# How loud is the underwater noise from operating offshore wind turbines?

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JASA ARTICLE

# How loud is the underwater noise from operating offshore wind turbines?

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**ABSTRACT:**
Offshore wind turbines are increasingly abundant sources of underwater low frequency noise. This increase raises concern for the cumulative contribution of wind farms to the underwater soundscape and possible impact on marine ecosystems. Here, available measurements of underwater noise from different wind turbines during operation are reviewed to show that source levels are at least 10–20 dB lower than ship noise in the same frequency range. The most important factor explaining the measured sound pressure levels from wind turbines is distance to the turbines with smaller effects of wind speed and turbine size. A simple multi-turbine model demonstrates that cumulative noise levels could be elevated up to a few kilometres from a wind farm under very low ambient noise conditions. In contrast, the noise is well below ambient levels unless it is very close to the individual turbines in locations with high ambient noise from shipping or high wind speeds. The rapid increase in the number and size of offshore wind farms means that the cumulative contribution from the many turbines may be considerable and should be included in assessments for maritime spatial planning purposes as well and environmental impact assessments of individual projects.

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## I. INTRODUCTION

Offshore wind is an increasingly important part of the transition to green energy and with this comes concerns for possible negative impacts on the environment. This concern has been addressed right from the beginning of the development of offshore wind energy (e.g., Gill, 2005; Danish Energy Agency, 2006; Wilson *et al.*, 2010). Early concerns were undoubtedly spawned by the sometimes intense debate over airborne noise from land-based turbines and the effects on humans (see, for example, Freiberg *et al.*, 2019), and this led to a number of studies to quantify the underwater noise radiated from offshore wind turbines. Unfortunately, most of these studies are only communicated in hard to obtain grey literature, and many are not written in English. A recent and notable exception from this is the study of underwater noise from a 3.6 MW turbine by Pangerc *et al.* (2016).

The early measurements were reviewed by Madsen *et al.* (2006), who concluded that the underwater noise from operating wind turbines is limited to low frequencies (below 1 kHz) and of low intensity, considerably lower than ship noise. They further concluded that noise from construction work, most importantly from percussive pile driving of turbine foundations, was by far the most significant source of underwater noise. However, despite the low intensity of the noise from individual turbines, the subsequent increase in the number of turbines installed in coastal waters worldwide and the increase in size of the individual turbines make it relevant to revisit these conclusions by reviewing more recent measurements and consider possible cumulative effects of larger turbines and larger wind farms. In European waters, it is, furthermore, relevant to evaluate whether the contribution from wind farms is of a magnitude that could impact the marine environment and thereby mandate monitoring and potential mitigation of the noise in fulfilment of the requirements of the European Union (EU) Marine Strategy Framework Directive (European Commission, 2008).

The underwater noise from operating wind turbines originates in the moving mechanical parts in the nacelle, almost exclusively with emitted energy at low frequencies, below 1 kHz, and typically with strong tonal elements at frequencies corresponding to gear mesh frequencies in the gearbox and their harmonics (Pangerc *et al.*, 2016). Wind induced vibration of the tower at high wind speeds has also been identified as a possible source of noise (Elmer *et al.*, 2007). In any case, the noise is transmitted through the tower and radiated from the foundation into the water. The different types of foundations used (Fig. 1) further raises the question of possible differences in emitted noise among foundation types. The most common type of foundation is a steel monopile; in shallow waters, concrete gravitational foundations are commonly used, and in deeper waters, tripods and jacket platforms dominate. Previous assessments, however, did not reveal any systematic differences between noise from turbines with different foundation types (Madsen *et al.*, 2006).

Another factor influencing the noise from wind farms is turbine size. As the size of the turbines increases so does the

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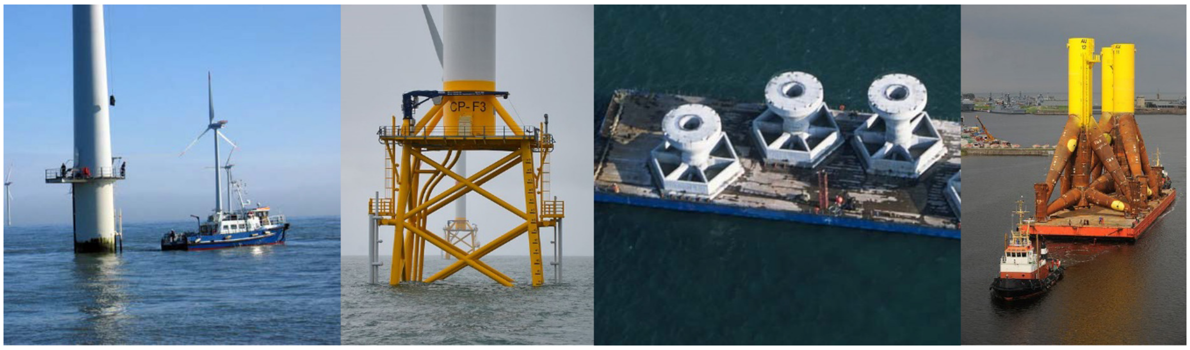


FIG. 1. (Color online) Different foundation types. From the left, Monopile (Horns Reef 1), Jacket (Thornton Bank), concrete (Nysted), and tripod (Alpha Ventus) are shown.

mechanical forces working on gears and bearings and, therefore, it may be expected that noise levels increase with turbine size as well. The size of turbines has increased more than one order of magnitude from the first 200 kW turbine studied by Westerberg (1994) to the 5–10 MW turbines currently being installed with prospects of even larger turbines in the coming years. However, as the turbines also become higher, the distance from the noise source in the nacelle to the water becomes larger too, and with the mechanical resonances of the tower and foundation likely to change with size as well, it is not straightforward to predict changes to the noise with increasing sizes of the turbines.

To address the possible influence of turbine size on radiated underwater noise, we review the available literature on turbine noise measurements. A secondary goal is to make these measurements more available and redo the assessment of the potential contribution of offshore wind farms on the underwater soundscape and possible effects on the marine environment.

## II. MATERIALS AND METHODS

### A. Compilation of measurements

Measurements of operational noise from offshore wind turbines were identified in both peer-reviewed literature and reports from research projects and environmental impact assessments. A full list of all identified literature with information about operational noise from offshore wind turbines is given in Table I. Several of the references discuss the same measurements, but all are included for completeness. Only measurements where the distance from the turbine was known are included in the following analysis.

Broadband sound pressure levels were, in a few cases, given directly in the text or figures (van Radecke and Benesch, 2012; Thomsen *et al.*, 2015; Pangerc *et al.*, 2016; Elliott *et al.*, 2019). In the remaining cases, the broadband level had to be estimated by various methods. Some studies provide one-third octave band spectra of the noise (Betke *et al.*, 2004; Elmer *et al.*, 2007; Tougaard *et al.*, 2009), in which case the broadband level could be estimated as the sum of the intensity in the bands dominated by turbine noise over background noise. In the remaining cases (Fristedt *et al.*, 2001; Ingemansson Technology AB, 2003; Andersson, 2011; Nedwell *et al.*, 2011a; Betke, 2014), power density spectra were the only available information. As the turbine noise is typically dominated by strong tonal components originating from the gear meshing, which (over short time) is expected to generate an almost constant pure tone, often with visible but energetically insignificant harmonics, the broadband level was assumed to be identical to the height of the strongest peak. Wind speed was given in most cases, but for one study (Nysted offshore wind farm, Elmer *et al.*, 2007), it had to be back-calculated from the turbine power curve (output power against wind speed) for the turbine type. Further details about the derivation of the individual data points are given in Table II.

Received levels of ship noise were used for comparison and obtained from Hermannsen *et al.* (2014), which should be consulted for details. Briefly, the noise of passing ships of different types and sizes was recorded with a hydrophone 7 m below the water surface and reported for the point of closest approach of the ship. Recordings were obtained on several occasions in shallow waters at different locations in the Western Baltic (Aarhus Bay and the Great Belt). Total sound pressure level (root-mean-squared, $L_{eq}$) over 30 s segments of the sound recordings were computed for the frequency range 25–1000 Hz and compared to the turbine noise.

### B. Statistical model

The measurements from the different studies (Table II) were obtained under very different conditions. The dataset is, therefore, not well balanced and not well suited to in-depth statistical analysis. With that in mind, a general linear model was used to assess overall correlations between estimated total sound pressure level ($L_{eq}$) and the parameters *distance* (hydrophone distance from foundation), *wind speed*, and *turbine size* (quantified by nominal power output in MW):

$$L_{eq} = C + \alpha \log_{10}\left(\frac{\text{distance}}{100\,\text{m}}\right) + \beta \log_{10}\left(\frac{\text{wind speed}}{10\,\text{m/s}}\right) + \gamma \log_{10}\left(\frac{\text{turbine size}}{1\,\text{MW}}\right).$$

TABLE I. List of offshore wind turbines, listed in order from smallest turbines to largest, where measurements of underwater noise have been identified. Not all studies have been used in the present analysis and several references treat the same measurements, but all are included for sake of completeness. Some wind farms are referred to by different names by different authors. For these, the most commonly used name is given as the first.

| Wind farm | Foundation | Turbine type | Size (MW) | References |
|---|---|---|---|---|
| Nogersund/Svante 1 | Tripod | Wind World W25<br>Two-stage spur gear | 0.2 | Westerberg (1994)<br>Wahlberg and Westerberg (2005) |
| Vindeby/Ravnsborg | Concrete | Bonus B35<br>Three-stage spur/planetary gear | 0.45 | Degn (2000)<br>Henriksen (2001)<br>Tougaard *et al.* (2009) |
| Bockstigen | Monopile | Wind World<br>Three-stage spur gear | 0.55 | Degn (2000)<br>Henriksen (2001)<br>Fristedt *et al.* (2001)<br>Tougaard *et al.* (2009) |
| Utgrunden | Monopile | Enron Wind 70<br>Three-stage spur/planetary gear | 1.4 | Ingemansson Technology AB (2003)<br>Betke *et al.* (2004)<br>Madsen *et al.* (2006)<br>Sigray and Andersson (2011) |
| Middelgrunden | Concrete | Bonus/Siemens<br>Three-stage planet./helical gear | 2 | Henriksen (2001)<br>Tougaard *et al.* (2009) |
| Horns Reef I/Horns Rev | Monopile | Vestas V80<br>Three-stage spur/planetary | 2 | Betke (2006)<br>Elmer *et al.* (2007) |
| Princess Amalia | Monopile | Vestas V80<br>Three-stage spur/planetary | 2 | Jansen and Jong (2016) |
| Nysted/Rødsand I | Concrete | Bonus/Siemens 2-3-82<br>Three-stage spur/planetary | 2.3 | Elmer *et al.* (2007) |
| Paludans Flak/Samsø | Monopile | Bonus/Siemens 2.3-82<br>Three-stage spur/planetary | 2.3 | Elmer *et al.* (2007) |
| Lillgrund | Concrete | Siemens 2.3-93<br>Three-stage spur/planetary gear | 2.3 | Sigray *et al.* (2009)<br>Andersson *et al.* (2011)<br>Sigray and Andersson (2011)<br>Bergström *et al.* (2013) |
| Northwind/Eldepasco | Monopile | Vestas V112<br>Four-stage spur/planetary | 3 | Thomsen *et al.* (2015)<br>Norro and Degraer (2016) |
| Gunfleet Sands | Monopile | Siemens SWT 3.6-107<br>Three-stage planetary/helical | 3.6 | Nedwell *et al.* (2011a)<br>Pangerc *et al.* (2016) |
| Lynn and Inner Dowsings | Monopile | Siemens SWT 3.6-107<br>Three-stage planetary/helical | 3.6 | Nedwell *et al.* (2011b)<br>Pangerc *et al.* (2016) |
| Sherringham Shoal | Monopile | Siemens SWT 3.6-107<br>Three-stage planetary/helical | 3.6 | Pangerc *et al.* (2016) |
| Alpha Ventus | Tripod | REpower 5M<br>Planetary gear | 5 | van Radecke and Benesch (2012)<br>Betke (2014) |
| Block Island | Jacket | Haliade 150<br>Direct drive | 6 | Elliott *et al.* (2019) |
| C-Power/Thornton Bank 2-3 | Jacket | Senvion 6.2M126<br>Three-stage spur/planetary | 6.15 | Thomsen *et al.* (2015)<br>Norro and Degraer (2016) |

The constant $C$, thus, expresses the mean $L_{eq}$ of all measurements, normalised to a distance of 100 m, a size of 1 MW, and a wind speed of 10 m/s. A least squares fit to the data and statistical test of significance of factors was conducted by the *fitlm* function in MATLAB (2014b, The MathWorks, Natick, MA).

## C. Noise radiation from multiple turbines

A simple model of the combined noise around a wind farm with multiple turbines was constructed in line with previous modelling of this type (Bergström *et al.*, 2013; van der Molen *et al.*, 2014) and in order to illustrate fundamental properties of noise radiated from multiple turbines in a wind farm. A 9 × 9 regular grid of turbines placed 500 m apart was used as the basis for the modelling. The noise from each turbine was modelled from a common source level, propagated with a simple spreading loss without absorption [$\kappa \log_{10} r$, where $\kappa$ is the slope (dB per decade of distance increase) and $r$ is the distance] in all directions from the turbine. Noise from the 81 individual turbines was treated as uncorrelated, which means that the total noise intensity at any point could be found as the sum of the contribution from the individual turbines.

TABLE II. Measurements of broadband noise levels derived from available sources.

| Wind farm | Distance (m) | Wind speed (m/s) | $L_{eq}$ (dB re 1 $\mu$Pa) | Dominant frequency (Hz) | Notes | Source |
|---|---|---|---|---|---|---|
| Vindeby | 14 | 13 | 127 | 25 | Sum of third-octave bands where turbine noise exceeded ambient noise by at least 6 dB | Tougaard *et al.* (2009) |
| Bockstigen | 20 | 8 | 113 | 25 | Sum of third-octave bands where turbine noise exceeded ambient noise by at least 6 dB | Tougaard *et al.* (2009) |
|  | 50 | 4 | 111 | 312 | Level of highest tonal peak in power density spectrum | Fristedt *et al.* (2001) |
|  | 50 | 5 | 111 | 216 |  |  |
|  | 50 | 6 | 87 | 216 |  |  |
|  | 200 | 4 | 92 | 312 |  |  |
|  | 400 | 4 | 81 | 312 |  |  |
| Utgrunden | 83 | 14 | 126 | 180 | Level of highest peak in power density spectrum | Ingemansson Technology AB (2003) |
|  | 160 | 12 | 109 | 180 |  |  |
|  | 463 | 12 | 103 | 180 |  |  |
|  | 110 | 3.5 | 104 | 63 | Sum of third-octave levels for all bands above 10 Hz | Betke *et al.* (2004) |
|  | 110 | 12 | 118 | 160 |  |  |
|  | 110 | 17 | 118 | 200 |  |  |
| Middelgrunden | 20 | 6 | 108.8 | 25 | Sum of third-octave bands where turbine noise exceeded ambient noise by at least 6 dB | Tougaard *et al.* (2009) |
|  | 40 | 13 | 115.3 | 175 |  |  |
| Horns Reef | 87 | 5.9 | 104 | 150 | Sum of third-octave bands | Elmer *et al.* (2007) |
|  | 87 | 8.9 | 108 | 150 |  |  |
|  | 87 | 11.9 | 118 | 150 |  |  |
|  | 87 | 15.4 | 118 | 96 |  |  |
|  | 87 | 15.6 | 118.5 | 150 |  |  |
| Nysted | 175 | 4 | 103 | 400 | Sum of third-octave bands; wind speed not given but is extrapolated from the power output and power curve, assuming a cut-in speed of 3.5 m/s and its maximum reached at 14 m/s | Elmer *et al.* (2007) |
|  | 175 | 5 | 92 | 315 |  |  |
|  | 175 | 6 | 96 | 135 |  |  |
|  | 175 | 8 | 101 | 135 |  |  |
|  | 175 | 10 | 103 | 135 |  |  |
| Paludans Flak | 100 | 9 | 123 | 134 | Sum of third-octave bands | Elmer *et al.* (2007) |
|  | 100 | 9 | 119 | 134 |  |  |
|  | 100 | 14 | 116 | 134 |  |  |
|  | 100 | 21 | 111 | 134 |  |  |
| Lillgrund | 160 | 12 | 102 | 127 | Level of highest peak in power density spectrum | Andersson *et al.* (2011) |
|  | 400 | 12 | 92 | 127 |  |  |
|  | 1000 | 12 | 86 | 127 |  |  |
| Northwind | 40 | 11 | 135 | 50 | Broadband levels | Thomsen *et al.* (2015) |
|  | 150 | 11 | 133 | 50 |  |  |
| Sherrington Shoal | 50 | 5 | 123 | 160 | Mean values taken from figure number at three selected sound speeds | Pangerc *et al.* (2016) |
|  | 50 | 8 | 125 | 160 |  |  |
|  | 50 | 10 | 126 | 160 |  |  |
| Gunfleet Sands | 30 | 4.5 | 125 | 150 | Average broadband across transects | Nedwell *et al.* (2011a) |
|  | 100 | 4.5 | 120 | 150 | Average codHT value + cod threshold |  |
| Alpha Ventus | 92 | 12 | 110 | 90 | Mean of values taken from Fig. 7.6.9 | van Radecke and Benesch (2012) |
|  | 100 | 14 | 118 | 90 | Highest peak in power density spectrum | Betke (2014) |
| Block Island | 50 | 6 | 114 | 14 | Broadband levels | Elliott *et al.* (2019) |
|  | 50 | 15 | 120.6 | 14 |  |  |
| C-Power | 40 | 11 | 137 | 50 | Broadband levels | Thomsen *et al.* (2015) |
|  | 60 | 11 | 128 | 50 |  |  |
|  | 150 | 11 | 122 | 50 |  |  |

## III. RESULTS

### A. Received noise levels

Individual noise levels derived from the literature are given in Table II and plotted in Fig. 2, together with levels of ship noise in the 25–1000 Hz range that were measured at different distances from the ships. There is a large scatter in the values, but overall the turbine noise levels were at least 10–20 dB below the received levels measured from ships for the same distance. A pronounced decrease in the level of the measured turbine noise is evident with the increasing distance from the turbine, whereas such a distance dependence

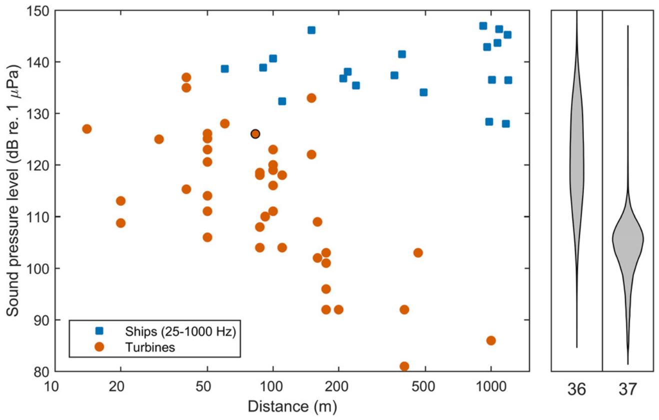


FIG. 2. (Color online) Sound pressure levels measured from offshore wind turbines and ships at various distances. Wind turbine measurements are taken from Table II. Data point from Madsen *et al.* (2006) are indicated by the black outline and ship noise from the recordings of Hermannsen *et al.* (2014) are summed in the frequency range 25 Hz–1 kHz. Violin plots to the right show distributions of measured broadband noise levels from a station next to a busy shipping lane (Great Belt, station 36) and a station at a low noise site (Baltic Sea, station 37). Measurements are from the BIAS project (Mustonen *et al.*, 2019).

is less clear for the ships, likely related to the bandwidth of the ship noise (only noise in the 25 Hz–1 kHz band was included).

### B. Effect of distance, size, and wind speed

By means of the general linear model [Eq. (1)], it was possible to separate the influence of the three factors *recording distance*, *wind speed*, and *turbine size* on the received noise level. All three factors turned out to be significant, and the effects are plotted separately in Fig. 3. The model had overall good explanatory power ($R^2 = 0.67$, $N = 46$). The effect of the recording distance was −23.7 dB/decade [standard error (SE) = 3.1 dB, $t = -7.55$, $p < 0.001$]. The effect of the wind speed was 18.5 dB/decade (SE = 5.8 dB, $t = 3.20$, $p = 0.003$), and the effect of the turbine size was 13.6 dB/decade (SE = 3.8 dB, $t = 3.62$, $p < 0.001$). The dataset was insufficiently balanced to allow for a test of differences between foundation types. The constant of the model was 109 dB re 1 $\mu\text{Pa}_{\text{rms}}$ (SE = 1.7 dB), which can be interpreted as the grand mean of all data, normalised to a recording distance of 100 m, a size of 1 MW, and a wind speed of 10 m/s.

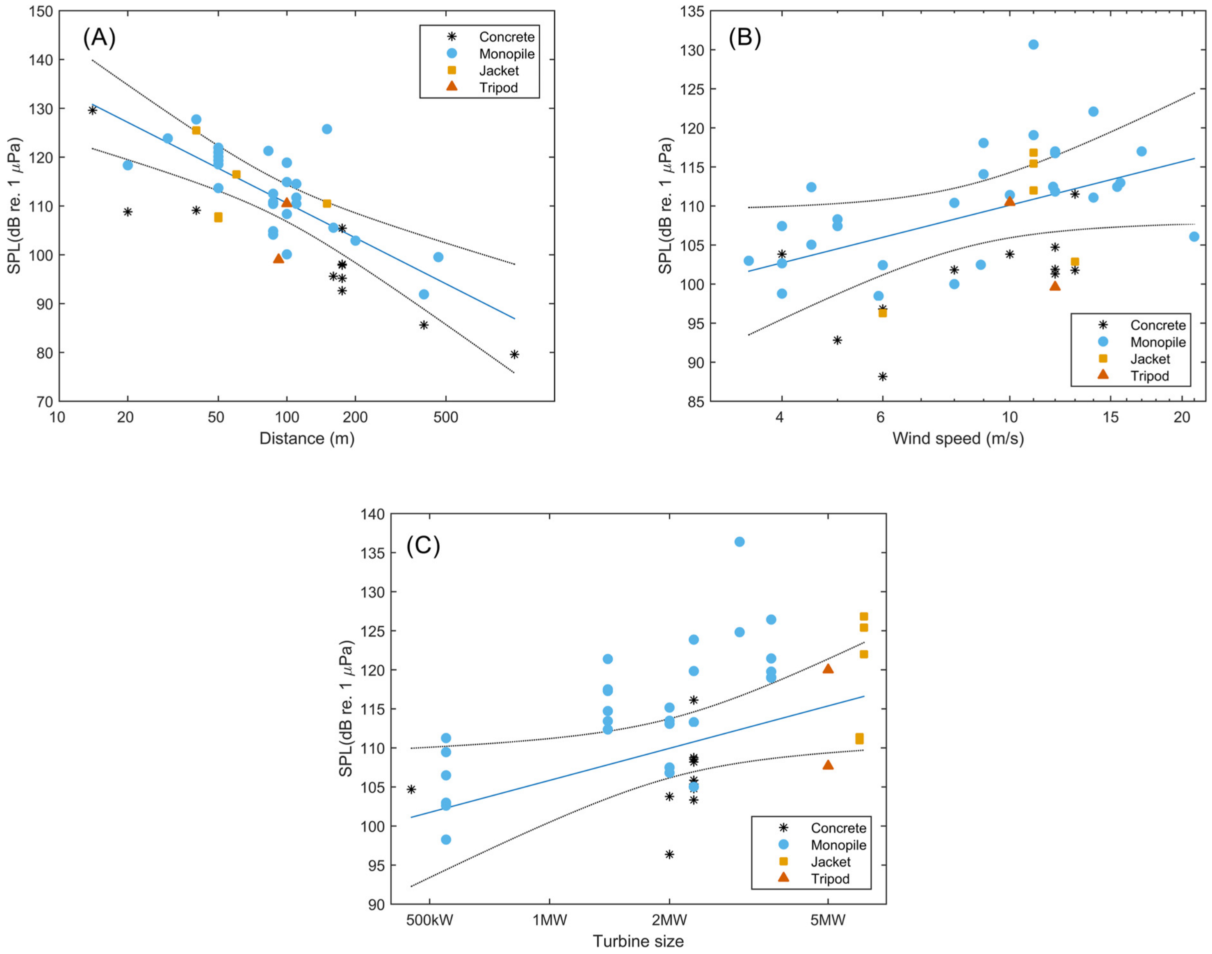


FIG. 3. (Color online) Influence of distance, wind speed, and turbine size on measured sound pressure level. For each of the three plots, the measurements have been normalised to a distance of 100 m, a wind speed of 10 m/s, and a turbine size of 1 MW except for the parameter plotted on the $x$ axis. Solid lines represent best fitting straight lines, and broken lines indicate the standard error.

### C. Noise from multiple turbines

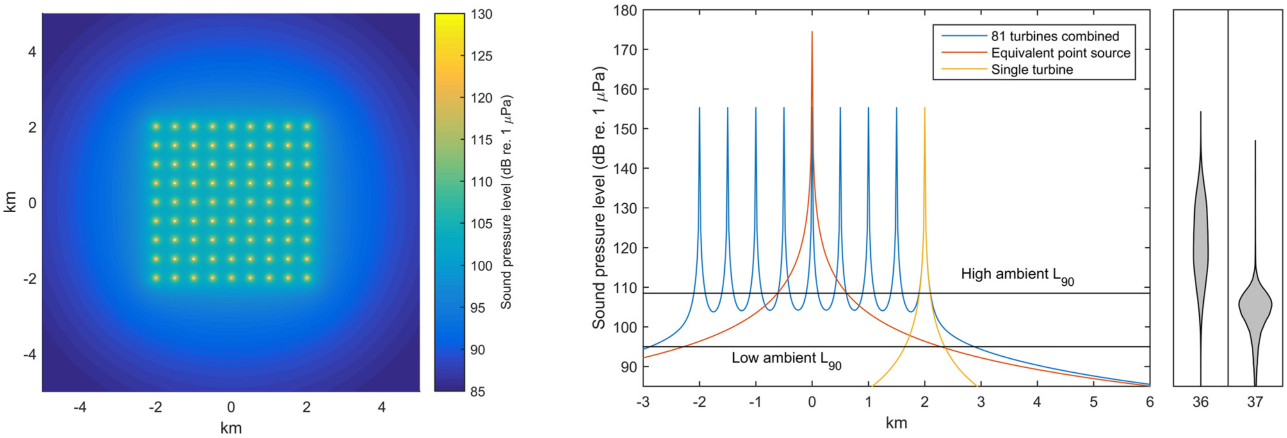
Figure 4 shows the idealised model of noise levels around 81 turbines placed in a regular grid with 500 m between turbines. The source level of the individual turbines was set to 156 dB re 1 $\mu$Pa, equal to the normalised level at 100 m (109 dB re 1 $\mu$Pa) back-calculated to 1 m by adding 47 dB ($23.7 \log_{10}(100m)$; the slope taken from the general linear model). Two regions and a transition zone are evident. The noise from the closest turbine dominates completely close to the turbines, whereas at distances of several kilometres, the noise becomes indistinguishable from that of a single point source with a source level larger than that of any individual turbine. In this simplified and idealised example, the equivalent point source level of the whole wind farm is 175 dB re 1 $\mu$Pa, and the difference of 19 dB corresponds exactly to the predicted difference between 1 and 81 identical sources ($10 \log_{10}(81/1) = 19$ dB). However, this combined source level is never realised anywhere within the wind farm because no physical point exists that is 1 m from the sound source as the source is distributed over many foundations. In contrast, at greater distance (several kilometres, much more than the separation between turbines), the sound appears as if it originated from a single point source with a higher source level than the individual turbines.

## IV. DISCUSSION

The noise levels from the individual offshore wind turbines reported in the literature were low, both on an absolute and relative scale, and comparable to or lower than noise levels measured within 1 km from commercial ships (Fig. 2). The highest level reported was 137 dB re 1 $\mu$Pa at a distance of 40 m. The noise level appears to decrease rapidly with distance, almost 24 dB/decade [Fig. 3(A)], much more than the 20 dB/decade predicted by simple spherical spreading. There are, however, very few actual measurements of propagation loss measured at various distances from the same turbine so it is difficult to assess the generality of this result, modelled across many different individual turbines in different water depths and distances. Early measurements from Bockstigen and Utrunden (Fristedt *et al.*, 2001; Ingemansson Technology AB, 2003; plotted in Madsen *et al.*, 2006) also indicate high propagation loss, whereas measurements from Gunfleet Sands (Nedwell *et al.*, 2011a) indicate a much shallower slope, and at least some parts of the noise (50–500 Hz) were measurable above ambient at least 1 km away from the turbine. New and better measurements from several different turbines in different environments are clearly required to address the question of propagation loss properly.

The second factor affecting the measured noise levels appears to be the size of the turbine, quantified as the nominal power output. The earlier review by Madsen *et al.* (2006) did not show such a relationship, but with the inclusion of much larger turbines into the dataset, the relationship becomes significant [13.6 dB/decade; Fig. 3(B)], although with considerable scatter in the data. This relationship is important as the size of turbines that are installed has increased more than one order of magnitude since the first turbines were installed 30 years ago. The average noise level 100 m from a turbine has increased almost 20 dB in the same period, and the size of the turbines is expected to increase even further in the future.

The third factor affecting noise levels is the wind speed [18.5 dB/decade; Fig. 3(C)]. As with the other measurements, the correlation is made across many different types of turbines under different circumstances, and the generality of the relationship can be questioned. In some cases, the relationship is even non-monotonic within the same measurement series (such as Horns Reef I; Elmer *et al.*, 2007). The large variance in the data is likely due to other factors



(A) (B)

FIG. 4. (Color online) Noise levels modelled around a 9 × 9 turbine offshore wind farm. The basis for the model was the mean sound pressure level estimated from the measurements (108 dB re 1 $\mu$Pa at 100 m), thus, simulating a 1 MW turbine at a wind speed of 10 m/s. Propagation was modelled with a loss of 24.6 dB/decade and contributions of individual turbines were summed in units of intensity ($\mu$Pa$^2$). The right plot shows a slice through the centre of the wind farm and the middle row of the turbines (indicated as a broken red line in the left plot) with the combined noise level from all turbines shown in blue. Appearing in yellow is the contribution of a single turbine, and appearing in red is the noise level propagating from an equivalent point source, i.e., a single turbine with an increased source level and which is indistinguishable from the 9 × 9 turbine wind farm at larger distances. Horizontal lines indicate $L_{90}$ exceedance levels (lower tenth percentile) of ambient noise in a heavily trafficked and quiet habitat (same stations as in Fig. 2).

that are not accounted for, most notably differences in the mechanical design of the turbine gearboxes and generators but perhaps also asymmetries in the towers and foundations and differences in wind conditions (stable wind versus very variable wind with strong gusts). This variation highlights that there are mechanical avenues for pursuing noise reduction designs if quieter turbines are desired. There are two sets of good measurements of turbine noise from the same turbine at many different wind speeds, from below the cut-in speed (where the turbine starts rotating) to well above the point where the power output reaches the maximum level. Both sets of recordings (Alpha Ventus, van Radecke and Benesch, 2012; Sherrington Shoal, Pangerc *et al.*, 2016) indicate a sigmoidal curve, with increasing noise from the cut-in speed (typically around 4 m/s) to the maximum power, is reached (at around 10–14 m/s), above which the curve becomes flat or even slightly decreasing with increasing wind (Pangerc *et al.*, 2016). The effect of wind speed is small, however, with lowest levels only 10–15 dB lower than the highest levels for the same turbine at different wind speeds.

The noise is generated in the nacelle of the turbine (evidenced by the strong gear mesh frequencies in the power density spectra) and radiated into the water through the foundation. It is, therefore, natural to expect to see differences in the radiated noise between different turbines, depending on the types of foundations used. The dataset, however, does not allow this to be explored further. Most of the measurements are from turbines with steel monopile foundations, whereas the largest turbines had jacket and tripod foundations, possibly confounding with turbine size. The lowest levels were measured from turbines with concrete foundations (Middelgrunden), but concrete foundations are often used in very shallow waters, creating another possible confounding correlation, due to the poor propagation of low frequency noise in very shallow water. As for propagation loss, new measurements, dedicated to addressing this issue, are required. Furthermore, all the turbines with one exception (Block Island) operate with gear boxes of various designs (see Table I), whereas many turbines produced and installed today are of the direct drive type without a gearbox, as are the turbines at Block Island. A direct drive reduces the rotation speed of the generator and is likely to affect the mechanical noise as well. In particular, it can be expected that the strong tonal peaks caused by gear meshing are absent in the noise from the direct drive turbines, partly supported by the measurements from the single direct drive turbine (Elliott *et al.*, 2019), where the power spectrum has a harmonic structure with a fundamental frequency of 14 Hz.

We posit that the possible impact of noise from offshore wind farms cannot be judged based on the levels of the individual turbines alone. The significance of the contribution to the anthropogenic soundscape and the potential impact of the wind farm noise on the local environment must be compared to and judged against the contributions from other sources in the area and the ambient noise conditions in general. The noise from individual turbines is significantly less than that of passing ships (Fig. 2; see also Madsen *et al.*, 2006), but in contrast to ships, wind turbines are static sources, meaning that their contribution to the local soundscape is much more persistent although not constant [cf. the relationship with wind speed; Fig. 3(C)]. Furthermore, wind turbines are not isolated, individual sources but distributed in large wind farms, often with several hundred turbines in a regular layout. This means that the combined and cumulative impact from the entire wind farm must be considered (as was done for multiple wind farms by van der Molen *et al.*, 2014). Even though the noise levels radiated from individual turbines are low and dominate completely close to the single turbine (Fig. 4), the combined contribution becomes important at larger distances from the wind farm, in particular at locations with low ambient noise. If the ambient noise is high, as it would be for a wind farm next to a shipping lane, the turbine noise will only be detectable above ambient very close to the individual turbines as was the case for the Princess Amalia wind farm, located close to a busy shipping lane (Jansen and Jong, 2016). In contrast, for locations with very low ambient noise, such as the example from the Baltic Sea in Fig. 4, the combined noise from all turbines is predicted to be audible over the ambient noise everywhere within the wind farm and outside at distances from the outer edge of the wind farm and at distances several times the distance between individual turbines. The summation of noise from several turbines in the measured levels is evident in measurements from the sequential shutdown of turbines, where the noise level decreased in a corresponding step-wise manner (Utgrunden, Ingemansson Technology AB, 2003; Paludans Flak, Elmer *et al.*, 2007).

The modelled scenario is highly simplified, intended only to serve as illustration and does not represent the actual complex conditions, which would be present around a real wind farm in shallow waters. The results can, therefore, not be generalised and used in an actual prediction of noise levels in a real assessment. Some of the important factors, which must be included in a model of an actual wind farm, are the high-pass filtering effect of shallow water, absorption or reflection by the sediment, and effects of a nonuniform sound speed profile, all of which can only be addressed through appropriate propagation modelling, possibly coupled with appropriate modelling of the sound radiation from the foundation itself.

## V. CONCLUSION

In summary, the conclusion from Madsen *et al.* (2006) that the underwater noise radiated from individual wind turbines is low compared to the noise radiated from cargo ships does still apply despite turbines now being larger and more measurements being available. The combined source level of a large wind farm is smaller or comparable to that of a large cargo ship. However, the cumulative contribution to the soundscape from multiple turbines within a wind farm (in some cases, many hundreds) and the fact that wind farms occupy larger and larger fractions of coastal and shelf waters means that their combined contribution of noise cannot be ignored. The contribution from wind turbines can, in particular, be expected to be significant in areas with low natural ambient noise and low levels of ship traffic, possibly large enough to raise concern for negative effects on species of fish and marine mammals. Such large-scale cumulative effects should be addressed in both strategic impact assessments in connection to maritime spatial planning and in environmental impact assessments of individual projects.

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