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Review on Generation Mechanisms, Monitoring Methods and Control Technologies of Underwater Noise from Offshore Wind Power

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Abstract. Offshore wind power development is expanding from nearshore fixed projects to large-capacity, clustered and deep-sea floating projects. As a result, underwater noise generated during construction, operation and decommissioning activities has become a key constraint in environmental impact assessment and engineering permitting. Based on relevant journal studies published publicly from 2016 to 2025, this paper systematically compares the acoustic characteristics of impact pile driving, structural vibration during operation, floating mooring systems and decommissioning operations along the chain of "sound source - structural transmission - marine propagation - monitoring characterization - ecological response - engineering control". It summarizes the applicable boundaries of empirical models, parabolic equation models and structure-fluid-acoustic coupling models, and concludes the combined application of hydrophones, vibration sensors, passive acoustic monitoring and acoustic telemetry. The review shows that relatively complete technical systems have been formed for the prediction and bubble curtain control of impulse noise during construction. The source intensity of low-frequency narrow-band noise during operation varies significantly with unit operating conditions, foundation forms and environmental conditions, and long-term ecological evidence remains insufficient. Evaluating the exposure of fish and invertebrates only by sound pressure may omit particle motion and seabed vibration. In the future, a standardized whole-life-cycle monitoring database should be established, and multi-physics models, ecological dose-response relationships and regional cumulative impact assessment should be incorporated into the same decision-making framework.

Keywords: offshore wind power, underwater noise, whole life cycle, sound propagation, monitoring technology

1. Introduction

Offshore wind power features large resource scale, proximity to coastal load centers and high power generation capacity per unit area. However, offshore construction directly couples structural impact, mechanical vibration and ship power noise into water bodies and seabeds. Underwater sound

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propagation is jointly constrained by the sea surface, seabed and sound velocity profile, and low-frequency components can maintain a long propagation distance in shallow seas. Therefore, underwater noise is no longer just a local disturbance during the construction period, but a whole-life-cycle environmental factor throughout site selection, foundation construction, operation and maintenance, and decommissioning disposal [1-4].

Research priorities have shifted in two aspects over the past decade. On the one hand, pile driving noise research has shifted from empirical attenuation estimation to pile-soil-water coupling, near-far field connection and joint modeling of noise reduction devices. On the other hand, with the increase of single-unit capacity and wind farm scale, structural radiated sound during operation, particle motion perceivable by fish, additional sound sources from floating platforms and cumulative exposure of multiple wind farms have gradually entered the assessment scope [2, 3]. This means that engineering evaluation can no longer use one broadband sound pressure level to summarize all risks, nor can construction period control experience be directly extrapolated to the operation period and decommissioning period.

Based on the above changes, this paper summarizes relevant studies from 2016 to 2025, focusing on four questions: what are the main sound sources and spectral differences at different life cycle stages; how environmental and structural parameters alter propagation; whether monitoring indicators can cover the perception mechanisms of different organisms; and how existing noise reduction measures trade off among effectiveness, cost and engineering constraints. This paper does not discuss onshore air noise and electromagnetic field effects, and the ecological part focuses on evidence directly related to acoustic exposure to ensure a clear review boundary.

2. Noise sources and acoustic characteristics in the whole life cycle

2.1. Construction phase

Impact pile driving remains the strongest underwater anthropogenic sound source in fixed offshore wind power construction. Hammering first excites axial stress waves in the pile body, then radiates into the water body through the pile wall, and inputs energy into the sedimentary layer through pile-soil contact. The superposition of direct sound in water and seabed re-radiated sound forms repeated pulses. Its spectrum is not a single low-frequency peak, but a broadband structure determined by hammer duration, pile diameter, penetration depth, soil layer impedance and water depth [1, 5-7]. Drilling, trenching, suction bucket installation and submarine cable laying usually present continuous or quasi-continuous sound with longer duration. Although their peak values are lower than those of impact pile driving, they may be superimposed for a long time with the main engines, thrusters and dynamic positioning noise of construction vessels.

The engineering controllability of construction sound sources is relatively strong, but the source intensity cannot be given a fixed value independent of working conditions. The same pile diameter may show significant differences under different hammering energy, penetration stages and seabed conditions. On-site evaluation should retain per-hammer records, and synchronize acoustic data with hammering energy, penetration volume and operation time, rather than only reporting the maximum sound level in a certain period.

2.2. Operation phase

Noise during the operation period is mainly generated along the path of "transmission system or electromagnetic excitation - nacelle and tower vibration - foundation and seabed coupling - water

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body radiation". Its common feature is low-frequency continuous background superimposed with narrow-band spectral lines related to rotational frequency, blade passing frequency and mechanical meshing. Field measurements of 3.6 MW monopile units, 3 MW jacket units in South Korea and 5.5 MW units in Yangjiang all show that the noise spectrum varies with wind speed, rotational speed and tower vibration, and site conditions can significantly alter the measurable frequency bands and attenuation laws [8-10]. In South Korean field tests, the peak at approximately 198 Hz was significantly enhanced near the rated speed, and underwater noise was highly correlated with tower acceleration, wind speed and rotational speed [9].

Operational sound is usually lower than nearby ship noise in the same frequency band, but "lower than ship noise" is not equivalent to ecologically negligible. Fixed positions, long-term operation and wind farm clustering can alter the local soundscape, and upsizing may change source levels and dominant frequencies [2, 11]. Therefore, operation period research should distinguish the wind turbine itself, operation and maintenance vessels and natural background, and perform source separation by combining at least SCADA operating conditions, tower vibration and multi-point underwater sound records.

2.3. Floating and decommissioning phases

In addition to the internal mechanical and electromagnetic excitations of the unit, floating wind power also adds potential paths such as six-degree-of-freedom platform motion, mooring system contact, dynamic submarine cables and more frequent operation and maintenance. Existing models and field data indicate that the floating sound field is more controlled by sea conditions, mooring arrangement and deep-water propagation conditions, but the repeatable source intensity database is still very limited [12, 13]. The decommissioning phase may include underwater cutting, pile extraction, heavy lifting and clustered operation of construction vessels. Its sound pattern depends on the demolition scheme, which may be either short-term impulses or continuous mechanical sound. Since decommissioning decisions simultaneously alter the artificial reef habitat, noise impacts cannot be evaluated separately from structure removal and habitat loss [4]. The comparison of typical noise sources and acoustic characteristics at each life cycle stage is shown in Table 1.

Table 1. Comparison of typical underwater noise characteristics in the whole life cycle of offshore wind power

Lifecycle phase	Representative source	Acoustic signature	Primary concern	Recommended metrics
Construction	Impact piling; drilling; trenching; vessels	Repeated impulse or quasi-continuous; broad low-to-mid frequency energy	Acute injury, startle and displacement	SPLpeak; SELss; SELcum; spectrum
Operation	Drive train; tower/foundation vibration; O&M vessels	Continuous low-frequency tones plus broadband components	Masking, chronic stress and habitat-use change	Leq; PSD; 1/3-octave; acceleration

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Table 1. (continued)

Floating-specific	Platform motion; moorings; dynamic cable	Tonal and transient components; strong sea-state dependence	Deep-water soundscape and mobile receptors	PSD; coherence with motion/SCADA; PAM
Decommissioning	Cutting; pile extraction; lifting; vessels	Intermittent impulse or continuous noise; evidence limited	Secondary disturbance and habitat transition	SPLpeak/SEL/Leq plus activity log

3. Propagation mechanism, influencing factors and prediction models

3.1. From structural excitation to far-field sound field

Noise propagation from offshore wind power can be divided into structural near field and marine far field. The near field focuses on the vibration coupling of pile bodies, towers, foundations and seabeds, while the far field is jointly controlled by geometric spreading, medium absorption, sea surface/seabed reflection, refraction and modal interference. For preliminary engineering screening, the transmission loss is commonly described by the following formula:

$$TL(r,f) = A\log_{10}(\frac{r}{r_0}) + \alpha(f)(r - r_0) \quad (1)$$

Where A is the expansion coefficient, α(f) is the frequency-dependent absorption coefficient, and r_0 is the reference distance. This formula is convenient for rapid estimation, but cannot explain waveguide effects and three-dimensional topographic diffraction in complex shallow waters. Especially in the low frequency band, seabed elastic parameters, sediment thickness and source depth changes may be more important than water body absorption.

Key inputs can be summarized into four categories: environmental parameters include water depth, temperature-salinity sound velocity profile, sea conditions and ambient sound; geological parameters include sediment sound velocity, density, attenuation and stratification; structural parameters include foundation type, pile diameter, penetration depth and connection stiffness; operating parameters include hammering energy, rotational speed, power and sea conditions. Results from the Yangjiang wind farm show that after incorporating real terrain and seabed parameters into the wide-angle parabolic equation, the model reproduces distance attenuation better than the simple spreading law [10].

3.2. Model system and applicable boundaries

Empirical models are suitable for project preliminary screening, ray, normal mode and parabolic equation models are suitable for medium and long distance propagation, and finite element/boundary element methods can resolve local coupling of pile-soil-water or tower-foundation-water. A more practical approach is to use finite element to obtain near-field vibration and radiation boundaries, and then transfer the equivalent sound source to the far-field model. Studies by Wilkes et al., Peng et al. and He et al. demonstrated the ideas of near-far field coupling, fast calculation and efficiency improvement respectively [6, 7, 14]. Three-dimensional models can

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also use real water depth and seasonal sound velocity fields to identify periods with high propagation loss, providing a basis for construction window optimization [15].

The main shortcoming of existing models lies not in the number of equations, but in input uncertainty and insufficient validation. Pile-soil contact, bubble group size distribution, complex seabed parameters and floating mooring boundaries are all difficult to calibrate on site. Wind farm scale superposition also involves asynchronous operating conditions of different units. Multi-physics models should report parameter sensitivity and confidence intervals, and be validated with independent measurement points, avoiding using a single "good fit" to replace transferability tests [16].

3.3. Field inversion and model validation

Model validation should distinguish three levels: source model, propagation model and receiver-end indicator. During the construction period, the equivalent source can be inverted using near-field pile wall vibration and hydrophone records at multiple distances, and then verified with far-field measurement points not involved in calibration. During the operation period, shutdown, partial load and rated working conditions should be covered, and order spectra and coherence functions are used to confirm that characteristic lines are indeed generated by the wind turbine. If only the total sound level is corrected at a single distance, parameter compensation will occur among seabed loss, source intensity and geometric spreading, making the model seem accurate but impossible to extrapolate. It is recommended to report measurement uncertainty, value range of environmental parameters, variation of model error with frequency and distance, and retain original working condition records for subsequent cross-site review. The overall analytical framework of sound source-propagation-receiver-governance is shown in Figure 1.

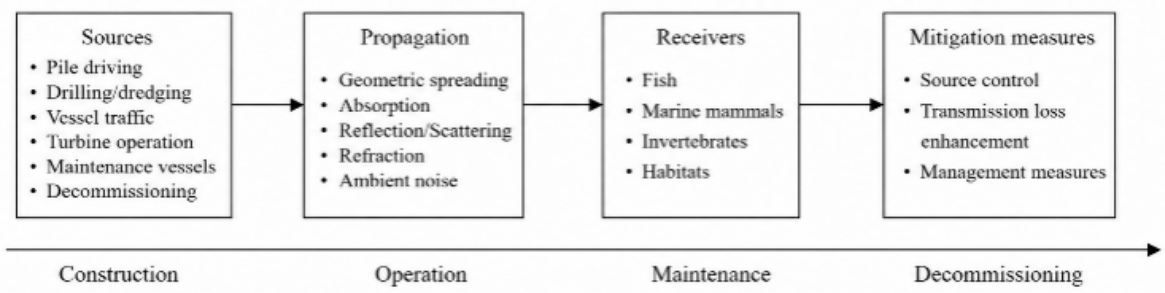

Figure 1. Overall framework of "sound source - propagation - receiver - governance" for underwater noise in the whole life cycle of offshore wind power

4. Monitoring technologies and evaluation indicators

4.1. Monitoring system design

Monitoring schemes should first serve the purpose. Compliance monitoring emphasizes specified distances and limit value determination; mechanism research requires synchronization of hydrophones, accelerometers and SCADA; ecological research should cover baseline period, operation period and recovery period, and record the activity of target species. During construction, multiple measurement points at near, medium and far distances should be arranged along the main propagation direction. During operation, a combination of fixed long-term stations and short-term cruise surveys is recommended. Equipment selection should simultaneously meet the requirements

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of dynamic range, frequency response and self-noise. Calibration information, sampling rate, sensor depth, meteorological and sea conditions, and vessel activities should be taken as necessary metadata of the dataset [8-10].

Hydrophone arrays can perform localization through time difference of arrival or beamforming. Coherence analysis between tower acceleration and underwater acoustic signals can identify structural transmission paths. Passive acoustic monitoring is suitable for long-term recording of cetacean acoustic activities, while acoustic telemetry can track the movement of tagged fish inside and outside the wind farm. The two complement traditional sound level monitoring rather than replacing each other.

4.2. Sound pressure, sound exposure and particle motion

Continuous noise is usually characterized by root mean square sound pressure level, while impulse noise is reported with both peak sound pressure level and sound exposure level. The editable formulas are as follows:

$$L_p = 20 \log_{10}\left(\frac{p_{rms}}{p_0}\right), \quad p_0 = 1\ \mu Pa \tag{2}$$

$$L_E = 10 \log_{10}\left[\frac{1}{p_0^2 t_0}\int_{t_1}^{t_2} p^2(t)\,dt\right], \quad t_0 = 1\ s \tag{3}$$

For multiple hammer strikes, cumulative sound exposure should be calculated under a unified time window and frequency weight. For operational sound, broadband Leq, power spectral density and 1/3-octave band results should be given simultaneously. Reporting only one total sound level will mask narrow-band spectral lines and differences in biological auditory frequency bands. More importantly, many fish and invertebrates mainly perceive particle motion or seabed vibration. A single hydrophone can only measure sound pressure and cannot fully describe their actual stimuli [17]. Therefore, in near-field ecological experiments, three-axis particle velocity/acceleration or geophones should be added, and it should be clarified whether sound pressure and particle motion can be converted by the local sound field relationship.

4.3. Data processing and quality control

Data processing should include clock synchronization, pulse event identification, ambient sound removal, spectrum analysis and uncertainty assessment. When multiple sources overlap during operation, separation can be performed using rotational speed order tracking, vibration-acoustic coherence, automatic identification systems for ships and wind turbine start-stop conditions [9, 10]. Ecological monitoring also needs to map acoustic exposure to animal occurrence rate, movement direction or physiological indicators on the same time axis. Directional hydrophone clusters and acoustic telemetry provide finer spatial information for this purpose [18, 19]. For cross-project comparison, sensor calibration, bandwidth, statistics and data missing rules must be unified; otherwise, results "both being SPL or SEL" are not directly comparable.

4.4. Comparability and monitoring blind spots

The value of long-term data depends on comparability. Baseline monitoring should at least cover representative sea conditions and main biological activity seasons. Construction monitoring must record each operation event. Operation monitoring should avoid misjudging wind and wave self-

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noise, mooring knocking or passing ships as wind turbine sound. Sensor suspension methods can also introduce cable vibration and flow noise, and low-frequency results must be evaluated in combination with flow velocity and self-noise. For receptors near the seabed, a single mid-water measurement point may underestimate sediment propagation; for mobile cetaceans, fixed points are difficult to represent the actual exposure path of individuals. Therefore, monitoring design should strike a balance between regulatory enforceability and receptor relevance. The technical route of underwater noise monitoring and evaluation is shown in Figure 2.

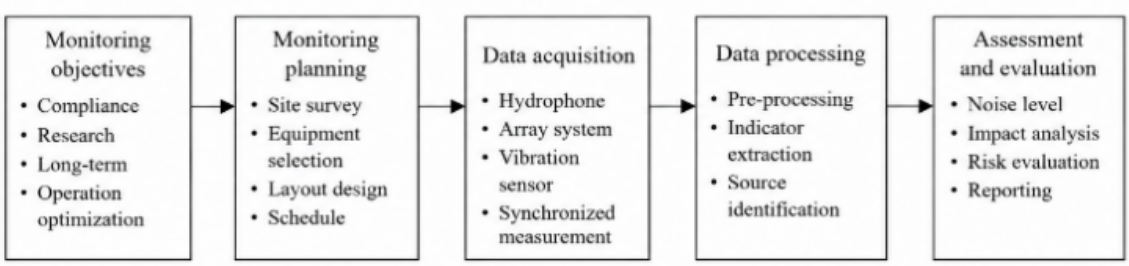

Figure 2. Technical route of underwater noise monitoring and evaluation for offshore wind power

5. Ecological effects and evidence boundaries

5.1. Fish and invertebrates

Ecological effects should be distinguished into tissue damage, temporary threshold shift, startle and avoidance, masking of communication or predation, and long-term physiological stress. Construction impulses have high peak values and fast rising edges, and the near-field risks are mainly auditory and tissue damage. Continuous low-frequency sound during operation is more likely to play a role through masking, habitat use change and chronic stress [3, 20]. The sensitivity of different species to sound pressure and particle motion varies greatly, and the reflection field in laboratory water tanks may amplify or alter stimuli. Therefore, exposure conditions must be fully reported [17].

A 2025 fish physiology experiment showed that pile driving sound could cause changes in some osmoregulation and metabolic indicators of large yellow croakers, while operational sound in the same experiment did not produce significant responses in all species, indicating that "presence of sound" cannot directly lead to "equivalent ecological damage" [21]. There are also confounding factors such as artificial reef attraction, predation pressure changes and ship activities in the field. Only by adopting inside-outside wind farm comparison, before-after operation comparison and individual tracking can noise effects be distinguished from habitat changes.

5.2. Marine mammals

Cetaceans are highly dependent on acoustic signals, and their risk assessment usually predicts temporary or permanent threshold shifts based on auditory frequency weighting, peak sound pressure and cumulative sound exposure [22]. Field studies more commonly observe behavioral avoidance and temporary habitat loss. Construction data from multiple wind farms in Germany show that harbour porpoise activities are disturbed by pile driving, and the scope and recovery process vary with noise reduction measures, construction sequence and background conditions [23]. Individual response distances may also decrease with continuous construction, reflecting the combined effects of habituation, selective departure or environmental changes [24]. Directional

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hydrophone clusters further confirmed that small cetaceans exhibit directional evasive movements under construction disturbance [18].

These results suggest that injury thresholds and behavioral thresholds cannot be mixed. Reaching a certain sound level does not necessarily lead to population effects, and being below the hearing injury threshold does not mean there is no habitat cost. Reliable evaluation needs to incorporate exposure intensity, duration, individual status, season and alternative habitats into the same analysis, and explicitly retain uncertainty.

5.3. Cumulative effects

The core problem brought by large-scale wind farm clusters is multi-source, long-term and cross-phase superposition. Recovery of individuals after one construction does not mean that they can still recover when encountering multiple projects continuously in the region. Similarly, although operational sound is close to the shipping background, it may also alter the soundscape due to fixed duration. Existing evidence is still mostly at the individual or short-term behavioral level, and extrapolation to population and food web scales requires caution [20, 19]. Therefore, cumulative assessment should be based on spatial exposure maps, temporal and spatial distribution of key species and project duration superposition, rather than simply adding maximum sound levels.

6. Noise control technologies and engineering applicability

6.1. Source control

Source control takes priority over propagation path remedies. During the construction period, impact input can be reduced by optimizing hammering energy and penetration procedures, pre-drilling, vibratory pile driving or alternative foundation types, but construction duration, bearing performance and total operation time should be evaluated simultaneously. Model studies show that hammer-pile-seabed coupling determines the radiable energy, and underwater sound levels cannot be inferred only by the rated hammer energy [1, 5]. During the operation period, direct drive, drive train isolation, tower/foundation damping and state control can be adopted in the design stage to reduce the transmission of characteristic frequency vibration to the foundation. Such measures are difficult to retrofit in later stages, so underwater acoustic performance should be incorporated into equipment procurement and type tests.

6.2. Propagation path control

Bubble curtains weaken underwater propagation by using the strong impedance difference and scattering absorption of the aerated water layer, and are currently the most widely used technology in pile driving noise reduction. Their effectiveness depends on bubble size distribution, air flow rate, curtain continuity, current deflection and sound wave diffraction. If the bubble curtain does not cover the main leakage path, local high insertion loss is difficult to translate into stable far-field benefits [5, 16]. Field studies show that bubble curtains can reduce temporary habitat loss of harbour porpoises [25]. Double-layer arrangement can further improve insertion loss when the total air volume is reasonably distributed, but simply adding one more layer does not necessarily bring stable benefits [26]. Isolation casings, cofferdams and composite barriers can achieve relatively stable physical isolation, but increase offshore installation complexity and cost. They are suitable for

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projects with strict limits, a small number of single piles or current conditions unfavorable to bubble curtains.

6.3. Management and receptor protection

Soft start, observer and PAM vigilance, temporary shutdown, construction windows in sensitive seasons and route management belong to risk avoidance and should not be described as reducing source intensity. Their effectiveness depends on assumptions such as species detection probability, vigilance radius and animal swimming speed. At the project level, a combined scheme of "source reduction - path attenuation - real-time monitoring - shutdown trigger" should be adopted. At the regional level, it is necessary to coordinate the construction periods and wind farm spacing of multiple projects in marine spatial planning, and incorporate noise, habitat, shipping and other pressures into good environmental status and cumulative impact assessment [27, 28].

6.4. Technology combination and selection logic

Noise reduction selection should not only compare nominal insertion loss. Construction schemes should simultaneously examine protected frequency bands, far-field stability, current adaptability, consequences of equipment failure, impact on pile driving efficiency and unit noise reduction cost. Soft mud seabeds, strong currents and large-diameter piles pose different requirements for bubble curtain continuity and diffraction control. Although cofferdam measures are costly, they may be more reliable when environmental limits are strict or bubble curtains are difficult to maintain. Operational period measures should prioritize spectral lines that coincide with structural modes and are long-term stable, and be verified through combined vibration and underwater sound acceptance. The most reasonable engineering solution is usually not the maximum noise reduction achieved by a single technology, but controlling exposure within an acceptable range at a lower comprehensive cost during ecologically sensitive periods. The applicability comparison of various main prevention and control measures is shown in Table 2.

Table 2. Applicability comparison of main underwater noise prevention and control measures for offshore wind power

Measure	Stage	Mechanism	Evidence / benefit	Main limitation	Maturity
Hammer-energy optimization / alternative installation	Construction	Reduce impulsive input at source	Direct reduction; can be linked to installation records	May extend duration or affect installation performance	High, site-specific
Single or double bubble curtain	Construction	Scatter, reflect and absorb propagating sound	Established field use; additional benefit possible with optimized double curtains	Sensitive to current, airflow and sound leakage paths	High
Isolation casing / cofferdam	Construction	Physical impedance barrier around pile	Relatively stable shielding	High cost and offshore handling complexity	Medium–high

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Table 2. (continued)

Drive-train isolation and structural damping	Operation	Interrupt vibration transmission to foundation	Targets persistent tonal components	Best implemented at design stage; limited field evidence	Medium
Soft-start, PAM/MMO and shutdown protocol	Construction	Allow avoidance and prevent close-range exposure	Flexible receptor protection	Does not reduce source level; detection uncertainty	High
Seasonal windows and regional coordination	All phases	Avoid sensitive periods and cumulative overlap	Low hardware demand; addresses population context	May constrain schedule; needs reliable ecological data	Medium–high

7. Research gaps and development trends

First, the amount of evidence for operational and floating offshore wind power is still significantly less than that for construction pile driving. Existing results mostly come from a few models and sites. Whether unit upsizing, direct drive, mooring wear and dynamic submarine cables form new dominant frequency bands cannot be extrapolated from individual cases [2, 11-13]. Long-term reference stations covering both fixed and floating units should be built, and acoustics, vibration, SCADA, sea conditions and operation and maintenance activities should be opened in a unified format.

Second, evaluation indicators should shift from "sound pressure-centered" to multi-physical stimuli. For fish, invertebrates and benthic organisms, particle motion and seabed vibration may be closer to actual perception than sound pressure [17]. Future standards should specify the performance of three-axis sensors, near-field measurement methods and the combined reporting format of sound pressure and particle motion.

Third, models should shift from deterministic prediction to verifiable uncertainty analysis. Structure-soil-underwater sound models can be used for source design, three-dimensional propagation models for construction window and monitoring point optimization, and data assimilation and machine learning for rapid correction. The premise is that training data has cross-site representativeness. Model outputs should give intervals and sensitive parameters, rather than only a single sound contour line.

Fourth, ecological research needs to bridge the chain of "physical exposure - individual response - spatial behavior - population consequence". Synchronous collection of acoustic telemetry, PAM, visual observation and physiological indicators can reduce confusion caused by artificial reef effects, food changes and ship activities [19]. Regional management should incorporate the time-space superposition of multiple wind farms, shipping and other marine engineering into cumulative impact assessment, and compare mitigation schemes at the early stage of project design rather than passive remediation at the construction permit stage [27, 28].

Fifth, decommissioning noise should be studied together with habitat transition. Complete removal, partial retention and in-situ reuse correspond to different cutting, pile extraction and vessel operations, and will also alter existing artificial reef communities. Future decommissioning

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environmental impact assessment should establish operation sound source lists and field verification procedures, and place short-term acoustic disturbance and long-term habitat benefits or losses within the same decision-making framework [4].

8. Conclusion

Underwater noise from offshore wind power presents clear life cycle differences: the construction period is dominated by high-intensity repeated impulses, the operation period is dominated by low-frequency continuous sound and narrow-band spectral lines related to working conditions, and there are new sound sources and data gaps in the floating and decommissioning stages. The sound field is jointly shaped by structure, seabed and water body. Simple spreading laws can only be used for preliminary screening, and near-far field coupling or three-dimensional propagation models validated on site should be adopted for complex sites. The monitoring system needs to connect hydrophones with vibration, SCADA, particle motion and ecological observation, avoiding using a single broadband sound level to replace complete exposure. Engineering control should follow the hierarchy of source priority, path attenuation and space-time avoidance, and be verified through on-site monitoring closed-loop. The most urgent task at present is not to continue stacking scattered cases, but to form comparable long-term databases and quantitative methods from individual responses to regional cumulative risks.

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