Underwater sound produced by operational floating wind turbines

Conference Paper · September 2024

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ABSTRACT

Deployment of offshore wind turbines is growing rapidly. Conventional "fixed bottom" wind turbines are limited to water depths of ~60 m, so deployment of offshore turbines to greater water depths requires floating systems. Both fixed bottom and floating turbines produce operational noise that impacts the marine environment. While the operational noises from fixed bottom turbines are relatively well understood, floating turbines are comparatively novel technologies and there is uncertainty as to the noise they will produce and its impact on the marine environment.

Results from acoustic surveys of two floating wind farms off the Scottish Coast are presented; Kincardine Wind Farm, which uses semi-submersible floating systems; and Hywind Scotland, which uses a floating spar structure. The acoustic signature of each consists of continuous tonal noise related to drivetrain vibration and transient broadband events related to the mooring systems. Sound propagation modelling was used to determine the source levels for turbines at each wind farm allowing a comparison of the noise signature of different floating structures. The sound level 100 m from the turbines related to drivetrain vibration were comparable to fixed bottom turbines.

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1. INTRODUCTION

The deployment of offshore wind turbines is rapidly growing, motivated by the need for renewable energy to address the climate emergency. The vast majority of deployed offshore wind turbines are founded on the seabed using structures such as monopiles, jackets or gravity bases. These "fixed bottom" wind turbines are constrained to relatively shallow water on continental shelves where the water is less than 60 m deep. Placing wind turbines on floating structures that are moored to the seabed will allow the placement of wind turbines in deeper waters extending the wind energy capacity beyond the continental shelves. In 2018 the globally installed floating offshore wind capacity was 57 MW, by 2030 global capacity could be as high as 4.3 GW [1]. In 2022, 56% of the global Floating Offshore Wind (FOW) capacity was installed in UK and specifically, Scottish waters [1]. Despite this rapid expansion, questions remain regarding potential long-term environmental impacts which could generate delays in the consenting process. One open question is the underwater noise produced by the normal operation of FOW and its long-term effects on the marine environment.

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 [2], [3], [4] [5]. 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 [6] [7]. Underwater noise from operating fixed wind turbines is typically generated by mechanical vibrations in the nacelle and exhibits tonal frequencies and harmonics corresponding to gear meshing frequencies in the gear box [8] [9]. Most emitted frequencies are expected at lower frequencies (< 1 kHz), with tonal elements at frequencies related to gear meshing and their harmonics (e.g., [8] [9]). The produced noise is generally comparatively low intensity, i.e., 10-20 dB lower than ship noise in the same frequency range [10]. 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., [11], [12], [13]).

Given the motivation to install wind energy capacity in deep water environments facilitating the need for FOW, it is vital that the underwater noise produced by these floating structures is characterized. It is reasonable to assume that similar mechanisms and the main noise sources are similar for fixed bottom and FOW turbines. However, the lack of a fixed foundation and the addition of structural elements such as the mooring lines will affect measured noise levels and tonal frequencies. This paper presents measurement and noise characterization of two FOW farms; Hywind Scotland and Kincardine Wind Farm (Figure 1).

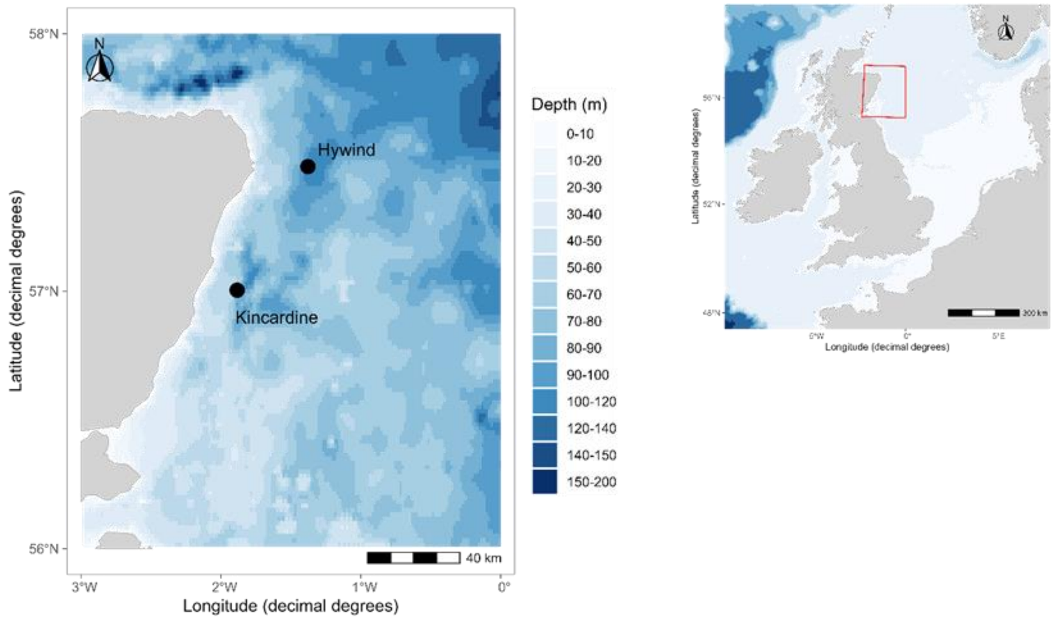

Figure 1: Position of the Kincardine and Hywind Scotland wind farms with depth of water shown (Left). Red box in inset indicates detailed map area in relation to UK coastline (Right).

2. WIND FARM SPECIFICATIONS

The two FOW turbine array sites within which data for this project was collected are located on the north-east coast of Scotland (Figure 1). Hywind Scotland is operated by Equinor, has been operating since 2017 and is located 25km to the east of Peterhead (Figure 1). Hywind Scotland consists of five Siemens SWT-6.0-154 wind turbines. Each turbine at Hywind Scotland has a rated power of 6 MW, a rotor diameter of 154 m and tip height of 178 m (Table 2). The Hywind Scotland turbines are direct-drive systems (i.e., they do not have gearboxes). The turbines at Hywind Scotland are founded on spar-buoy floating foundation (see example in Figure 2). The average water depth a Hywind Scotland ranges between 95 m and 120 m.

The Kincardine Offshore Wind Farm is operated by Principle Power, has been operational since 2020 and is located about 15 km off the coast of Aberdeen and consists of five Vestas V164 turbines founded of a semi-submersible floating foundation (see example in Figure 2). The turbines at Kincardine are relatively larger than Hywind Scotland, each have a rated power of 9.5 MW with rotor diameters of 164 m and tip heights of 190 m (Table 1). The Kincardine turbines use include gearboxes in their power transmission systems. Average water depth at the Kincardine site is shallower than Hywind Scotland with a range between 60 m and 80 m. Both Kincardine and Hywind Scotland use chain catenary mooring systems with three mooring lines per FOW turbine.

Figure 2: Visualization of floating structures used to founder FOW turbines. The spar-buoy on the left is an example of the foundations used at Hywind Scotland. The semi-submersible on the right is an example of the foundations used at Kincardine wind farm (after [14]).

Table 1: Overview of wind turbine specification at the Kincardine and Hywind Scotland wind farms.

	Kincardine	**Hywind Scotland**
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 system	Gearbox	Direct Drive
Foundation type	Semi-submersible	Spar-buoy
Mooring lines (per turbine)	3	3
Mooring system	Chain catenary	Chain catenary

3. MEASUREMENT METHODOLOGY

Acoustic monitoring of Kincardine wind farm was conducted between November 2nd 2021 to January 25th 2022. Three acoustic monitoring moorings were deployed at distances of 200m, 600m and 1500m from the turbines at Kincardine (Figure 3). Hywind Scotland was monitored from 14th May 2022 to 15th June 2022 with moorings deployed at 300m, 600m and 2400m (Figure 3). Both study sites used similar mooring designs. At the sites furthest away from the monitored turbine, the mooring consisted of a one-channel broadband sound recorder (Soundtrap 500 HF; Ocean Instruments, NZ) and an automated echolocation click detector (F-POD; Chelonia Ltd., UK). The recorders were approximately 1-8 m above the seabed and moored with a sub-surface recovery system (VR2AR acoustic release; Innovasea, Canada with an ARC rope canister; RS Aqua, UK) using chain link weights of about 70-90kg (Tables 1 & 2). The moorings at the 200/300m and 600m sites consisted of a lander with a 4-channel recorder

(Soundtrap 4300STD) paired with an F-POD (i.e., Kincardine 600 m and Hywind 300 m) or a one-channel acoustic broadband recorder (Soundtrap 300 HF) (i.e., Hywind 600 m) (Table 2).

Recordings made with the 4-channel Soundtrap recorders were duty-cycled and 15 minutes of each hour were recorded using a 96,000 Hz sample rate and 16-bit resolution. The first channel of the 4-channel recording was selected for noise level and signal structure analysis. The single-channel Soundtrap recorders (Tables 2) were set up to record continuously at a sample rate of 96,000 Hz and 16-bit resolution. Both recorders thus provided an effective analysis bandwidth of 10 – 48,000 Hz.

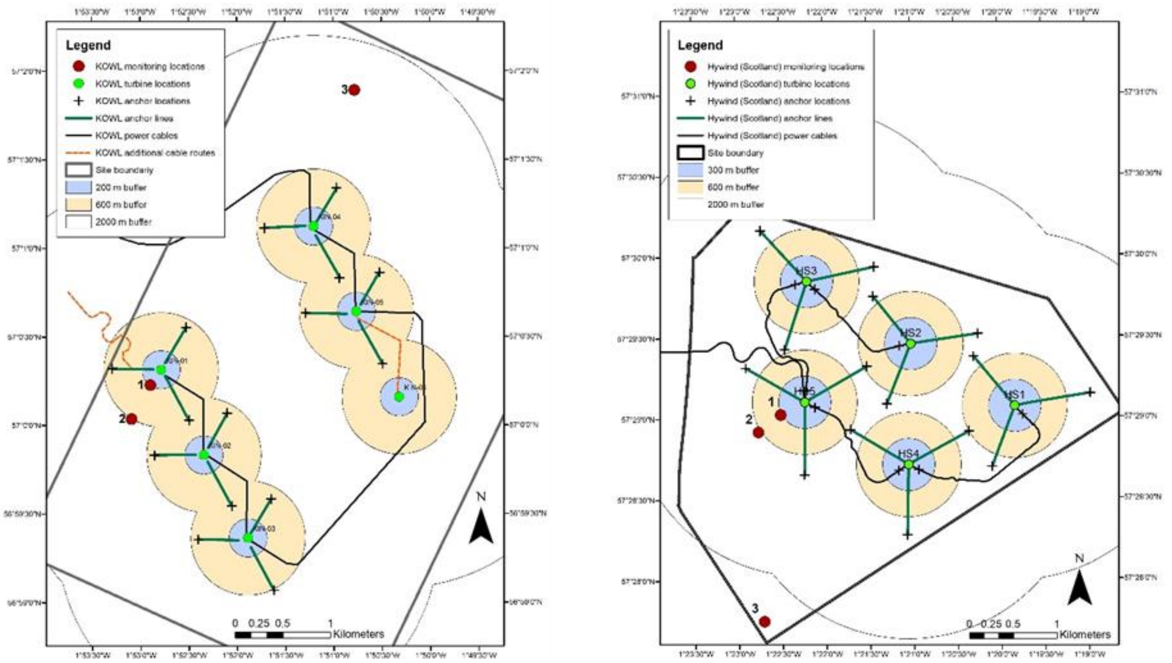

Figure 3: Map of turbine (green dots) and turbine anchor (black crosses) locations. Red dots indicate acoustic recording locations at 200m, 600, and 1500m (Kincardine; left panel) and 300m, 600m, and 2400m (Hywind Scotland, right panel). Note that only 5 turbines had been deployed at the Kincardine site at the time of recording. The site in the lower right corner had not been developed yet.

4. UNDERWATER NOISE CHARACTERISATION

Long-term spectral averages (LTSA; 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. 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 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 vessel noise and data were sub-divided into a full and cleaned dataset, from which periods of obvious vessel 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.

Table 2: Specifications of acoustic monitoring at Hywind Scotland and Kincardine wind farms

Distance to Closest Turbine	Latitude	Longitude	Acoustic Recording Instruments	Seabed /Strap HF Depth (m)	Duty Cycle (Strap)
Hywind Scotland					
300 m	57.484	-1.377	Soundtrap 500 HF (1ch); F-POD	105 / 1.0	Continuous
600 m	57.482	-1.381	Soundtrap 4300STD (4ch); Soundtrap 300 HF (1ch)	104 / 1.0	15min / hour; Continuous
2400 m	57.463	-1.379	Soundtrap 500 HF (1ch); F-POD	104 / 8.0	Continuous
Kincardine					
200 m	57.004	-1.883	Soundtrap 4300STD (4ch)	65.7 / 1.0	15min / hour
600 m	57	-1.887	Soundtrap 4300STD (4ch); F-POD	64.7 / 1.0	15min / hour
1500 m	57.031	-1.848	Soundtrap 500 HF (1ch); F-POD	77.1 / 5.0	Continuous

At both Kincardine and Hywind Scotland wind farms two noise sources related to the operating turbines were identified. The first noise source is associated with the operation of the turbines, i.e., from the generator and other drivetrain components, which is more prominent at low frequencies. The noise related to drivetrain components tends to be tonal in nature, similar to that observed in fixed bottom wind turbines [8] [9]. 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 Third Octave Level (TOL) SPL time series measured at Kincardine 200m is shown in Figure 4. The transient events related to the mooring system appear as vertical lines in the spectrogram shown in Figure 4, while the noise related to the drivetrain related noise appear as horizontal lines below 100 Hz in Figure 4.

4.1. Discriminating between drivetrain and mooring line noise

To allow the comparison of drivetrain related noise from FOW to equivalent fixed bottom wind turbines it is necessary to isolate the continuous tonal noise associated with the generators and gearbox (when present) from the transient events related to the mooring systems (that are not present for fixed bottom wind turbines. The following procedure was used to discern times when drivetrain noise dominated the measured noise levels, and where impulse noise dominated the measured noise levels.

1. Calculate the k-point (k = 60) moving average of every third octave frequency band data point.
2. Disregard any third octave bands below frequency F = 900 Hz.
3. Count every occasion where the SPL in each 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 third octave bands have been counted as having an 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, simply by removing them. An example of the filtered data sets (operational and impulsive peaks) for the Kincardine 200m is shown in Figure 5.

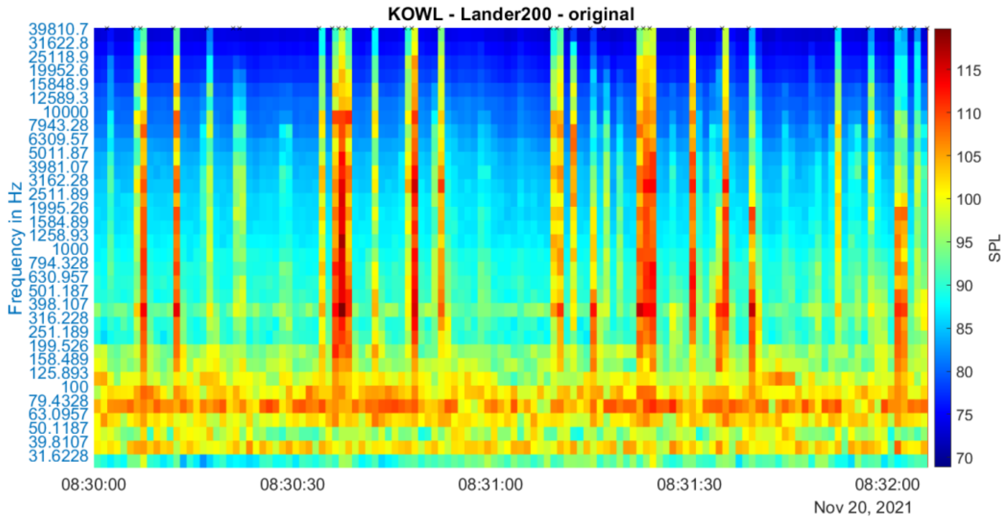

Figure 4: Example of one-third octave sound pressure levels (SPL dB re 1 μPa) measured at the Kincardine 200m lander, with impulse noise events visible as broadband, short duration noise. Noise associated with the turbine operation is most prominent at lower frequencies (< 100 Hz).

5. SOURCE LEVEL OF DRIVETRAIN RELATED NOISE

The source levels (SPL in dB re 1 μPa at 1 m from source) related to drivetrain noise were calculated by backward propagation modelling from the nearest hydrophone (Lander at 200m at Kincardine, and Lander at 600m at Hywind Scotland). 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 2.3) to determine the source levels related to operational noise from floating wind turbines.

Source levels were 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. 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). Source levels related to wind speeds of 6, 9, 12 and 15 m/s measure at the hub height of the rotor were calculated based on equivalent measured sound pressure levels.

The source levels calculated for single floating offshore wind turbines at Kincardine and Hywind are shown in Figure 6 and Figure 7, respectively. Generally, the source levels increase with wind speed at both wind farms (Table 2). Total source levels for the turbines deployed at Kincardine are slightly (i.e., 2-3 dB) greater than those for Hywind at all wind speeds (Table 2).

Drivetrain related noise at Kincardine showed relatively high tonal content in the 31 Hz, 63 Hz and 315 Hz third octave bands (Figure 6). Hywind had relatively higher operational noise levels in the one-third octave band centred at 25 Hz one-third octave band especially in higher wind speeds (Figure 7). Both sites show elevated operational source levels also for the 300-600 Hz frequency band.

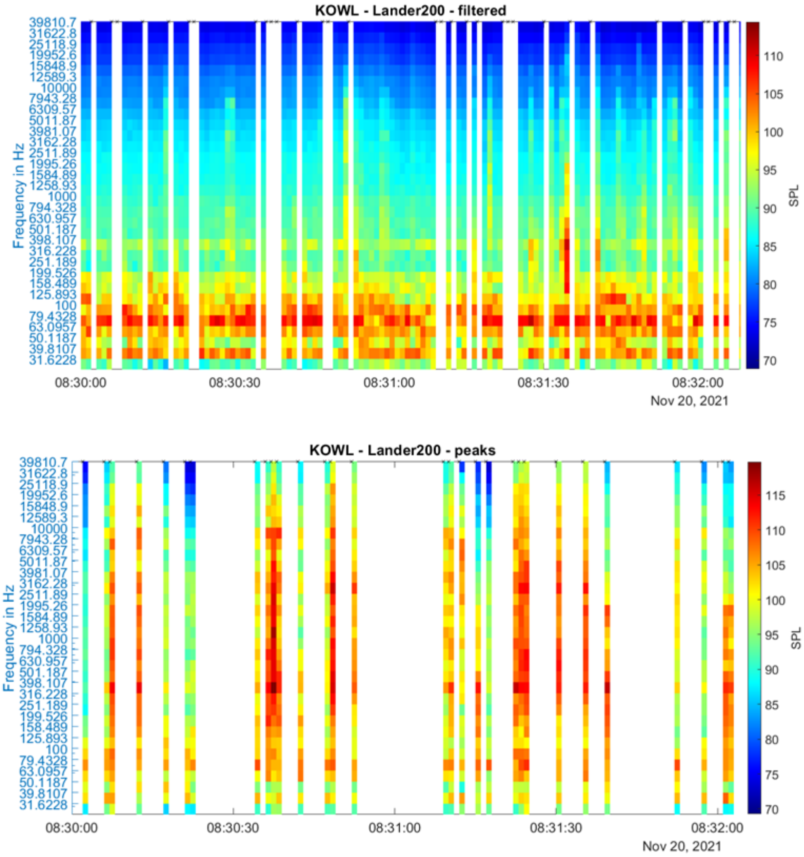

Figure 5: Example of one-third octave sound pressure levels (SPL dB re 1 µPa) measured at the Kincardine 200m lander, filtered to remove significant impulsive noise events (a) and to remove non-impulsive sections of data (b).

Table 2. Total source levels for floating offshore wind turbines deployed at Hywind compared to Kincardine at different wind speeds.

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

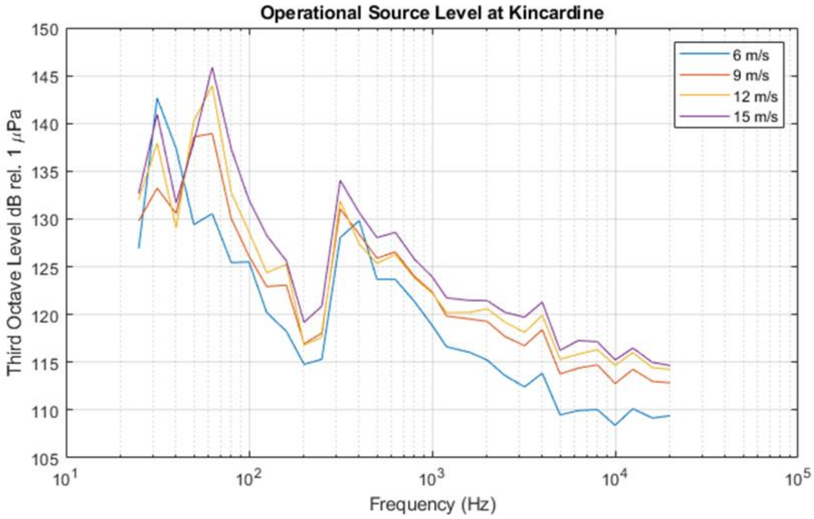

Figure 6. Source level (SPL in dB re 1 μPa at 1 m from source) of operational noise from a floating offshore wind turbine at Kincardine based on backward propagation of underwater noise from the Lander deployed at 200m to the closest turbine. The source level is for continuous noise related to rotational machinery in the drivetrain and excludes transient sounds.

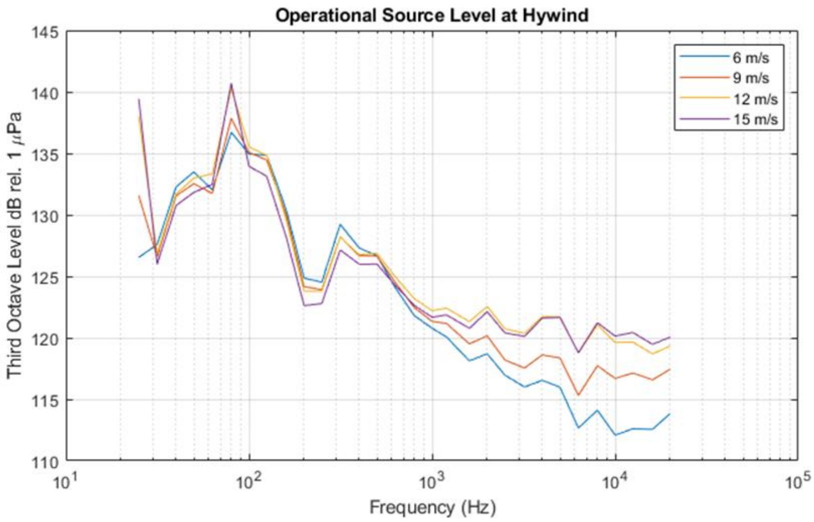

Figure 7. Source level (SPL in dB re 1 μPa at 1 m from source) of operational noise from a floating offshore wind turbine at Hywind based on backward propagation of underwater noise from the Lander deployed at 600m from the closest turbine. The source level is for continuous noise related to rotational machinery in the drivetrain and excludes transient sounds.

5.1. Drivetrain noise from FOW and fixed bottom wind turbines

The source levels related to drivetrain noise from a single wind turbine (Table 2, Figure 6 and 7) were used model the noise level at a distance of 100 m and at wind speed of 10 m/s. This allowed a comparison of sound emissions from the FOW wind turbines at Kincardine and Hywind Scotland to fixed bottom wind turbines reported by [6]. The noise levels produced by the floating wind turbines are similar to fixed bottom wind turbines that use jacket foundations and have comparable rate power and jacket foundation structures (Figure 8).

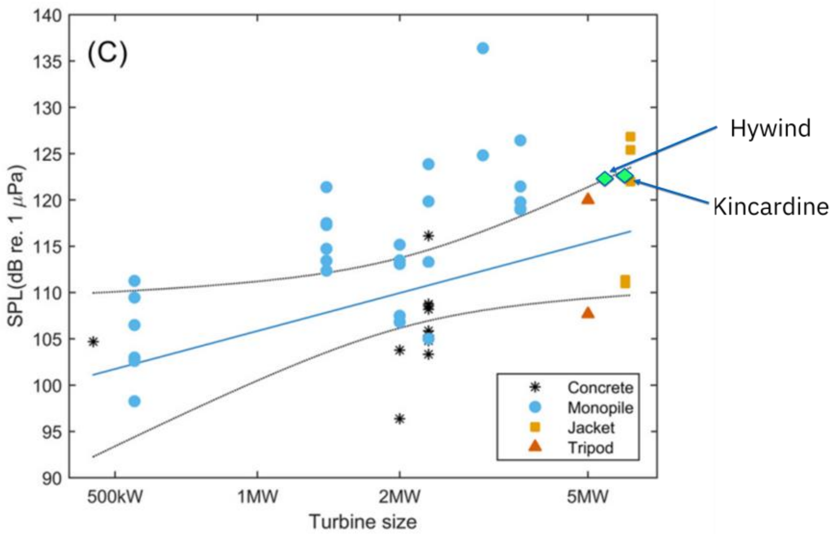

Figure 8. Influence on turbine size on SPL at 100 m from offshore wind turbines after [6]. The SPL was normalized to represent wind speed at 10 m/s (see [6]). Fixed bottom turbines that use concrete gravity bases, steel monopile, tripod and steel jackets as foundations are shown. The equivalent normalized SPL for Hywind Scotland and Kincardine are shown.

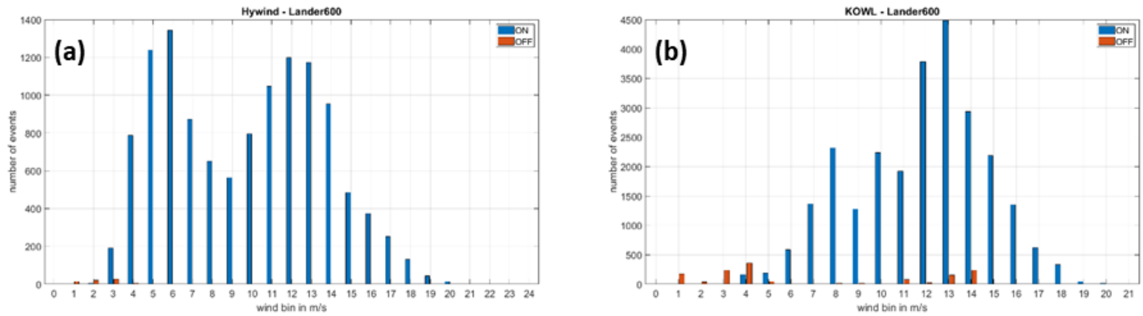

Figure 9. Number of transients events collected by the lander deployed at 600m from the closest for Hywind (a) and Kincardine (b). Blue histogram ('on') = all turbines with power output > 20 kW. Red histogram ('off') = at least one turbine with power output < 20 kW.

6. MOORING SYSTEM NOISE

The biggest difference between fixed and floating offshore wind turbines in relation to underwater noise generation is mooring-related noise. An increase in broadband impulses or transients related to the mooring structures was found both at Kincardine and Hywind during periods of higher wind speeds and significant wave height. 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 [15] for Hywind). These impulses, with energy often being distributed across the whole available analysis bandwidth (i.e., 0 - 48,000 Hz), were generally of short duration (i.e., 1-2 seconds 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 (Figure 9).

7. DISCUSSION

The source levels related to drivetrain vibration were calculated by backward propagation modelling to the five turbines at each wind farm, based on the range to the given wind turbines. The calibration of the models was performed using data when it was known that all turbines were operational and exporting electrical power. The backward propagation approach does, however, assume that the source levels are identical for turbines in the given wind farm. It is like that the source levels will have some variability related to their engineering tolerances and local operational conditions (i.e., spatial variability in wind speed, turbulence intensity, etc.). The approach also assumes that the range between sensor position and wind turbines is constant. However, floating wind turbines can move tens of meters with changing currents and wind directions. The source levels related to drivetrain vibration reported here therefore represent averages of engineering variability and range between sensor and each turbine.

The source levels related to drivetrain vibration at both Kincardine and Hywind Scotland tend to increase with wind speed (Figures 6 and 7). This increase in noise generation with wind speed has also been observed in onshore wind turbines [16]. The source level of the calculated for the Vestas V165 turbines at Kincardine are higher than the Siemens SWT-6.0-154 turbines at Hywind Scotland at equivalent wind speeds (Table 2). The high levels at Kincardine may be attributed to the Vestas turbines having a higher rated power (9.5 MW) compared to the Siemens turbines (6.0 MW); this is consistent with the general trend of source level increasing with rated power (Figure 8). The difference the floating foundation may also attribute to the difference in source level related to drivetrain vibration given that the spar-buoys at Hywind Scotland and the semi-submersible at Kincardine have vary different geometries and different surface areas in contact with the water from which noise can radiate. Differences in noise radiation for different foundation geometries have been noted in fixed bottom turbines ([6] [9]).

The topology of the source level spectra is also different at Kincardine and Hywind Scotland. Kincardine has spectral peaks in the third octave bands centred at 31 Hz, 63, Hz and 315 Hz. These peaks are likely related to the low-speed, intermediate, and high-speed step-up stages in the gearbox. The Hywind turbines do not contain gearbox, rather the spectral peaks the third octave bands centred at 20 Hz and 80 Hz are related to interaction between coils and stators in the generator.

Noise related to the mooring systems of the FOW turbines at Kincardine and Hywind Scotland are transient in nature and broadband compared to the drivetrain noise. There are 18 mooring lines at each wind farm, and it was not possible to determine which line was responsible for which transient event using omnidirectional hydrophones. It was therefore not possible determine the range to the even and determining a source term for mooring line noise using backward propagation model is not viable. A directional acoustic survey of mooring line noise would be a valuable contribution to better understanding noise from FOW.

The number of mooring line events was significantly higher at Kincardine than Hywind Scotland (Figure 9). Mooring line noise is likely due to rapid changes in axial load on the lines in response to swell and changes in wind conditions. The observation that Kincardine had a greater number of detected transient events attributed to the mooring system may be due to seasonality, as Kincardine was surveyed in winter (Nov-Jan) while Hywind Scotland was survey in late spring-early summer (May-Jun). The difference in geometry between the semi-submersible compared to the spar-buoy may also contribute to differences in mooring line noise.

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