Graphical Abstract

Can aerodynamic noise from large offshore wind turbines affect marine life?

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Highlights

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- Propose an approach to predict the noise generated by offshore turbines that is transmitted underwater.
- Quantify the underwater aerodynamic noise footprint of three large offshore turbines (5 MW, 10 MW, and 22 MW).
- Quantify the underwater aerodynamic noise of farms composed of 100 and 150 turbines.
- We confirm that the noise emissions of large offshore farms will soon pose to marine life.

Can aerodynamic noise from large offshore wind turbines affect marine life?

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Abstract

The pressing demand for offshore wind energy has driven a significant increase in the size of wind turbines, as exemplified by the proposed 22 MW turbine in the IEA Task 55—REFWIND. In addition, today it is common to see offshore farms with 100 or 150 turbines. The combination of turbines of increasing sizes in populated farms facilitates energy production but can lead to non-negligible aerodynamic noise emissions, which can be heard underwater. This paper quantifies the underwater aerodynamic noise footprint of three large offshore turbines (5 MW, 10 MW, and 22 MW) and farms composed of these types of turbines. By comparing the underwater noise spectra with audiograms of marine animals, we confirm that the noise emissions of large offshore farms will soon pose an environmental problem. The proposed methodology allows wind turbine designers to predict and mitigate the impact of noise while promoting sustainable energy.

Keywords: Wind turbine Noise, Marine life, Offshore energy, Sustainable energy

1. Introduction

In recent years, the size of offshore wind turbines has increased steadily in response to the growing demand for clean energy production. For example, the offshore wind turbine proposed within the IEA Task 55—REFWIND

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would produce 22 MW power with a rotor diameter of 284 m [1] or the recently announced MySE 22MW offshore turbine from Mingyang Smart Energy with a rotor of 310+ meters [2]. In addition to the increasing turbine sizes, we face a rapid increase in the number of turbines gathered in farms. Today, the largest offshore wind farms (e.g., London Array, Gemini, Hornsea Project One and Two [3]) include more than 150 turbines. Simple acoustics shows that with 150 turbines, the sound pressure level increases by 43 dB the noise of an individual turbine. The combination of increasingly large turbines in farms with hundreds of turbines motivates this research: Can aerodynamic noise from large offshore wind turbines affect marine life?

Until now, turbine design for offshore environments has focused on maximizing energy production (e.g., [4, 5, 6]) and paid limited attention to the acoustic footprint and subsequent effects on the environment. In fact, there is a lack of regulation regarding the noise production of turbines in offshore environments. Although larger turbines offer improved energy efficiency and production, they also pose potential environmental risks [7], particularly with respect to acoustic noise emissions. As turbines grow in size, the noise transmitted underwater escalates, disrupting marine ecosystems. Marine mammals are especially vulnerable to noise, which can interfere with their communication, navigation, mating, and feeding behaviors. A commonly cited problem concerning marine renewable energy devices is the masking problem [8], where the noise generated by the turbines can mask communication between animals [9].

The propagation of sound in the sea is enhanced by the higher speed of sound in water than in air (1480 m/s for water vs. 343 m/s for air) and the lower sound attenuation in water (0.1 dB/km in seawater at 1 kHz vs. 5 dB/km for air). These physical factors, together with the channeling of sound in shallow waters, explain the concerns of biologists regarding the installation of large offshore wind farms, which can acoustically affect marine life even at long distances. For example, [10] measured underwater noise 20 km from a small offshore wind farm composed of only 16 wind turbines.

Wind turbine noise may be classified as mechanical and aerodynamic acoustic noise. The first type has a defined tonal character and is produced by mechanical components such as the gearbox and bearings (and/or generator or cooling systems) located within the device nacelle and may be controlled/minimized by appropriate insulation of the nacelle. The second type is more complex and is caused by the interaction of the blades moving through the air. Previous studies on offshore wind turbine noise have only considered mechanical noise as it is directly propagated into the water through the vibrating tower (or platform) [11, 12, 13, 14, 15, 10]. A common justification for ignoring the aerodynamic noise of offshore wind turbines is based on Snell's law [16], which states that only one portion of the noise produced in the air propagates into the water. For flat air-water interfaces, Snell states that only a cone of 13° angle below the source can propagate sound into the water; therefore, this limits the propagation of airborne noise sources. Furthermore, the higher acoustic impedance of water compared to air (i.e., the acoustic impedance of water is 3500 times higher than the air's) leads to a high attenuation of the sound waves when entering water (29.5 dB attenuation). Taking these factors into account, we will show that for large offshore wind turbines and wind farms of hundreds of turbines, aerodynamic noise penetrates underwater and can potentially affect marine life.

This paper explores the impact of increasing turbine sizes in large farms on marine life to warn turbine manufacturers and regulatory bodies about their impact on the marine ecosystem. In what follows, we compute the aerodynamic noise of 5 MW, 10 MW, and 22 MW wind turbines and compare the underwater transmitted sound to the hearing thresholds of many marine animals. We confirm that these emissions will soon become an environmental problem when large offshore farms with hundreds of turbines are built.

2. Methodology

2.1. Wind turbine noise predictions

Aerodynamic noise, caused by the interaction of the flow with the structure, is the main source of noise of modern wind turbines [17]. Figure 1 sketches the typical aerodynamic environment and the sources of noise of an offshore wind turbine. The atmospheric turbulence interacts with the leading edge of the rotating blades, causing a low-frequency noise, known as leading edge (LE) noise. Additionally, the turbulent boundary layer on the blades that interacts with the finite trailing edge causes mid- to high-frequency noise, referred to as trailing edge (TE) noise. Overall, the wide range of turbulent scales – from hundreds of meters in atmospheric flow to millimeters in boundary layer flow – encountered by the wind turbine blades cause aerodynamic noise to exhibit a broadband nature, covering a wide range of frequencies. This is particularly critical for marine environments, as it can affect a variety of marine species with different hearing thresholds.

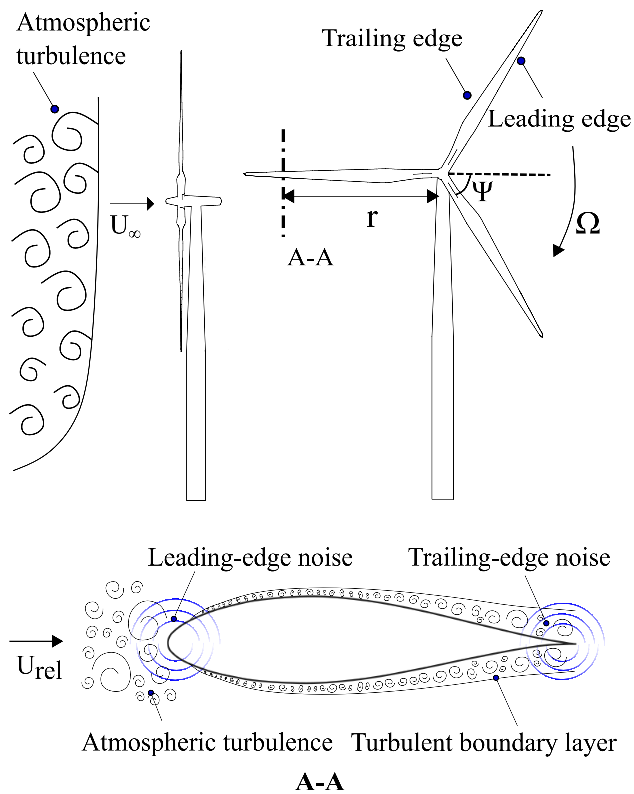


Figure 1: Aerodynamic noise sources for an offshore wind turbine.

To compute the total aerodynamic noise of the wind turbine, we follow the method proposed by Schlinker-Amiet [18] for rotatory noise sources. We consider the strip theory approach, where the blade is divided into n segments. Each segment is considered as a 2D airfoil (as shown in the A-A cut in Figure 1). For each segment, leading- and trailing-edge noise ($S_{pp|\mathrm{LE}}$ and $S_{pp|\mathrm{TE}}$) are calculated as uncorrelated noise sources, such as: $S_{pp|seg} = S_{pp|\mathrm{LE}} + S_{pp|\mathrm{TE}}$.

Leading- and trailing-edge noise (LE and TE) is predicted using Amiet's theory [19, 20] and the extension of Roger, M. and Moreau, S. [21] to consider the back-scattering effect caused by airfoils of finite chords. The von Kármán model [22] calculates the inflow turbulence spectrum used as input for predicting leading-edge noise. An extension of TNO-Blake model [23] computes the wall pressure spectrum to calculate trailing-edge noise. The boundary layer characteristics used as input in the TNO-Blake model are computed by XFOIL [24] using the flow conditions (angle of attack, α and relative velocity,

U_{rel}) obtained with the blade element momentum theory (BEMT). The transition for XFOIL simulations was fixed at 5% of the chord. BEMT solutions are obtained using the open-source code OpenFAST [25], which includes the Prandlt tip and root loss correction factors and the Pitt / Peters skewed wake correction model.

The relative motion of the segment with respect to a fixed observer, due to the rotation of the blades, induces a delay between the noise emission and the location of the observer. This delay is quantified by a Doppler factor ($(\omega_e/\omega)^2$) that is incorporated in the prediction method as the difference between the emitted frequency (ω_e) and the received frequency (ω). Subsequently, the total blade noise is calculated as the sum of all segments, computed at every azimuth angle (Ψ in Figure 1):

$$S_{pp|\mathrm{blade}}(\omega, \Psi) = \sum_{1}^{n} S_{pp|\mathrm{seg}}(\omega_e, \Psi)(\omega_e/\omega)^2. \quad (1)$$

The average noise produced by the wind turbine in one rotation ($S_{pp|\mathrm{WT}}(\omega)$) is then calculated as:

$$S_{pp|\mathrm{WT}}(\omega) = \frac{B}{2\pi} \int_{0}^{2\pi} S_{pp|\mathrm{blade}}(\omega, \Psi)\mathrm{d}\Psi, \quad (2)$$

where B is the number of blades. More information on the noise prediction methodology can be found in Botero-Bolívar, L. et al. [26].

To compute the noise generated by a wind farm, we assume that each turbine acts as an uncorrelated noise source with equal intensity and is positioned at the same relative location with respect to the observer, i.e., adding a factor of $10 \log_{10} N$, where N is the number of wind turbines. In an actual scenario, a single global observer for the wind farm would be at a different relative location for each wind turbine within the farm. This introduces a significant dependence of the noise produced by the wind farm on its layout, which is beyond the scope of this work.

2.2. Air-water interface modeling

The noise is calculated at two observers downstream of the turbine, as shown in Figure 2 left. The the Air-side observer is located exactly at the air-water interface and the Water-side observer is located at 10 m depth from the air-water interface, both at a specific downstream position that is defined for each case analyzed in the results. Here, we pay particular attention to the propagation of noise in air-water media, which is considered in the direction of the noise propagation and in the attenuation due to the change of media.

For the Air-side observer, the far-field noise is calculated directly at the observer, following the standard procedure of wind turbine noise prediction addressed by [26]. However, for the Water-side observer, the far-field noise is not computed directly at the observer because of the change of media. To consider this phenomenon, the following procedure is considered (the algorithm with the methodology is addressed in Appendix A). The refraction of the sound waves due to the change of media is computed following the Snell's law that establishes:

$$c_w \sin\phi = c_a \sin\theta; \tag{3}$$

where c_w and c_a are the speed of sound in water and air, respectively, and ϕ and θ are the angles formed by the sound wave and an axis perpendicular to the air-water interface in the air and the water, respectively, as shown in Figure 2 right. In this research, we consider a planar air-water interface. ϕ is calculated for each blade segment at each azimuth location, considering the location of the noise source and the Water-side observer. With this angle (ϕ) an *interface observer* is defined. The far-field noise of each segment is then first calculated at the interface observer following the noise prediction approach for a single medium, and then, the noise is propagated from this interface observer to the Water-side observer through the water media. The blade noise, i.e., the sum of all the segments, and the full wind turbine noise over the rotation, is calculated at the water-side observer.

According to Snell's law, for an air-water interface, the maximum value of ϕ is $\approx 13°$, which locates the interface observer very close to the noise source, and therefore the far-field condition assumed in Amiet´s theory is not satisfied. To overcome this limitation, LE and TE noise are precomputed at a *far observer* (see Figure 2 right) which is located in the same direction with respect to the blade segment as the interface observer but at an arbitrarily long distance from the noise source ($d_1 + d_2$ in Figure 2). Later, segment noise is rescaled to the interface observer considering a spherical propagation of the noise, i.e., following the expression $10 \log_{10}(1/r^2)$, where r is the distance between the interface observer and the far observer, i.e., d_2 in Figure 2.

The transmission loss of the acoustic waves across the air-water interface is calculated following plane wave theory [27]:

$$TL_{1\to 2} = \frac{4gz}{(1+gz)^2}; \tag{4}$$

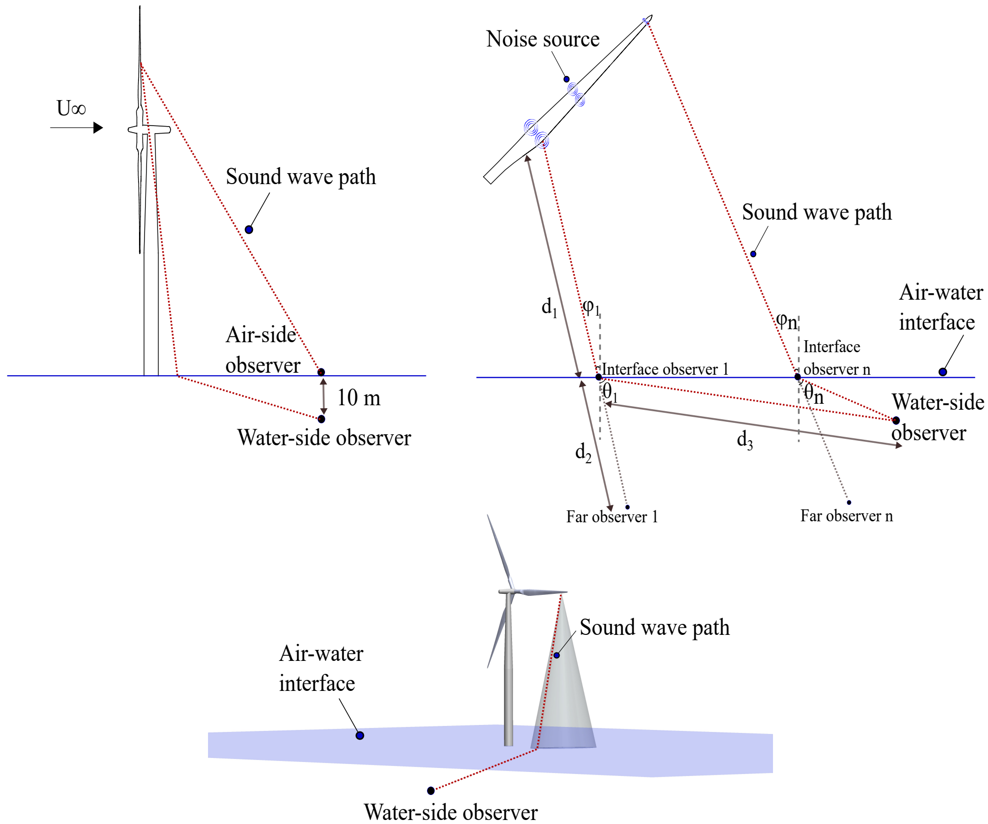


Figure 2: Sketches of wind turbine noise trajectories for an Air-side and a Water-side observers.

where g is the ratio between the densities of medium 1 and 2, and z is the ratio between the speeds of sound. For the air-water interface, the factor $gz \approx 1/3600$, which gives an intensity transmission loss of 29.5 dB.

The propagation from the interface observer to the Water-side observer is carried out using a cylindrical propagation, i.e., following the expression $10\log_{10}(1/r)$, where r is the distance from the interface observer to the Water-side observer, i.e., d_3 in Figure 2. Cylindrical propagation is appropriate for underwater noise in shallow waters [28, 16].

The atmospheric attenuation (A) is considered for both, Air-side and Water-side observers, as follows:

$$A = \alpha_a r; \tag{5}$$

where α_a is the attenuation in dB/m and r is the distance from the noise source to the observer. For the Air-side observer d is the linear distance from the noise source, i.e., each segment, and for the Water-side observer d is the distance from the noise source to the interface observer (d_1 in Figure 2). α_a is calculated as the attenuation of a pure tone sound wave because of traveling through the atmosphere. It is calculated by the standard ANSI/ASA S1.26 [29, 30]. The atmospheric conditions used in this research for the calculation of atmospheric attenuation are: $T = 15$ °C and $T_{\mathrm{ref}} = 20$ °C; $P = 98$ kPa and $P_{\mathrm{ref}} = 101.325$ kPa; and $h = 86\%$; where T and T_{ref} are the source and reference temperatures, P and P_{ref} are the source and reference atmospheric pressures, and h is the relative humidity.

2.3. Offshore wind turbine models

In our study, we consider three offshore wind turbines that span a wide range of geometric and operational conditions, to consider the effect of size on aerodynamic noise and effect on the marine life: the NREL 5 MW [31], the DTU 10 MW [32], and the IEA 22 MW [1]. Table 1 summarizes the geometrical details and nominal operational conditions of the turbines. We assume a turbulence intensity of 9% and an integral length scale of 100 m for all cases since these are typical values for offshore sites [33, 34]. Those values are used to compute the von Kármán spectrum to predict LE noise. The effect of turbulence intensity is also discussed in the results section.

Table 1: Geometrical and operational (nominal) conditions of three large offshore wind turbines

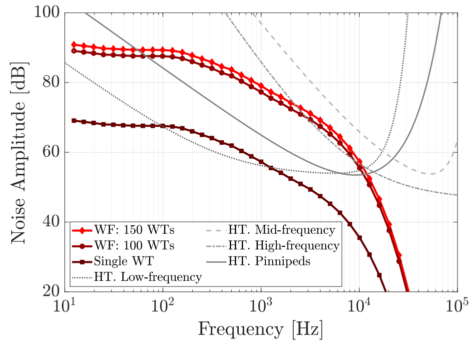
Characteristic	NREL 5 MW	DTU 10 MW	IEA 22 MW
Hub height [m]	90.0	119.0	170.0
Rotor diameter [m]	126.0	178.4	284.0
Nominal wind velocity [m/s]	11.4	11.4	10.0
Rotor angular velocity [rpm]	12.1	9.6	6.9
Blade tip velocity [m/s]	79.0	90.0	102.0
Blade Pitch [deg.]	0.0	0.0	5.7

3. Results and Discussion

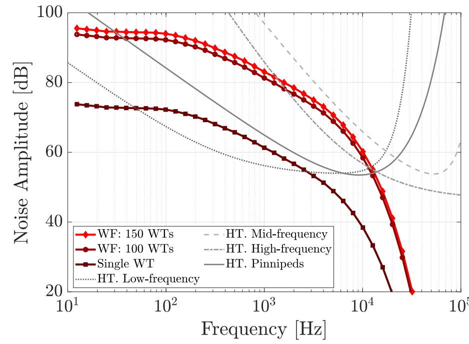
Figure 3 shows the far-field aerodynamic noise spectra generated by a single wind turbine and groups of 100 and 150 wind turbines for each case, compared to the hearing thresholds of various functional hearing groups, i.e., low-, mid-, and high-frequency cetaceans and pinnipeds [35, 8, 36]. The figure shows that aerodynamic noise from the three wind turbines affects the low-frequency hearing group even when considering only a single wind turbine.

When considering farms, Figure 3 shows that a group of 100 turbines causes a general increase in the amplitude of aerodynamic noise spectra, with a footprint underwater of 15 dB louder than the hearing threshold of some marine animals for the case of the 5 MW wind turbine and up to 25 dB for the case of the 22 MW wind turbine. In these cases, the aerodynamic noise of large offshore farms would be perceived by groups of marine animals in a wide frequency range. Low frequencies are better perceived by animals and are also more critical as a result of their longer propagating distances underwater (larger wavelengths), i.e., the acoustic footprint of the wind turbines is larger. Having established a potential problem, we now focus on the largest turbine, the IEA 22 MW offshore turbine. The effect of inflow turbulence on the aerodynamic noise propagated underwater is shown in Figure 4. The same analyses have been conducted for the smaller turbines, showing similar results (not included for the sake of brevity). The results show that inflow turbulence noise significantly increases total aerodynamic noise in the low-frequency range (up to 1 kHz). This increase is perceived by low- and mid-frequency cetacean hearing groups. Additionally, as mentioned before, low-frequency noise is more critical. Therefore, turbulence intensity plays a crucial role in the underwater aerodynamic noise of offshore wind turbines. However, the mechanical noise associated with the generator and radiated from the tower has a typical noise footprint for frequencies lower than 200 Hz and also needs to be considered to establish the dominance of LE noise of the total radiated noise of the wind turbine in this frequency range [12, 14, 15].

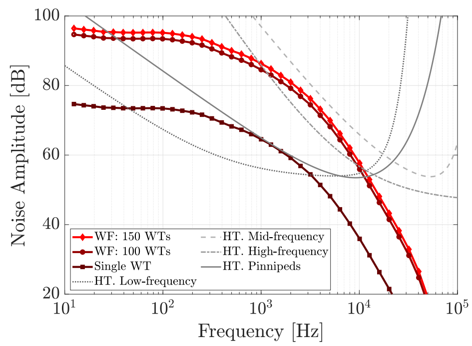
Our study shows that the main source of noise from offshore wind turbines that affects marine animals is produced by the trailing edge of the blade. The latter is produced at frequencies where marine animals have their highest hearing sensitivity (near the inflection point of the audiograms). Furthermore, trailing-edge noise is generated for all operating conditions and does not depend on the inflow characteristics or mechanical components, which make this source of noise more critical. This information should drive manufacturers and regulators to push for the inclusion of noise reduction techniques in offshore wind turbines, such as trailing-edge serrations [37], and consider noise emissions in optimization-related tasks [38].



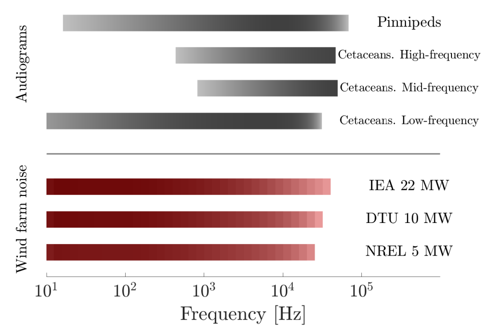
(a) NREL 5 MW wind turbine



(b) DTU 10 MW wind turbine



(c) IEA 22 MW wind turbine



(d) Overlap of wind farm noise (150 WT) and marine animals' audiograms

Figure 3: One-third octave far-field noise spectra for a Water-side observer (10 m deep) at 100 m downwind the turbine compared to the hearing threshold of several groups of marine animals. WT: wind turbine; WF: wind farm with 100 and 150 WTs; HT: hearing threshold. Color scales from 20-100 dB in figure (d).

Figure 5 compares the far-field noise for an Air-side observer (i.e., located on the air-water surface) and for a Water-side observer at 10 m depth (see Figure 2), both located 500 m downwind of the turbine. For the former, the noise is computed directly at the observer location for two conditions: including and neglecting atmosphere attenuation. The figure shows that atmospheric attenuation causes a significant drop in far-field noise for frequencies higher than 1 kHz. If we also consider human hearing capacity (up to 20 kHz), then the aerodynamic noise of wind turbines is usually neglected at high frequencies (higher than 10 kHz). However, when considering underwater noise, the high-frequency range is less attenuated, and at the Water-side observer,

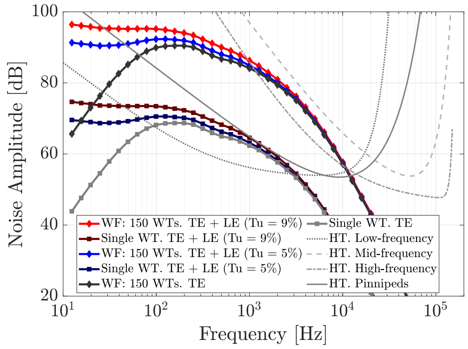


Figure 4: Effect of the turbulence intensity on the aerodynamic noise generated by the IEA 22 MW wind turbine. Water-side observer (10 m deep) at 100 m downwind of the turbine. TE: trailing-edge noise; LE: leading-edge noise; Tu: turbulence intensity

the noise is louder than at the Air-side observer for frequencies higher than 5 kHz. This can be explained by direct airborne and indirect waterborne noise trajectories (see subsection 2.2). For a Water-side observer, the sound wave travels through the air (medium with the highest attenuation) a maximum distance of $\approx (H + R)/\cos(13^o)$, where H is the height of the hub and R is the wind turbine radius, which is much shorter than the distance from the source of the noise to an observer located downwind outside the water. This significantly reduces the atmospheric attenuation of the noise, which is more effective at higher frequencies. Furthermore, marine animals have hearing thresholds in a wider frequency range than humans, therefore, high frequencies are still relevant when analyzing marine environments.

Finally, we discuss the directivity pattern in air and underwater. Figure 6a shows the directivity radiation pattern of a single IEA 22 MW wind turbine considering Air-side observers at a radius of 500 m for several centered frequencies (F_C) and the integrated overall sound pressure level (OSPL) over the entire frequency range. In air, the wind turbine radiates noise as a dipole aligned with the wind inflow with the lowest radiation amplitude on the rotor plane. Consequently, the selected Air-side observer in Figure 5 is aligned with the dipole main axis, whereas for the Water-side observer, only the noise that propagates underwater is the one near the rotor plane, following Snell's law. This also explains the lower noise radiated underwater than in air, mainly in the low-frequency range.

Figure 6b shows the directivity of the IEA 22 MW wind turbine at 10 m depth. Underwater, the turbine also radiates noise as a dipole aligned with

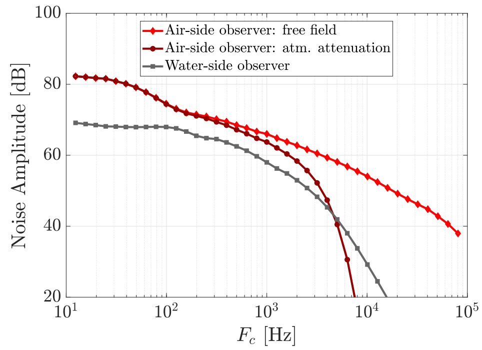
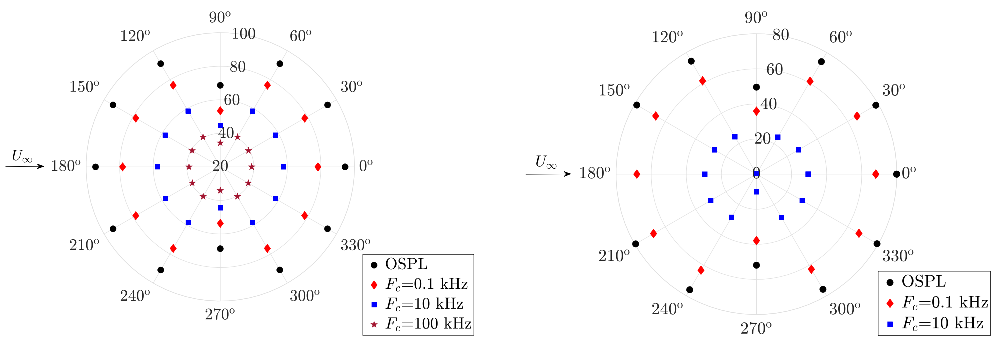


Figure 5: IEA 22 MW wind turbine far-field noise prediction for a Water-side observer (10 m deep) and an Air-side observer at 500 m downwind of the turbine including (atm. attenuation) and neglecting (free field) atmospheric attenuation.



(a) Air-side directivity

(b) Water-side directivity

Figure 6: Direcitivity pattern of a single IEA 22 MW wind turbine for Air-side and 10 m deep Water-side observers for several center frequencies and the overall sound pressure level (OSPL).

the inflow velocity, as in air. However, the dipole is not symmetric with respect to the inflow axis. The radiated noise is larger within the lower half of the figure (radiating more noise in the half-plane corresponding to 180 to 360º). This region with higher noise corresponds to the blades rotating downward, which radiate higher noise [17]. This asymmetry is not shown in air because the noise is propagated directly to the observer (and not following the Snell cone), and therefore the symmetry in directivity is preserved.

4. Conclusions

Turbine design for offshore environments has prioritized energy production, often neglecting the acoustic footprint. Today, there are no regulations regarding wind turbine noise in offshore sites, leading to an uncontrolled increase in the size of the turbines and the number of turbines in farms (often more than 100 turbines).

In this work, we have quantified the underwater acoustic footprint of three large offshore turbines: a 5 MW, a 10 MW, and a 22 MW turbine. We have compared the radiated noise underwater with animal audiograms and scaled the noise emissions for farms of 100 and 150 turbines. The results confirm that aerodynamic noise will become an environmental problem for large offshore wind turbines in the near future.

In this paper, we have shown that aerodynamic noise, specifically trailing-edge noise, is the most critical for marine environments. Even with the large impedance difference between air and water, we have shown that noise can propagate underwater and be heard by marine animals over a large frequency range. Therefore, to minimize the environmental impact of offshore wind farms, manufacturers need to incorporate strategies to reduce this type of noise, such as in onshore environments (e.g., serrated trailing edges on blades). This would ensure the preservation of marine life while generating sustainable energy. This dual focus will be crucial in balancing the benefits of renewable energy with the preservation of the marine ecosystem.

Appendix A. Algorithm of wind turbine noise prediction at the Water-side observer

Figure A.7 shows the algorithm to calculate the aerodynamic wind turbine noise at the Water-side observer.

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Authors' contributions

- Laura Botero-Bolívar: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing - original draft.
- Oscar A. Marino: Investigation, Methodology, Validation, Writing - review & editing.
- Martín de Frutos: Investigation, Methodology, Validation, Writing - review & editing.
- Esteban Ferrer: Conceptualization, Methodology, Validation, Funding acquisition, Project administration, Resources, Supervision, Writing - review & editing.

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Data availability

The data that support the findings of this study are available from the corresponding author, Botero-Bolívar, L., upon reasonable request. Furthermore, the algorithm to predict wind turbine noise is available in Botero-Bolívar [39].

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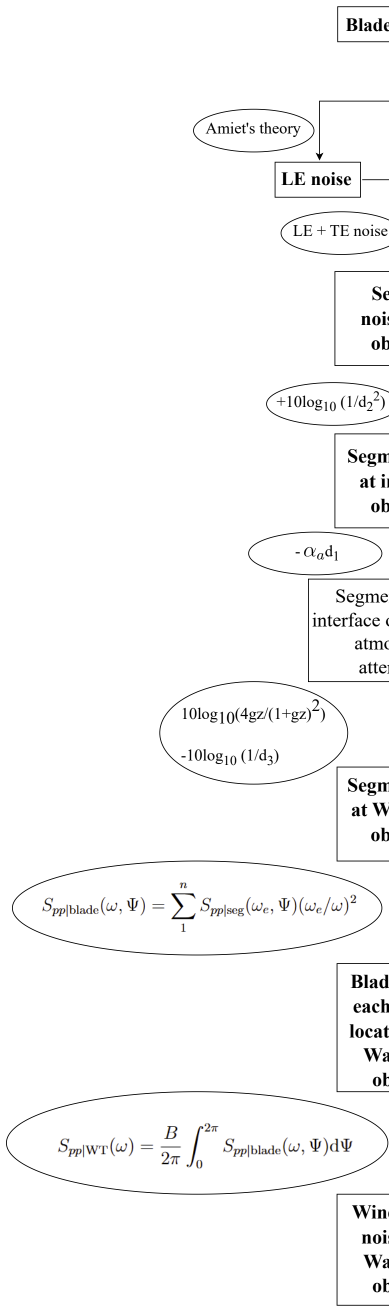

Figure A.7: Algorithm for the wind turbine noise prediction at the Water-side observer