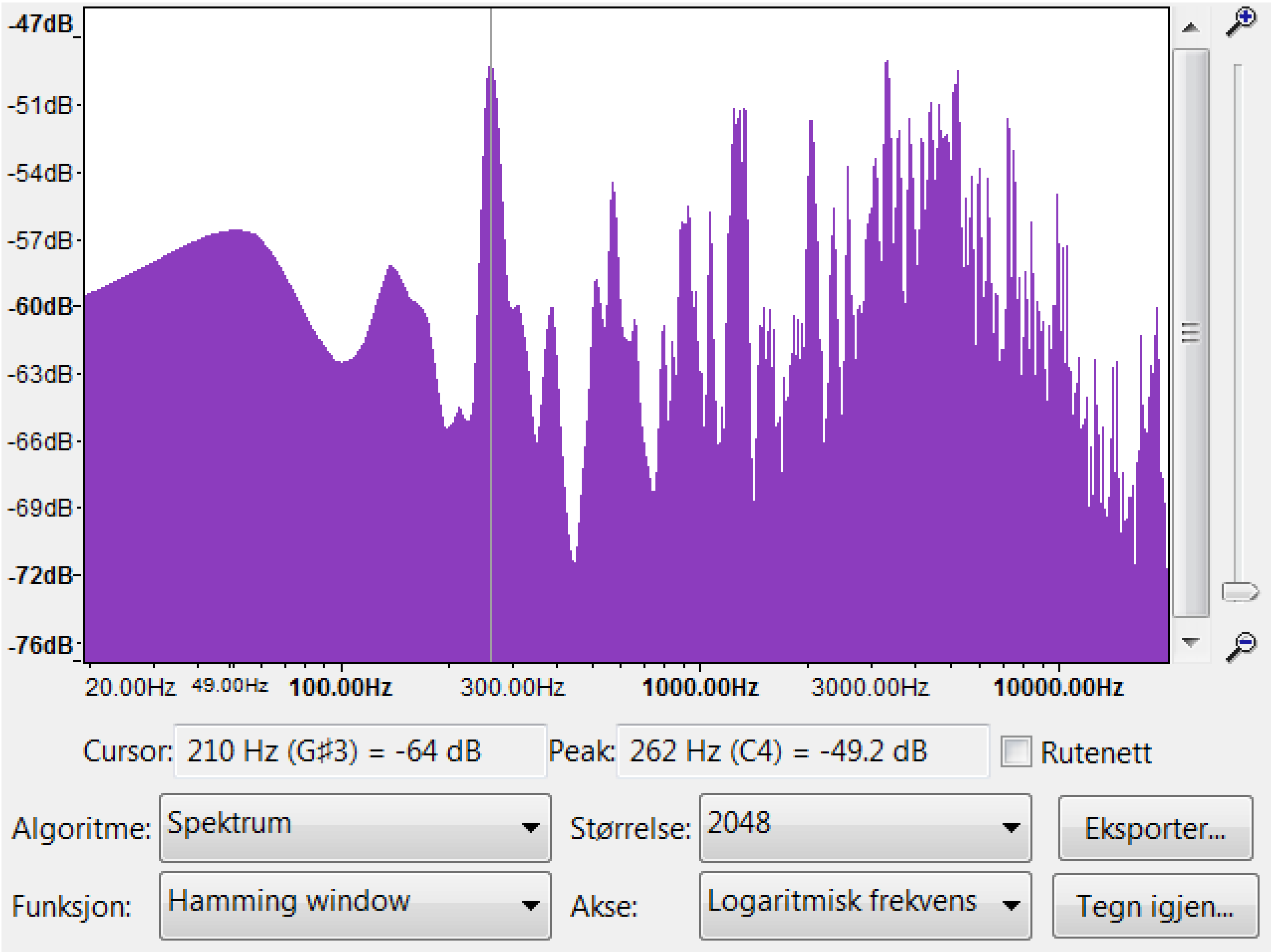

Fig. 10.

4.5 Sound propagation solvers

Continous sound

For frequencies 12.5Hz to 400Hz a solver for the parabolic wave equation was used, and for frequencies above 400 Hz a solver for ray tracing. Frequency for simulations was 12.5Hz to 16kHz.
Specific settings for parabolic wave equation an ray tracer solver in dBSea are given in appendix X

Impulsive sound
For calculation of SEL A ray tracer was used throughout the frequency spectrum. Frequency spectrum was 31.5Hz to 12.5kHz. For calculation of SPL a split solver with parabolic wave equation up to 400Hz and a ray tracer for higher frequencies.

5 Results

5.1 Continuous sound SPL.

The sound velocity profile used for the April and July simulations resulted in less propagation loss at distances from the sound sources for the April simulations (better propagation conditions), differences are relatively small (Fig.11). Because of this we use the simulation for April for the further assessment.

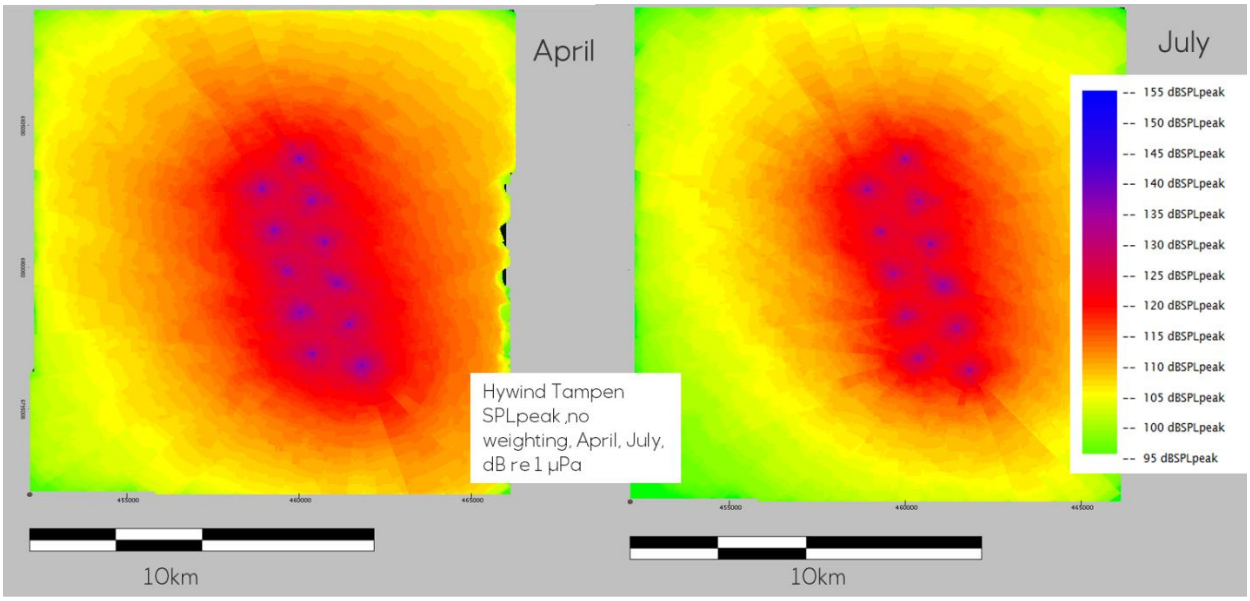

Fig. 11 Sound pressure levels SPLpeak for April and July simulation. Highest level from all depth projected to the surface.

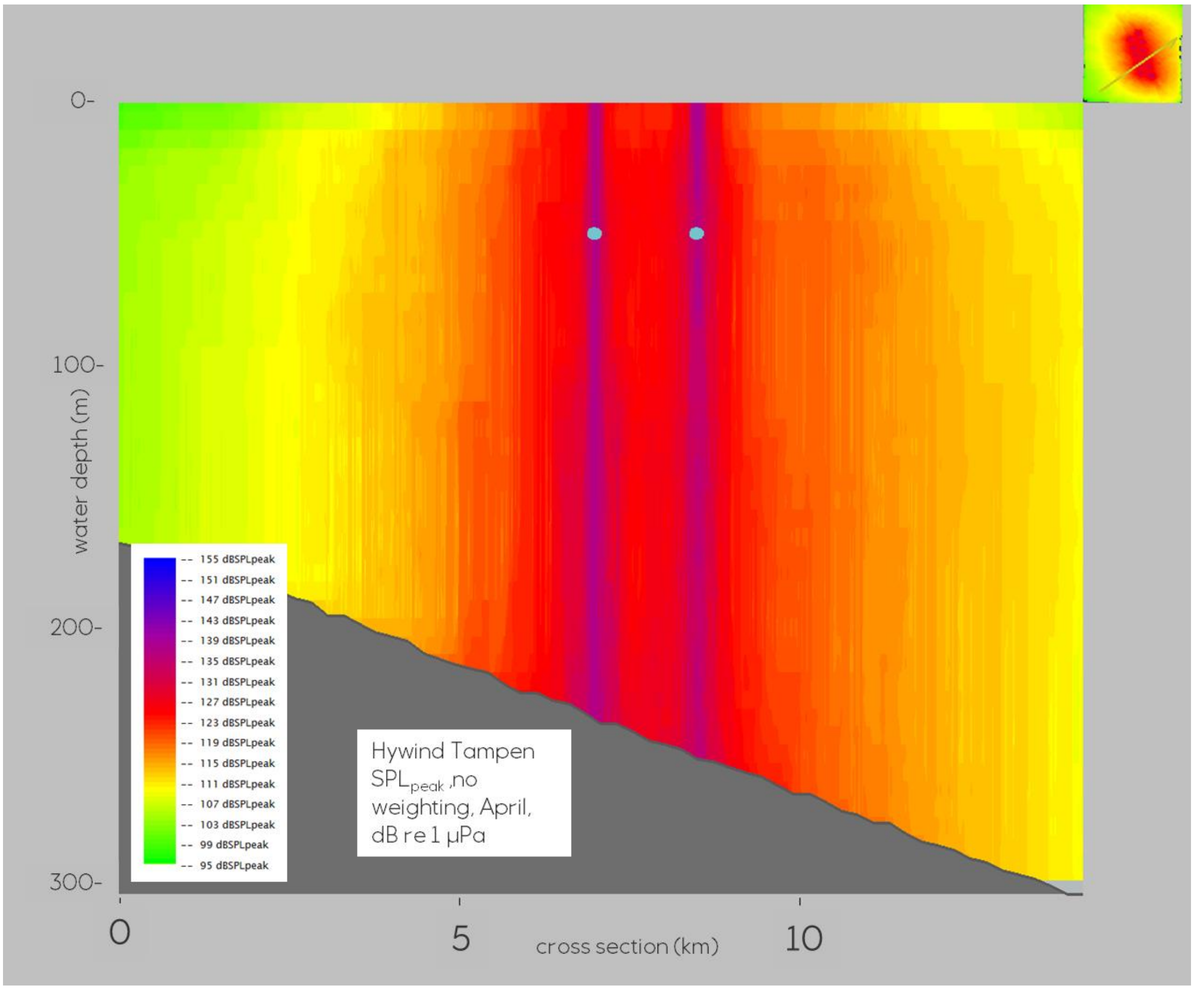

Fig 12 . Sound pressure levels SPLpeak for April across positions HY4 and HY8 (position of transect in insert)

Sound propagation around each wind turbine is almost circular with a slightly better propagation into the north-east direction where the water depth increases. Sound propagation is also fairly uniform at different water depth (Fig 12) with a slightly reduced sound strength at the surface.
In the risk assessment for possible impacts it is always the distance of the highest value that is considered, and all graphical displays show the highest value projected to the surface.

If a non-impulsive sound has the potential of exceeding the peak sound pressure level threshold associates with impulsive sound (Table 2) these tresholds are recommended for consideration according to the NOAA guedelines.
For the Hywind Tampen continuous sound none of the sound pressure thresholds for injury are exceeded.

The threshold for behavioural reaction of SPL 160 db re 1 µPa is not exceeded at any distance to the wind turbines. The lower threshold limit of SPL 120 dB re 1 µPa is about at 2000m distance to the wind mills (Fig 13). Ambient sound SPL in the area is about 112dB re 1µPa in average and 132dB re µPa at noisy days. The the indicated distance to the 120dB isopleth is also showing the audible distance at a days above average ambient sound. On days with average ambient sound levels the noise from Hywind Tampen will be audible to animals at about 4km.

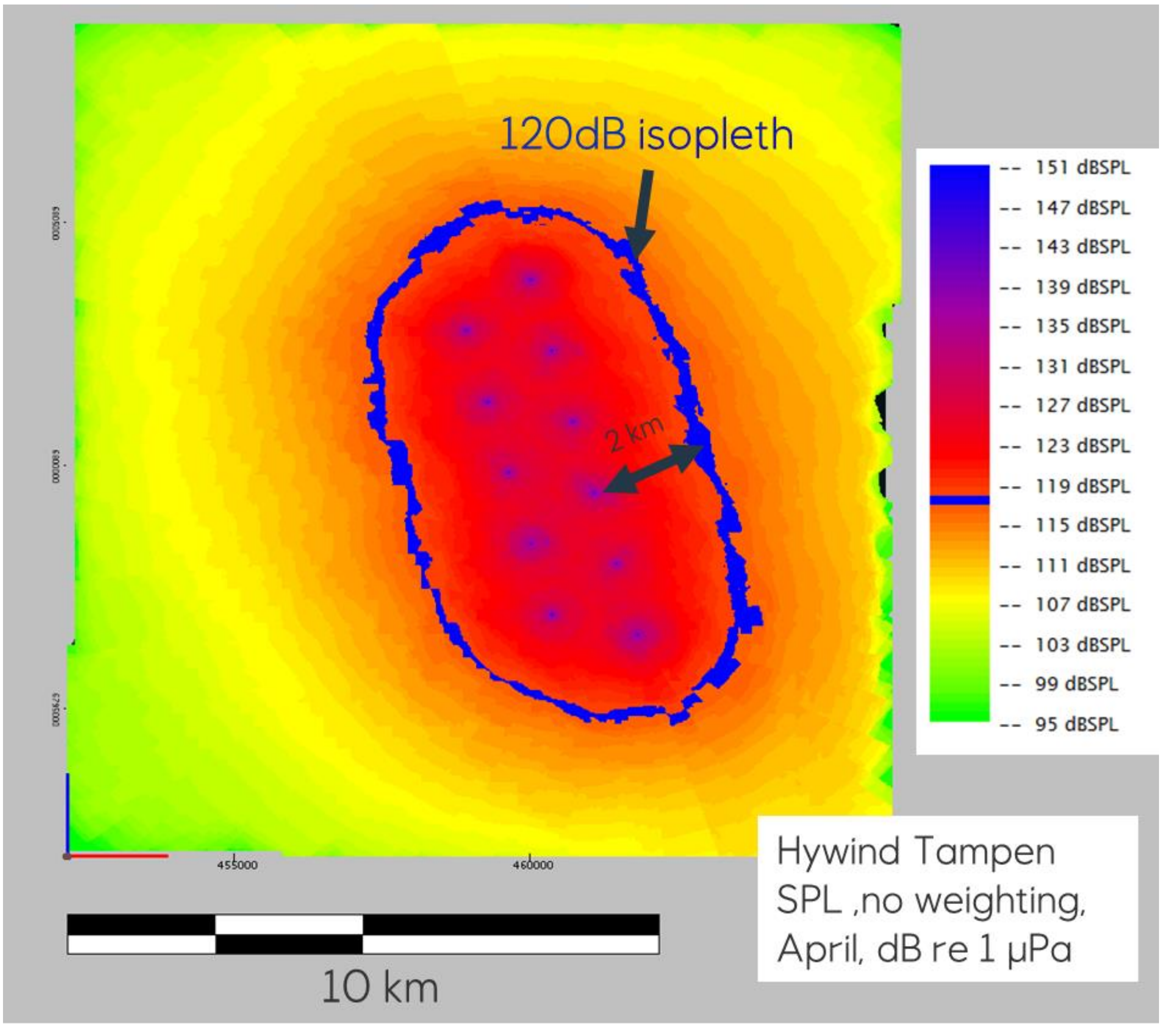

Fig. 13 Isopleth of the 120dB re 1 µPa threshold limit for behavioural disturbance (Table 4) around the Hywind Tampen windmills.

5.2 Continuous sound SEL

Sound exposure patterns follow the spatial pattern for sound pressure for the unweighted SEL calculations (Fig 14, SELcum24h unweighted). There are very small differences in the sound propagation when SEL weighted functions are use, because different frequencies propagate different..
Unweighted SEL and weighted SEL for all species groups from Table 2 are shown in Fig. 14.

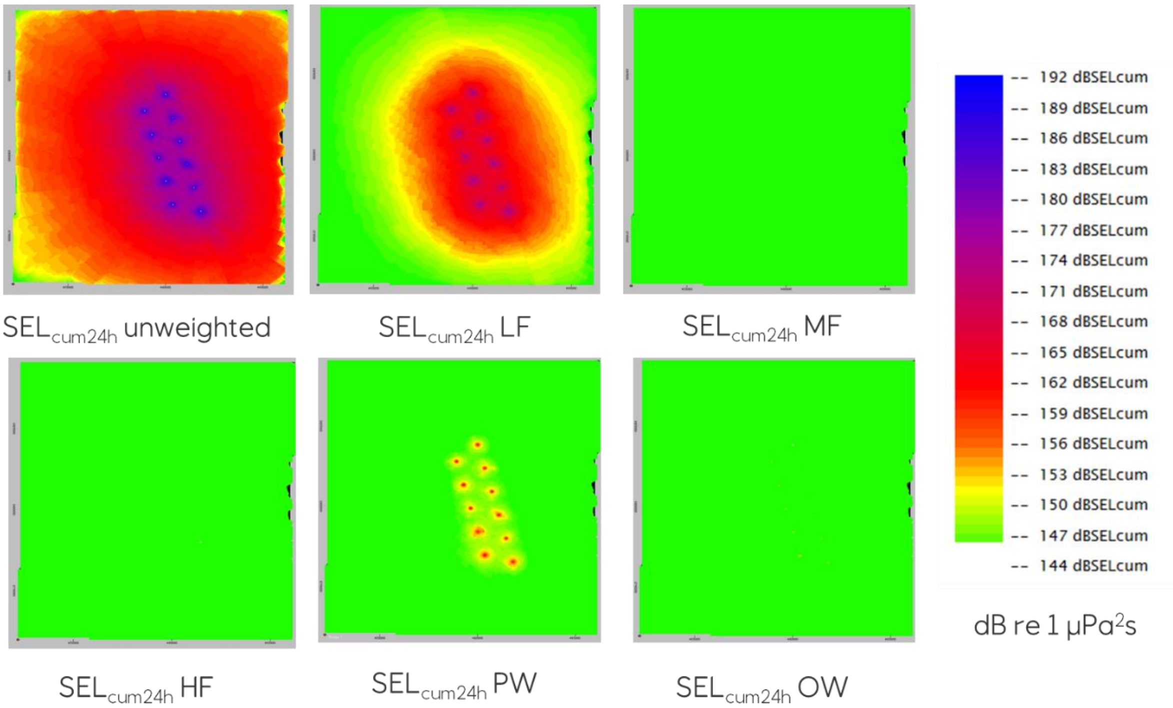

Fig.14 Weighted SEL values for groups of marine mammals according to table 6. .

NOAA criteria				
Project	L_E = SELcum re 1 µPa^{2}s			
Hywind Tampen operational sound				
Hearing group			range (average) (m)	range max (km)
PTS Onset Threshold levels non impulsive sound				
Low-Frequency (LF) Cetaceans	$L_{E,p,\ LF,24h}$	199 dB	NA	NA
Mid-Frequency (MF) Cetaceans	$L_{E,p,\ MF,24h}$	198 dB	NA	NA
High-Frequency (HF) Cetaceans	$L_{E,p,\ HF,24h}$	173 dB	NA	NA
Phocoid Pinnipeds (PW)	$L_{E,p,PW,24h}$	201 dB	NA	NA
Otariid Pinnipeds (OW)	$L_{E,p,\ OW,24h}$	219 dB	NA	NA
TTS onset thresholds for non-impulsive sounds				
Low-Frequency (LF) Cetaceans	$L_{E,p,\ LF,24h}$	179 dB	45	52
Mid-Frequency (MF) Cetaceans	$L_{E,p,\ MF,24h}$	178 dB	NA	NA
High-Frequency (HF) Cetaceans	$L_{E,p,\ HF,24h}$	153 dB	NA	NA
Phocoid Pinnipeds (PW)	$L_{E,p,PW,24h}$	181 dB	NA	NA
Otariid Pinnipeds (OW)	$L_{E,p,\ OW,24h}$	199 dB	NA	NA

Table 6. NOAA risk critaria for marine mammals and relevant distances for threshold values. NA shows that the respective threshold value is not exceeded.

5.3 Transient sound (snapping sound)

The SPLpeak at the source is with 203dB re 1 µPa just above the PTS threshold limit for high frequency cetaceans but will drop below this threshold at a short distance (around 1 meter) to the source. It is well below threshold limits for single and multiple impulses suggested by Southall (2007). This peak value corresponds to a SPL of 173dB re 1 µPa, this is below the threshold limit for injury but above the threshold values for behavioural disturbance of 160 dB re 1 µPa (strong reaction) and 140dB re µPa (mild reaction). The 140dB threshold limit for weak reaction would be exceeded at distances below 160m, those for the 160dB threshold for strong reaction at 16m form the source. It again has to be stressed that the available information on the origin of the transient sound only allows a coarse estimate.

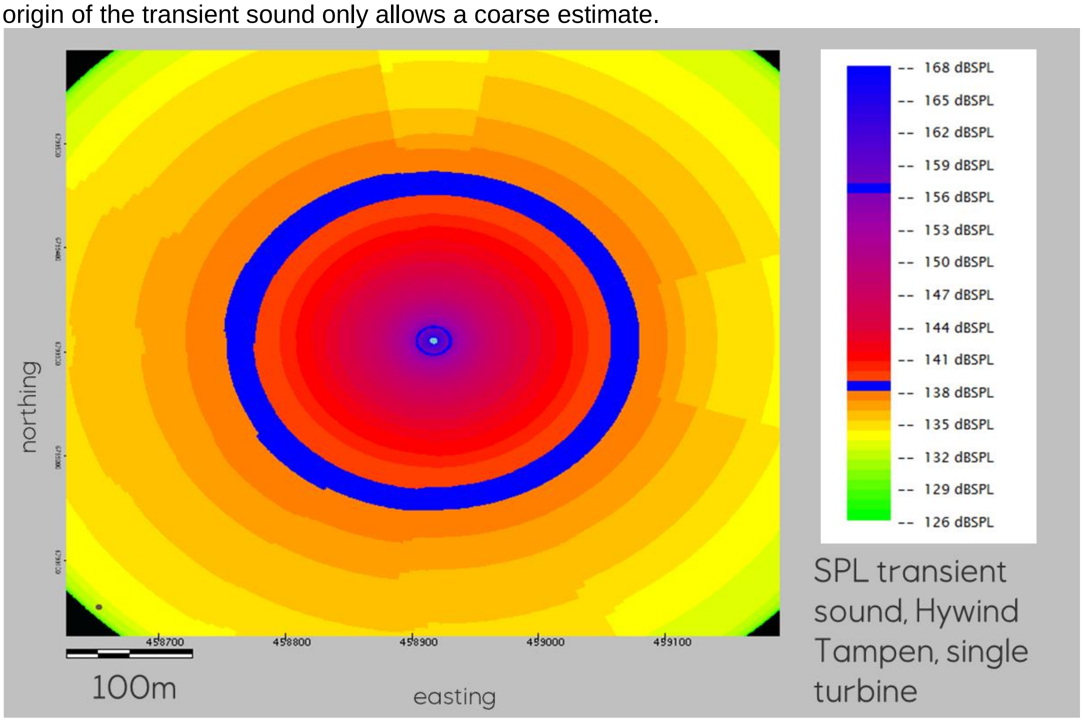

Fig. 15. SPL around a single turbine with indication of threshold limit for mild behavioural reaction to marine mammals. Average distance to the SPL 140 dB re 1µPa isopleth is 160m, those to the SPL 160 dB re 1 µPa isopleth is about 8m.

The SEL_{cum24h} values also stay below the threshold levels for injury (Fig. 16) for all groups of marine mammals..

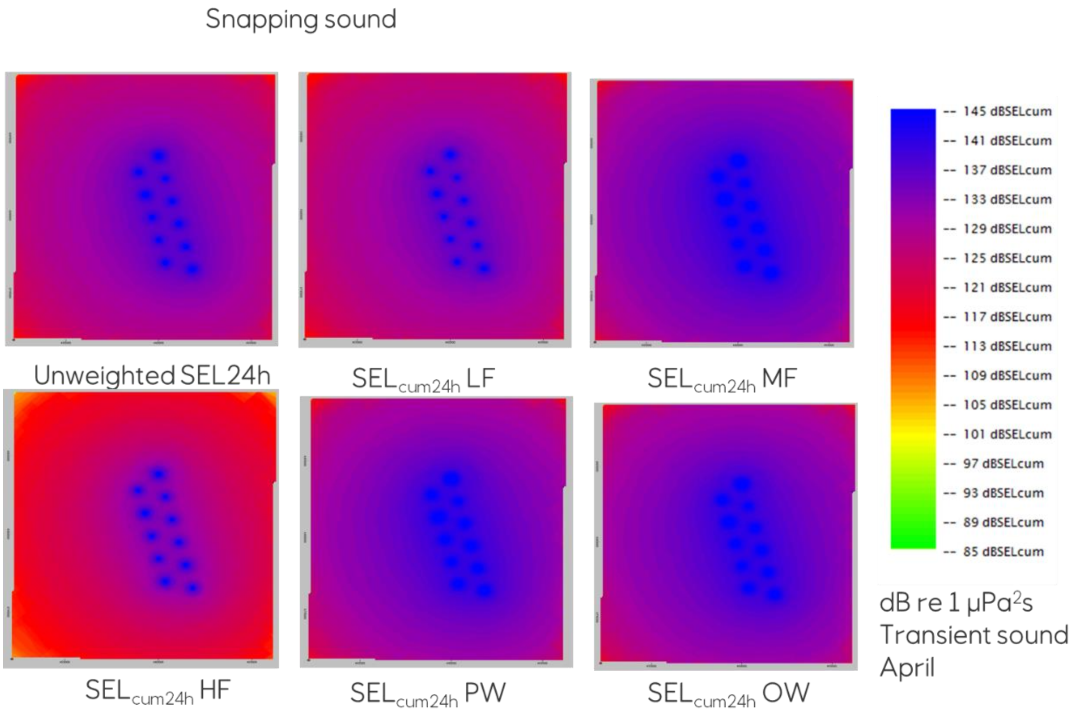

Fig 16. SELcum 24 of this transient sound as unweighted and weighted SEL_{cum24h} shows that the threshold limits for injury are not exceeded at any distance to the wind tubines.

6 Risk evaluation of sound originating from Hywind Tampen windturbines.

6.1 Continous sound evaluated on SPL and SEL metrics

The threshold limits for injury (PTS and TTS) are not exceeded in the vicinity of Hywind Tampen wind turbines except those for low frequency cetaceans where the respective SEL threshold limit is exceeded within a radius of 52m around each individual wind turbine. This however does not pose a risk to marine mammals. In order to receive/observe this threshold limit an animal from the group of the low frequency cetaceans has to be present within this zone for 24hours. The probability that this happens is almost zero. An actively moving/migrating animal will pass this zone within a few seconds, and even a none moving animal drifting with the currents will only be exposed for a short time. The ambient noise in the area is estimated to about 112 dB re 1 µPa SPL, this means the sound created by Hywind turbines is on average not audible to marine mammals beyond a distance of 4km.
The overall risk for marine mammals from continuous sound form Hywind Tampen during operations is evaluated as non existing.

6.2 Transient sound

Risk assessment for the transient is based on many assumptions related to the origin of the sound and the strength of the sound on it source. It is further not established if this so called “snapping” sound is an inherent property of the Hywind design or if it is a property only be found on the Hywind 1.
Risk assessment is included in this study because the strength of the snapping sound is close to some of the threshold values (SPL 180dB re 1 µPa for harassment B definition) and needs consideration in case it is an

inherent property of the Hywind design. It is highly recommended to verify the presence or absence of this feature on the Hywind Scotland installation. In case of absence this risk assessment has not to be repeated for future Hywind installations.
The risk is however evaluated as low in general. Higher sound pressures can only be expected very close to the sound source, and the the probability of being close to the source of the transient sound is small for any marine mammal. The sound energy animals would be exposed to if staying in the are for a longer period, is also relatively low and does not pose a risk. It can not be expected that animals stay for 24hours in the area, and even if they the received sound energy is below any threshold levels for injury. Behavioural reactions can be expected at relatively close distances to the wind turbines, e.g. avoiding. Though it is not expected that this has negative impact on individuals or populations of marine mammals.

Overall the risk for marine mammals originating from the transient sound is evaluated as non-existing.

Due to the risk of formally exceeding some threshold levels for the transient sound it is recommended to do sound measurements at newer Hywind installations, e.g. in Scotland, to find out if the new design of the mooring creates similar sound or not.

7 Appendix

JASCO 2011: Hywind Acoustic Measurement Report, Jasco Report NO 00229
Xodus 2015: Technical Note on Underwater Noise A-100142-S20-TECH-001

NOAA (2018): 2018 Revision to : Technical Guidance for Assessing the Effects of Anthropogenic Sound on Marine Mammal Hearing (Version 2). https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-acoustic-technical-guidance

Tollefsen, Christina D. S. (2013): Reccomendations for calculatintg sound speed profiles from field data. Defence R&D Canada Atlantic; Technical Memorandum DRDC Atlantic TM 2013-156

Ballard M.S and Lee Kevin M.2017. The Acoustics of Marine Sediments, Acoustics Today, volume 13 issue 3 Fall 2017