SAMS Scottish Association for Marine Science Xi Engineering Consultants

Characterisation of underwater operational noise of two types of floating offshore wind turbines

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Supergen Offshore Renewable Energy

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Executive Summary

The offshore renewable energy sector has grown rapidly in recent years. Floating Offshore Wind (FOW) will add significant additional capacity soon, but questions remain regarding long-term environmental impacts which could prove problematic for consenting. For example, given typical turbine lifespans up to 30 years, operational turbine noise emissions related to the machinery and mooring systems may constitute a continuous source of year-round underwater noise over several decades.

This project collected acoustic data from two floating offshore wind farms, currently deployed off the Scottish east coast: Kincardine and Hywind Scotland. At Kincardine five turbines rated at 9.5 MW were deployed on semi-submersible foundations, while at Hywind Scotland five 6 MW rated turbines were deployed on spar-buoys.

Like operational noise of fixed offshore wind turbines, noise emissions from FOW turbines were concentrated in the frequencies below 200 Hz and showed distinct tonal features, likely related to rotational speed, between 50 and 80 Hz at Kincardine and 25 and 75 Hz at Hywind Scotland. Median one-third octave band levels below 200 Hz were between 95 and 100 dB re 1 µPa at about 600 m from the closest turbine for both wind farms. These measured received levels are similar to those measured for operational noise from fixed offshore wind turbines at comparable distances. Emitted noise levels showed strong positive correlations with wind speed and slightly weaker positive correlations with wave height.

The biggest difference between fixed and floating offshore wind turbines in relation to underwater noise generation is mooring-related noise. During higher wind speeds the number of impulsive sounds or transients from mooring-related structures increased at both Kincardine and Hywind Scotland. Transients were observed more frequently at Kincardine compared to Hywind Scotland, at similar wind speeds, which was also illustrated by higher mean kurtosis values at the former location.

Source levels for turbine operational noise (25 Hz – 20 kHz) increased with wind speed at both recording locations. At a wind speed of 15 m/s operational noise levels were found to be about 3 dB higher at Kincardine (148.8 dB re 1µPa) as compared to Hywind Scotland (145.4 dB re 1 µPa), which might be a function of the different power ratings, gear box vs direct drive technology, and/or the difference in mooring structure of the two turbines (i.e., semi-submersible vs spar-buoy).

Assuming 15 m/s wind speed, predicted noise fields for unweighted sound pressure levels were above median ambient noise levels in the North Sea for maximum distances of 3.5 - 4.0 km from the centroid of the Kincardine 5-turbine array, and 3.0 - 3.7 km for the 5-turbine array at Hywind Scotland.

At both FOW farm locations, recorded porpoise detections were reduced at the recording site closest to the turbine compared to the site further away.

Overall, this work underscores the importance of considering the cumulative noise output of large FOW turbine arrays in marine spatial planning and environmental impact assessments of new projects, especially in marine regions where boundaries of several FOW projects overlap with one another or other marine space uses.

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1. Introduction

Following an increasing demand for clean energy, the offshore renewable energy sector, including Floating Offshore Wind (FOW) has grown rapidly in recent years (Figure 1). FOW is expected to add significant additional energy generation capacity in the near future and will expand global wind energy generation further into deeper waters and offshore habitats. While in 2018 the globally installed floating offshore wind capacity was 57 MW, by 2030 global capacity could be as high as 4.3 GW (Hannon et al. 2019). In 2022, 56% of the global FOW capacity was installed in UK and specifically, Scottish waters (Hannon et al. 2019). Because of this rapid expansion, questions remain regarding potential long-term environmental impacts which could generate delays in the consenting process.

Research of underwater noise impact from offshore wind energy on marine life has in the past concentrated on the construction phase, with a particular focus on pile driving (Graham et al. 2019, Thompson et al. 2020, Jones et al. 2021, Jézéquel et al. 2022). However, with increasing turbine size and their expansion into deeper waters, the operational noise of offshore wind turbines and turbine arrays has received more attention in recent years (Tougaard et al. 2020, Stöber & Thomsen 2021).

Operational underwater noise is expected to be similar between fixed and floating offshore wind turbines, as above water structures where most noise will be generated (e.g., tower, nacelle, turbine, and rotors) are comparable between these two forms of energy generation. In both cases, most emitted frequencies are expected in the lower frequencies (< 1 kHz) with tonal elements at frequencies related to gear meshing and their harmonics (e.g., Pangerc et al. 2016). The produced noise is generally comparatively low intensity, i.e., 10-20 dB lower than ship noise in the same frequency range (Madsen et al. 2006). However, in contrast to passing vessels, underwater noise produced by static FOW and fixed turbine arrays will become a relatively persistent source of underwater noise in the deployment areas. As is the case with chronic shipping noise, permanently increased underwater noise levels might create barrier effects, exclude animals from important habitats, increase stress levels, or result in a reduction of communication space (e.g., Clark et al. 2009, Rolland et al. 2012, Erbe et al. 2019).

Recent estimates of cumulative underwater noise from fixed offshore wind turbine arrays have highlighted that contributions from increasingly large arrays can change local soundscapes and should therefore be considered in Environmental Impact Assessments (EIAs) and Marine Spatial Planning (MSP) applications (Tougaard et al. 2020). Similar relationships between array size and cumulative operational noise generation are to be expected for FOW arrays but have not yet been assessed. Empirically validated noise propagation models and assessments that take turbine-related parameters and environmental context (e.g., turbine type, size, mooring type, wind speed, and ambient noise conditions) into account are therefore needed to inform the ongoing planning and consenting process for FOW installations.

Only a small number of field recordings of FOW turbines currently exist. The Hywind Demo turbine, rated at 2.3 MW, was the first full-scale FOW turbine and was recorded over a period of 148 days in 2011 at a test site off Stavanger, Norway (Martin et al. 2011). During this initial study, distinct operational noise measured at about 150 m distance from the turbine could be related to gear meshing and power generation and was reported to not exceed spectral density levels of 115 dB re 1 $\mu Pa^2 Hz^{-1}$ (Xodus Ltd. 2015). However, it should be noted that this study lacked detail and figures should therefore be considered preliminary (Putland et al. 2021). A second study at Hywind Scotland also

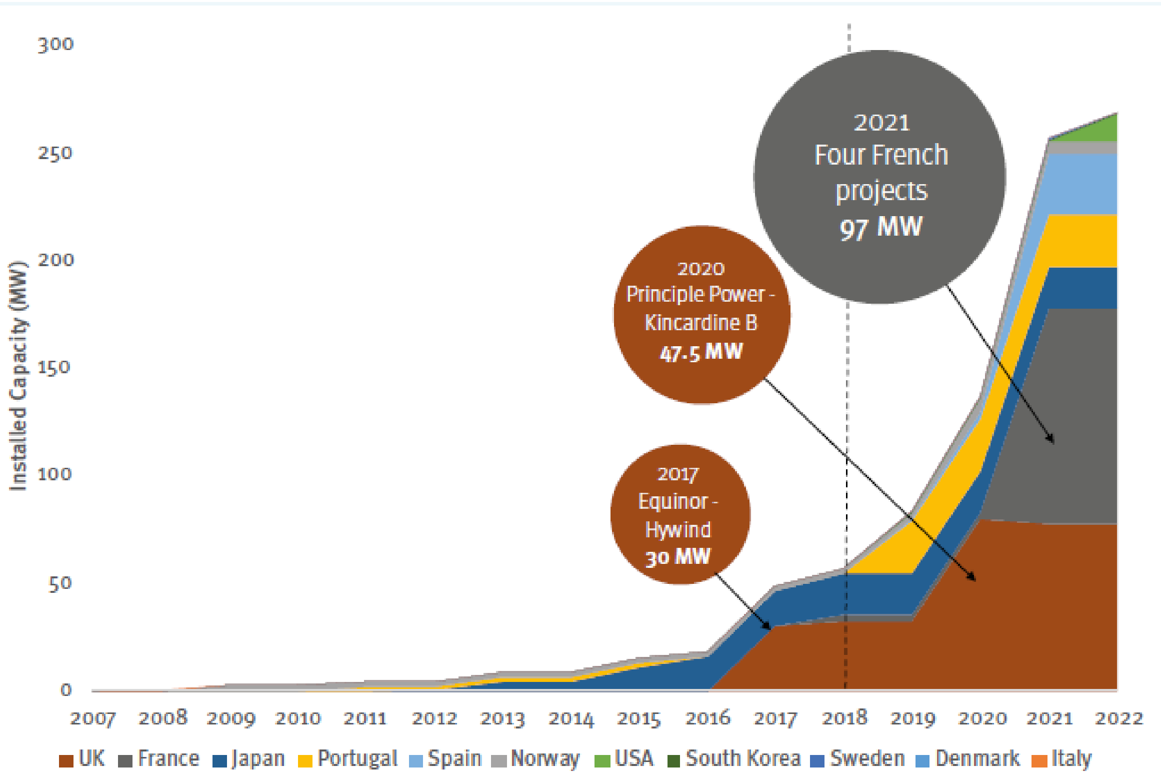


Figure 1. Cumulative installed capacity of floating offshore wind projects up to 2022 by country, excluding projects in early planning and decommissioning. Figure from: Hannon et al. (2019).

found distinct low-frequency tonal signatures of the turbine operational noise reported median broadband source levels (back calculated to 1 m) ranging from 162.5 to 167.2 dB re 1 μPa^2m^2 (Burns et al. 2022). Individual turbines at Hywind Scotland have a capacity of 6 MW[1].

The biggest difference between floating and fixed wind turbine structures is their mode of attachment to the seabed. There are three main FOW support structure designs (i.e., tension-leg, spar-buoy and semi-submersible design) in current use, which are all moored instead of fixed to the seabed and can be deployed in different water depths (Figure 2). The tension-leg platform design is the least developed of the three designs. In this design, steel cables, wire ropes and chains connect a partially submerged platform standing on 3-5 arms to the seafloor. Tension-leg platforms are less mobile compared to the other designs and are therefore likely best for intermediate water depths (e.g., 70-200 m; Putland et al. 2021). Spar-buoy designs have the largest sub-surface structure, a cylinder that is attached to anchored mooring lines. While the large draft provides stability, assembly of these structures needs to be performed in waters deeper than 100 m and is thus logistically challenging. The design might also prove difficult to maintain with increasing turbine size, as the cylinder size will have to increase to support the weight increase of the turbine (Putland et al. 2021). Semi-submersible platform structures have an active ballast system to keep the platform upright, which involves transferring water between linked columns onto which the turbine is installed. This platform design has a relatively large surface area which increases stability. The platform is anchored to the bottom by several mooring lines (Putland et al. 2021).

[1] https://www.equinor.com/energy/hywind-scotland; last accessed 01/03/2023.

The flexible mooring lines consist of steel cables, chains or wired ropes, and are dependent on water depth and turbine structure type; they are a source of noise which is not present in fixed offshore wind turbine arrays. While the long, flexible cables are not likely to produce a lot of strumming noise, periodic tension releases along the cables of the mooring system may produce ‘snaps’, as described from initial data recorded near Hywind Demo (Martin et al. 2011). At 150 m from the source, measurement of these transient sounds (containing energy over the full recording bandwidth of 0-20 kHz) indicated received peak sound pressure levels could exceed 160 dB re 1µPa (Xodus Ltd. 2015).

The current project aimed to add additional data about the operational and mooring related underwater noise produced by FOW turbine arrays. The immediate aim of the project was to characterise and understand noise outputs of two existing FOW turbine arrays, with different structural designs, that at the time of writing are deployed in Scottish waters. At the first site (Kincardine; Principle Power/Grupo Cobra) FOW turbines are built on semi-submersible platforms, while at the second site (Hywind Scotland; Equinor), turbines are installed on spar-buoy platforms.

This report characterises the noise signature and summarises the measured underwater received noise levels produced by the two different turbines and deployment structure designs under varying environmental conditions. The results will be compared to the limited existing data on FOW turbine underwater noise (Martin et al. 2011, Xodus Ltd. 2015, Burns et al. 2022). Furthermore, sound propagation modelling has been used to estimate operational source levels of the operating turbines and predict cumulative noise outputs of the deployed small-scale (i.e., 5 turbines) arrays of FOW turbines. Together, these data will underpin initial assessments of the spatial footprint of operational FOW turbine noise and the potential risks such sustained noise may pose to acoustically sensitive marine species, such as marine mammals.

Figure 2. Fixed and floating offshore wind structure designs. Fixed turbines: Driven monopile, steel jacket tower; Floating turbines: semi-submersible, tension leg platform, spar-buoy (left to right). (Illustration: Joshua Bauer, National Renewable Energy Laboratory; US Department of Energy).

2. Methodology

2.1. Data Collection

2.1.1. Study Sites, Turbine Models and Deployment Platforms

Both FOW turbine array sites at which data for this project were collected are located on the north-east coast of Scotland. The Kincardine offshore wind farm (Principle Power/Grupo Cobra) is located about 15 km off the coast of Aberdeen, while Hywind Scotland (Equinor) is about 25 km to the east of Peterhead (Figure 3). With capacities of 30 MW (Hywind) and 47.5 MW (Kincardine), these two pilot projects are the first and biggest in the world to deploy electricity generating FOW turbine arrays (Figure 1; Hannon et al. 2019). Hywind Scotland started generating power in 2017[2] and Kincardine in 2021[3]. Both sites have five turbines currently installed. While the turbines at Kincardine are mounted on semi-submersible platforms, the turbines deployed at Hywind are installed on spar-buoys (Figures 2 & 4; Table 1). In both cases, platforms are anchored to the seabed with three mooring cables. Water depth at the Kincardine site is in the range of 60-80 m, while the Hywind array is deployed in slightly deeper waters, ranging from 95-120 m.

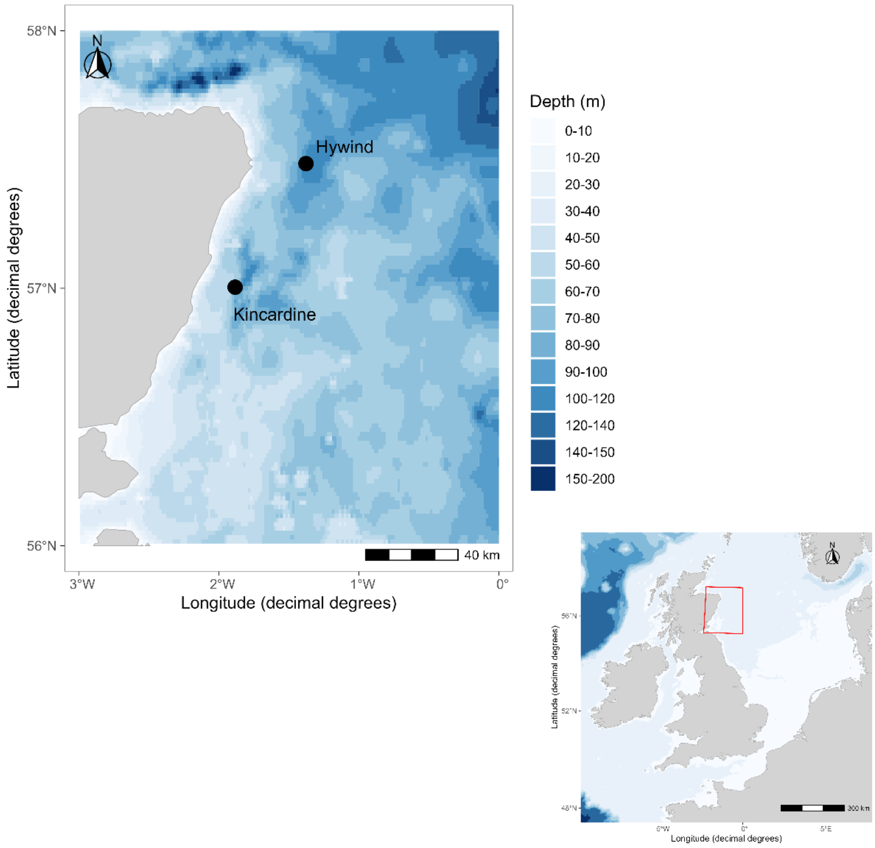


Figure 3. Overview map showing the location of the Kincardine and Hywind Scotland floating offshore wind farm sites off north-east Scotland. Red box in in inset indicates detailed map area in relation to UK coastline.

[2]https://www.equinor.com/energy/hywind-scotland; last accessed 01/03/2023.
[3] https://www.grupocobra.com/en/proyecto/kincardine-offshore-floating-wind-farm/; last accessed 01/03/2023.

Figure 4. Pictures of floating offshore wind turbine mounted on a semi-submersible platform at Kincardine (left), and on a spar-buoy platform at Hywind Scotland (right).

The turbines deployed at Kincardine are Vestas V164 models, rated at 9.2 MW and with a rotor diameter and tip height of 164 m and 190 m, respectively. These turbines are gearbox-driven turbines whereas the turbines deployed at Hywind Scotland are direct-drive turbines with a capacity of 6 MW and rotor diameter and tip height of 154 m and 178 m, respectively (Table 1).

Table 1. Overview of turbine parameters for Kincardine and Hywind Scotland offshore wind farms.

	Kincardine[4]	**Hywind Scotland[5]**
Number of Turbines	5	5
Turbine Model	Vestas V164	Siemens SWT-6.0-154
Rated Power (MW)	9.5	6
Rotor Diameter (m)	164	154
Tip height (m)	190	178
Drivetrain	Gearbox	Direct Drive
Foundation	Semi-submersible	Spar-buoy
Mooring lines (per Turbine)	3	3

2.1.2. Mooring Design and Deployment setup

At both study sites, three acoustic monitoring moorings were deployed at varying distances from the target turbine. Moorings were deployed at distances of 200 m and 600 m from turbine KIN01 and

[4] https://www.principlepower.com/projects/kincardine-offshore-wind-farm; last accessed 01/03/2023.
[5] https://www.equinor.com/energy/hywind-scotland; last accessed 01/03/2023.

1,500 m from KIN04 at Kincardine; and 300 m, 600 m and 2,400 m from turbine HS5 at Hywind Scotland (Figure 5). The acoustic moorings followed two designs.

At the sites furthest away from the monitored turbines, and the Hywind Scotland 300 m site, the mooring consisted of a one-channel broadband sound recorder (ST500HF; Ocean Instruments, NZ[6]) and an automated echolocation click detector (F-POD; Chelonia Ltd., UK[7]). The recorders were approximately 5 m above the seabed and moored with a sub-surface recovery system (VR2AR acoustic release; Innovasea, Canada[8] with an ARC rope canister; RS Aqua, UK[9]) using chain link weights of about 70-90 kg (Figure 6, Tables 2 & 3).

The moorings at the 200 m and 600 m sites consisted of a lander with a 4-channel recorder (ST4300STD) paired with an F-POD (i.e., Kincardine 600 m and Hywind Scotland 300 m) or a back-up one-channel acoustic broadband recorder (ST300HF) (i.e., Hywind Scotland 600 m) (Figure 7, Tables 2 & 3). The hydrophones of the 4-channel array were approximately 1 m above the seabed, whilst the F-POD or ST300HF was deployed about 5 m above the seafloor.

The total deployment period at the Kincardine site lasted from 02/11/2021 to 25/01/2022. However, the 1,500 m mooring was recovered on 12/12/2021 already (Table 2). The recorders at the Hywind Scotland site were deployed for one month, from 14/05/2022 to 15/06/2022 (Table 3).

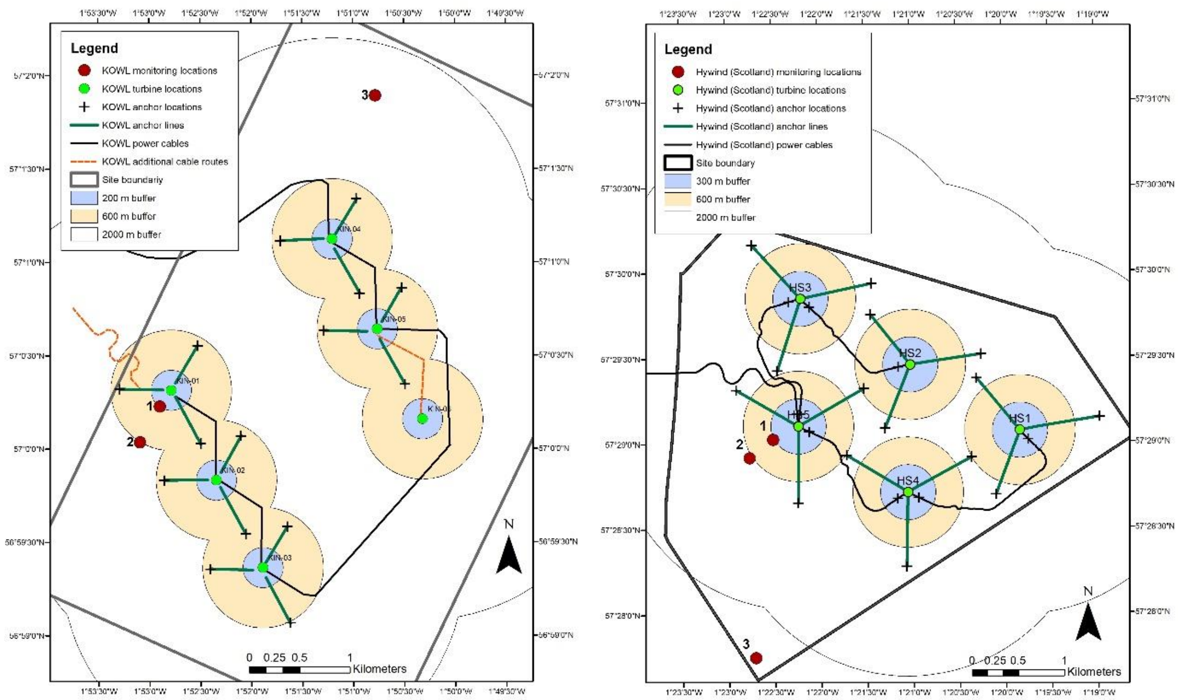


Figure 5. Overview of Kincardine (left) and Hywind Scotland (right) wind farms. Turbine locations indicated by green circles; anchor points indicated by black crosses. Red dots indicate acoustic recording locations at 200 m, 600 m, and 1,500 m (Kincardine); and 300 m, 600 m, and 2,400 m (Hywind Scotland). Note that only 5 turbines had been deployed at the Kincardine site. The site in the lower right corner had not been and will not be developed in the future.

[6] https://www.oceaninstruments.co.nz; last accessed 01/03/2023.
[7] https://www.chelonia.co.uk/; last accessed 01/03/2023.
[8] https://www.innovasea.com/fish-tracking/products/acoustic-receivers/; last accessed 01/03/2023.
[9] https://rsaqua.co.uk/; last accessed 01/03/2023.

Table 2. Deployment information for Kincardine (Principle Power/Grupo Cobra). Full deployment period: 02/11/2021 – 25/01/2022. The 1,500 m mooring was recovered on 12/12/2021. ST = Soundtrap (broadband recorder); ch = channel.

Distance to Closest Turbine	Latitude/Longitude (°N/E)	Acoustic Recording Instruments	Water Depth/ ST above Seabed (m)	Duty Cycle (ST)
200 m	57.004 / -1.883	ST4300STD (4ch)	65.7 / 1.0	15 min / hour
600 m	57.000 / -1.887	ST4300STD (4ch); F-POD	64.7 / 1.0	15 min / hour
1,500 m	57.031 / -1.848	ST500HF (1ch); F-POD	77.1 / 5.0	Continuous

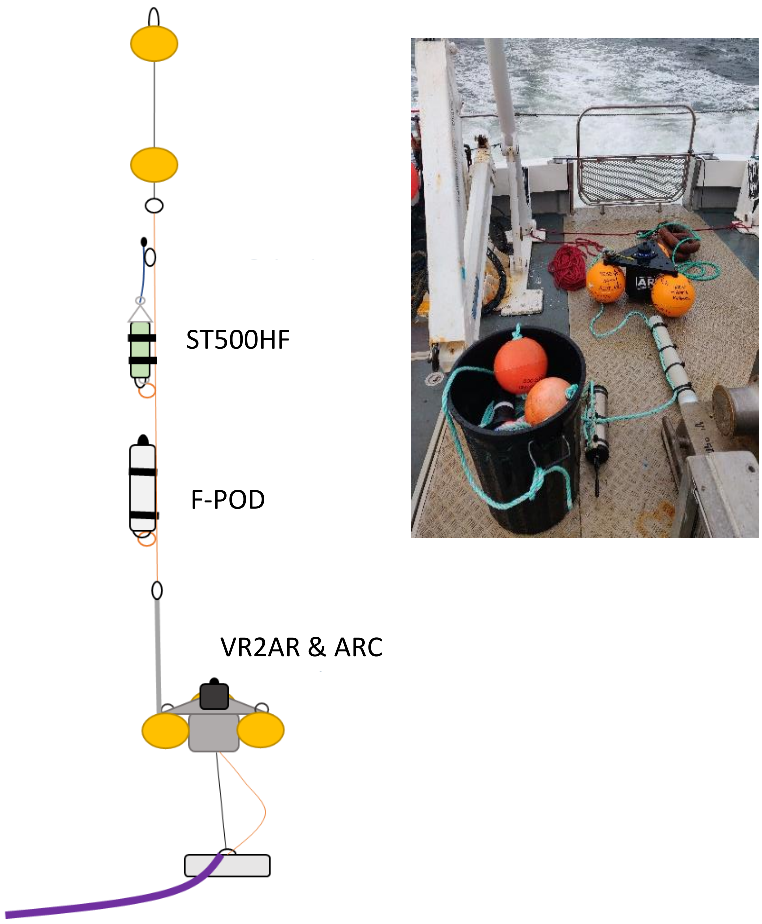


Figure 6. Mooring design for single channel ST500HF/F-POD deployments using a VR2AR/ARC acoustic release system for mooring recovery. Deployed at Kincardine 1,500 m and Hywind Scotland 300 m and 2,400 m (see Tables 2 & 3). Figure of mooring design adapted from L Scala (Seiche).

Table 3. Deployment information for Hywind Scotland (Equinor). Full deployment period: 14/05/2022 – 15/06/2022. ST = Soundtrap (broadband recorder); ch = channel. Note that data collection at the mooring positioned at 300 m failed due to a faulty hydrophone.

Distance to Closest Turbine	Latitude/Longitude (°N/E)	Acoustic Recording Instruments	Water Depth/ ST above Seabed (m)	Duty Cycle (ST)
300 m	57.484/ -1.377	ST500HF (1ch); F-POD	105 / 5.0	Continuous
600 m	57.482/ -1.381	ST4300STD (4ch); ST 300HF (1ch)	104 / 1.0 & 5.0	15 min / hour; Continuous
2,400 m	57.463/ -1.379	ST500HF (1ch); F-POD	104 / 5.0	Continuous

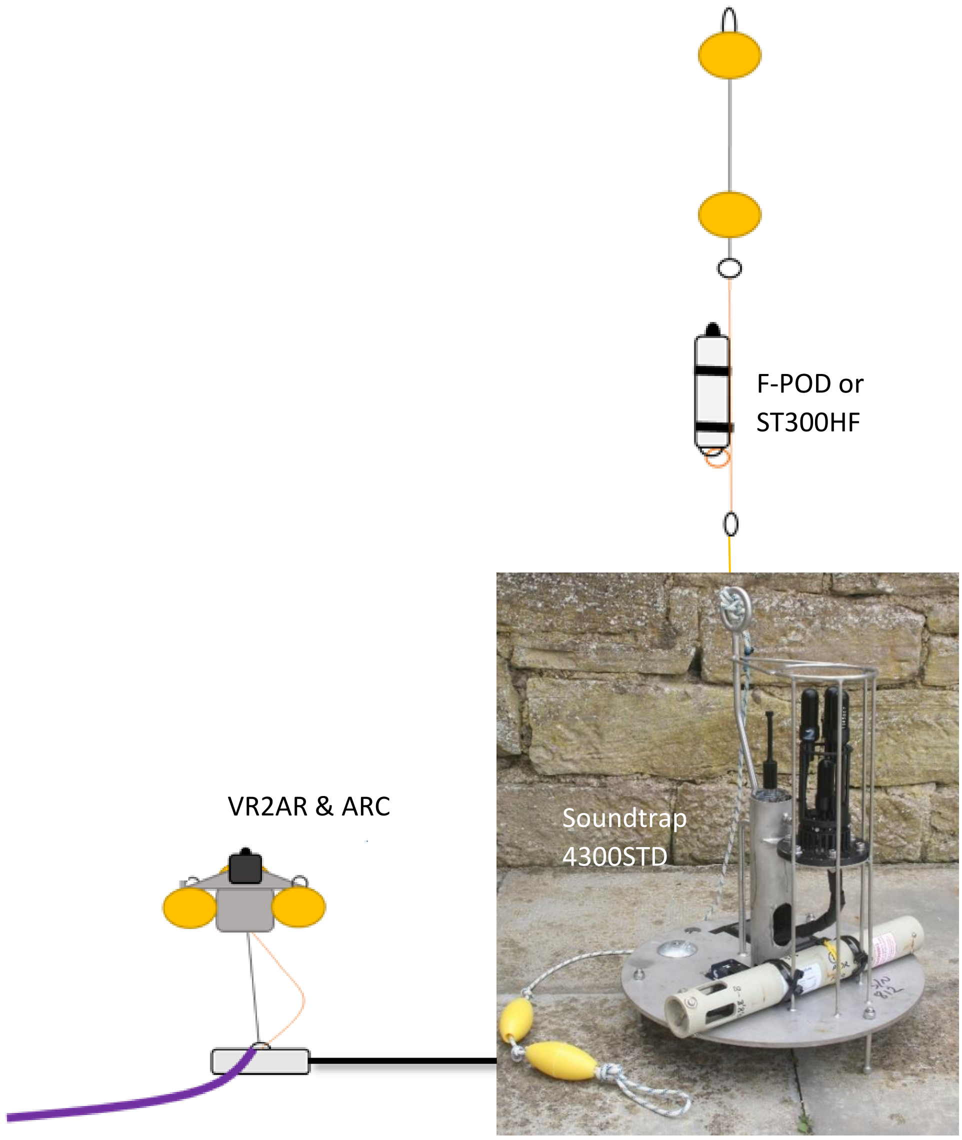


Figure 7. Mooring design for4-channel ARU/F-POD deployments using a VR2AR/ARC acoustic release system for mooring recovery. Deployed at Kincardine 200 and 600 m and Hywind Scotland 600 m (see Tables 2 & 3). Figure of mooring design adapted from L Scala (Seiche).

2.1.3. Recording Parameters

The landers deployed closest to the target turbine (i.e., 200 m and 600 m at Kincardine and 600 m at Hywind Scotland) were 4-channel ST4300STD recorders with four high-frequency hydrophones (HTI-99-HF; High-Tech, Inc.[10]) in a tetrahedral arrangement (Graham et al. 2023; Figures 6 & 7). A duty-cycled (1 minute on/29 minutes off) motion datalogger (OpenTag; Loggerhead Instruments[11]) was attached to the acoustic lander array to confirm that the device remained stationary and the position of the hydrophones in relation to the turbine did not change over time. Hydrophones were spaced 5 cm apart to attempt estimating the bearings of higher frequency sounds ('snaps') produced by the turbine mooring structure, following methods developed to track small cetaceans around marine structures (Gillespie et al. 2020, Graham et al. 2023). While 4-channel recordings were successfully collected during this project, they have not yet been analysed in detail and bearing estimations to 'snaps' will thus not form part of the current report. However, this analysis is planned as part of more in-depth future analyses of the noise signature created by the turbine mooring structures.

Recordings made with the 4-channel broadband recorders (ST4300STD) were duty-cycled and 15 minutes of each hour were recorded, using a 96 kHz sample rate and 16-bit resolution. The first channel of the 4-channel recording was selected for noise level and signal structure analysis (see section 2.2). The single-channel broadband recorders (ST500HF and ST300HF; Tables 1 & 2) were setup to record continuously at a sample rate of 96 kHz and a 16-bit resolution. All recorders thus provided an effective analysis bandwidth of 10 Hz – 48 kHz.

The F-POD autonomous echolocation click detector was used for monitoring harbour porpoise activity in the vicinity of the turbine arrays. Comparable to its precursor the C-POD, the device detects click trains in the range of 20-170 kHz and allows porpoise detections at ranges of up to a few hundred metres (Dähne et al. 2013, Chelonia Ltd. 2023). Contrary to broadband acoustic recorders, which record the full acoustic signal for detailed post-processing after deployment, automated click detectors process data in the field and only record selected features of signals such as frequency, time, and amplitude characteristics. The recorded click detection data were summarised as detection positive minutes (DPM) for harbour porpoises (*Phocoena phocoena*). The F-PODs were programmed using the FPOD.exe software provided by the manufacturer (Chelonia Ltd., UK). Devices recorded continuously with a default 'Limit on clicks per minute' of 16,000, and the 'High pass filter' set to 20 kHz. A tilt sensor recorded the POD's deflection from vertical and the tilt switch, which turned the device off when it was close to horizontal, was activated. All other F-POD settings were left as per the manufacturer's default setup.

2.2. Acoustic Data Analysis

Long-term spectral averages (LTSA; in dB re 1 µPa/√Hz) showing power spectral density levels over the full analysis bandwidth averaged over 30 seconds were generated and viewed using PAMGuard (Gillespie et al. 2008).

All available data were subset by the number of operational turbines and only periods with all five turbines in operation were used for subsequent analyses. To count as operational, or 'on', every

[10] http://www.hightechincusa.com; last accessed 01/03/2023.
[11] https://www.loggerhead.com; last accessed 01/03/2023.

turbine had a power output greater than 20 kW. For 'off', all turbines had a power output less than 20 kW. Data points where only some turbines were 'on', and others were 'off' were discarded.

No attempt was made here to isolate noise levels of individual turbines. The resulting cropped dataset was manually checked for loud (i.e., > 10 dB signal-to-noise ratio) vessel noise and data were sub-divided into a full and cleaned dataset, from which periods of obvious vessel and dolphin presence were deleted. Since median noise levels were similar between both data sets, subsequent analyses and source level determination were carried out using the full data set.

After initial inspection of the acoustic raw data, sound pressure levels (SPL; in dB re 1 µPa) were quantified in one-third octave bands with nominal centre frequencies from 25 Hz – 40 kHz over a 1-second time window, using the one-third octave level (TOL) function in PAMGuide, implemented in MATLAB (Merchant et al. 2015, The Mathworks 2021). In addition, peak sound pressure levels (peak SPL in dB re 1 µPa) were computed for each one-third octave band using a 1-second time window, by applying a custom-written MATLAB script. All TOL data were aggregated, correlated with, and plotted by wind speed, significant wave height and surface velocity using R (R Core Team 2022).

Wind speed and operational data, such as rotational speed per minute (RPM), were provided by the developers. For Kincardine, operational data were unavailable for some of the turbines from 02/11/2021 – 16/11/2021, and this period was thus excluded from analysis. At Kincardine average wind speed for each turbine was provided on a 10-minute resolution. At Hywind Scotland windspeed was measured at the nacelle of each turbine (i.e., about 100 m above sea level) and resampled at a 1-second resolution.

Current velocity data (in m/s) and significant wave height data (in m) for the deployment periods at Kincardine and Hywind Scotland were obtained from the EU Copernicus Marine Service products NORTHWESTSHELF_ANALYSIS_FORECAST_PHY_004_013[12] (dataset MetO-NWS-PHY-qh-SSC), and NORTHWESTSHELF_ANALYSIS_FORECAST_WAV_004_014[13] (dataset MetO-NWS-WAV-hi), respectively. Quarter-hourly instantaneous surface horizontal velocity data were extracted for the physical ocean model grid point closest to the KIN01 (Kincardine; Figure 5) and HS5 (Hywind Scotland; Figure 5) wind turbines, and residual sea surface current speed derived from the eastward and northward sea water velocity components. Likewise, hourly instantaneous sea surface significant wave height was also extracted for the model grid point closest to the KIN01 and HS5 turbines.

Studies on terrestrial mammals have shown that kurtosis values of impulsive sounds may play an important role in determining auditory injury (Hamernik et al. 2003). Kurtosis, which describes the 'tailedness' of the probability distribution of sound pressure values, has therefore recently been suggested as a useful metric to assess the impact of impulsive signals in soundscape assessments (Martin et al. 2020, Wilford et al. 2021). While Gaussian noise (and wind dominated underwater noise) is represented by kurtosis values of about 3, a kurtosis value of 40 represents the threshold above which a signal is considered impulsive (Wilford et al. 2021). To characterise and compare the impulsiveness of the recorded turbine signals, kurtosis was quantified over 30-second analysis windows using a custom-written script implemented in MATLAB.

[12] https://doi.org/10.48670/moi-00054; last accessed 01/03/2023.
[13] https://doi.org/10.48670/moi-00055; last accessed 01/03/2023.

2.2.1. Impulse Detection and Filtering

During the initial review of the raw data, two noise sources related to the operating turbines were identified. The first was noise associated with the operation of the turbines, i.e., from the generator, and passing blades, which is more prominent at low frequencies. The second is noise associated with the movement of mooring lines holding the turbines in place, which could be observed as infrequent transient broadband 'impulse' noise of short duration (about one second), with higher frequency content. An example of the measured one-third octave SPL time series measured at Kincardine 200 m is shown in Figure 8.

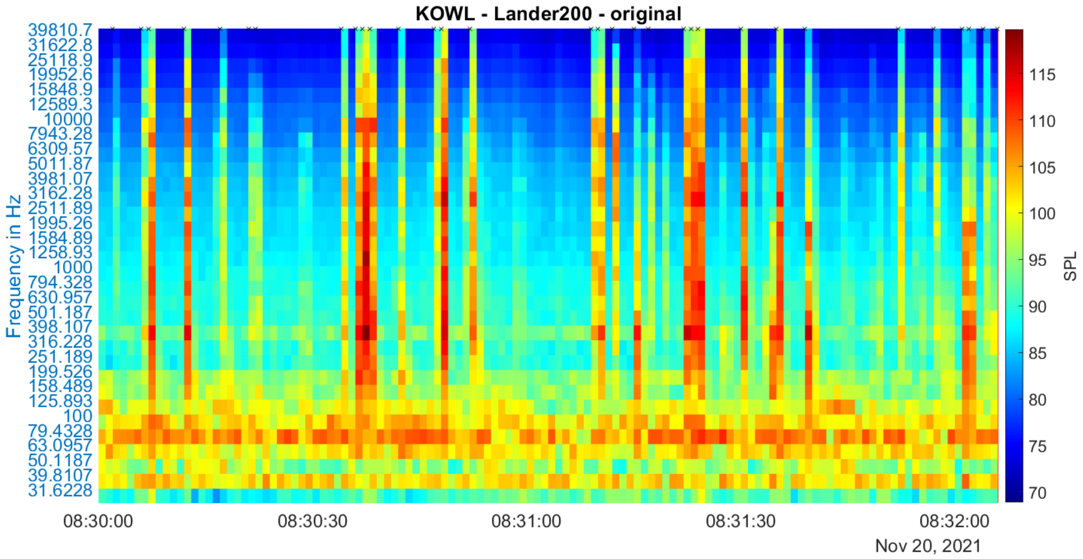


Figure 8. Example of one-third octave sound pressure levels (SPL; in dB re 1 µPa) measured at the Kincardine 200 m lander, with impulse noise events visible as broadband, short duration noise. Noise associated with the turbine operation is most prominent at lower frequencies (< 100 Hz).

To characterise the source level of the operational turbines, it is desirable to analyse the turbine operational and impulse noise separately. The following procedure was used to identify periods when operational noise or impulse noise dominated the measured noise levels.

1. Calculate the *k*-point (k = 60) moving average of every one-third octave frequency band data point.
2. Disregard any one-third octave bands below frequency F = 900 Hz.
3. Count every occasion where the SPL in each one-third-octave band is greater than the corresponding moving average value by threshold T = 1 dB.
4. Where for any data point of third-octave band SPLs, P = 50 % or more of the one-third octave bands have been counted as having a SPL greater than the k-point moving average by at least T dB, that data point is marked as containing an impulse noise event.

The occasions where impulse noise was detected were then filtered out of the data. An example of the filtered data sets (operational and transients) for the Kincardine 200 m data is shown in Figure 9.

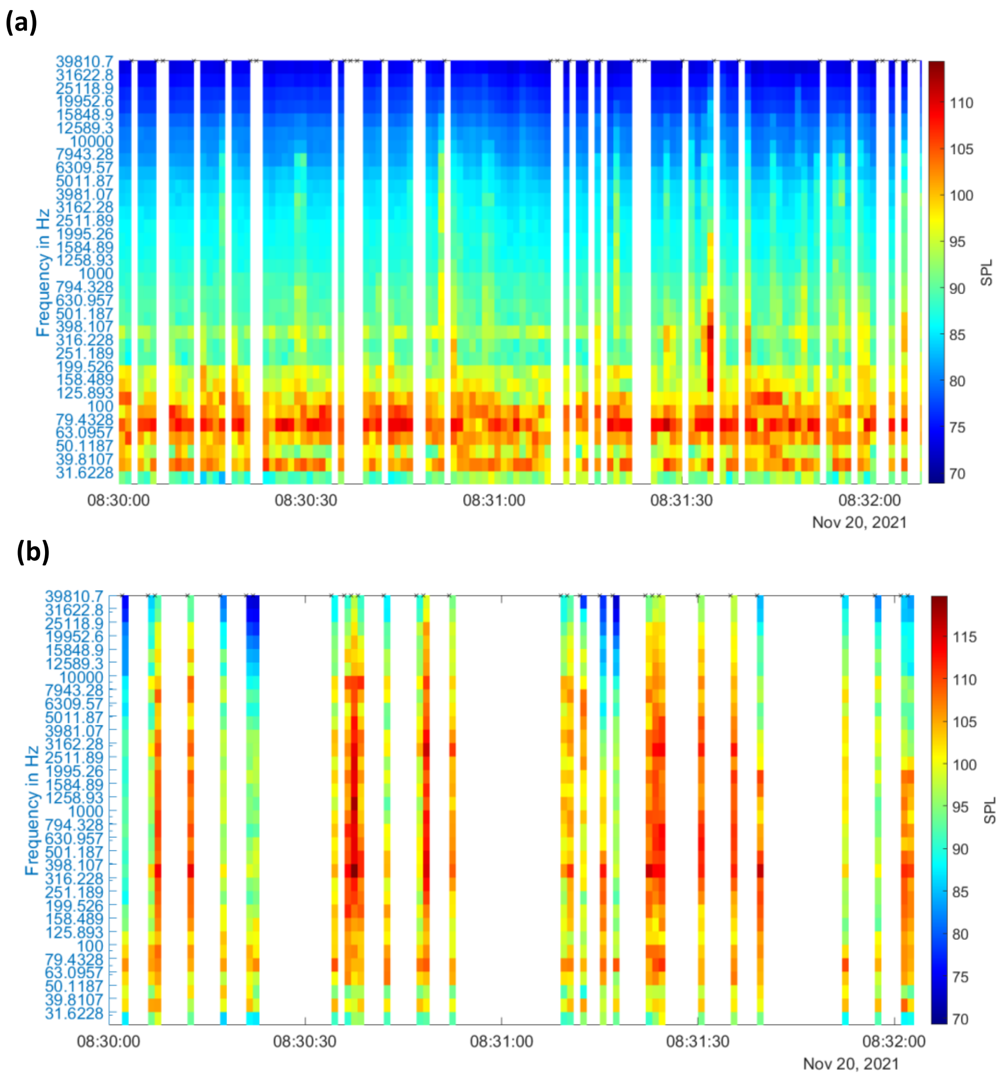


Figure 29. Example of one-third octave sound pressure levels (SPL; in dB re 1 µPa) measured at the Kincardine 200 m lander, filtered to remove significant impulsive noise events (a) and to remove non-impulsive sections of data (b).

The logarithmically averaged SPL of the filtered data in each one-third octave band was calculated over 1-minute intervals, and the mean turbine power and wind speed (at the closest turbine to the acoustic recorder) was also calculated for each 1-minute interval.

For source level calculations (see section 2.3.1), the data set was sorted into rounded 'bins' against wind speed (Figure 10). For example, the 4 m/s wind speed bin includes averaged wind speeds from ≥ 3.5 m/s to < 4.5 m/s. For each wind speed bin, the median SPL of the entire set of 1-minute sections of operational noise data, for each one-third octave band, was calculated, along with the standard deviation of the whole data set. Additionally, for each wind speed bin, the median SPL of the entire set of impulse noise data, for each one-third octave band, was calculated, along with the standard deviation of the whole transient noise data set. The impulse noise data were not logarithmically averaged into 1-minute intervals, instead the median across every impulse of the data set was taken (Figure 9b). Where there was only one event in each wind speed (and therefore the median would be that data point), that bin was discarded (Figure 10).

Data from each acoustic recorder was subjected to the impulse detection and filtering processing individually, applying the same analysis settings.

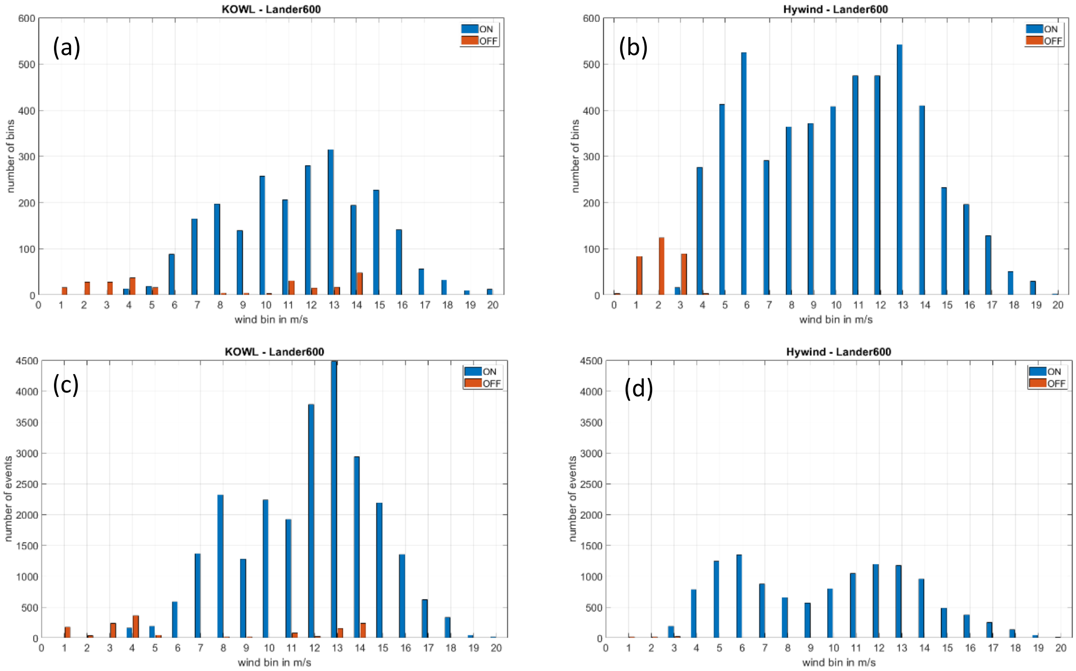


Figure 45. Number of 1-minute operational noise events, by wind speed bin, collected by the lander deployed at 600 m from the closest turbine for Kincardine (a) and Hywind Scotland (b). Number of transient events collected by the same lander for Kincardine (c) and Hywind Scotland (d). Blue histogram ('on') = all turbines with power output > 20 kW. Red histogram ('off') = at least one turbine with power output < 20 kW.

2.3. Sound Field Modelling

2.3.1. Approach and Assumptions

The transmission loss between floating wind turbines and the acoustic recorders were modelled using a combination of a parabolic equation solver and ray tracing. The modelled transmission loss values were combined with measured TOL and peak SPLs, excluding the noise from transient events (see section 2.2.1) to determine the source levels related to operational noise from floating wind turbines.

Far-field operational underwater noise was modelled at third-octave bands between 25 Hz and 20 kHz. Noise propagation was modelled at low frequency using a parabolic equation solver and at high frequency using a ray tracing approach. The parabolic equation solver is range dependent and is most appropriate for low frequency modelling when the seabed sedimentary sequence is deeper than the water column (see section 2.3.2.3). A sensitivity analysis was conducted to determine the frequency at which solver switching occurred and it was found that the results were stable when the model switch occurred at 315 Hz (i.e., modelled with the parabolic equation solver for third-octave bands below 315 Hz).

The source levels were calculated by backward propagation modelling from the nearest hydrophone (acoustic array lander at 200 m at Kincardine, and the lander at 600 m at Hywind Scotland). Source levels related to wind speeds of 6, 9, 12 and 15 m/s were calculated based on equivalent measured sound pressure levels. Identical modelling assumption were used for the backward propagation models and the far-field operational noise models.

The modelling approach assumed that the five foundations at Kincardine and Hywind Scotland each emit the same noise levels as a function of frequency. The turbines are modelled as points sources representing the semi-submerged foundations at 15 m below the surface for Kincardine and the spar-buoys at 39 m below the surface for Hywind Scotland, respectively. The median source level values were calculated when all five turbines were operational; the backward propagation models therefore used five sources placed at their correct geometric positions.

2.3.2. Modelling Environment

2.3.2.1. Geometry

The positions of turbines were based on information provided by Principle Power/Grupo Cobra (Kincardine) and Equinor (Hywind Scotland). The bathymetry values used to model noise propagation are based on the UKHO data which were downloaded from https://seabed.admiralty.co.uk/ on 03/11/2022:

- 2009 HI1155 Todhead Point to Bosies Bank Blk4 4m SB
- 2009 HI1155 Todhead Point to Bosies Bank Blk6 8m SB
- 2009 HI1155 Todhead Point to Bosies Bank Blk3 4m SB
- 2009 HI1155 Todhead Point to Bosies Bank Blk5 8m SB

2.3.2.2. *Sound Profile*

Table 4 details the sound speed profile used in all noise propagation models (Bailey 1978).

Table 4. Speed of sound with depth after (Bailey 1978).

Depth (m)	Speed of Sound (m/s)
0	1504.49
10	1503.01
20	1501.51
30	1496.19
40	1487.31
50	1484.08
60	1481.94
70	1480.93
80	1480.32
90	1480.09
100	1480.25
110	1480.42
120	1480.58
130	1480.75

2.3.2.3. *Seabed*

The geo-acoustic profile of the seabed of the models was based on the profile described in (Burns et al. 2022) (Table 5).

Table 5. Geo-acoustic model for Hywind Scotland as described in (Burns et al. 2022).

Depth (m)	Speed of Sound (m/s)	Density (kg/m^3)	Attenuation (dB/wavelength)
0	1716.4	1950	0.89
0.7	1483.2	1385	0.44
7.6	1559.5	1620	0.325
25	1586.2	1645	0.46
50	1631.8	1695	0.705
100	1716.7	1790	1.055
200	1904.5	1995	1.055

3. Results

3.1. Data Overview

Across all deployed recorders a total of 89 days of broadband acoustic data were recorded at both Kincardine and Hywind Scotland. In addition, a total of 128 days of click detections were collected at two of the Kincardine recording sites and 64 days of click detection data were collected across two sites at Hywind Scotland (Table 6).

To use the same broadband data across all recorders within each site, the final dataset for each recorder deployed at Kincardine was cropped to 22 days (02/11/2021 - 23/11/2021) and 25 days at Hywind Scotland (14/05/2022 - 07/06/2022). As explained above, the period from 02/11/2021 to 16/11/2021 were excluded from wind speed correlation analyses due to missing data.

Table 6. Total available recording days (including deployment and recovery days) for broadband acoustic recorders (BB) and automated click detectors (F-POD) deployed at the Kincardine and Hywind Scotland recordings sites**.** Full deployment period at Kincardine: 02/11/2021 – 25/01/2022. The 1,500 m mooring was recovered on 12/12/2021. Full deployment period at Hywind Scotland: 14/05/2022 – 15/06/2022. Full analysis period, for which data were available for all recording locations at each wind farm, highlighted in bold.

Recording Site	Distance to Closest Turbine (m)	Acoustic Recorder	Recording Start	Recording End	Total Days BB/F-POD
Kincardine	200	ST4300STD (4ch; ch1)	**02/11/2021**	**23/11/2021**	**22**
	600	ST4300STD (4ch; ch1)	02/11/2021	24/11/2021	23
		F-POD	02/11/2021	24/01/2021	84
	1500	ST500HF (1ch)	02/11/2021	12/12/2021	44
		F-POD	02/11/2021	12/12/2021	44
Total					**89/128**
Hywind Scotland	300	ST500HF (1ch)	--	--	No data
		F-POD	14/05/2022	15/06/2022	32
	600	ST4300STD (4ch; ch1)	**14/05/2022**	**07/06/2022**	**25**
		ST300HF (1ch)	14/05/2022	15/06/2022	32
	2400	ST500HF (1ch)	14/05/2022	15/06/2022	32
		F-POD	14/05/2022	15/06/2022	32
Total					**89/64**

3.2. Measured Received Sound Levels (Raw Data)

Long-term spectral averages for the raw data recorded at the 600 m lander at both Kincardine and Hywind Scotland are compared in Figure 11. At both sites most energy is concentrated below 500 Hz. While both sites show likely mooring-related impulsive noise, these broadband transients are observed more frequently at the Kincardine site (Figure 11a) compared to the Hywind Scotland site (Figure 11b).

For both Kincardine and Hywind Scotland, data collected at 600 m to the closest turbine showed median one-third octave band levels below 200 Hz to be around 95 - 100 dB re 1µPa (Figure 12). At

Kincardine, median noise levels were slightly higher at the 200 m compared to the 600 m recording location, as expected due to the reduced distance to the operational turbine (Figure 12a). In contrast, median noise levels for the 10 kHz centred one-third octave band were about 75 dB re 1µPa at both Kincardine and Hywind Scotland (Figure 12).

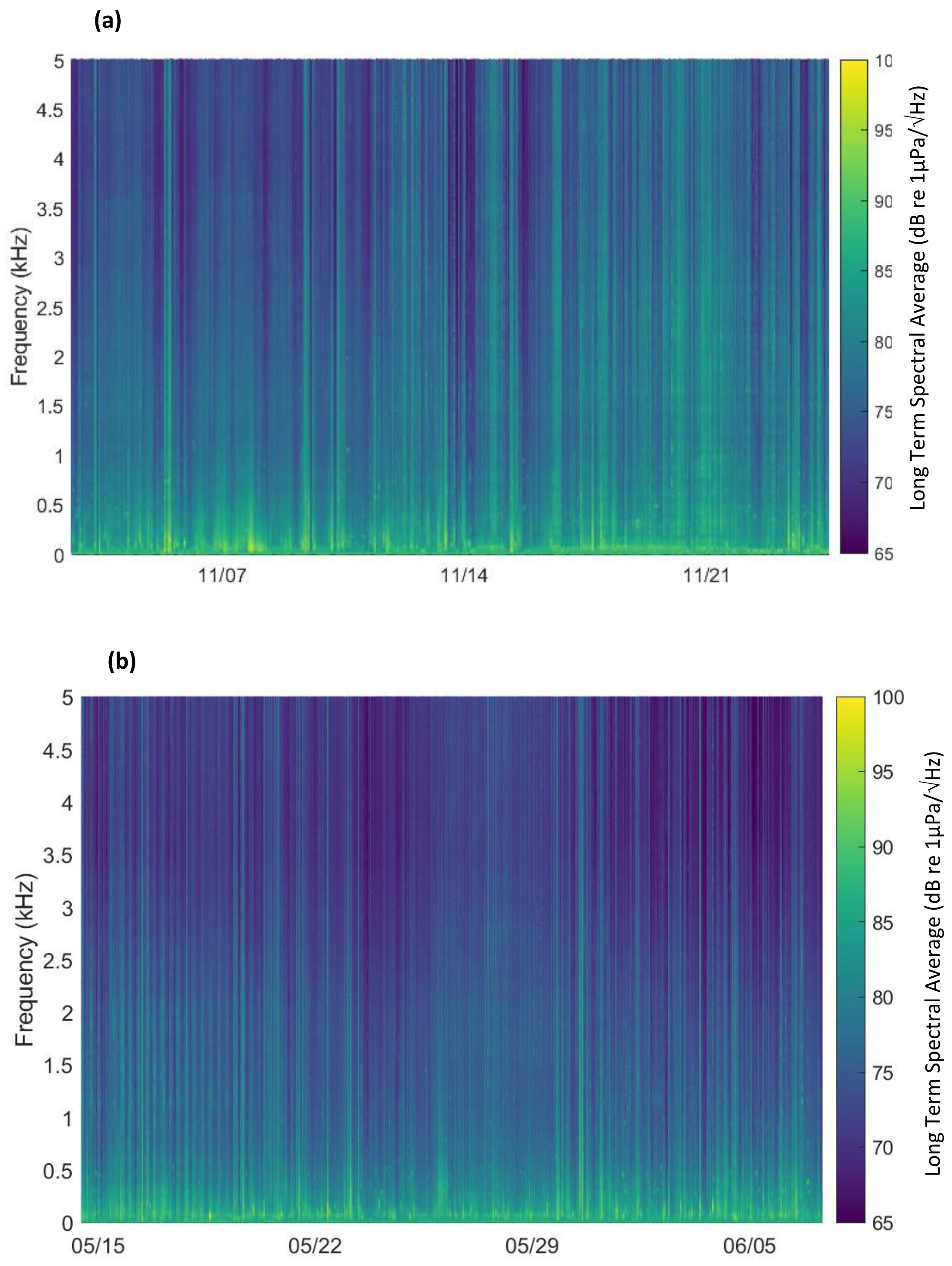


Figure 53. Long-term spectral average (LTSA) plot of the full dataset recorded at the 600 m site at (a) Kincardine and (b) Hywind Scotland. Data decimated to 10 kHz; FFT size: 512, Hop size: 256; averaged over 30 seconds.

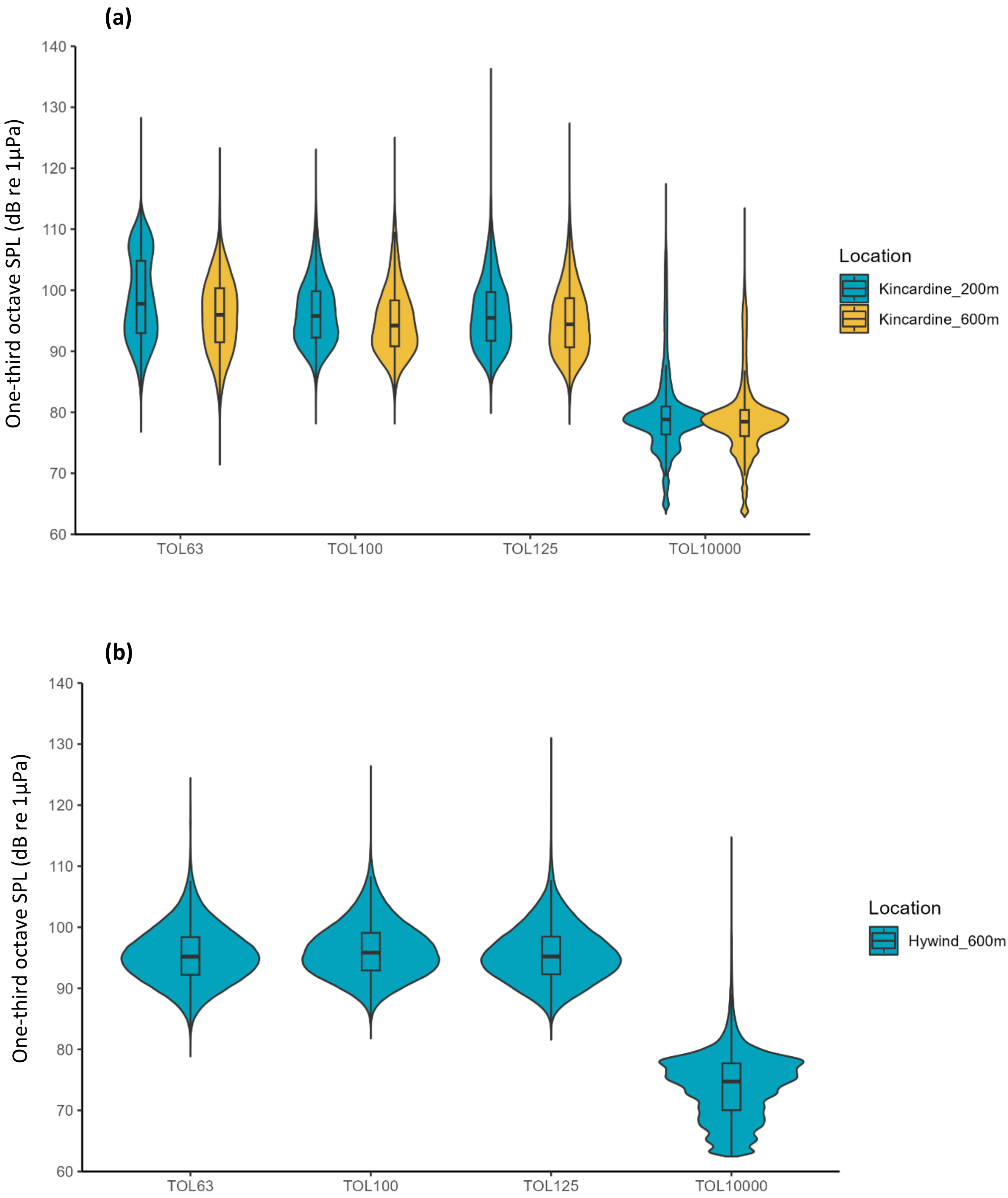


Figure 61. Grouped boxplots of selected one-third octave sound pressure levels (SPL; in dB re 1 µPa) measured at 200 m and 600 m at the Kincardine site (a), and at 600 m at the Hywind Scotland site (b). All available data which could be matched between recording sites for each wind farm have been included. Lower and upper bounds of boxes represent lower and upper quartiles, respectively. Solid lines represent medians, and whiskers indicate furthest data points within 1.5 x interquartile range. The widths of the violin outlines show the kernel probability density of the data. One-third octave band nominal centre frequencies (x-Axis) in Hz.

When comparing median noise levels for the 125 Hz centred one-third octave band recorded at different distances to the closest turbine at the Kincardine site, median noise levels were lowest at the site furthest (i.e., 1,500 m; median: 91.3 dB re 1µPa) from the turbine, as expected (Figure 13a). At this location a bi-modal distribution of noise levels was also observed. Median noise levels at 200 m and 600 m at this location were measured to be 95.5 and 94.4 dB re 1µPa, respectively (Figure 13a).

Surprisingly, when comparing median noise levels between the 600 m and the 2,400 m Hywind Scotland sites, noise levels at 125 Hz were considerably higher at the 2,400 m site (median: 110.2 dB re 1µPa) compared to the site at 600 m (median: 95.2 dB re 1µPa) (Figure 13b). Similar to the Kincardine 1,500 m site, a bimodal distribution of noise levels was also observed at the 2,400 m site at Hywind Scotland..

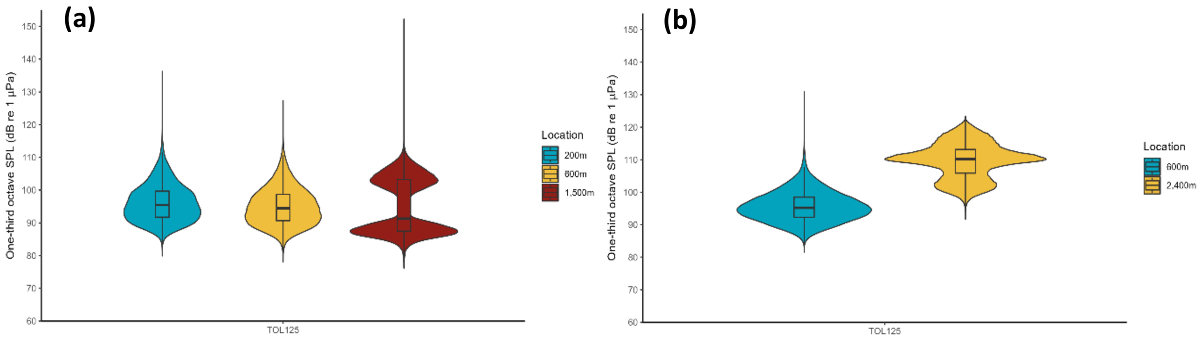


Figure 62. Grouped boxplots of sound pressure levels (dB re 1 µPa) for the one-third octave band with a nominal centre frequency of 125 Hz measured at 200 m, 600 m, and 1,500 m at the Kincardine site (a), and at 600 m and 2,400 m at the Hywind Scotland site (b). All available data which could be matched between recording sites for each wind farm have been included. Lower and upper bounds of boxes represent lower and upper quartiles, respectively. Solid lines represent medians, and whiskers indicate furthest data points within 1.5x interquartile range. The widths of the violin outlines show the kernel probability density of the data.

3.3. Filtered Operational Noise Levels and Environmental Conditions

After detection and filtering of transient signals (see section 2.2.1), one-third octave band levels representing predominantly operational noise were matched with available wind speed time series, as provided by Principle Power/Grupo Cobra (Kincardine) and Equinor (Hywind Scotland).

To assess the influence of passing vessels and dolphin presence on measured received noise levels, one-third octave levels binned by wind speed are presented for all filtered operational data, as well as for the data manually cleaned from obvious vessel and dolphin presence (Figures 14-16). Wind speed bins containing a limited number of samples (see Figure 10) were excluded from these plots.

At Kincardine, highest median third-octave band levels were found to be between 50 Hz and 80 Hz. For these frequencies, peak median noise levels were between 105-110 dB re 1 µPa for wind speeds equal to or above 12-15 m/s at the 200 m lander (Figure 14). At the 600 m lander, for the same wind speeds and frequency bands, they were about 5 dB lower, between 100-105 dB re 1 µPa (Figure 15). Another, smaller peak at higher wind speeds was recorded for the frequency bands centred between 30 and 40 Hz (Figures 14 and 15). Median noise levels were considerably lower at wind speeds below 9-12 m/s, when peak noise levels also shifted below 50 Hz (Figures 14 and 15).

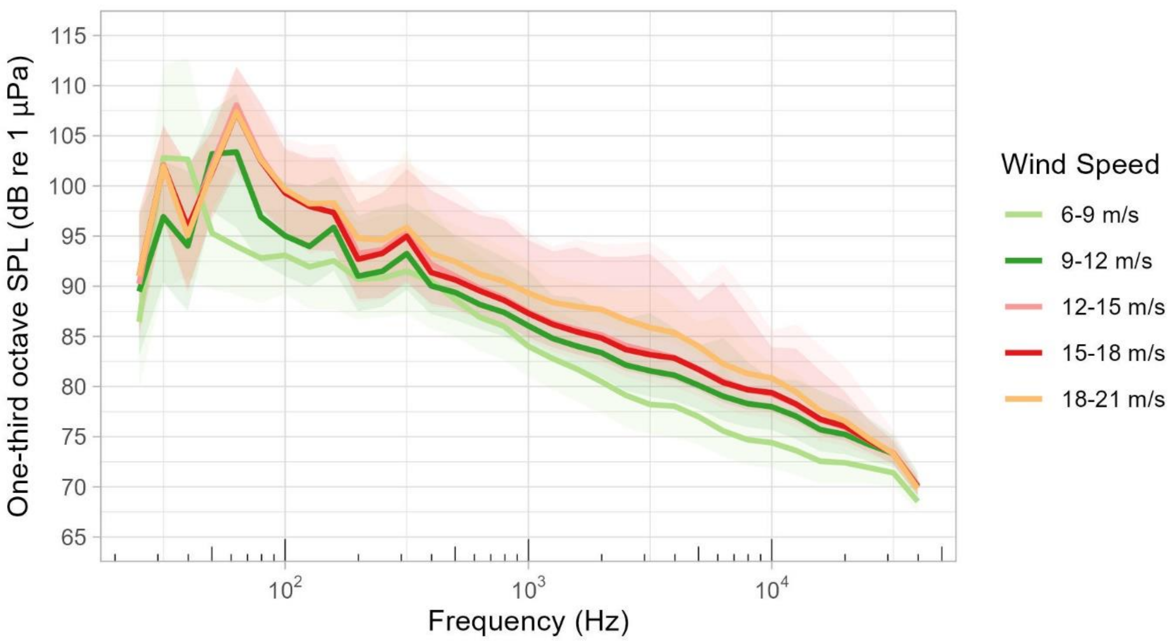
At Hywind Scotland, 600 m from the closest turbine, peak noise levels were found for the 25 Hz and 80 Hz centred one-third octave bands (Figure 16). Peaks reached between 95-100 dB re 1 µPa in these bands. Except for the lowest wind speed bin (0-3 m/s) reductions of noise levels due to decreasing wind speed were generally less pronounced (Figure 16) than at Kincardine (Figure 15). At Kincardine, dominant frequencies shifted from about 31.5-40 Hz at wind speeds of 6 m/s to 63-80 Hz at 15 m/s (Figure 15; Table A1). A similar shift in dominant frequency was not observed at Hywind Scotland, where most energy is concentrated at about 80 Hz, independent of wind speed (Figure 16; Table A2).

As indicated by the results described above, at both Kincardine and Hywind Scotland, turbine operational noise in the lower frequencies (< 100 Hz) increased with wind speed, which was also indicated by strong positive correlations between the 25 Hz and 80 Hz centred one-third octave bands and wind speed (Figure 17). The correlograms also show noise levels in the 3.2 and 12 kHz centred one-third octave bands to be strongly positively correlated to wind speed.

Like wind speed, wave height was correlated, albeit less strong, with the 25 Hz and 80 Hz centred one-third octave bands at Hywind Scotland and the 25 Hz band at Kincardine. At both recording locations, wave height was also correlated to the 12 kHz one-third octave band (Figure 17). Surface velocity was weakly correlated with the 25 Hz centred one-third octave band at Kincardine and did not show much correlation to received levels measured at Hywind Scotland (Figure 17).

Cleaning the data from occasional vessel noise and dolphin presence did not affect the overall noise level statistics (Figures 14-16) and it was thus decided to use the full dataset for all analyses going forward, including back-calculating source levels, and predicting the overall noise footprint of the turbines.

(a)



(b)

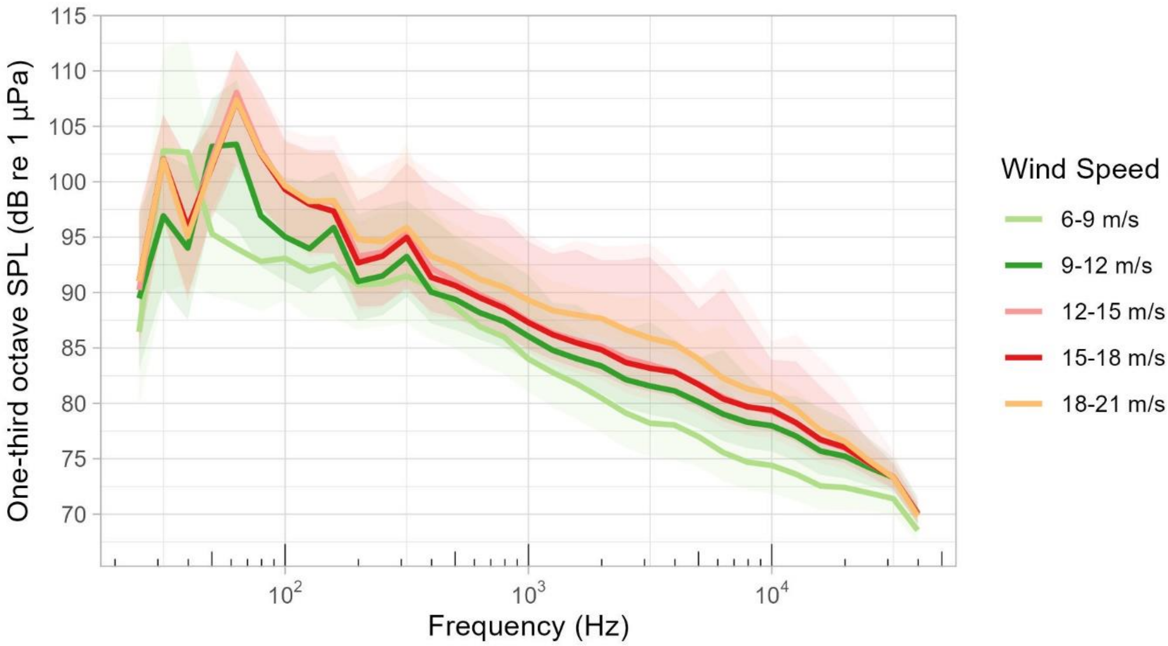
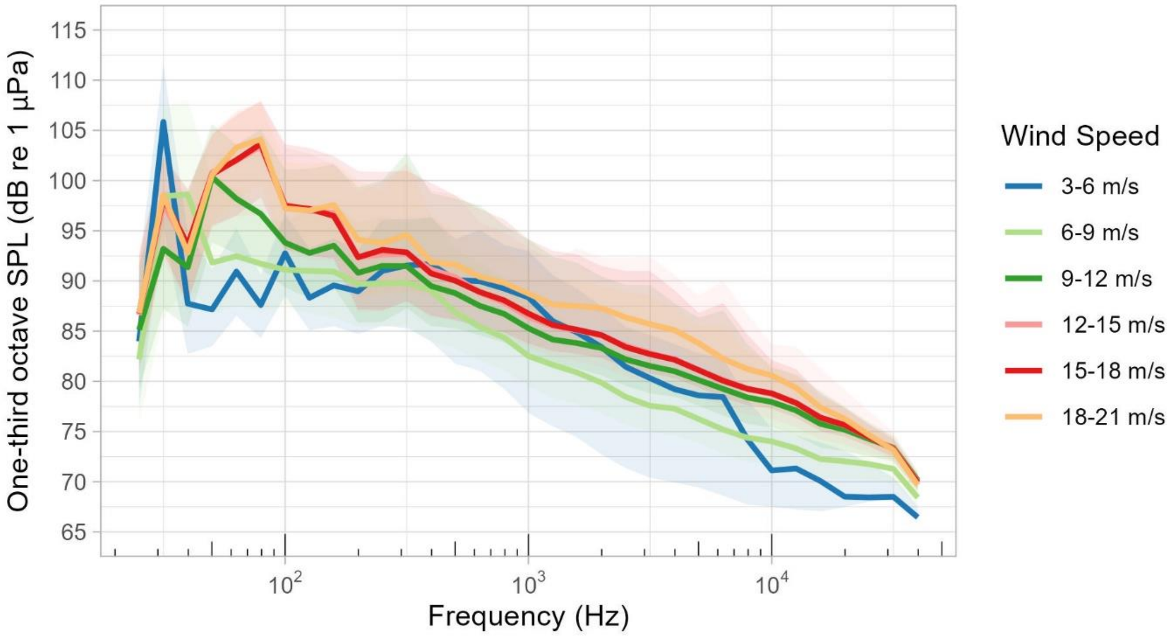


Figure 72. Median 1-second third-octave band levels (solid lines) and 5th and 95th percentiles (transparent bands), for filtered operational noise, split by wind speed bin measured at the Kincardine 200 m lander. (a) all data and (b) data cleaned from obvious vessel and dolphin presence.

(a)



(b)

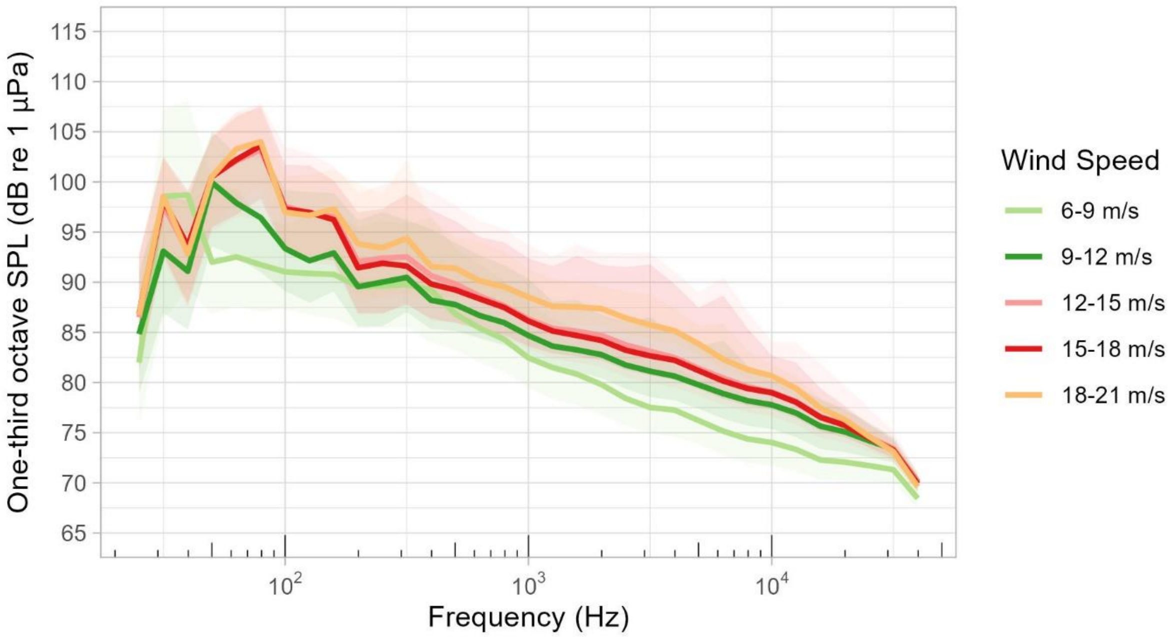
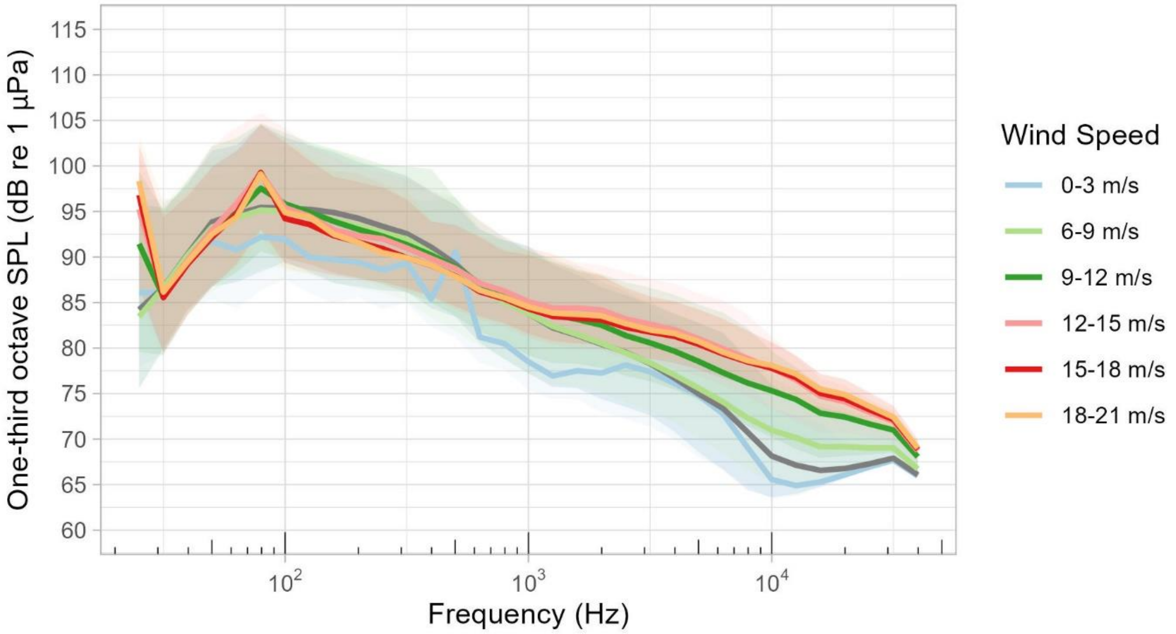


Figure 73. Median 1-second third-octave band levels (solid lines) and 5th and 95th percentiles (transparent bands), for filtered operational noise, split by wind speed bin measured at the Kincardine 600 m lander. (a) all data and (b) data cleaned from obvious vessel and dolphin presence.

(a)



(b)

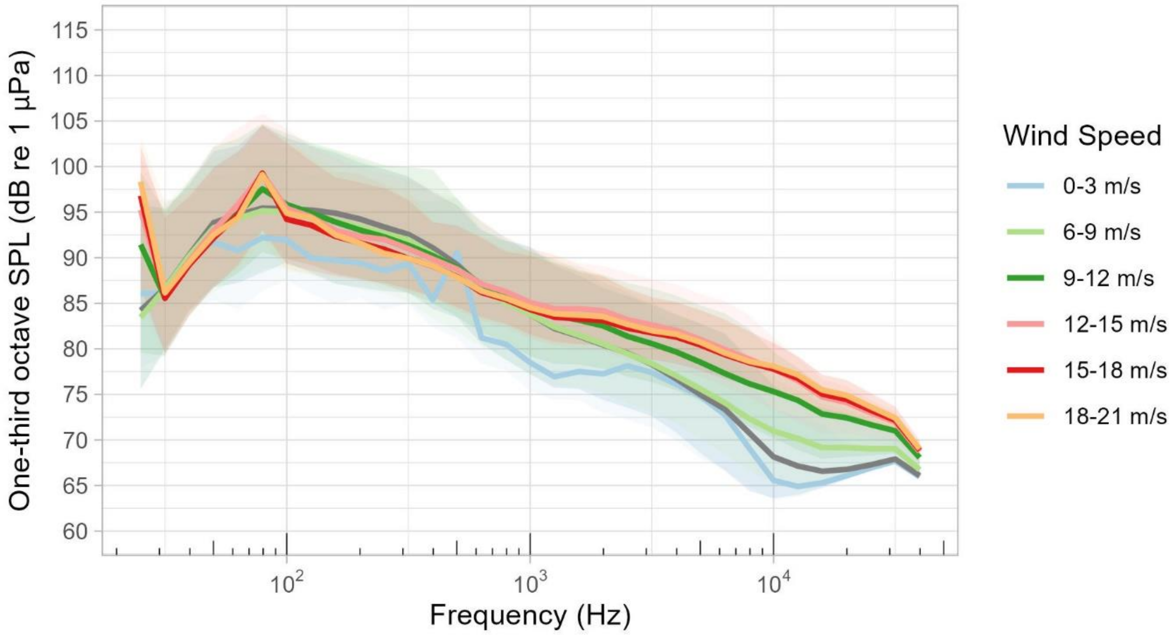


Figure 82. Median 1-second third-octave band levels (solid lines) and 5th and 95th percentiles (transparent bands), for filtered operational noise, split by wind speed bin measured at the Hywind Scotland 600 m lander. (a) all data and (b) data cleaned from obvious vessel and dolphin presence. The lowest (0-3 m/s) and the highest (18-21 m/s) wind speed bin had fewer data points (< 5,000) compared to the other bins (> 25,000).

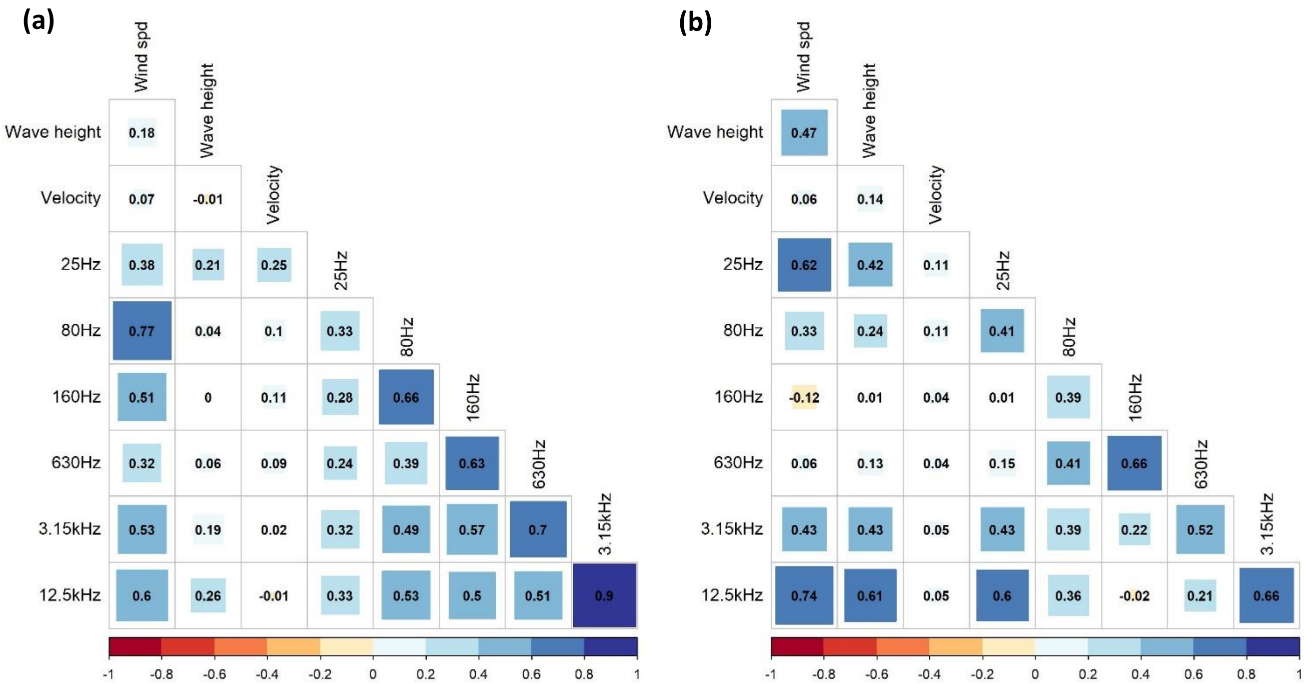


Figure 90. Correlogram comparing selected 1-second third-octave band levels (SPL in dB re 1 µPa) with wind speed, wave height and velocity for filtered operational data from (a) the Kincardine 600 m recording location and (b) the Hywind Scotland 600 m recording location.

3.4. Filtered Transient Noise Levels and Environmental Conditions

Under comparable environmental conditions (wind speed, wave height, and velocity), noise levels of the transient data, containing mostly mooring-related but also some operational noise, were higher at Kincardine than at Hywind Scotland (Figure 18). Likewise, the variability in received noise level was higher at Kincardine than at Hywind Scotland (Figure 18). Additionally, the differences in measured transient noise levels when comparing lower vs higher wind speeds, were higher at Kincardine than at Hywind Scotland, with noise levels generally increasing with higher wind speeds (Figure 18).

For Kincardine, filtered transient data showed a strong correlation with the 80 Hz third-octave band, like the operational data (Figure 19), reflecting the operational component of the transients. At this site, the received sound level of the transients, recorded at 600 m from the turbine increased across all third-octave bands with increasing wind speed, except for the frequency band centred around 40 Hz (Figure 18). The results revealed a weaker positive relationship with significant wave height for most selected frequency bands (Figure 19).

At Hywind Scotland, the strongest positive correlation between transient noise and wind speed was with the 25 Hz third-octave band (Figure 19). For frequencies ≥ 100 Hz, noise levels showed stronger positive correlations with wind speed for frequency bands starting at about 2 kHz (Figure 19). A similar pattern was visible for the relationship with significant wave height, which revealed a stronger positive relationship for higher frequencies. For most selected frequency bands, the relationships with wave height were stronger at Hywind Scotland compared to Kincardine (Figure 19).

At both Kincardine and Hywind Scotland, the correlation with surface velocity revealed weak positive correlations at lower frequency bands and weakly negative linear relationships for higher frequency bands. However, the switch from a positive to negative correlation occurred at higher frequencies at Hywind Scotland compared to Kincardine (Figure 19).

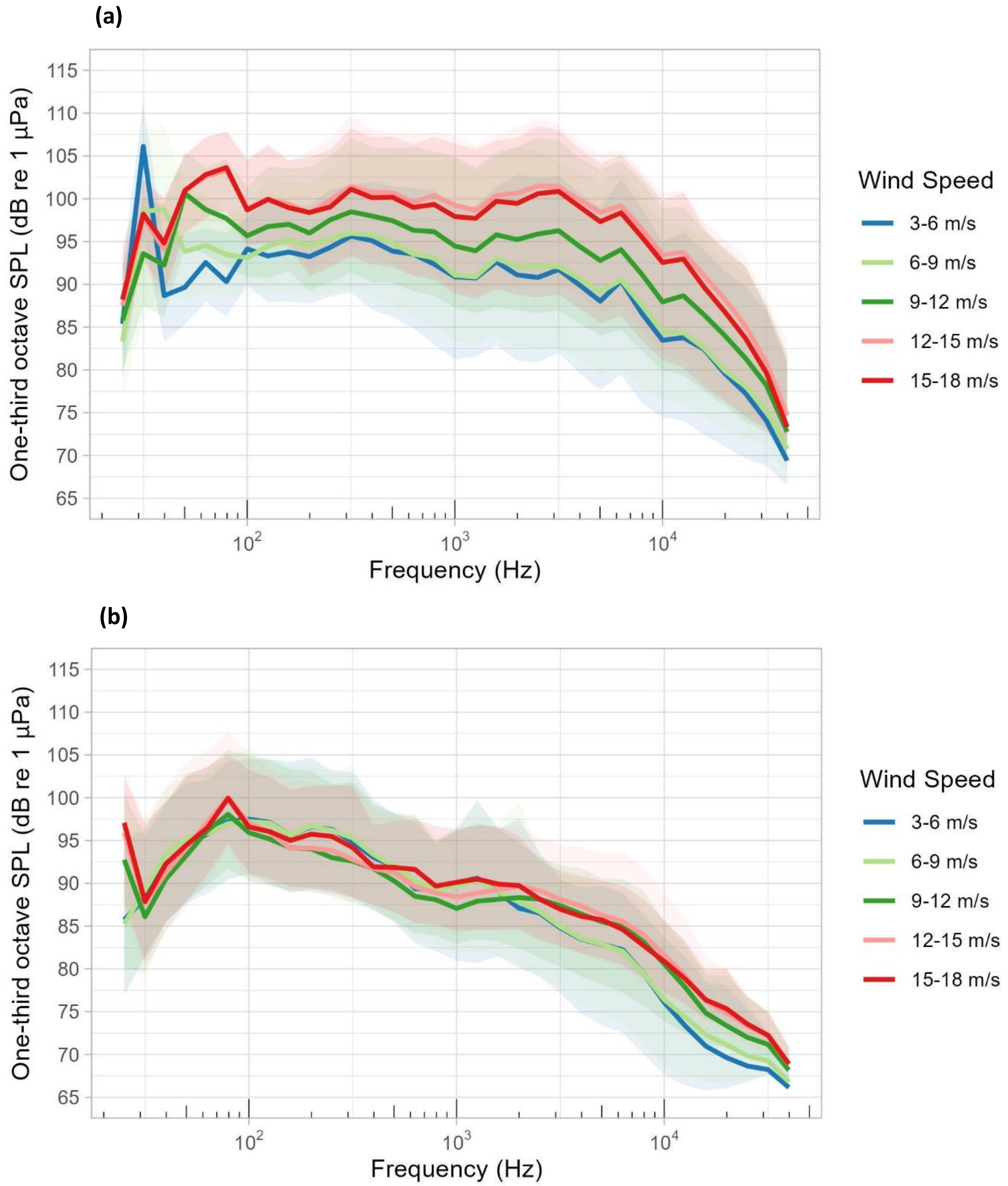


Figure 99. Median 1-second third-octave band levels (solid lines) and 5th and 95th percentiles (transparent bands), for filtered transient noise, split by wind speed bin measured at the (a) Kincardine 600 m lander and (b) Hywind 600 m lander. All available data were used.

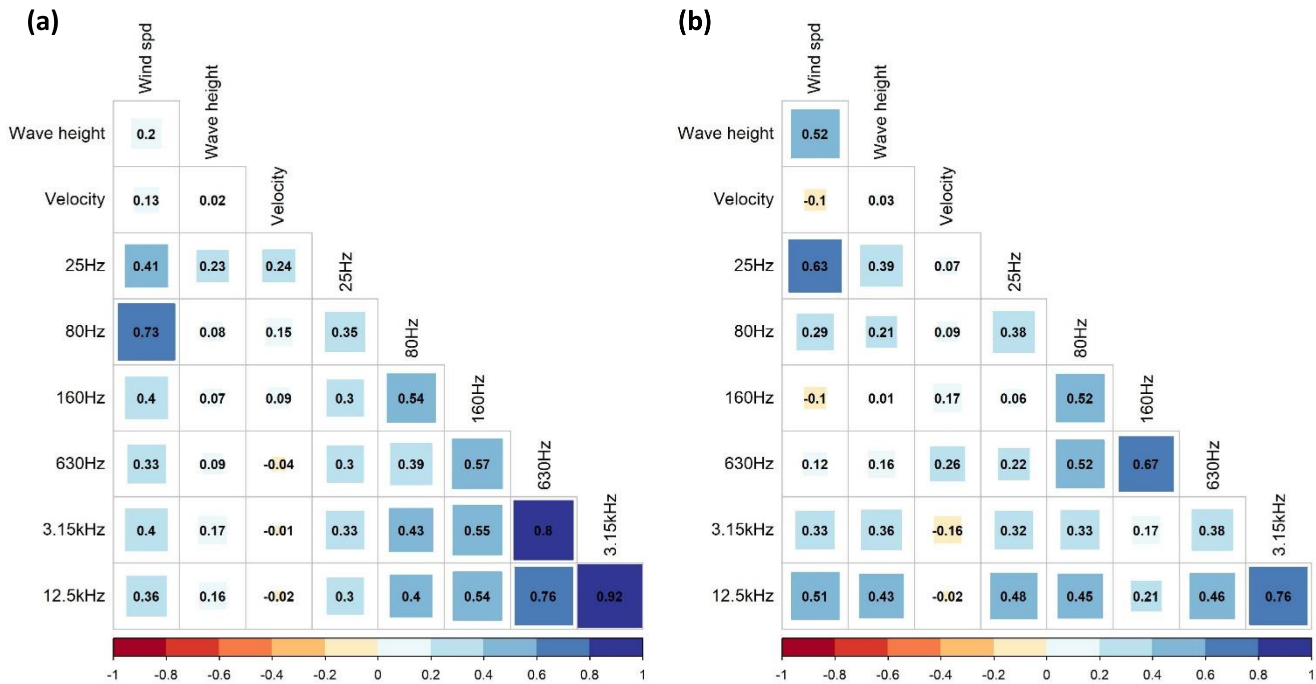


Figure 108. Correlogram comparing selected 1-second third-octave band levels (SPL in dB re 1 µPa) with wind speed, wave height and velocity for filtered transient data from (a) the Kincardine 600 m recording location and (b) the Hywind Scotland 600 m recording location.

3.5. Detailed Acoustic Analysis

3.5.1. Turbine Operational Noise

As described above, most acoustic energy measured from operational turbines at Kincardine as well as Hywind Scotland was found below 100 Hz (Figures 14-16). Distinct tonal sounds were apparent between approximately 30 and 120 Hz, with most energy concentrated between about 50 Hz and 80 Hz. As shown in section 3.4, the 80 Hz centred one-third octave band noise levels were strongly positively correlated with wind speed (Figure 17a). Tonal features were visible up to 350 Hz but were much less dominant at these higher frequencies (Figure 20b).

At Hywind Scotland two dominant tones at 25 Hz and about 75 Hz (Figure 21a) were found in many of the recordings, although they were not always present (Figure 21b). The noise in the 25 Hz and 80 Hz centred one-third octave bands, where these tones occurred, were also strongly positively correlated with wind speed (Figure 17b). Like at Kincardine, tonal signal components at Hywind Scotland were also visible at frequencies up to about 350 Hz although they were much less dominant in those bands (Figure 21b).

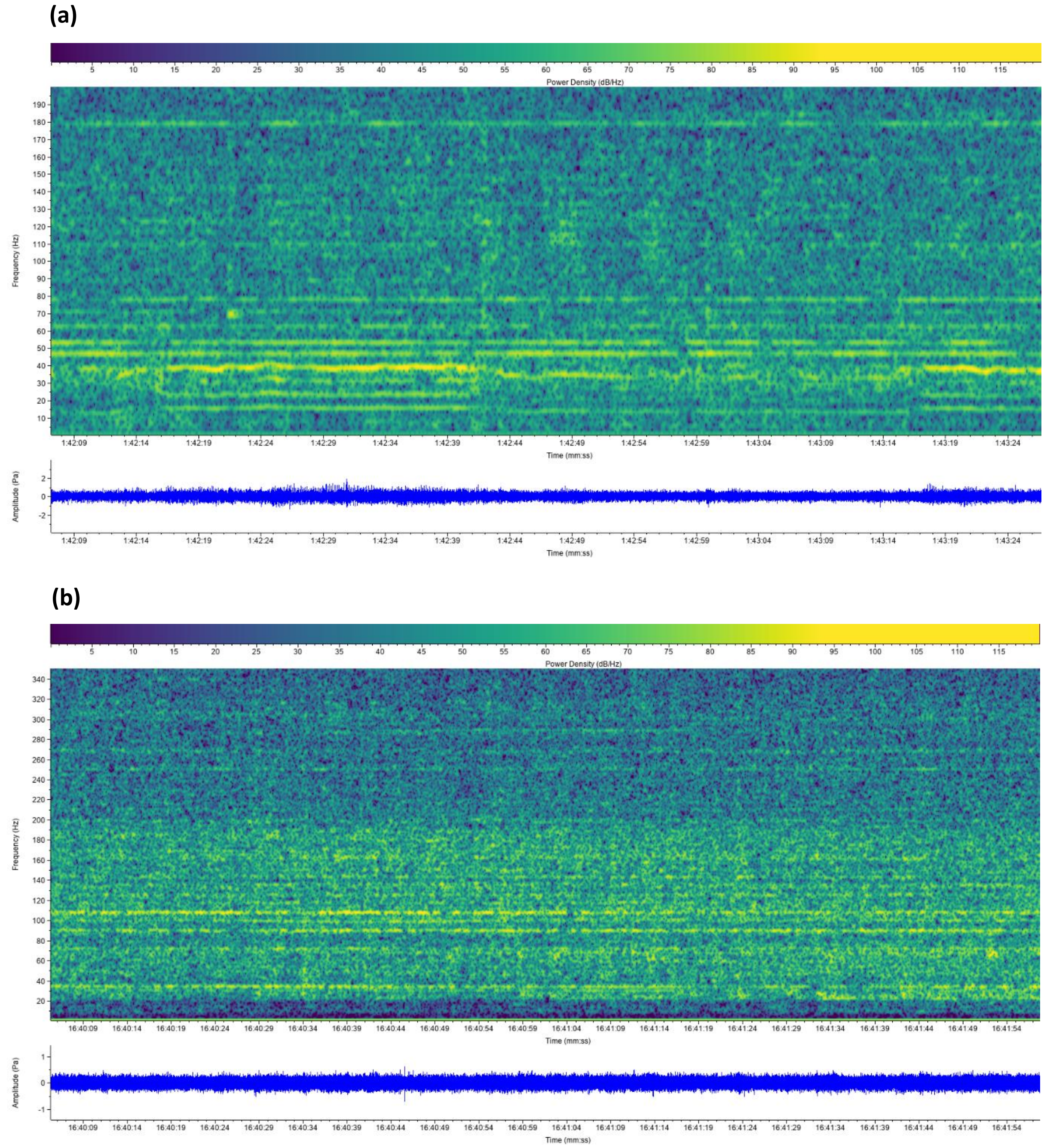


Figure 116. Example spectograms and waveforms of operational turbine noise recorded at the Kincardine 20 0m site on 09/11/2021. (a) 0-200 Hz and (b) 0-350 Hz. Sample rate: 96,000 Hz, FFT size: 65,536 points, 95% overlap.

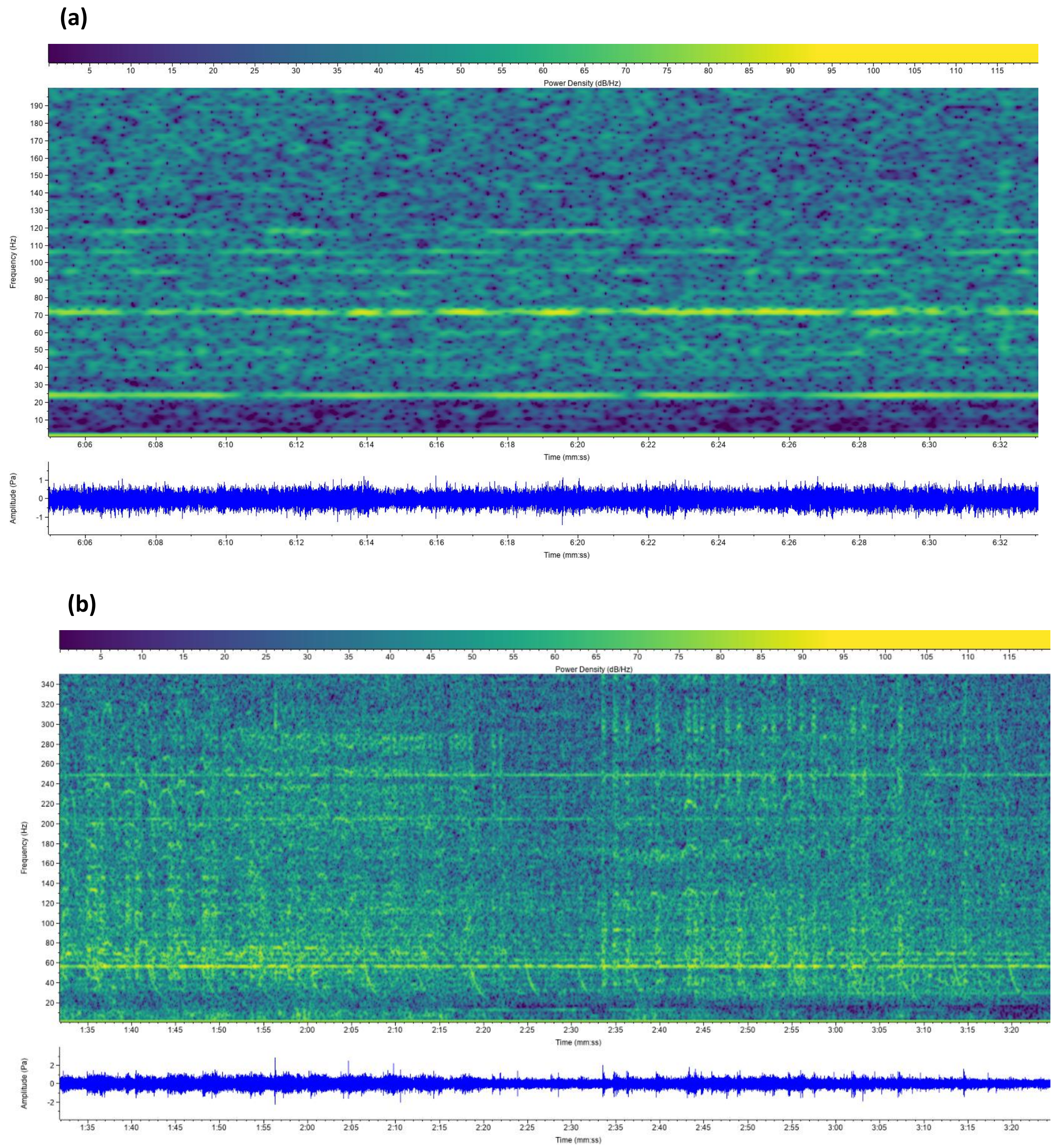


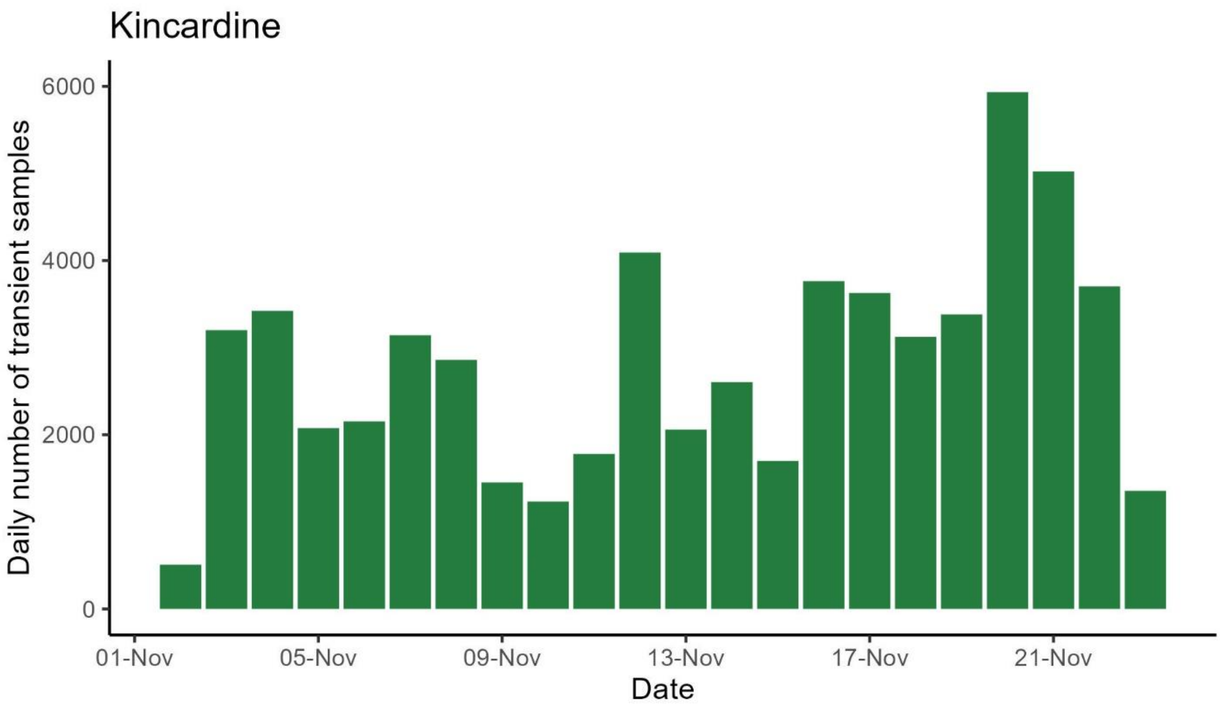
Figure 126. Example spectograms and waveforms of operational turbine noise recorded at the Hywind Scotland 600 m site on (a) 15/05/2022 (0-200 Hz) and (b) 14/05/2022 (0-350 Hz). Sample rate: 96 kHz, FFT size: 65,536 points, 95% overlap.

3.5.2. Mooring System Noise

An increase in broadband impulses or transients related to the mooring structures was found both at Kincardine and Hywind Scotland during periods of higher wind speeds and significant wave height. There were a variety of different signals observed at both sites, examples of which are shown in Figures 23 and 24 and Appendix A.

Observed transients consisted either of individual 'snaps' or 'bangs', or series of rapidly repeated transients with an audible sound quality of 'rattling' and 'creaking' (as described by Burns et al. (2022) for Hywind Scotland). These impulses, with energy often being distributed across the whole available analysis bandwidth (i.e., 10 - 48 kHz), were generally of short duration (i.e., 1 second or less) but were produced in sequences often lasting for several minutes at a time.

Overall frequency of occurrence of these transients was variable at both sites but considerable higher at Kincardine compared to Hywind Scotland (Figures 10, 11 & 22). This finding was corroborated by the kurtosis analysis which showed a mean 30-seconds kurtosis value of 8.1 for Kincardine and 3.3 for Hywind Scotland (Figure 25). When comparing the empirical cumulative distribution function of kurtosis values between the 600 m and the 2,400 m recording sites at Hywind Scotland, results were relatively similar, indicating that the soundscape around the array of spar-buoys was comparable in terms of impulsiveness to that of the vessel noise dominated control site. In contrast, at Kincardine the comparison between data collected at 600 m and 1,500 m showed considerably higher kurtosis values for the 600 m recording location (Figure 26).



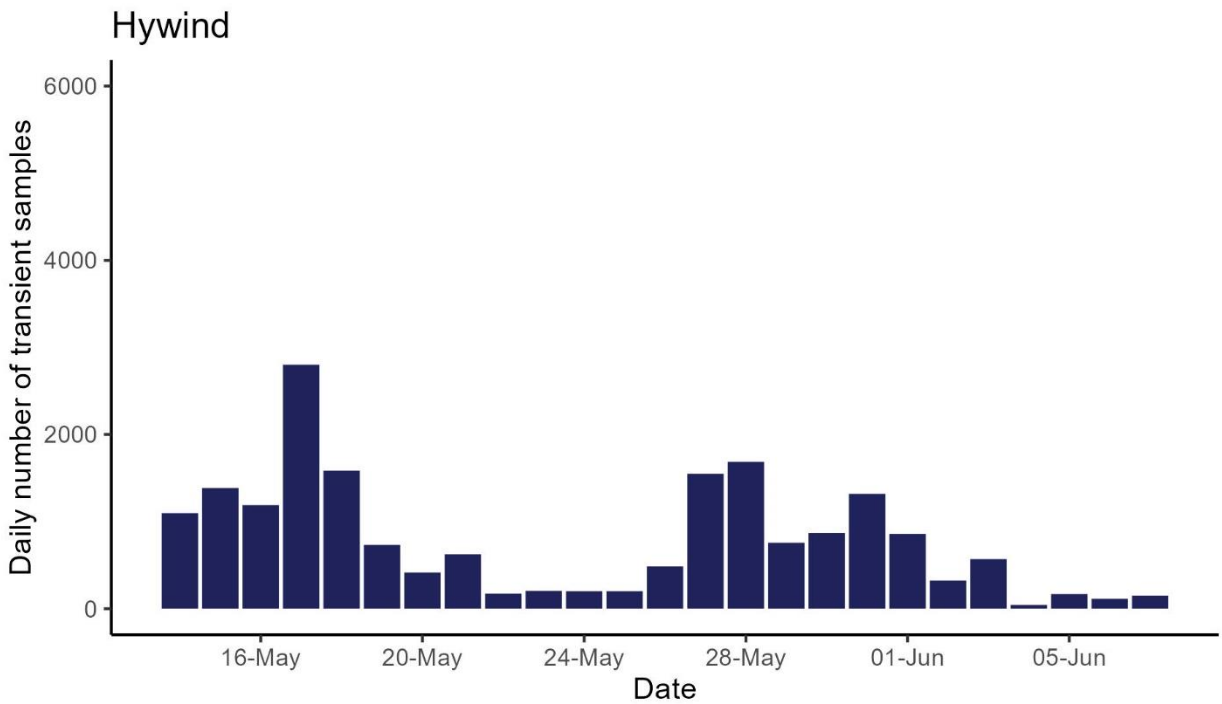
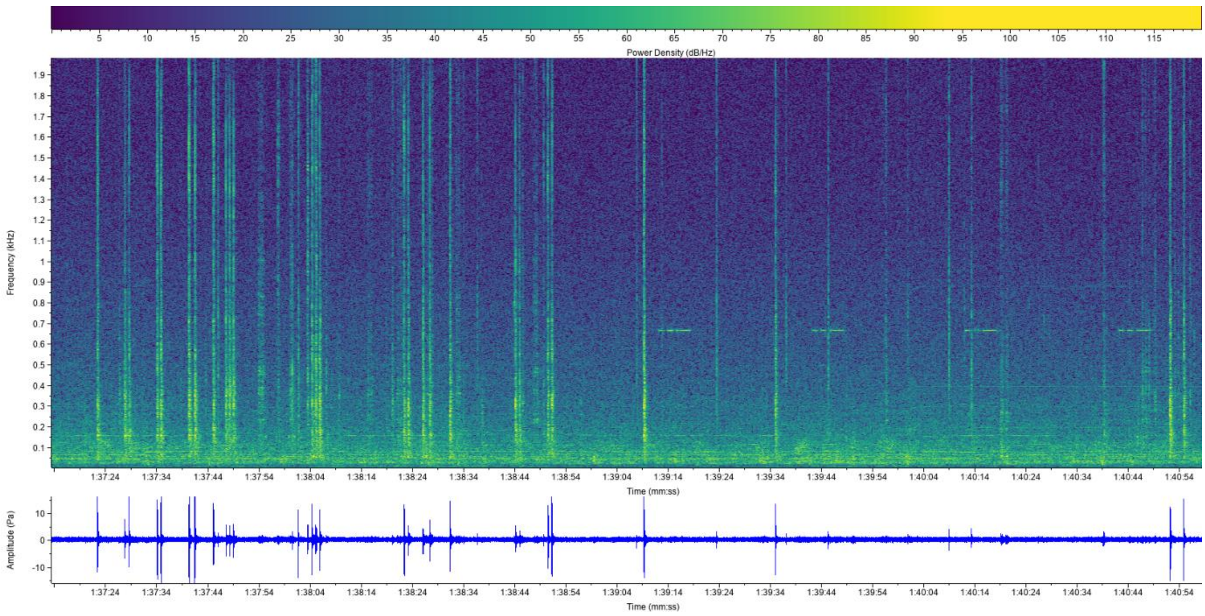


Figure 127. Daily presence of transients for each recording day, measured at the Kincardine 600 m lander (top) and the Hywind Scotland 600 m lander (bottom).

(a)



(b)

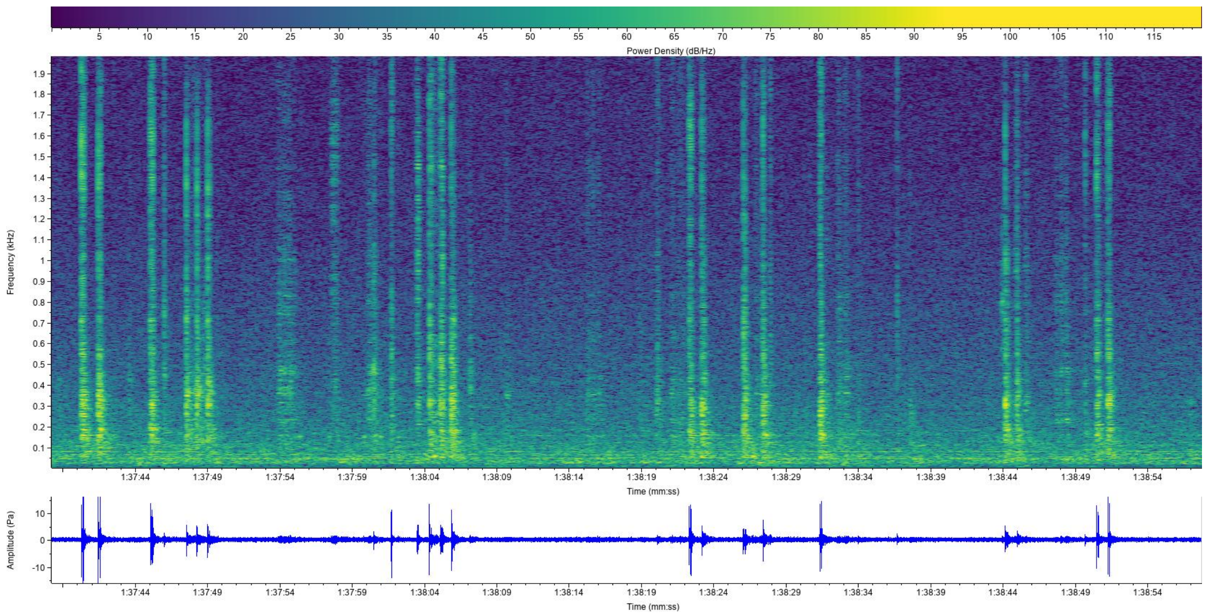


Figure 136. Example spectograms and waveforms of mooring related transient noise recorded at the Kincardine 200 m recording location on 20/11/2021 (0-2 kHz) (a) three minutes and (b) zoomed in to 1 minute. Sample rate: 96 kHz, FFT size: 65,536 points, 95% overlap.

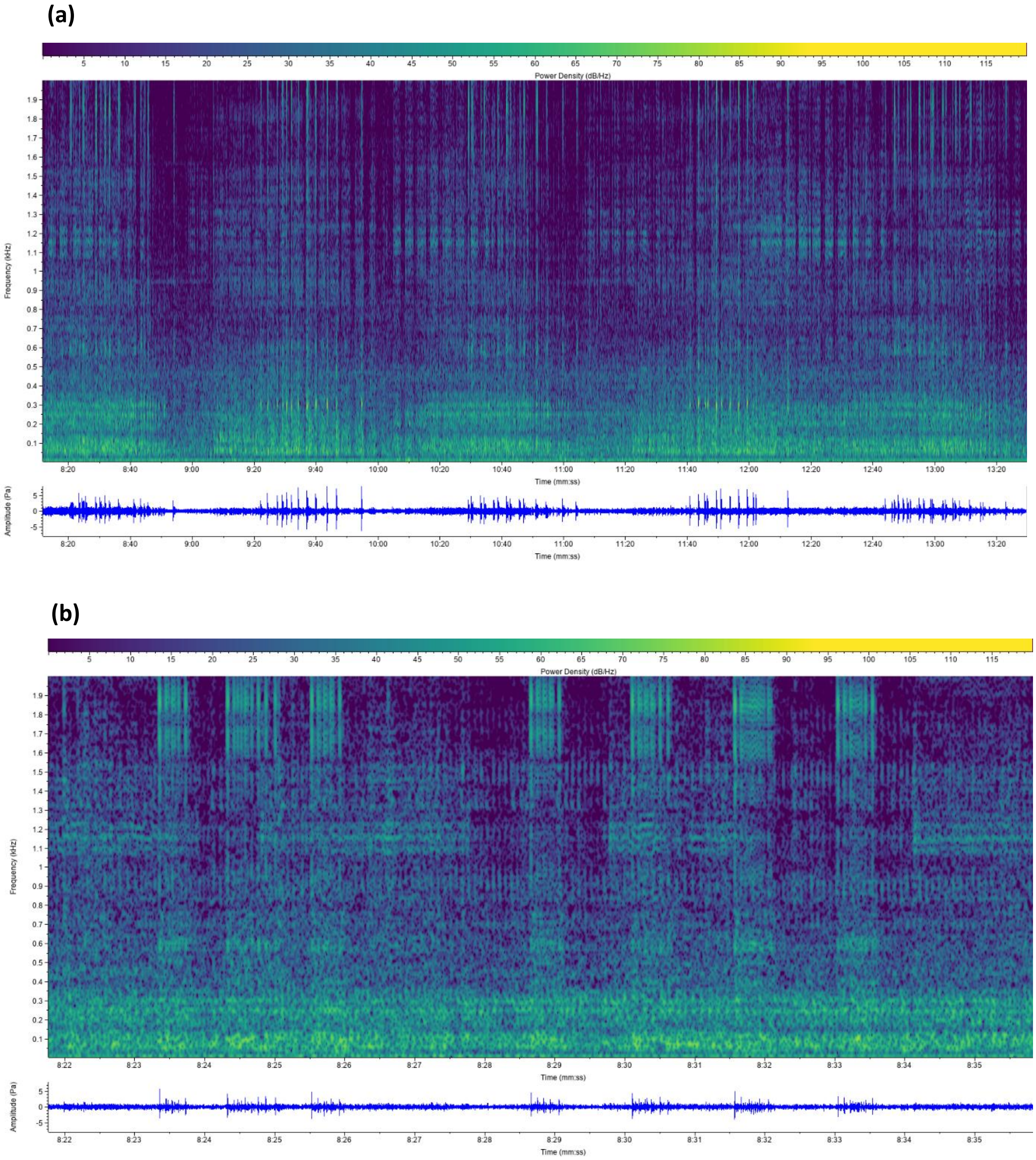


Figure 145. Example spectograms and waveforms of mooring related transient noise recorded at the Hywind Scotland 600 m recordings location on 14/05/2022 (0-2 kHz) (a) five minutes and (b) zoomed in to 15 seconds. Sample rate: 96 kHz, FFT size: 65,536 points, 95% overlap.

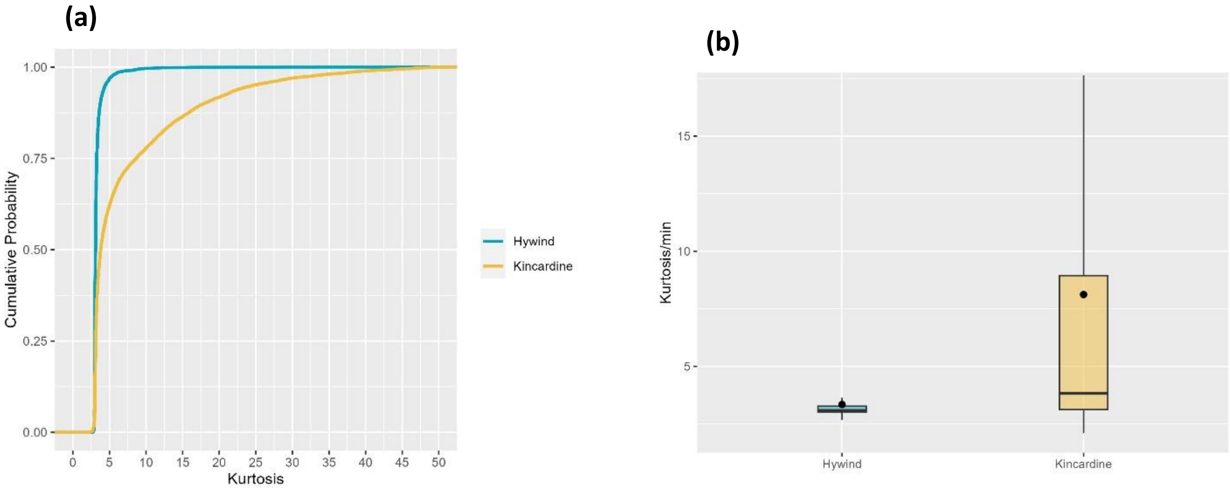


Figure 154. (a) Empirical cumulative distribution of kurtosis values quantified over a 30-second analysis window for all available data at Kincardine (yellow) and Hywind Scotland (blue). (b) Boxplot comparing kurtosis values measured at Hywind Scotland and Kincardine. Lower and upper bounds of boxes represent lower and upper quartiles, respectively. Solid lines represent medians, and whiskers indicate furthest data points within 1.5x interquartile range. Dot indicates the mean. Outliers excluded for plotting purposes.

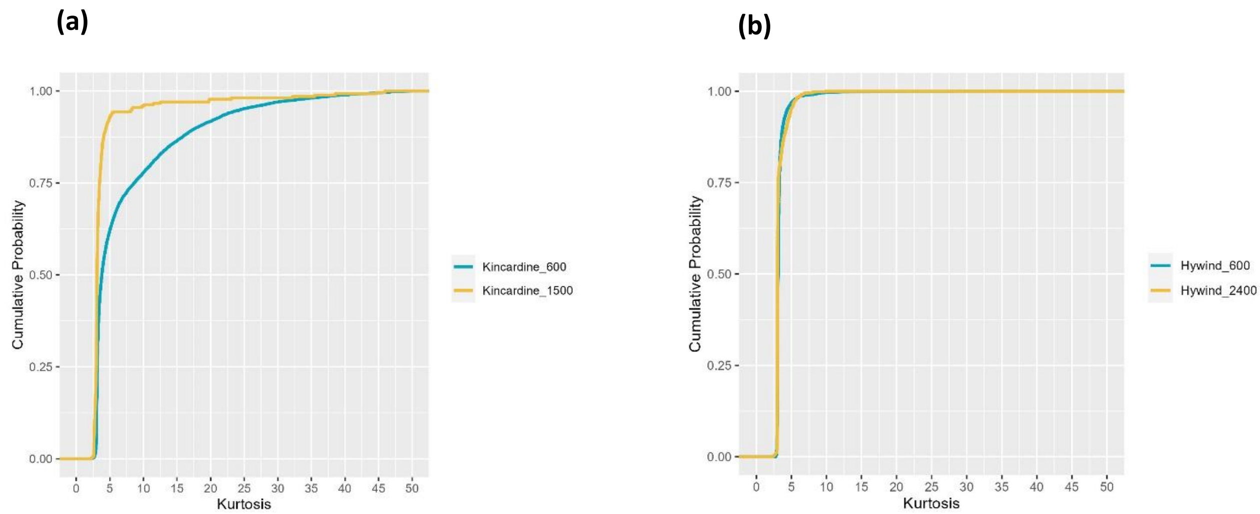


Figure 164. (a) Empirical cumulative distribution of kurtosis values quantified over a 30-second analysis window for all available data (a) Kincardine 600 m (blue) and 1,500 m (yellow), and at (b) Hywind Scotland 600 m (green) and 2,400 m (yellow).

3.6. Source Levels and Predicted Noise Fields of Operational Noise

The one-third octave band source levels calculated for single floating offshore wind turbines at Kincardine and Hywind Scotland are shown in Figure 27 and Figure 28, respectively. These source levels are for continuous operational noise related to rotational machinery in the turbines' drivetrain and exclude other noises of a transient nature such as those related to mooring systems (see sections 2.2.1, 3.4 and 3.5.2). Appendix B lists the third-octave source levels (dB re 1 µPa) for turbines at each wind farm.

The total source levels (25 Hz – 25 kHz) for operational noise across a range of wind speeds are in the range of 143-149 dB re 1 µPa for both turbine types (Table 7). However, source levels for the turbines deployed at Kincardine are slightly greater (i.e., 2-3 dB) than those for Hywind Scotland at all wind speeds (Table 7; Figures 27 & 28; Appendix B).

As was obvious in the measured received level plots presented in sections 3.3, peaks of back-calculated source levels varied between the two sites, with Hywind Scotland showing higher operational noise levels in the one-third octave band centred at 25 Hz one-third octave band especially under higher wind speed conditions. A second peak was calculated at 80 Hz for this site whereas the main peak in operational noise level for Kincardine was slightly lower in the 63 Hz one-third octave band (Figures 27 & 28; Tables B1 & B2). Both sites showed elevated operational source levels also for the 300-600 Hz frequency bands (Figures 27 & 28; Tables B1 & B2).

Frequencies of peak source levels varied by wind speed (Figure 29; Tables B1 & B2). This is particularly obvious at Kincardine, where a shift of peak source levels from 31.5 to 63 Hz can be observed between wind speeds of 6 m/s compared to higher windspeeds (Figures 27 & 29; Tables B1 & B2). Overall, maximum differences between operational source levels between the low and the high wind speed categories (e.g., 6 m/s vs 15 m/s) were between 10 and 15 dB, with higher source levels typically related to higher wind speeds (Tables B1 & B2).

Table 7. Total source levels across the 25 Hz – 20 kHz frequency range for floating offshore wind turbines deployed at Kincardine compared to Hywind Scotland at different wind speeds.

	Source Level (dB re 1 µPa)			
	Wind Speed			
	6 m/s	**9 m/s**	**12 m/s**	**15 m/s**
Kincardine	144.8	144	147.1	148.8
Hywind Scotland	143.4	143.7	145.4	145.4

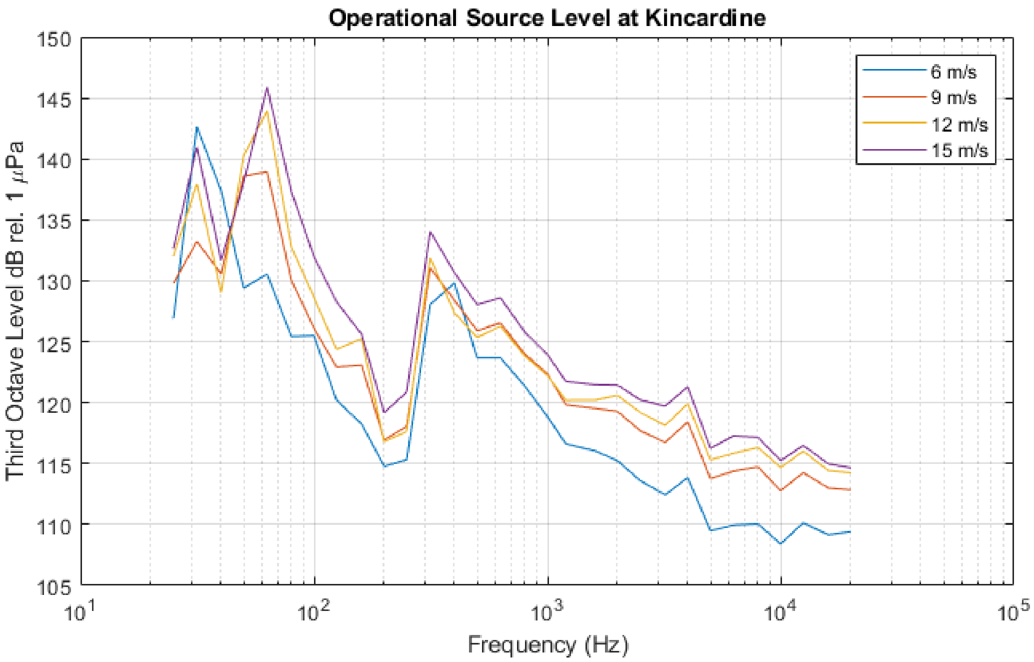


Figure 169. Source level of operational noise from a floating offshore wind turbine at Kincardine based on backward propagation of underwater noise from the Lander deployed at 200 m to the closest turbine. The source level is for continuous noise related to rotational machinery in the drivetrain and excludes transient sounds.

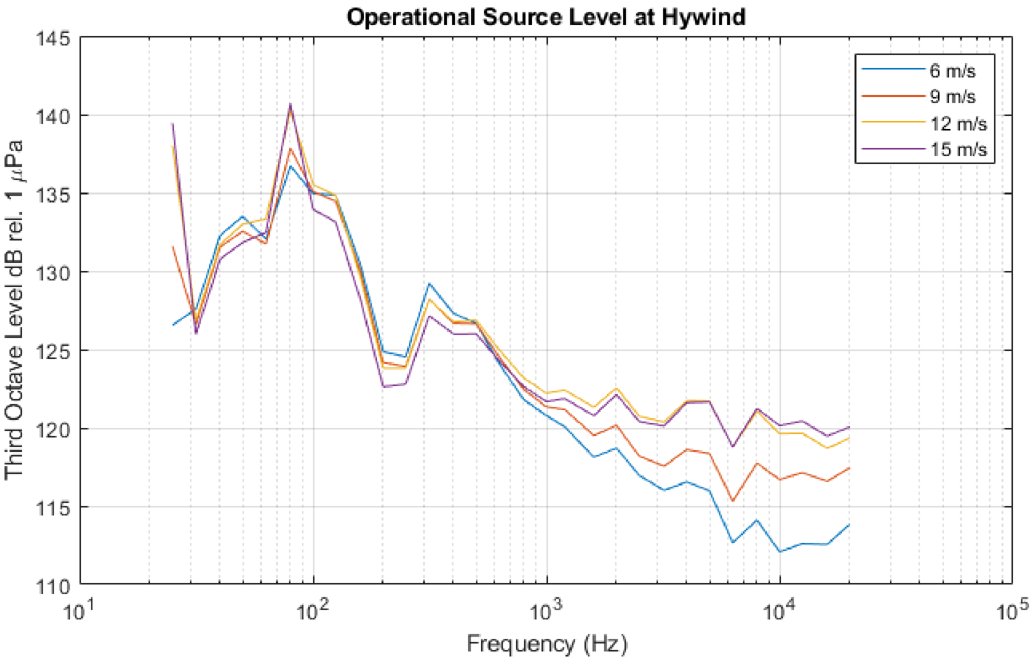


Figure 168. Source level of operational noise from a floating offshore wind turbine at Hywind Scotland based on backward propagation of underwater noise from the Lander deployed at 600 m from the closest turbine. The source level is for continuous noise related to rotational machinery in the drivetrain and excludes transient sounds.

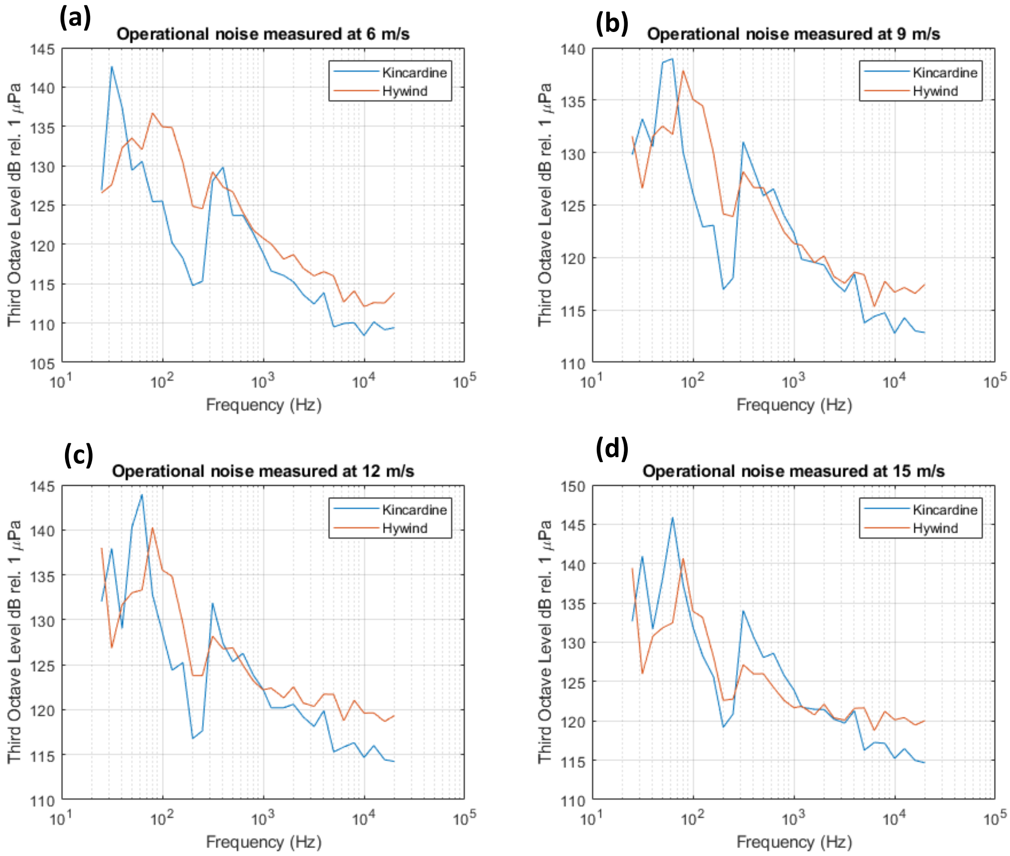


Figure 178. Comparison of source level of operational noise from a floating offshore wind turbine at Kincardine and Hywind Scotland. The source level is for continuous noise related to rotational machinery in the drivetrain and excludes transient sounds.

The back-calculated source levels for the operational noise of individual turbines for both Kincardine and Hywind Scotland were used in a next step to predict the cumulative noise field for the deployed 5-turbine arrays at both sites for unweighted and frequency-weighted sound pressure levels 9 m and 39 m depths (Figures 30 - 33; Tables 8 & 9).

Impacts of underwater noise on marine mammals are often estimated using auditory weighting functions (National Marine Fisheries Service 2018). Such weighting functions are generally based on species' (or functional species groups) hearing range and sensitivity, and existing data on physiological or behavioural responses to noise. Auditory frequency weighting considers that animals are not equally sensitive to all frequencies and is an important concept for the assessment of audibility and potential impacts of different sources of underwater noise, as well as the development of noise exposure guidelines based on these data (Tougaard & Dähne 2017).

Based on phylogenetic relationships and best available knowledge on auditory systems, physiological and behavioural responses to noise, marine mammals have been defined into functional hearing groups for which similar auditory weighting functions should be applied (Southall et al. 2019). These groupings are low-frequency cetaceans (LF), high-frequency cetaceans (HF), very high-frequency cetaceans (VHF), sirenians (SI), phocid carnivores in water (PCW), phocid carnivores in air (PCA), and other marine carnivores in water and air (OCW, OCA) (Southall et al. 2019).

In general, a sound signal can be detected by an animal up to the distance where the received sound level matches its hearing threshold at a certain frequency band. However, if the ambient sound in respective frequency bands is higher than the animal's hearing threshold, the maximum detection distance is determined by the distance at which the received sound levels equal ambient sound over a similar frequency range (Madsen et al. 2006). This simple approximation of signal audibility is generally applicable for broadband sounds. It should be noted, that due to the shape of their auditory filters, it is likely that marine mammals can detect the discrete tonal frequencies present in the noise produced by FOW turbines at a few decibels below ambient sound levels (Au 1993, Madsen et al. 2006, Erbe et al. 2015).

Using the 100 dB contour to approximate median ambient noise levels for the 20 Hz – 20kHz frequency range in many parts of the North Sea (Putland et al. 2022), the predicted noise fields for the different scenarios, showed that unweighted sound pressure levels for the 5-turbine array scenarios were above ambient for maximum distances of 3.5 - 4.0 km from the centroid of the array at Kincardine and 3.0 - 3.7 km at Hywind Scotland (assuming 15 m/s wind speed, Figure 30; Tables 8 & 9). Median and maximum distances varied depending on modelled water depth (i.e., 9 m vs 39 m) by about 0.5 - 0.7 km (Figures 31 & 32; Tables 8 & 9).

When modelled sound pressure levels were frequency-weighted for low-frequency species (e.g., baleen whales), maximum distances to the array centre were between 2.3 and 2.5 km at Kincardine and between 2.1 and 2.3 km at Hywind Scotland (Figure 33; Tables 8 & 9). These distances were considerably smaller when the data were frequency-weighted for very high frequency species such as harbour porpoises and pinnipeds in water (Southall et al. 2019, Figures C1 & C2).

Frequency-weighted sound exposure levels over 24 hours (SEL 24h) were also calculated based on these models and compared to recommended thresholds for temporary or permanent auditory damage in marine mammals recommended by the National Marine Fisheries Service (2018). When just looking at operational noise, and excluding transient mooring noise, none of the thresholds for permanent or temporary hearing threshold shifts (PTS and TTS) were reached for the modelled scenarios.

(a)

(b)

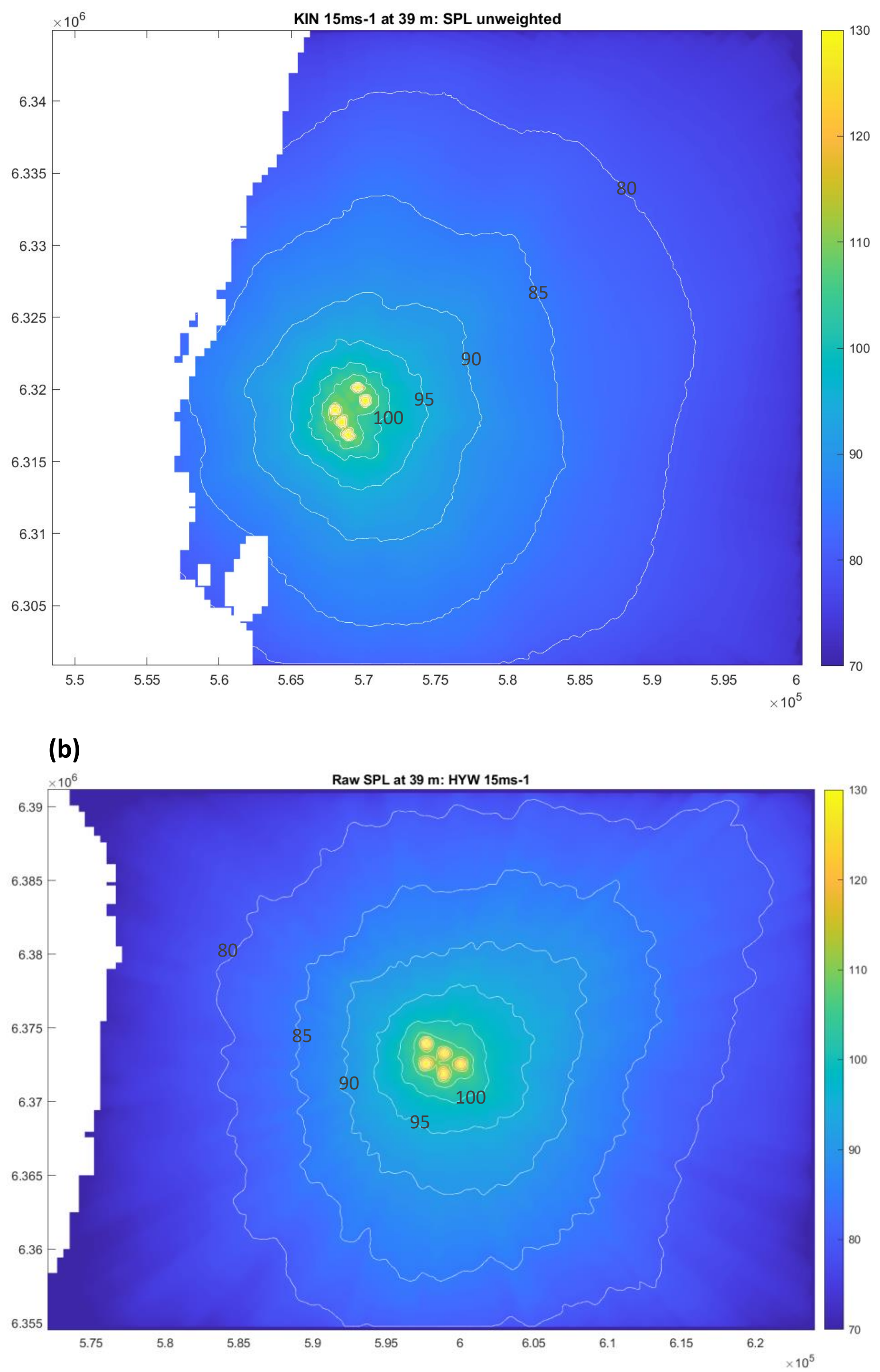


Figure 187. Unweighted sound pressure level map (25 Hz – 20 kHz) at 39 m water depth and a wind speed of 15 m/s, for (a) Kincardine and (b) Hywind Scotland. Scale: one-third octave sound pressure level (dB re 1 µPa).

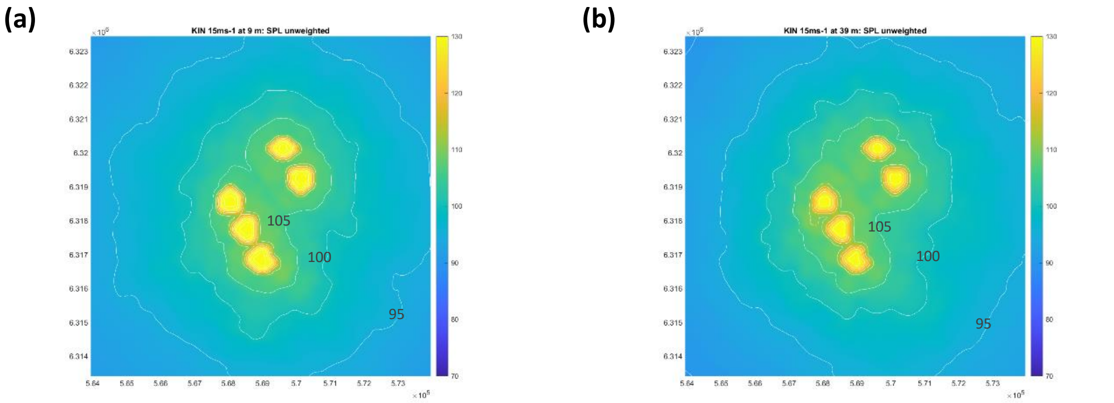


Figure 196. Unweighted sound pressuare level map (25 Hz – 20 kHz) at Kincardine for (a) 9 m, and (b) 39 m water depth and a wind speed of 15 m/s. Scale: one-third octave sound pressure level (dB re 1 µPa).

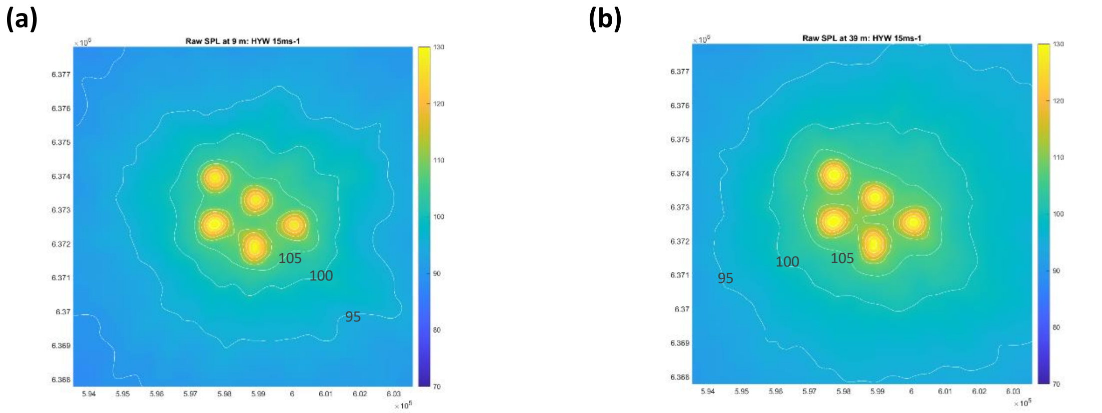


Figure 205. Unweighted sound pressure level map (25 Hz – 20 kHz) at Hywind Scotland for (a) 9 m, and (b) 39 m water depth and a wind speed of 15 m/s. Scale: one-third octave sound pressure level (dB re 1 µPa).

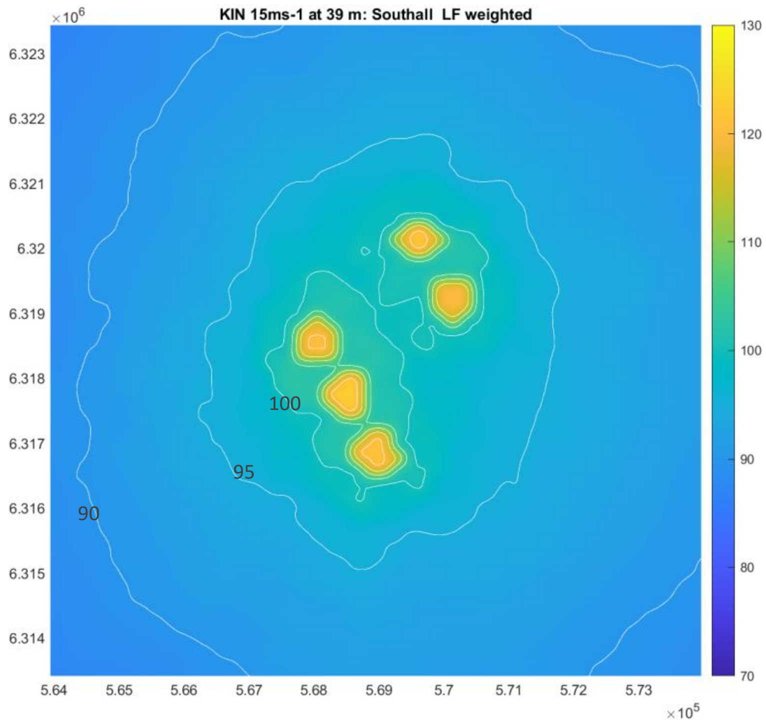
Table 8. Median and maximum distances to centroid of modelled 100 dB sound pressure levels (SPL) contour for the unweighted and low-frequency species weighted sound pressure level maps at the two different depths modelled (see Figures 30, 31 & 33) for the 15 m/s wind speed scenario for Kincardine.

	Depth	Median Distance (m)	Maximum Distance (m)
Unweighted SPL	**9 m**	2,941	3,907
	39 m	3,030	3,496
LF weighted SPL	**9 m**	1,765	2,470
	39 m	1,852	2,331

Table 9. Median and maximum distances to centroid of modelled 100 dB sound pressure levels (SPL) contour for the unweighted and low-frequency species weighted sound pressure level maps at the two different depths modelled (see Figures 30, 32 & 33) for the 15 m/s wind speed scenario for Hywind Scotland.

	Depth	Median Distance (m)	Maximum Distance (m)
Unweighted SPL	**9 m**	2,351	3,029
	39 m	2,880	3,714
LF weighted SPL	**9 m**	1,428	2,111
	39 m	1,665	2,323

(a)



(b)

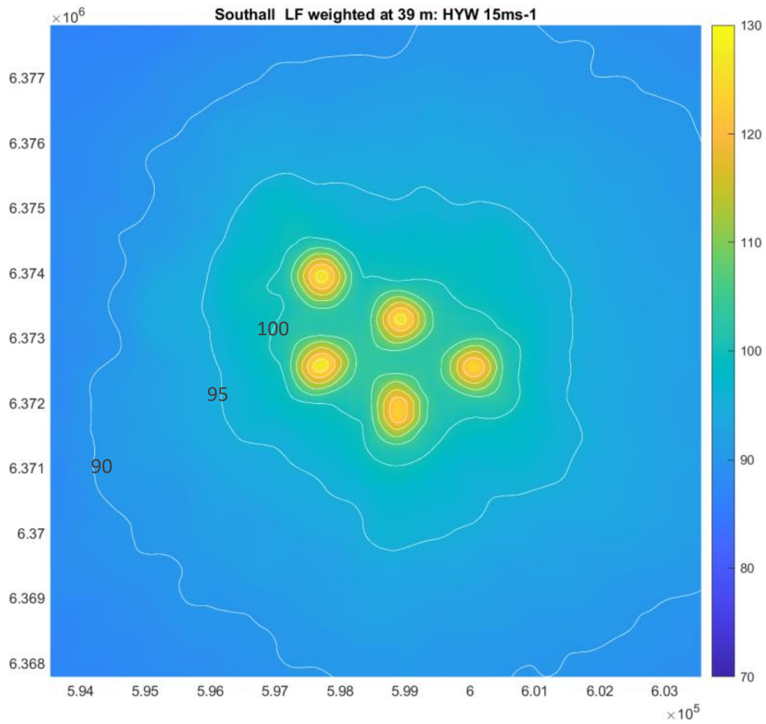


Figure 215. Low-frequency weighted sound pressure level map (25 Hz – 20 kHz) at 39 m water depth and a wind speed of 15 m/s, for (a) Kincardine and (b) Hywind Scotland. Scale: one-third octave sound pressure level (dB re 1 μPa).

3.7. Harbour Porpoise Presence

Harbour porpoises were frequently detected at both recording locations using the automated click detectors (F-PODs). However, daily detection positive minutes (DPM) at Kincardine, recorded in November 2021, were by an order of magnitude higher than at Hywind Scotland, where data collection took place during May and June 2022 (Figures 34 & 35). At both locations daily patterns of occurrence were similar for the two click detectors deployed at different distances from the target turbine. However, at both locations, recorded DPMs were considerably reduced at the site closest to the turbine compared to the site further away (i.e., 600 m compared to 1,500 m at Kincardine, and 300 m compared to 2,400 m at Hywind Scotland) (Figures 34 & 35).

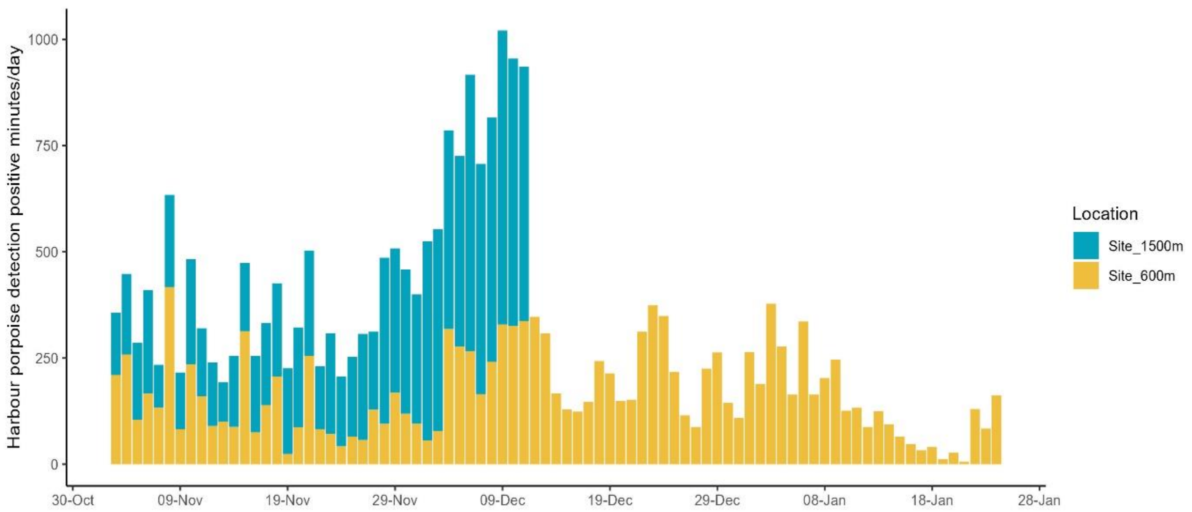


Figure 216. Stacked time series of harbour porpoise detection positive minutes (DPM) per day recorded at the two Kincardine sites at 600 m and 1,500 m from the closest turbine. Full deployment period: 02/11/2021 – 12/12/2021 and 02/11/2021 – 25/01/2022 for the 1,500 m and 600 m detector, respectively.

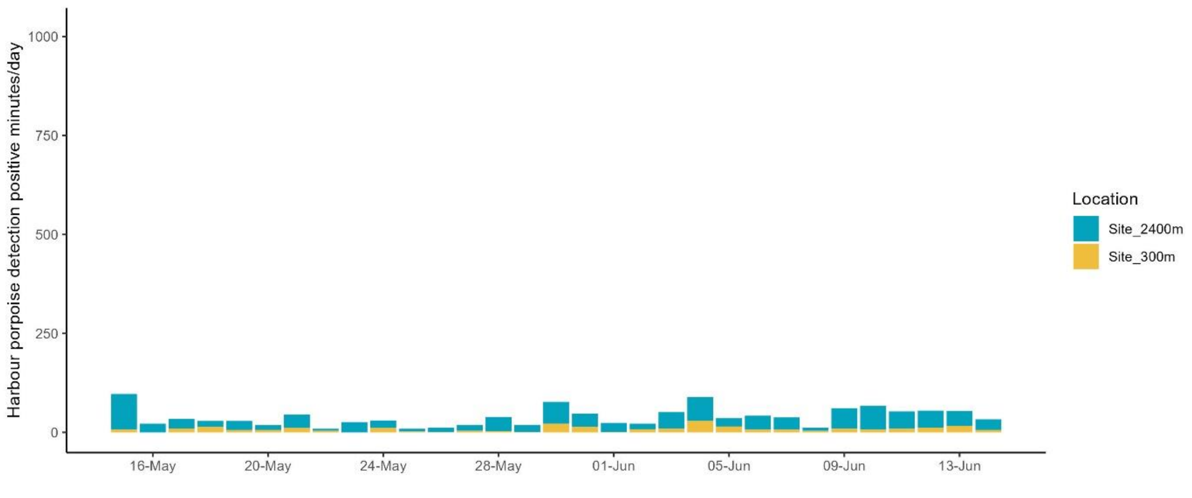


Figure 224. Stacked time series of harbour porpoise detection positive minutes (DPM) per day recorded at the two Hywind Scotland sites at 300 m and 2,400 m from the closest turbine. Full deployment period: 14/05/2022 – 15/06/2022.

4. Discussion and Conclusions

This project aimed to describe, compare and model operational and mooring noise from two floating offshore wind (FOW) farms, currently deployed off the Scottish east coast. Data were collected at the Kincardine FOW farm from November – January 2021/2022 and at the Hywind Scotland FOW from May to June 2022. At Kincardine five Vestas V164 turbines rated at 9.5 MW were deployed on semi-submersible foundations, while at Hywind Scotland five 6 MW rated Siemens SWT-6.0-154 turbines were deployed on spar-buoys (Table 1).

At both recording locations, most turbine operational noise is concentrated below 200 Hz (Figures 14-16). Median one-third octave band levels in this frequency range were between 95 and 100 dB re 1 µPa at about 600 m from the closest turbine. These noise levels are above expected ambient noise levels due to wave and wind conditions according to the Wenz curves (Wenz 1962). They are also very similar to those measured for operational noise from fixed offshore wind turbines at comparable distances (Tougaard et al. 2020, Stöber & Thomsen 2021).

As expected, at Kincardine median noise levels were higher closer to the turbine than at distance (i.e., median noise levels (at 125 Hz) were 91.3 dB re 1 µPa at 600 m compared to 95.5 dB re 1 µPa at 1,500 m). However, at Hywind Scotland, noise levels at the 2,400 m recording site were higher than at 600 m from the turbines and substantially higher than ambient levels (i.e., median levels (at 125 Hz) of 110.2 compared to 95.2 dB re 1 µPa; Figure 13). Given that both FOW farm locations were at similar water depths (see Table 2), it is likely that this difference is due to the far site at Hywind Scotland experiencing considerably more vessel traffic compared to the site closer to the turbine This assumption was corroborated during an opportunistic review of the raw acoustic data, which showed increased vessel presence at this site. However, a detailed analysis of vessel traffic by either automatic acoustic detection of vessel noise or integration of Automated Identification System (AIS) ship tracking data with the collected acoustic data was outside the scope of this project. This result does highlight that selecting appropriate 'control sites' to collect ambient sounds for comparison with turbine noise, can be difficult, especially in busy marine regions such as the North Sea. This is true even across relatively short distances. Data collection at the deployment site, before new projects are being constructed, ideally across several seasons, is therefore the best way to obtain comparable ambient sound data.

At Kincardine and Hywind Scotland noise levels at the site furthest away from the turbine showed a bi-modal distribution compared to recordings made at the closer sites (Figure 13). This might be related to a difference in the deployment setup at these sites. Instead of using a lander to deploy the acoustic recorder, an inline mooring was used at the far sites instead (see Figure 6, Tables 2 & 3). The recorder was thus located higher in the water column (i.e., 5 m vs 1 m above the seabed), which might have resulted in the data being potentially slightly more affected by mooring self-noise due to tidal currents. However, since the focus of this project was to describe and model the characteristics of operational turbine noise, and only the data of the nearby recorders were used for back-calculating turbine source levels, the overall results of this study were not affected by this potential contamination at the far sites.

Aerodynamically produced noise generally does not influence underwater noise levels due to reflection off the water surface (Marmo et al. 2013, Tougaard et al. 2020), but noise generated by the turbine generators and gearbox (if present) is radiated into the water and seabed via the partially submerged turbine tower. Like operational noise of fixed offshore wind turbines, operational noise from the measured floating offshore wind turbines was concentrated in the frequencies below 100 Hz and showed distinct tonal features between 50 and 80 Hz at Kincardine (Figure 10). At Hywind Scotland dominant tones were observed at about 25 and 75 Hz (Figures 21), which was also found by Burns et al. (2022) in a separate study of the Hywind Scotland turbines. The one-third octave bands in which these tones occurred showed strong positive correlations with wind speed and weaker but still positive correlations with wave height (Figure 17). These observed tonal features are likely related to rotational speed of the turbine blades (Burns et al. 2022).

Similar to what was reported by Burns et al. (2022), at both recording locations, the operational noise levels of the 3.2 and 12 kHz centred one-third octave bands were also strongly positively correlated to wind speed, which is expected, as these frequencies are most impacted by noise generated by wind and wave action according to the Wenz curves (Wenz 1962).

The obvious shift to higher frequencies with higher wind speeds at Kincardine and relatively consistent dominant tonal features at Hywind Scotland (Tables A1 & A2), independent of wind speed, might be a consequence of differences in the drivetrain of the turbines, with Kincardine using a gearbox and Hywind Scotland featuring direct drive turbines. Additionally, since no attempt was made to isolate sounds from individual turbines in this project, some of the observed changes in frequency of dominant tonal signals with changing wind speed, are due to contributions of different operational turbines within the five-turbine arrays. In their analysis of recordings from Hywind Scotland, Burns et al. (2022) showed that the acoustic signature of the individual turbines within the array were quite different, which they assigned to a combination of factors, including differences in small-scale wind pressure fields, generator loadings and blade pitch settings.

The biggest difference between fixed and floating offshore wind turbines in relation to underwater noise generation is the presence of mooring-related noise. During higher wind speeds the number of impulsive 'snaps' or transients from mooring associated structures increased at both Kincardine and Hywind Scotland. As described by Burns et al. (2022) these sounds either occurred individually or in rapid repetitions, creating a 'rattling' or 'creaking' noise. These impulses were generally of short duration and broadband, covering the whole recording bandwidth (i.e., 10 – 48 kHz). Occurrence of these transients was variable at both sites, but generally higher for the semi-submersible platforms deployed at Kincardine compared to the spar-buoy platforms deployed at Hywind Scotland (Figure 22). There also appeared to be a stronger relationship between wind speed and transient noise levels at Kincardine compared to Hywind Scotland (Figures 18 & 19).

The difference in number of transients in both data sets is also illustrated by comparing the kurtosis values within and between the two wind farm locations. While at Kincardine a clear difference could be observed between the data recorded at 600 m compared to 1,500 m from the closest turbine, such a difference was not observed at Hywind Scotland (Figure 26). Mean kurtosis values calculated over 30 seconds in both datasets were 8.1 and 3.3 for Kincardine and Hywind Scotland, respectively. While several individual 'snap' events within the recorded signal did reach higher kurtosis values, particularly at Kincardine (Figure 25), this means that the overall signal recorded near both floating offshore wind farms is not classified as fully impulsive (i.e., $\beta < 40$; see Hamernik et al. 2007, Martin et al. 2020). Application of non-impulsive frequency weighted noise threshold values for determining auditory injury risk to marine mammals for the recorded signal is therefore appropriate (see National Marine Fisheries Service 2018 and Burns et al. 2022 for a more detailed discussion of injury risk estimation).

Source levels for operational noise (25 Hz – 20 kHz), for which the transient 'snaps' were filtered increased with wind speed at both recording locations. At a wind speed of 15 m/s, levels were found to be about 3 dB higher at Kincardine as compared to Hywind Scotland (i.e., 148.8 compared to 145.4 dB re 1 µPa). Levels were more similar for both turbine types in the lower wind speed conditions (i.e., 1-2 dB difference, Table 7).

The power rating for the Kincardine turbines was 9.5 MW compared to 6 MW for the Hywind Scotland turbines, which together with the use of gear box (Kincardine) compared to direct drive (Hywind Scotland) technology and a difference in mooring structure (see Table 1), are likely responsible for the observed difference in source levels between the two wind farms. An increase of received broadband sound pressure levels with turbine size and when comparing direct drive and gear box technology has also been predicted for fixed offshore wind turbines (Stöber & Thomsen 2021).

Noise levels were analysed by wind speed and compared between Kincardine and Hywind Scotland. A wide range of wind speeds (0-21 m/s) and associated variability in signal levels were observed at both recording locations. However, a one month recording period is relatively short and in future work longer term recordings, covering several seasons and a range of weather conditions at both sites would allow to capture more of the total signal variability for both types of turbines.

It is important to note that the propagation modelling carried out here to estimate turbine source levels, assumes that all noise recorded at the recording device is from the monitored wind turbine. However, the signal will include ambient noise as well, which will necessarily be part of the back-propagated signal, which means that the source levels reported here are likely over-estimated, especially in situations where the turbine signal is close to ambient noise conditions. The source levels for operational noise calculated for Hywind Scotland are also not directly comparable to those measured by Burns et al. (2022) at the same location, due to differences in methodology (e.g., filtering of transient sources, different propagation models and the frequency range over which source they were calculated (i.e., 10 Hz – 25 kHz for Burns et al. (2022) and 25 Hz – 20 kHz for this study).

In fixed offshore wind farms, cumulative noise fields from turbine arrays have been shown to extend beyond the noise footprint of individual turbines potentially ranging to several kilometres under low ambient noise conditions (Tougaard et al. 2020, Stöber & Thomsen 2021). Using the 100 dB contour to approximate median ambient noise levels in many parts of the North Sea (for the 20 Hz – 20 kHz band; Putland et al. 2022), predicted noise fields for unweighted sound pressure levels for the 5-turbine arrays were above ambient for maximum distances of 3.5 - 4.0 km from the centroid of the array at Kincardine and 3.0 - 3.7 km at Hywind Scotland (assuming 15 m/s wind speed, Figure 30; Tables 8 & 9). Distances over which FOW array noise might be detectable over ambient conditions will increase, for example in locations with lower ambient noise conditions and wind speed scenarios, under different propagation conditions (e.g., in deep water habitats) and/or involving an increased number of turbines (Tougaard et al. 2020). This underscores the importance of considering the cumulative noise output of large turbine arrays in environmental impact assessments of new projects.

At both FOW farm locations daily patterns of harbour porpoise occurrence were similar for the two click detectors deployed at different distances from each target turbine. However, for both wind farm arrays, recorded porpoise detections were reduced at the recording site closest to the turbine compared to the site further away. While these results are preliminary, they might indicate longer term displacement and/or reduced vocalisation behaviour of harbour porpoises closer to turbines rather than attraction to devices. As these FOW farms have only been operational for a short period these observed occurrence pattern may change over time as FOW farms become more mature.

The sound propagation modelling for this project, as well as the study by Burns et al. (2022), rendered the floating offshore wind turbines as point sources of noise. In the future, more detailed, directional measurements will be required to characterise the turbines as spatially distributed sound sources by separating and characterising noise emissions related to different parts of the FOW turbine, its sub-structure and moorings, for both semi-submersible and spar buoy designs. The outcomes of such an analysis would provide further clarity regarding the extent to which, for environmental impact assessment purposes, it is sufficient to treat FOW turbines as point sources. Alternatively, a distributed sound source analysis would be required to determine the full extent of the environmental risk. Such work should also consider near-field and far-field analyses, and the extent to which spar and semi-submersible sub-structure designs may require comparable or more bespoke approaches to acoustic monitoring. Future work could also help to determine whether sub-structure and mooring designs are key drivers of FOW related noise emissions. Interactions between mooring and operational turbine noise and environmental parameters should be explored more extensively than was possible in this project. Based on this information, potential mitigation options could be developed where necessary. The latter would ideally be performed through engagement with turbine, mooring and platform engineers and designers.

In conclusion, this project provided one of the first assessments of underwater noise produced by small arrays of two types of FOW turbines and mooring systems. The results highlight the importance to consider both operational and mooring-related noise when assessing impacts of FOW farms on the behaviour of marine species. The cumulative noise output of large FOW turbine arrays should also be considered in environmental planning and impact assessments of new projects, especially in regions where boundaries of several FOW projects overlap with one another, or other marine space uses.

5. Acknowledgements

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7. Appendix A. Mooring Noise Examples

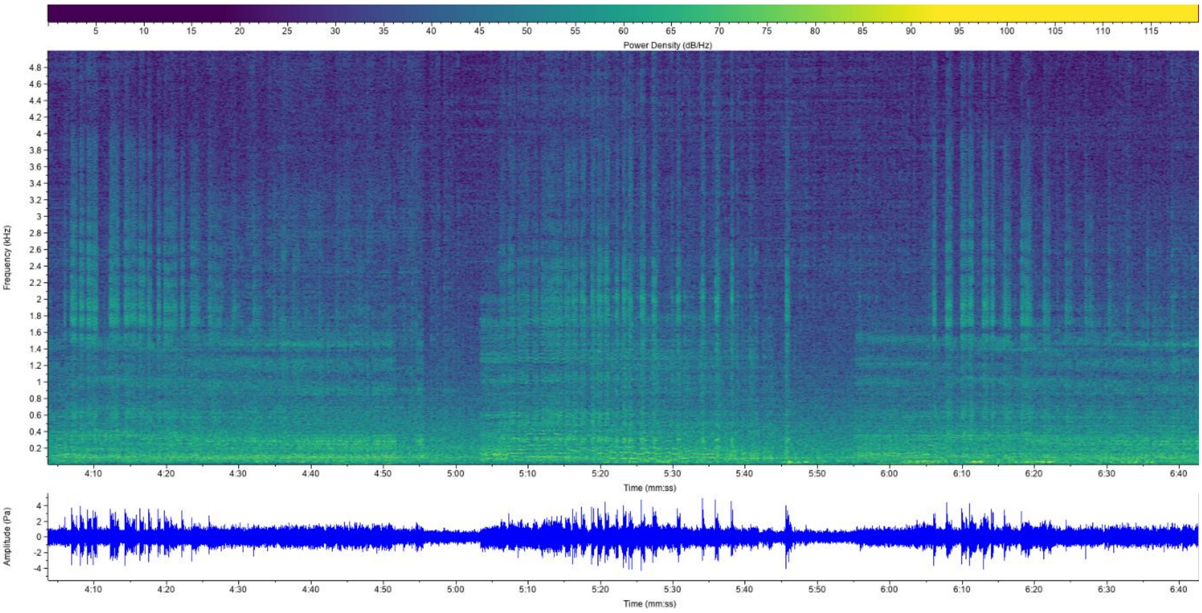


Figure A 1. Example of persistent mooring noise recorded at Hywind Scotland, 600m from the target turbine.

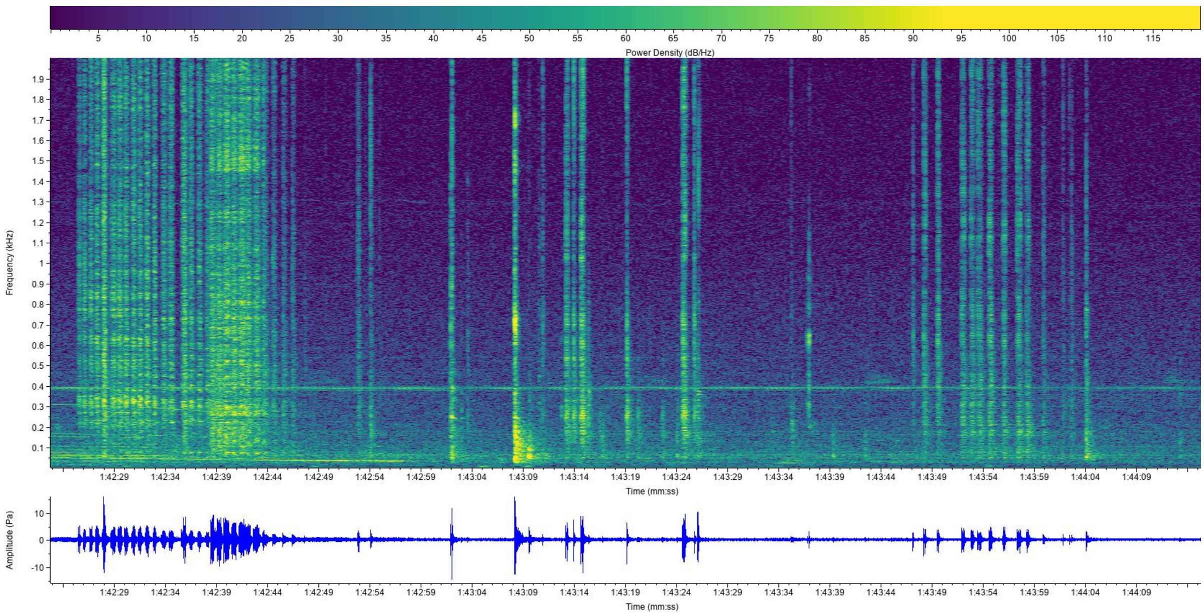


Figure A 2. Example of persistent mooring noise recorded at the Kincardine site 600m from the target turbine.

8. Appendix B. Source Levels

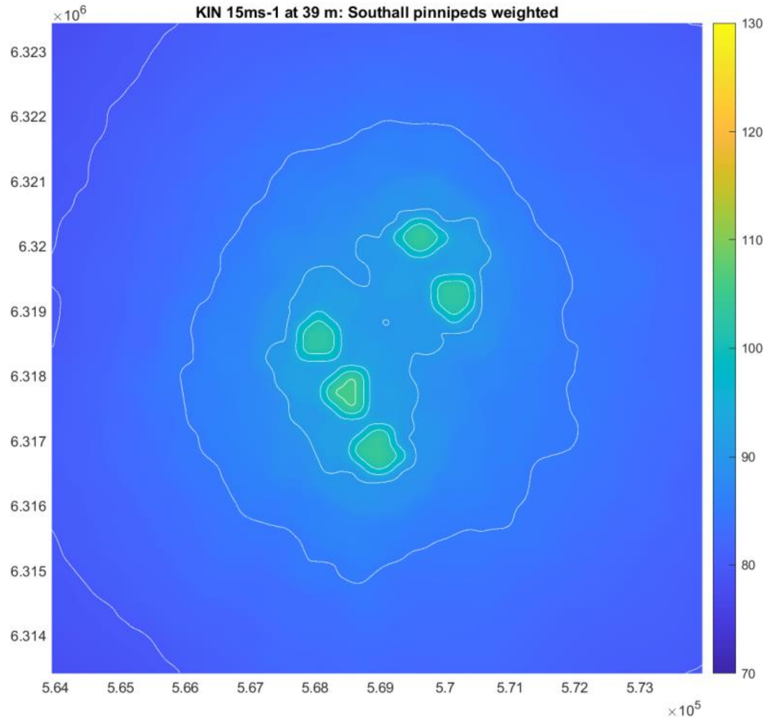
Table B 1. Overview of estimated one-third octave band source levels for different wind speeds at Kincardine. Table values are conditionally formatted with colours indicating relative loudness (green: low to red: high).

Kincardine Source Level (dB re 1 µPa)				
	Wind Speed			
Frequency	**6 m/s**	**9 m/s**	**12 m/s**	**15 m/s**
Total	**144.8**	**144**	**147.1**	**148.8**
25	126.9	129.8	132	132.6
31.5	142.7	133.2	137.9	141
40	137.4	130.6	129.1	131.7
50	129.4	138.6	140.3	138
63	130.6	138.9	143.9	145.9
80	125.4	130.1	132.8	137.3
100	125.5	126.1	128.6	132
125	120.2	122.9	124.4	128.3
160	118.2	123.1	125.2	125.6
200	114.8	116.9	116.8	119.2
250	115.3	118	117.6	120.9
315	128	131	131.9	134.1
400	129.8	128.4	127.4	130.7
500	123.7	125.9	125.4	128
630	123.7	126.5	126.3	128.6
800	121.4	124	123.8	125.8
1000	118.9	122.4	122.2	124
1200	116.6	119.8	120.2	121.7
1600	116	119.5	120.2	121.5
2000	115.2	119.3	120.6	121.4
2500	113.6	117.7	119.2	120.2
3200	112.4	116.7	118.1	119.7
4000	113.9	118.4	119.9	121.3
5000	109.5	113.8	115.3	116.3
6300	109.9	114.4	115.8	117.3
8000	110	114.7	116.3	117.2
10000	108.4	112.8	114.7	115.2
12500	110.1	114.3	116	116.5
16000	109.2	113	114.4	115
20000	109.4	112.8	114.3	114.7

Table B 1. Overview of estimated one-third octave band source levels for different wind speeds for Hywind Scotland. Table values are conditionally formatted with colours indicating relative loudness (green: low to red: high).

Hywind Scotland Source Level (dB re 1 µPa)				
	Wind Speed			
Frequency	**6 m/s**	**9 m/s**	**12 m/s**	**15 m/s**
Total	**143.4**	**143.7**	**145.4**	**145.4**
25	126.5	131.6	138	139.4
31.5	127.6	126.6	126.8	126
40	132.3	131.5	131.7	130.8
50	133.5	132.5	133	131.8
63	132	131.7	133.3	132.5
80	136.7	137.8	140.3	140.7
100	134.9	135.1	135.5	133.9
125	134.8	134.5	134.8	133.1
160	130.4	130	129.6	128.2
200	124.9	124.2	123.8	122.6
250	124.5	123.9	123.8	122.8
315	129.2	128.2	128.2	127.1
400	127.3	126.7	126.8	126
500	126.7	126.6	126.9	126
630	124.1	124.5	125	124.3
800	121.8	122.5	123.2	122.6
1000	120.8	121.3	122.2	121.7
1200	120.1	121.2	122.4	121.9
1600	118.1	119.5	121.3	120.8
2000	118.7	120.2	122.6	122.1
2500	117	118.2	120.7	120.4
3200	116	117.5	120.4	120.1
4000	116.5	118.6	121.7	121.6
5000	116	118.4	121.7	121.7
6300	112.7	115.3	118.8	118.8
8000	114.1	117.7	121	121.2
10000	112.1	116.7	119.6	120.1
12500	112.6	117.1	119.6	120.4
16000	112.6	116.6	118.7	119.5
20000	113.8	117.4	119.3	120.1

9. Appendix C. Model Results



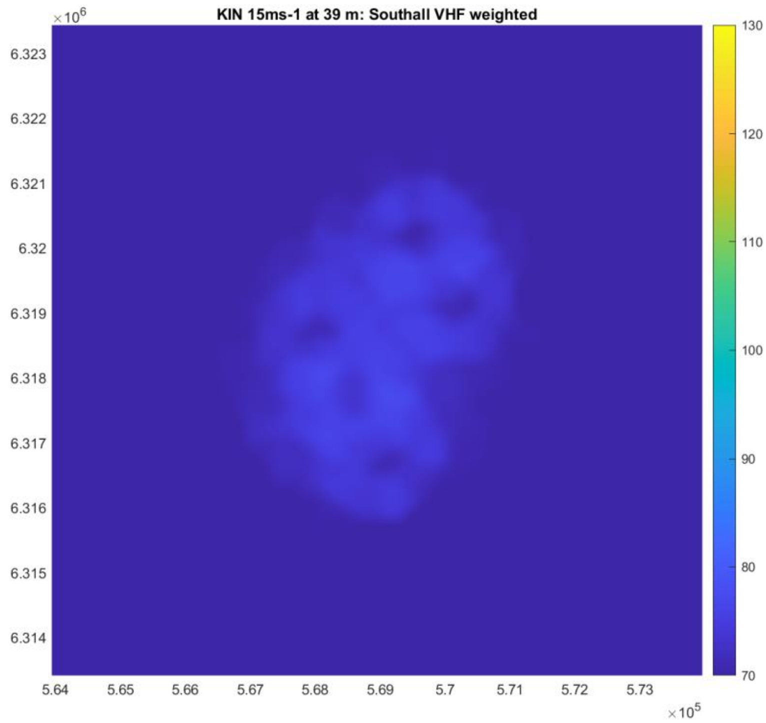


Figure C 3. Weighted sound pressure level map (25 Hz – 20 kHz) at 39 m water depth and a wind speed of 15 m/s, for (a) Pinnipeds and (b) Very-high frequency cetaceans at Kincardine. Scale: one-third octave sound pressure level (dB re 1 µPa).

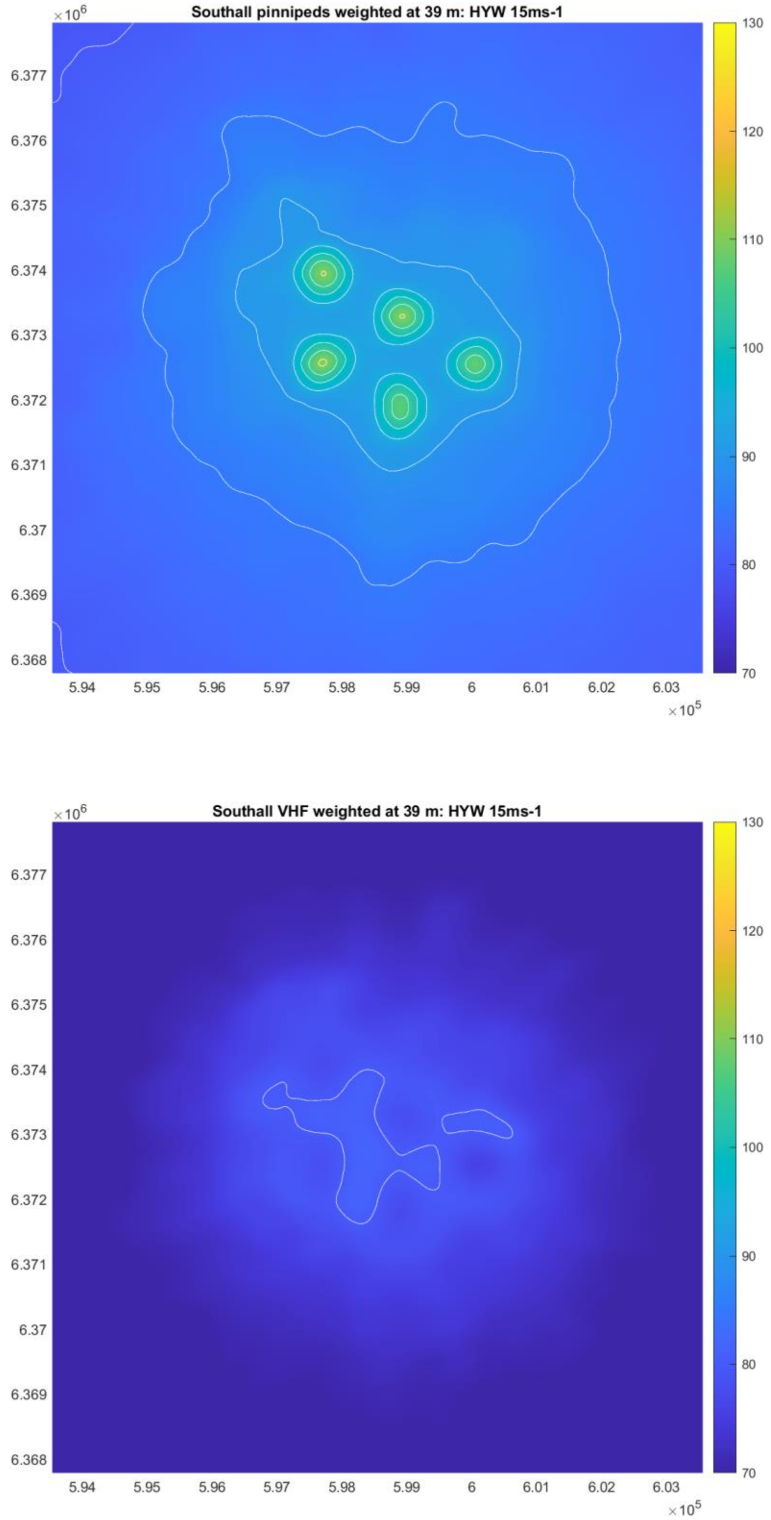


Figure C 2. Weighted sound pressure level map (25 Hz – 20 kHz) at 39 m water depth and a wind speed of 15 m/s, for (a) Pinnipeds and (b) Very-high frequency cetaceans at Hywind Scotland. Scale: one-third octave sound pressure level (dB re 1 µPa).