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Review

Underwater Noise in Offshore Wind Farms: Monitoring Technologies, Acoustic Characteristics, and Long-Term Adaptive Management

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Abstract

The rapid global expansion of offshore wind energy (OWE) has established it as a critical component of the renewable energy transition; however, this development concurrently introduces significant underwater noise pollution into marine ecosystems. This paper provides a comprehensive review of the acoustic footprint of OWE across its entire lifecycle, rigorously distinguishing between the high-intensity, acute impulsive noise generated during pile-driving construction and the chronic, low-frequency continuous noise associated with decades-long turbine operation. We critically evaluate the engineering capabilities and limitations of current underwater acoustic monitoring architectures, including buoy-based real-time monitoring nodes, cabled high-bandwidth systems (e.g., cabled hydrophone arrays with DAQ/DSP and fiber-optic distributed acoustic sensing, DAS), and autonomous seabed archival recorders (PAM deployment). Furthermore, documented biological impacts are synthesized across diverse taxa, ranging from auditory masking and threshold shifts in marine mammals to the often-overlooked sensitivity of invertebrates and fish to particle motion—a key metric frequently missing from standard pressure-based assessments. Our analysis identifies a fundamental gap in current governance paradigms, which disproportionately prioritize the mitigation of short-term acute impacts while neglecting the cumulative ecological risks of long-term operational noise. This review synthesizes recent evidence on chronic operational noise and outlines a conceptual pathway from event-based compliance monitoring toward long-term, adaptive soundscape management. We propose the implementation of integrated, adaptive acoustic monitoring networks capable of quantifying cumulative noise exposure and informing real-time mitigation strategies. Such a paradigm shift is essential for optimizing mitigation technologies and ensuring the sustainable coexistence of marine renewable energy development and marine biodiversity.

Keywords: underwater noise; offshore wind farms; passive acoustic monitoring; marine bioacoustics; particle motion; adaptive management

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1. Introduction

Global economic and social development has driven a continuous increase in electricity demand. Traditional fossil fuels, due to their inherent limitations such as finite reserves, non-renewability, and severe environmental pollution, are increasingly unable to meet the energy demands of a sustainably developing society. Against this backdrop, offshore wind power, characterized by its clean, low-carbon, and sustainable nature, is garnering significant international attention [1,2]. Offshore wind power not only effectively avoids competing with land-based development but also leverages the high wind speeds and abundant energy resources endemic to coastal regions. It offers multiple advantages, including large individual unit capacity and high power generation efficiency [3,4]. According to statistics from the Global Wind Energy Council (GWEC), the current global installed capacity of offshore wind power stands at 83 GW, sufficient to power 73 million households. GWEC's market intelligence team forecasts that annual offshore wind power installations will grow from 8 GW in 2024 to 34 GW by 2030 [5]. This rapid growth trajectory is projected to continue, with annual growth rates reaching 28% by 2029 and 15% by 2034, indicating that the industry will surpass the 30 GW milestone in 2030 and reach 50 GW by 2033 (Figure 1). China, for instance, has led global installations for seven consecutive years, becoming the country with the largest cumulative installed capacity of offshore wind power globally [6], followed by the United Kingdom, Taiwan, China, Germany, and France. The top five markets accounted for 94% of new capacity added in 2024. Although recent growth has been concentrated in established markets in Europe and China, the GWEC report indicates that offshore wind power is expanding into new regions such as Asia-Pacific and Latin America. In Japan, South Korea, the Philippines, Australia, Brazil, and Colombia, governments are collaborating with industry stakeholders to develop policies and regulations that will accelerate the rapid growth of offshore wind power. The United States, Vietnam, and European countries, including the Netherlands, Germany, and Belgium have also formulated their own offshore wind power development plans [7].

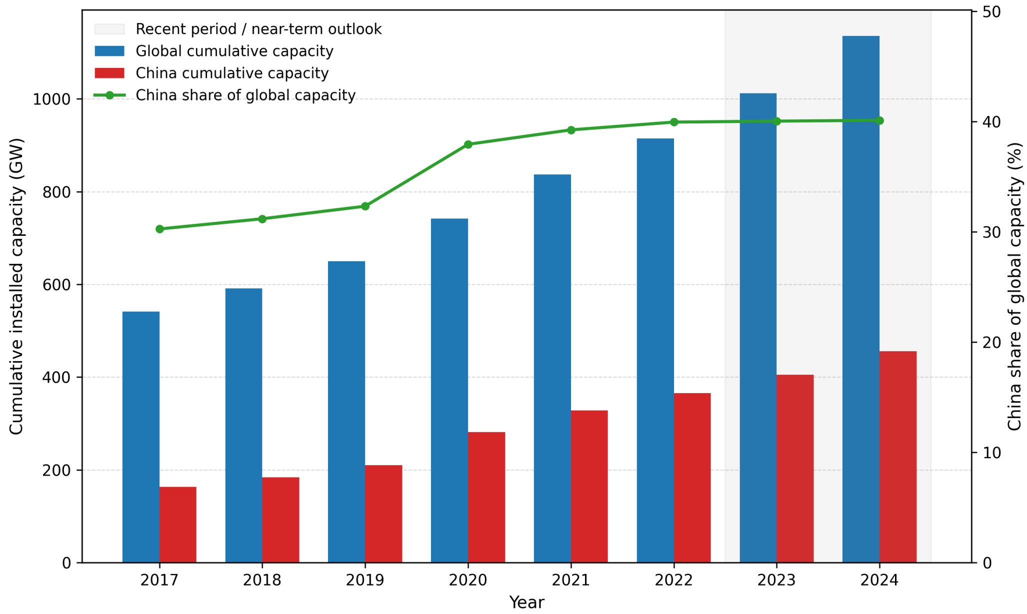

Figure 1. Global and China offshore wind power development.

However, while OWE provides substantial green energy, its development and operation concurrently generate significant underwater noise pollution [8,9]. In recent years, with the increase in marine development activities—including the construction of offshore wind farms and platform pile driving—the environmental and ecological impacts of underwater noise pollution have become increasingly prominent. Given that sound waves propagate far more efficiently in underwater environments than light signals, the acoustic disturbances generated during construction pose potential threats to the behavior, communication, feeding, and reproduction of marine mammals, fish, and other species. This disruption, in turn, threatens the equilibrium of entire marine ecosystems [10]. Since 2008, marine pile driving—a common method for constructing offshore wind farm platforms—has been a focus of research. The intense pulsed noise generated during pile driving is concentrated in the low-frequency range, reaching extremely high sound levels that propagate into higher frequency bands. Intense transient noise can directly cause physical damage to nearby marine life, while persistent construction noise disrupts critical behaviors such as foraging and migration, as well as population dynamics [11]. In response to this growing challenge, the international community has introduced a series of countermeasures and regulations. In 2008, the European Union adopted the Marine Strategy Framework Directive (MSFD), which explicitly incorporated underwater noise into legislation for the first time and promoted the development of international standards for measuring and reporting underwater noise [12]. In 2017, the United Nations declaration "Our Ocean, Our Future: A Call for Action" listed underwater noise as a matter of concern. Subsequently, starting in 2018, the United Nations Informal Consultative Process on Oceans and the Law of the Sea further amplified attention to this issue through multi-stakeholder engagement [13]. In 2019, the United Nations General Assembly Resolution 74/19 also placed underwater noise on its agenda, encouraging the International Maritime Organization (IMO) to jointly advance related actions. Concurrently, the International Organization for Standardization (ISO) has successively published technical specifications covering areas such as underwater radiated noise from ships, impact pile driving noise measurement, and noise mitigation systems. It released the first internationally recognized standard for deep-sea ship acoustic measurement and specifications for standardizing impact pile driving noise measurement, laying a solid foundation for transnational and cross-sectoral scientific collaboration [14]. In 2020, the European Commission (within the Horizon Europe mission "Restoring our oceans and waters by 2030") and the Joint Programming Initiative Healthy and Productive Seas and Oceans (JPI Ocean) explicitly incorporated underwater noise into their future work programs. The importance of underwater noise was further emphasized in the implementation plan for the United Nations Decade of Ocean Science for Sustainable Development. These initiatives reflect a growing international consensus on the significance of this issue. Industry stakeholders have also funded and advanced noise impact assessments, risk framework development, and noise mitigation technology R&D through dedicated working groups and joint industry programs [15–18].

While source-based mitigation measures are available for most noise sources, for example, in pile driving operations, they include employing a "soft-start" procedure—initially activating the impact hammer at a lower energy level and gradually increasing it to the minimum energy required to achieve the desired penetration depth—while optimizing the driving sequence to shorten the duration of individual pile operations [19], these measures have been extensively discussed in the academic literature for various pulse noise sources [19–25]. To avoid pulse noise emissions, many industries have explored alternative methods. In offshore wind foundation installation, alternatives to impact pile driving exist, such as employing quieter gravity foundations or suction pile foundations [25]. However, the selection of specific installation methods is primarily constrained by factors including cost, geological conditions, and logistical support. For certain seismic surveys, Feltham et al. proposed an alternative approach [21,22]. In recent years, the industry has made significant progress in developing fully commercialized marine vibrators. Establishing mitigation zones (or exclusion zones) around noise sources is a critical strategy to ensure that protected species are not present in the area before noise operations commence or continue. Acoustic deterrent devices (ADD) represent another option for reducing injury risks by repelling specific species from mitigation zones, particularly for noise sources such as blasting and pile driving that may be especially disruptive [26]. Simultaneously, the extensive application of AlS data, source models, and passive acoustic monitoring (PAM) equipment supports underwater noise detection and assessment, demonstrating potential for further development [27].

Despite these mitigation efforts, a critical gap persists: current research and management paradigms remain largely confined to assessing and mitigating short-term, high-intensity noise events, while paying insufficient attention to the cumulative ecological effects of chronic, low-intensity noise generated over the decades-long operational lifespan of offshore wind farms. Unlike other pollutants, once noise ceases, the physical disturbance vanishes, yet its chronic impacts on biological populations and ecosystem structure may persist long-term or even accumulate. Therefore, understanding and managing these chronic cumulative effects represents a core challenge to the sustainable development of OWE [28].

Despite the relative maturity of source mitigation measures for high-intensity transient noise, such as piling (e.g., bubble curtains and soft-start procedures) and their core position in Environmental Impact Assessments (EIA) across various countries, current regulatory and monitoring paradigms still exhibit significant lag. Existing monitoring activities typically possess highly "event-oriented" characteristics, meaning they only conduct short-term data sampling during specific construction windows. This "snapshot" monitoring mode cannot capture the dynamic evolution of the soundscape caused by wind speed changes, equipment aging, and maintenance operations during the decades-long operation period of wind farms. Furthermore, unlike the terrestrial environment, the underwater acoustic channel possesses high time-variance and multi-path effects; single, short-term measurement data make it difficult to separate the complex coupling relationship between background noise and turbine radiation noise. Therefore, there is growing recognition that event-oriented monitoring may not capture the multi-decadal evolution of operational soundscapes, necessitating approaches that support longer-term monitoring, which are increasingly being explored. This paper aims to bridge this cognitive and technical gap by reviewing existing monitoring technology bottlenecks and eco-acoustic characteristics, arguing for the necessity and technical pathways of establishing a long-term, three-dimensional underwater noise monitoring network.

This paper is structured in seven sections. Section 2 outlines mainstream underwater noise monitoring technologies. Sections 3 and 4 conduct an in-depth analysis of the noise characteristics throughout the entire life cycle of offshore wind farms and their impacts on key marine biological groups (fish, marine mammals, and invertebrates). Sections 5–7 further explore the central role of long-term monitoring within a sustainable governance framework, identify current research gaps, and provide scientific recommendations for future research directions and policy development. These recommendations aim to advance the ecologically friendly development of the offshore wind industry.

This review synthesizes OWF underwater noise across the full project lifecycle with an emphasis on how monitoring technologies can support long-term governance. We (i) organize dominant noise sources and monitoring metrics by lifecycle stage, distinguishing acute construction signals from chronic operational exposures; (ii) compare monitoring architectures in terms of data quality, endurance, spatial coverage, and their suitability for cumulative-impact assessment; (iii) highlight particle motion as a critical but under-measured component for fish and invertebrates and (iv) outline an adaptive monitoring-and-management pathway linking measurements and models to decision triggers and mitigation.

2. Underwater Noise Monitoring Technology System

The intensifying processes of industrialization, tourism, and urbanization have subjected coastal marine ecosystems to severe anthropogenic pressures [29,30]. Consequently, understanding the dynamic evolution of marine environments and their interactions with human activities has become a key research focus. Simultaneously, against this backdrop, the increasingly prominent issue of marine noise poses new challenges to existing management paradigms for marine protected areas [31]. Particularly near critical habitats, the scale of economic activities may need to be restricted to minimize anthropogenic disturbance to marine life, thereby safeguarding fragile marine ecosystems [32]. Effectively addressing this challenge requires collecting environmental data across broad spatiotemporal scales. This enables comprehensive monitoring of marine ecosystems, providing a robust foundation for developing scientifically grounded conservation and management strategies [33]. Notably, over the past decade, marine noise monitoring technology has advanced rapidly, emerging as a critical domain in marine ecological conservation [34–36]. Particularly in the offshore renewable energy sector, the rise of floating offshore wind farms—facilities that mount wind turbines on floating platforms to generate power in deep-sea waters—has created an urgent need for specialized monitoring protocols tailored to the unique acoustic characteristics of such installations [36]. The FLOWN-MIT (Floating Offshore Wind Noise Mitigation) initiative, led by ORE Catapult in collaboration with partners including Equinor and JASCO Applied Sciences, exemplifies this trend. This project aims to deepen understanding of underwater noise from wind farms and develop mitigation strategies [37]. Against this backdrop, the construction and operation of offshore wind farms are receiving increasing attention. Given that wind farms continuously generate underwater noise throughout their entire lifecycle—particularly during the operational phase—establishing a highly reliable long-term monitoring and assessment system is paramount for effective governance. Underwater noise monitoring systems built upon advanced technologies such as virtual instrumentation and embedded computing enable real-time acquisition, processing, storage, and early warning of acoustic data in marine environments. To fully leverage these capabilities, the system should be deployed on an efficient, continuously operational observation platform, enabling more comprehensive, real-time, and accurate noise monitoring [38]. Furthermore, implementing data acquisition and monitoring systems significantly enhances the overall operational efficiency of equipment information systems, providing critical support for subsequent marine environmental management and decision-making [39].

To achieve the aforementioned monitoring objectives, reliance on diverse observation platforms is essential. These platforms can be broadly categorized into surface-based and submerged platforms based on their deployment locations. They can be integrated with specific monitoring systems to establish multifunctional observation networks. Platform selection is primarily dictated by the information requirements for a given area. For instance, buoy-based coastal monitoring systems are well-suited for coastal surveillance and water status control due to their relatively simple installation and maintenance, coupled with low operational costs. Additionally, buoys can be equipped with hydrophones for efficient underwater noise monitoring [40]. This section will focus on reviewing three mainstream underwater acoustic monitoring technology systems: buoy monitoring systems, DASP (Data Acquisition and Signal Processing) systems, and Passive Acoustic Monitoring (PAM) systems.

2.1. Surface Real-Time Telemetry (Buoys)

Ocean buoys serve as automated observation platforms for marine environments and constitute a vital component of modern three-dimensional marine environmental monitoring systems. Their core advantage is the capacity for continuous, long-term, and automated data collection, particularly maintaining stable operation under harsh sea conditions where other monitoring methods prove impractical [41]. Among these, hydro-meteorological buoys are the most commonly used type. Typically referring to disc-shaped buoys with a diameter of no less than 10 m, they are capable of automatically collecting and transmitting marine hydro-meteorological data around the clock. The monitoring system consists of a buoy body, mooring system, and shore-based receiving equipment, with various sensors mounted on the buoy body [42]. Primary observation parameters include wind direction, wind speed, air temperature, humidity, atmospheric pressure, precipitation, visibility, water temperature, salinity, waves, ocean currents, chlorophyll, and ocean noise. These data are extensively utilized in weather forecasting, sea state prediction, and natural disaster warnings (e.g., hurricanes, tsunamis) [43–46]. Reviewing the development history of ocean buoys worldwide reveals that hydro-meteorological buoys were the earliest deployed and most widely used type, with their development laying the foundation for modern ocean buoy technology [47].

The buoy monitoring system comprises various components, including the buoy body, support frame, power supply equipment, protective devices, and sensors such as hydrophones, as shown in Figure 2. The buoy body serves as the carrier for the support structure and various instruments at sea, featuring diverse shapes such as disc-shaped, cylindrical, boat-shaped, spherical, ellipsoidal, and conical [48]. To meet the structural strength, durability, and lightweight requirements for long-term noise monitoring, composite materials known for their durability and low maintenance are predominantly used for the buoy body, such as ultra-high molecular weight polymer, and fiberglass. Additionally, buoyancy materials fill all compartments except the equipment bay. Future materials research will focus on developing superior lightweight, corrosion-resistant, biofouling-resistant, and highly durable materials to withstand prolonged exposure to harsh marine environments [49]. Research has also proposed hybrid power systems combining wind, solar, and wave energy. Integrating wind turbines, wave generators, and traditional solar panels further enhances the reliability of the system's power supply [50].

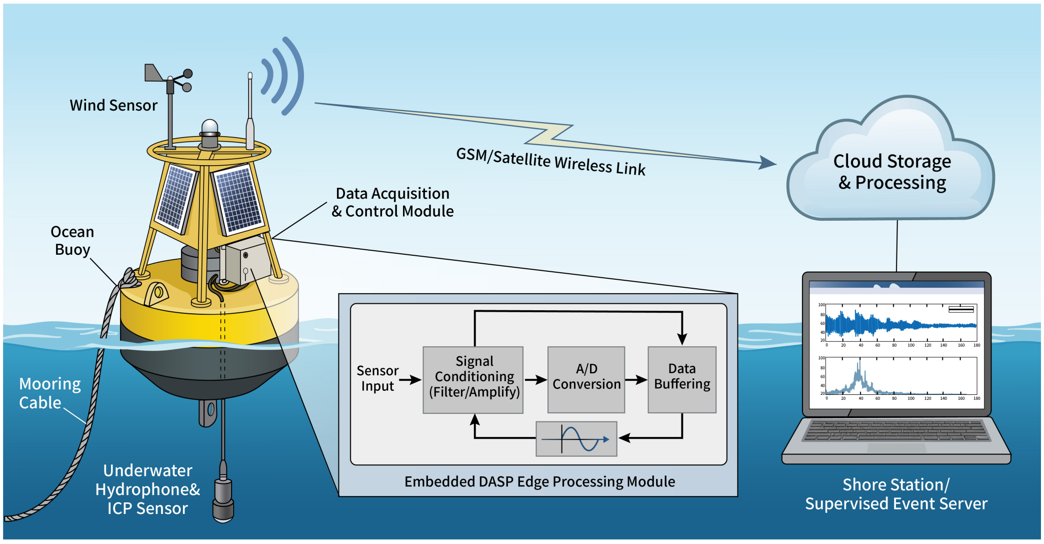

Figure 2. Schematic diagram of the ocean buoy monitoring system. The system integrates multi-parameter sensors powered by solar panels.

The technology for data acquisition and transmission in ocean buoy monitoring systems is also continuously evolving. Their core control modules typically employ high-reliability, low-power microprocessors, enabling sensors to conduct automated, long-term, continuous monitoring data collection under command control. Should the buoy drift or become lost, it can be promptly corrected on-site or retrieved by tracking its movement trajectory. Long-term operational reliability also depends on mitigating seawater corrosion and biofouling. This requires protective measures such as applying long-lasting antifouling paint, installing sacrificial anodes below the waterline for cathodic protection, and applying aluminum spray coating to the outer surfaces for corrosion resistance. Prior to deployment, the surfaces below the waterline are coated with long-lasting antifouling paint to prevent marine organism attachment. Regular maintenance and removal of fouling organisms are also critical measures to ensure the buoy system's reliable operation.

In summary, through comprehensive optimization of structural design, energy solutions, data management, and protective measures, buoy monitoring systems have become critical infrastructure for marine environmental and noise monitoring.

2.2. Cabled Monitoring Systems: Hydrophone Arrays with DAQ/DSP and Fiber-Optic Distributed Acoustic Sensing (DAS)

Cabled monitoring systems typically provide continuous power supply and high-bandwidth data transmission, enabling real-time, high-dynamic-range measurements. Two representative pathways are (i) cabled hydrophone arrays integrated with DAQ/DSP pipelines and (ii) fiber-optic distributed acoustic sensing (DAS), which enables quasi-continuous spatial sampling along a fiber route. To avoid conceptual overlap with PAM, we clarify that in this review, 'DAQ/DSP system' refers to an engineering architecture characterized by (i) high-fidelity acquisition, (ii) near-real-time/edge signal processing, and (iii) low-latency telemetry or cabled backhaul for compliance or operational decision-making. By contrast, PAM is treated as a passive listening methodology and analysis workflow that can be implemented on multiple platforms; in practice, it is most often deployed as autonomous archival recorders with delayed data recovery for long-duration soundscape and ecological inference. Thus, the main practical distinction lies in latency, available power/bandwidth, and on-site computing capacity rather than whether the system is 'passive'. This measurement system [51] primarily consists of a 24-bit signal acquisition analyzer, ICP sound pressure sensor, air pressure sensor, sound pressure calibrator, sound level meter, data recorder, data analysis processor, high-frequency low-noise cable, and instrument-specific case, as shown in Figure 2. The software environment primarily comprises the DASP-V10 Engineering Edition platform software, acoustic testing software, triple-measurement technology and virtual extended channel sampling software, transfer function analysis software, signal generation software, waveform editing and processing software, and engineering test verification system software [52].

The workflow of the DAQ/DSP system begins with the acquisition of sensor signals. The acquired analog signals are transmitted via cables to the signal conditioning circuit for filtering, rectification, and amplification. The analog-to-digital conversion circuit converts the preprocessed analog signals into digital signals for data buffering. Once the buffer reaches a certain capacity, the data are transferred to physical storage media for archiving, facilitating subsequent data analysis [53]. The system supports real-time data analysis, enabling instant display of signal waveforms and spectral analysis. For post-processing, the DAQ/DSP system can retrieve stored data to perform period, correlation, and power spectrum analyses in both time and frequency domains [54]. Time-varying parameter analysis enables in-depth investigation of the temporal and spectral characteristics of noise signals and their correlations, thereby providing a foundation for analyzing the underwater noise signatures of equipment related to offshore wind farms [55].

The DAQ/DSP monitoring system typically employs piezoelectric scalar hydrophones, such as the HTI-96-MIN hydrophone and the IcListenHF smart hydrophone. In recent years, the latest systems have begun incorporating MEMS vector hydrophones. MEMS hydroacoustic sensors offer significant advantages, including lightweight design, ease of deployment, and low power consumption, making them suitable for applications such as unmanned underwater vehicles and long-term deployed buoy networks. Simultaneously, the encapsulation design ensures reliable operation in high-pressure, corrosive underwater environments [56–58]. Furthermore, superior high-frequency response capabilities enable the precise detection and processing of high-frequency underwater noise signals, demonstrating significant technical advantages in applications such as high-resolution underwater imaging and coastal ecological environment monitoring [59]. The recent integration of cloud computing technology, which not only addresses limitations in local storage capacity and the cumbersome process of manual data transfer but also transforms DAQ/DSP from a localized data collection tool into a networked governance instrument, allowing stakeholders to access real-time data remotely. This system features simple operation and comprehensive functionality, enabling long-term unattended remote monitoring [60–62]. However, the long-term reliability and sensor lifespan of these integrated systems require further validation to ensure their viability for decades-long governance frameworks.

2.3. Portable High-Precision Measurement (PAM)

Passive Acoustic Monitoring (PAM) is an acoustic technique that enables non-invasive research on marine organisms and environments by recording and analyzing underwater soundscapes, positioning it as a key tool for ecosystem-based management. As an alternative to traditional survey methods, PAM captures environmental acoustic signals—including biological, geological, and anthropogenic sounds—through soundscape recording and subsequent analysis [63]. This technology demonstrates broad application potential in species behavior monitoring, population dynamics assessment, and environmental change studies [64]. PAM systems typically comprise acoustic sensors, data storage devices, signal processing software, and communication modules. They capture continuous acoustic signals for scientific analysis by detecting the acoustic signatures of target species or environmental sound sources [65]. Since sound detection remains unaffected by light conditions or water currents, passive acoustic monitoring offers distinct advantages in complex, inaccessible marine environments. This capability allows for effective monitoring under challenging conditions such as severe weather, tidal fluctuations, turbid waters, or nocturnal animal activity. Moreover, this non-invasive approach reduces observer bias and minimizes anthropogenic disturbance compared with traditional visual surveys [66]. Passive acoustic monitoring systems take diverse forms, including fixed underwater recording devices, floating acoustic buoys, and towed hydrophone arrays, capable of providing real-time monitoring or archival data. Real-time monitoring supports immediate mitigation of impacts from human activities on ecosystems, while archival data inform long-term policy and adaptive management strategies [67–70], as illustrated in Figure 3.

In recent years, PAM systems have seen increasingly widespread application in fields such as biodiversity assessment, habitat restoration, and research on the impacts of climate change on species distribution. By analyzing the acoustic characteristics of different species, PAM can infer their behavioral patterns, habitat selection, and migration routes, enabling long-term, dynamic tracking of specific populations—particularly marine mammals [71–73]. Most PAM systems target echolocation signals used by dolphins for positioning, navigation, and foraging. On the application front, some PAM systems also integrate active intervention capabilities. For instance, in marine engineering zones, upon detecting acoustic signals from endangered marine mammals, the system can trigger acoustic deterrent devices (ADDs) to safely deter them [74]. Passive acoustic monitoring (PAM) technology, leveraging its unique advantages in acoustic soundscape analysis and assessing the ecological impacts of human activities, has become one of the core technologies in marine ecological assessment and underwater acoustic monitoring [75].

From a practical design perspective, operational turbine noise is mainly concentrated in the low-frequency band (typically <1 kHz), whereas construction activities can extend to higher frequencies and higher levels. Therefore, monitoring systems focused on compliance for operational noise may prioritize low-frequency performance and long-duration stability, while multi-taxa ecological monitoring often requires a broader bandwidth to capture biological signals and odontocete activity. Battery endurance of autonomous PAM recorders is highly configuration-dependent and is primarily controlled by sampling rate, duty cycle, and data storage; consequently, deployments can range from weeks (continuous high-rate recording) to multiple months when duty-cycled and/or configured for low-frequency channels.

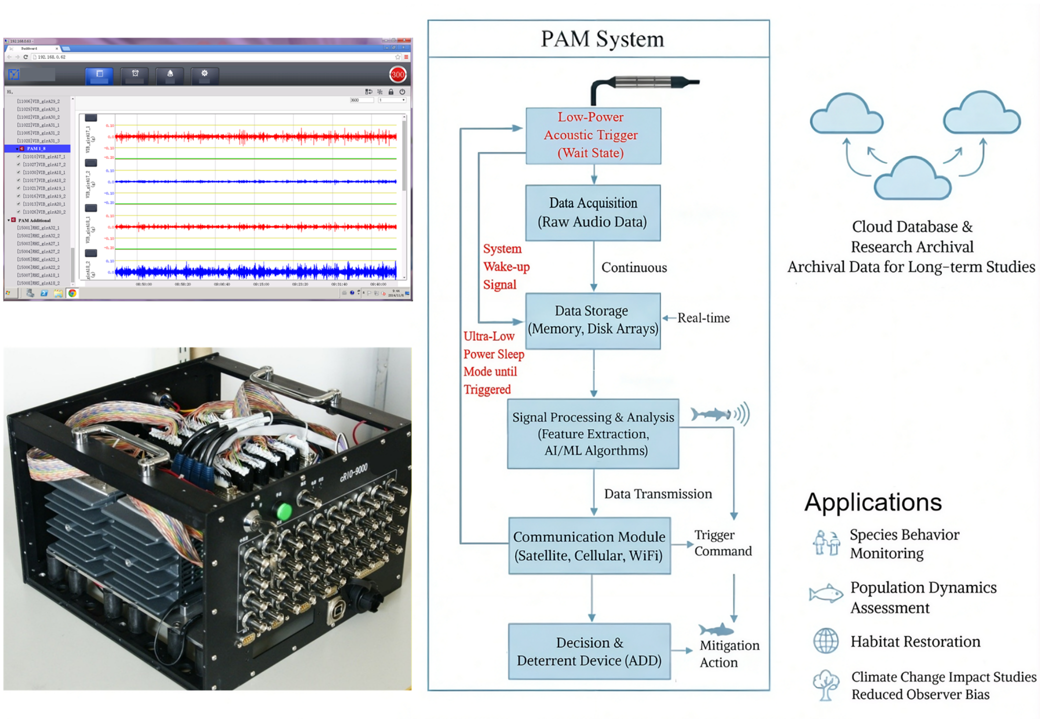

Figure 3. Operational framework of the passive acoustic monitoring (PAM) system. The flowchart highlights the system's low-power acoustic trigger mechanism, which activates data acquisition from a sleep state.

2.4. Multi-Element Fusion Monitoring System

In the face of complex marine environments and diverse monitoring needs, single monitoring technologies often struggle to balance timeliness with data depth. By structuring the comparison around Latency and Modality, Table 1 summarizes the engineering trade-offs between these architectures.

To increase practical value, we further provide typical selection envelopes: (i) key frequency bands of concern across lifecycle stages (Table 2) and (ii) engineering implications for platform choice (real-time powered systems vs long-term autonomous archival recorders).

In summary, no single monitoring architecture is sufficient. Buoy-based real-time nodes and seabed archival recorders represent two PAM deployment modalities with different engineering trade-offs (telemetry versus endurance/self-noise). Cabled systems—including cabled hydrophone arrays with DAQ/DSP and emerging fiber-optic DAS—provide continuous power and high bandwidth but may involve higher installation and maintenance costs. Therefore, an ideal underwater noise monitoring network for offshore wind farms should fuse the strengths of different technologies: using flexible, easily maintained buoy systems as the foundational platform; integrating the lightweight, real-time signal processing capabilities of DASP systems and embedding the biological acoustic monitoring expertise of PAM systems. This fusion strategy aims to create a comprehensive, adaptable, integrated monitoring network. This network enables not only precise, long-term dynamic assessment of the spatiotemporal distribution of the wind farm noise field but also synchronous monitoring of potential impacts on surrounding marine ecology—particularly interference with acoustically sensitive marine organisms—thereby providing critical technical support and a scientific decision-making basis for environmental impact assessment, risk control, and sustainable development of offshore wind farms.

Table 1. Engineering characteristics and applicability comparison of mainstream underwater acoustic monitoring architectures (deployment modalities) for offshore wind farms.

Monitoring Architecture	Key Components	Primary Advantages	Engineering Limitations	Typical Application Scenario	Ref.
Buoy-based real-time PAM node (surface telemetry)	Surface buoy, hydrophone, DAQ module, embedded processor, telemetry (4G/satellite), renewable power	Real-time transmission; flexible deployment; supports early warning and multi-parameter sensing	Weather vulnerability; surface-motion self-noise; limited power/bandwidth; periodic maintenance	Construction compliance; short-term near-field monitoring; early warning	[76]
Autonomous seabed recorder (archival PAM)	Seabed lander, hydrophone, battery, large local storage, clock	Long-term baseline; low self-noise; full-bandwidth recording; easy redeployment	No real-time; recovery required; risk of loss; clock drift	Baseline soundscape; long-term exposure/ecological studies	[63,64]
Cabled hydrophone array + DAQ/DSP	Hydrophone(s)/array, subsea cable, junction box, onshore station, DAQ + edge processing	Continuous power & high bandwidth; real-time; high sampling/dynamic range	High cost; installation complexity; spatial coverage limited by array layout	Long-term fixed-site monitoring; near-field turbine monitoring	[77]
Fiber-optic distributed acoustic sensing (DAS)	Fiber-optic cable + interrogator, DAS processing, edge/cloud pipeline	km-scale quasi-continuous spatial coverage; can leverage existing fiber routes; event detection over large areas	Measures strain/strain-rate; calibration needed to infer acoustic metrics; coupling-dependent sensitivity; data volume	Wide-area monitoring; detection of shipping/piling events; corridor surveillance	[51,52]
Integrated multi-platform network	Combination of above + cloud server + data fusion/AI	Combines strengths; scalable; enables cross-validation & management oriented products	multi-platform communication and maintenance; time synchronization; cross-sensor calibration; big-data storage, processing, and QA/QC high-volume datasets	Full life-cycle monitoring and management decision support	[78]

Table 2. Acoustic characteristic parameters of major noise sources across the full life cycle of offshore wind farms.

Lifecycle Phase	Noise Source	Dominant Frequency Range	Typical Source Level (dB re 1 μPa @ 1 m)	Acoustic Signature	Ref.
Preparation	Geophysical Sonar/Airguns	10 Hz–100 kHz	210–250 (Peak)	High-intensity, highly directional short pulses.	[79]
Construction	Impact Pile Driving	50 Hz–1 kHz	225–260 (Peak)	Repetitive, extremely high-energy broadband pulses; characterized by rapid rise times.	[35]
	Vibratory Pile Driving	100 Hz–2 kHz	180–210 (RMS)	Continuous signal primarily composed of the fundamental frequency and its harmonics.	[35]
	Construction Support Vessels	20 Hz–1 kHz	160–190 (RMS)	Continuous broadband noise, modulated by propeller cavitation.	[35]
Operation	Mechanical Vibration (Gearbox/Generator)	10 Hz–500 Hz	140–170 (RMS)	Low-frequency line spectra; intensity is positively correlated with wind speed.	[80]
Decommissioning	Underwater Cutting and Blasting	50 Hz–5 kHz	190–280 (Peak)	Highly destructive shockwaves (blasting) or high-frequency metal cutting sounds.	[81]

3. Full Life Cycle Acoustic Characteristics of Offshore Wind Farms

3.1. Introduction to Underwater Noise and Offshore Wind Turbines

To effectively evaluate underwater noise, it is first necessary to clarify its fundamental definitions and key physical parameters. Sound is essentially a pressure wave generated by the vibration of objects within a medium, such as air or water [82,83]. Underwater noise is commonly quantified using sound pressure metrics such as sound pressure level (SPL, dB re 1 μPa) and sound exposure level (SEL, dB re 1 $\mu Pa^2 \cdot s$). SPL is typically used for continuous sources (e.g., vessels and turbine operation), whereas SEL integrates acoustic energy over discrete events (e.g., impact pile driving) and is often complemented by peak SPL for impulsive signals. Importantly, underwater sound fields comprise both pressure and particle motion. This distinction is ecologically critical because many fishes and invertebrates respond primarily to particle motion, whereas marine mammals are often assessed using pressure-based metrics. For instantaneous peaks in impulsive noise, the peak sound pressure level (SPL_peak) is typically employed for characterization [14,84].

In addition to intensity, frequency (Hertz, Hz) is another key parameter that determines the pitch of sound. More importantly, sound waves propagate through a medium via two physical mechanisms: as a pressure wave (sound pressure) and through the vibration of particles within the medium (particle motion) [14]. This distinction is ecologically critical: marine mammals perceive sound primarily through sound pressure, whereas most fish and invertebrates are sensitive mainly to particle motion, although some fish also possess pressure perception capabilities [85,86].

As an emerging anthropogenic noise source, offshore wind farms are increasingly drawing attention for their contribution to the marine soundscape, particularly in the low-frequency range. This shift has sparked widespread concern regarding the underwater noise generated by wind farms and its potential impacts on marine ecosystems [87,88]. Early studies have indicated that the noise intensity generated by individual wind turbines during the operational phase is relatively low, primarily concentrated in the low-frequency band below 1 kHz. Operational turbine noise is continuous but relatively low-intensity; reported source levels are generally lower than those of many large commercial vessels [79], although overlaps may occur depending on vessel class and operating conditions. At broader spatial scales, shipping often dominates chronic low-frequency sound, whereas turbine operational noise is most relevant as a persistent, spatially fixed contribution near wind farms. Consequently, research and regulatory attention historically focused on construction-phase noise (i.e., pile driving) as the most significant acute noise event throughout a wind farm's lifecycle to date. Despite the low noise intensity of individual turbines, the cumulative effect of this chronic noise becomes increasingly pronounced as the global number of offshore wind turbines grows. Recent studies have further focused on cumulative noise effects. Although the sound source level of individual turbines is lower than that of ships, research by Tougaard et al. [89] indicates that in low-background noise environments, the cumulative noise from an entire wind farm can still propagate several kilometers. Therefore, with the rapid expansion in the number and scale of global offshore wind farms, the cumulative spatiotemporal effects of their noise and the associated ecological impacts have become critical considerations in marine spatial planning and project environmental impact assessments.

3.2. Types and Characteristics of Underwater Noise

Offshore wind farms generate underwater noise of varying types and characteristics throughout their entire lifecycle. To systematically assess their environmental impact, analysis is typically conducted across four distinct phases: preparation, construction, operation, and decommissioning [90].

During the pre-construction preparation phase, primary activities include physical site surveys and baseline ecological and environmental assessments. Key noise sources during this stage comprise the following: echo sounders and side-scan sonars used for mapping seabed topography and sediment, along with various vessels conducting survey tasks. In certain marine areas, blasting operations for seabed dredging may also be conducted to level the seabed [91]. Offshore wind turbines typically consist of blades, nacelles, towers, and pile foundations, with box transformers usually installed at the base of the tower [92]. The support structure comprises the tower, foundation, and connecting components. The foundation is welded to the tower to form a fixed offshore wind turbine tower. Equipment such as the nacelle, hub, and blades are sequentially installed on the tower, as shown in Figure 4. These elements constitute noise sources during the preparatory phase [93]. Highlighting pathways for vibration transmission that are relevant to where long-term operational-noise sensors can be mounted and what components dominate different lifecycle phases.

The construction phase represents the period of highest acute noise intensity and the most severe short-term environmental impact throughout the entire lifecycle of an offshore wind farm. Its primary noise sources can be categorized into the following three types:

(1) Pile driving. The installation procedure for offshore wind turbines involves initial pile driving at sea. The entire turbine structure is supported by pile foundations [35], making a well-designed pile configuration crucial for securing the turbine. Offshore wind turbines typically employ fixed structures, though floating designs represent a future development trend [94,95]. Offshore pile foundations are categorized into three types: monopiles, tripods, and tubular frames. Given that most offshore wind projects are located in shallow waters, monopile foundations are predominantly

used for turbine installation. Monopile installation methods are further divided into two categories: impact pile driving and vibratory pile driving [96]. Impact pile driving utilizes a hammer to drive piles with high-energy strikes, whereas vibratory pile driving employs rotating eccentric weights to generate oscillations that drive the pile. As pile diameters increase, underwater impact pile driving becomes the primary source of high-intensity pulsed noise during offshore wind farm construction, as shown in Figure 5. This method features high sound source levels, with each impact producing a pulsed broadband waveform. Since multiple impacts are required per pile column to complete the task, the noise manifests as a continuous sequence of pulse trains. The intensity of underwater noise generated by pile driving primarily depends on parameters such as pile diameter, hammer impact energy, water depth, and seabed geology. Impact pile driving noise manifests in the time domain as a high-intensity continuous pulse train, with each impact lasting approximately 100 ms and pulse intervals of about 1–2 s. Its energy is predominantly concentrated in the low-frequency range, with peak sound source levels reaching up to 235 dB (re 1 μPa) for 2-m diameter steel pipe piles. This represents a 30 dB to 50 dB (re 1 μPa) increase over background noise in the same frequency band [97,98]. Noise source intensity is influenced by multiple factors, including pile diameter, hammering energy, water depth, and seabed geology.

(2) Construction Machinery. Various machinery at the construction site—such as loaders, cranes, and excavators—along with electrical wiring installation and dredging operations, generate noise. Such mechanical engineering noise constitutes the primary offshore construction noise source [99].

(3) Transport vessels. Construction operations involving earthwork distribution and the transportation of equipment and materials require extensive vessel deployment. Their frequent passage through the construction area generates significant disturbance noise. Vessel noise comprises mechanical noise, propeller noise, and hydrodynamic noise, with mechanical and propeller noise being the primary sources [100,101]. Ship mechanical noise originates from vibrations transmitted through the hull structure from onboard machinery, radiating into the water. This includes noise from mechanical imbalance, mechanical impact, and bearing noise, exhibiting low correlation with ship speed. At low speeds, propeller noise and hydrodynamic noise are relatively weak, with mechanical noise dominating the vessel's noise profile. At high speeds, propeller noise becomes the primary source of vessel noise [102].

Operational underwater noise is primarily generated by wind turbine operation, particularly low-frequency noise transmitted into the water through structural vibration via various pathways such as the tower and pile foundations [103,104]. There are three pathways for noise propagation from operating turbines to the underwater environment: direct refraction of airborne noise sources through the sea surface into the water, transmission through the turbine tower into the water, and radiation from the tower to the seabed and then into the water; Ref [105], illustrates farm-scale superposition and the concept of a cumulative SPL footprint, linking individual-turbine noise to chronic cumulative exposure metrics discussed in Section 4 and the adaptive monitoring approach in Section 5, as shown in Figure 6. Monitoring data from Xiamen University [106] indicates that operational noise is characterized by continuous, low-frequency sound, with energy predominantly concentrated below 1.5 kHz and an overall intensity that decreases significantly with increasing frequency. Although a distinct broadband spectral signature is identifiable in specific frequency bands (e.g., 120 Hz–1.5 kHz), the noise level is generally lower than that of vessel noise in the same area and may even be masked by natural environmental noise (e.g., wind waves, rainfall).

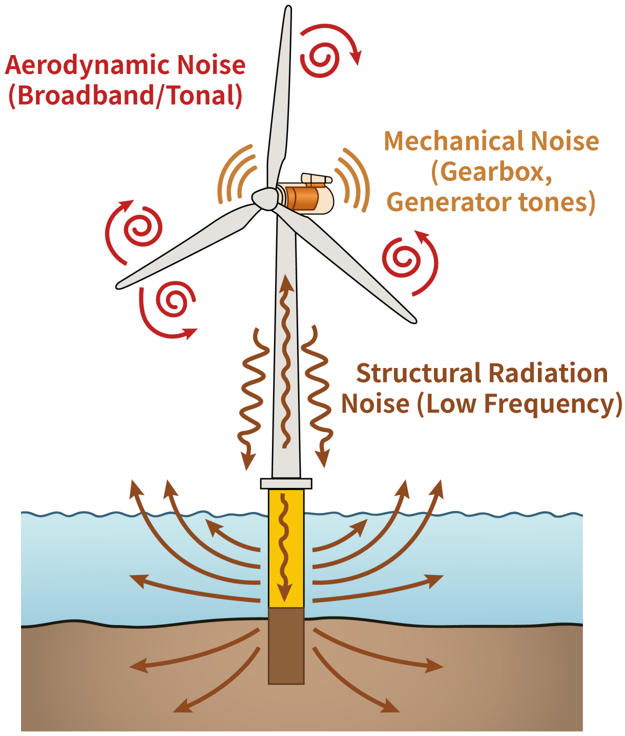

Figure 4. Structural components of an offshore wind turbine and associated noise sources.

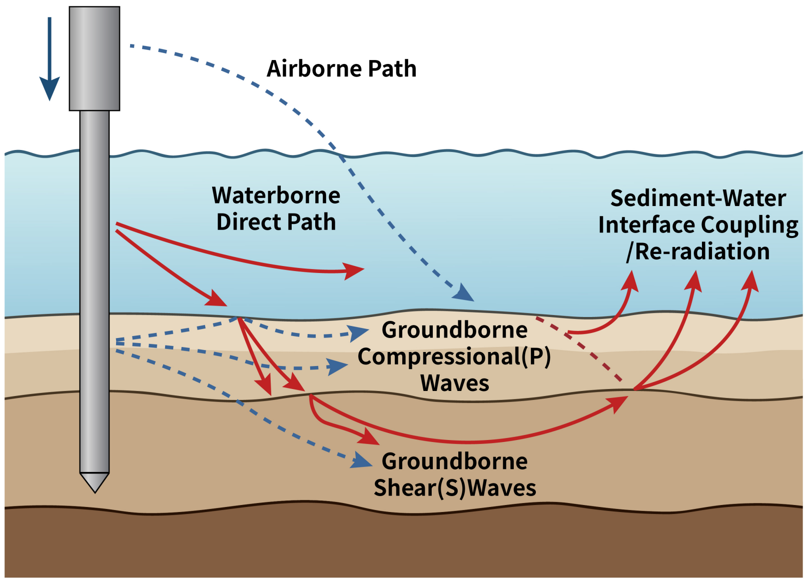

Figure 5. Propagation paths of impulsive noise induced by impact pile driving. The schematic demonstrates the transmission of acoustic energy through three distinct pathways: the airborne path, the waterborne path, and the groundborne path.

The final stage of a wind farm's lifecycle is decommissioning, during which noise primarily originates from facility dismantling operations [107]. Underwater noise during decommissioning is primarily associated with specific activities in the process, typically involving the dismantling of wind turbines, towers, foundations, subsea cables, and offshore substations. Key noise sources include the following:

(1) Demolition machinery noise: Noise generated by heavy equipment (e.g., cranes, crushers, excavators) used to dismantle wind turbines, towers, and foundations [108].

(2) These machines generate high-intensity noise during operation. Transportation noise: Demolished components require removal via vessels or land transport vehicles, and noise generated during transportation is also significant [109].
(3) Underwater operation noise: If decommissioning involves underwater operations (e.g., seabed cable recovery), underwater machinery (e.g., submarines, underwater cutters) may also produce noise [110]. In contrast to the construction and operational phases, noise from decommissioning is typically transient and intermittent, occurring in scheduled bursts according to the dismantling plan. Furthermore, since heavy machinery is required for dismantling, its impact on surrounding waters is relatively limited.

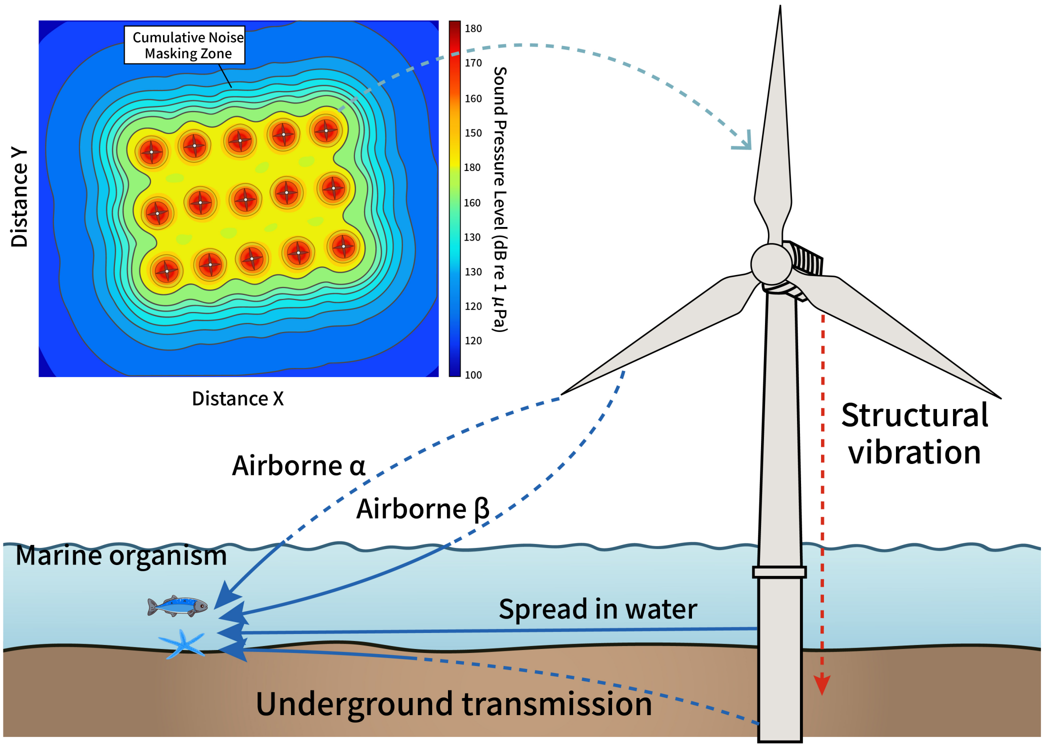

Figure 6. Schematic diagram of underwater noise propagation from offshore wind turbines during operation. The inset (top-left) illustrates the cumulative sound pressure level (SPL) field resulting from the simultaneous operation of multiple wind turbines.

However, significant uncertainty remains regarding the acoustic impacts of decommissioning, particularly for foundation removal. Potential demolition techniques include underwater cutting (e.g., abrasive waterjet cutting) or the use of explosives (blasting) [111,112]. Although measured noise data for jet cutting is currently lacking, underwater blasting—as a high-intensity pulsed noise source—has well-established predictive models for its acoustic characteristics and biological effects [113,114].

3.3. Comparison of Full Life Cycle Major Noise

The full life cycle of offshore wind farms involves various noise sources with distinct properties, exhibiting significant differences in time-domain structure and frequency-domain distribution. Table 2 summarizes the key acoustic parameters of major noise sources in each stage. This comparison motivates a dual strategy: acute-impact mitigation during construction vs. long-term soundscape monitoring during operation to evaluate cumulative exposure.

As summarized in Table 2, support vessels are typically reported at 160–190 dB 1 μPa @ 1 m (RMS), whereas single-turbine operational source levels are commonly

140–170 dB (RMS). These ranges highlight that operational noise is not necessarily the dominant chronic source at regional scales, but may contribute to local cumulative exposure where multiple turbines operate simultaneously.

Unlike the high-intensity impulsive noise during the construction phase, operation phase noise mainly originates from the vibration of wind turbine mechanical components (gearboxes, generators) and aerodynamic noise generated by blade rotation. These vibrations are transmitted through the tower to the base and radiate continuous noise dominated by low-frequency tonal components underwater [92]. As shown in Table 2, the energy of operation phase noise is mainly concentrated in the low-frequency band from 10 Hz to 500 Hz, which happens to overlap with the auditory sensitivity range of many fish (such as cod, herring) and baleen whales. Although the source level (SL) of a single wind turbine is low (typically between 140 and 170 dB re 1 μPa @ 1 m) [115], studies by Tougaard et al. point out that in large wind farms, the superposition effect of tens or even hundreds of wind turbines may cause background noise levels to increase by 10–20 dB within a range of several kilometers [33], forming a long-term "acoustic fog" effect, causing continuous compression of the communication space of marine organisms [87,116].

4. Ecological Impact Mechanisms and Thresholds

Although offshore wind farms generate high noise levels during construction and decommissioning, these phases are relatively transient. In contrast, the persistent, low-intensity noise generated over decades of operation has increasingly drawn international attention for its long-term cumulative effects [117]. Research indicates that anthropogenic underwater noise affects marine life across a broad spectrum, ranging from negligible behavioral alterations to direct mortality. Specific effects depend on the noise's acoustic characteristics (such as sound pressure level and frequency) and the distance between the organism and the noise source [18]. However, a comprehensive understanding of the underlying physiological and ecological mechanisms remains elusive. Current research primarily focuses on fish and marine mammals, while studies on the vast population of marine invertebrates—particularly benthic organisms—have lagged, with some conclusions remaining controversial [118].

4.1. Overview of Biological Impacts

The World Health Organization (2011) noted that underwater noise has been recognized as a global pollutant, considered one of the significant forms of pollution threatening marine environments and the health of marine life [119]. In both terrestrial and aquatic ecosystems, anthropogenic underwater noise is ubiquitous. One potential impact of offshore wind farm development is the generation of underwater noise. Although the full extent of underwater noise impacts remains unclear, it has been suggested that such noise may disrupt communication among animal populations, drive them away from feeding or breeding grounds, or divert them from migration routes. Noise can originate from various activities, including offshore and underwater operations. Artificial noise sources are diverse, encompassing commercial shipping, oil and gas exploration, fishing activities, and coastal engineering projects in addition to offshore wind development [85]. The biological effects of such noise can be broadly categorized as follows: behavioral responses, physiological stress, and physical injury [120]. Approximately 170,000 species of multicellular marine invertebrates and 20,000 species of marine fish are known. Existing research indicates that most studied fish species possess auditory capabilities [121]. Concurrently, a growing body of studies reveals that marine mammals and invertebrate groups not only detect sound and vibration but also exhibit behavioral responses to acoustic cues [122,123].

The effects of underwater noise on marine life fall into three categories: masking animal communication, inducing constant vigilance and physiological changes in animals, and causing temporary or permanent hearing damage [124,125].

(1) Masking Animal Communication: Masking refers to the concealment, suppression, or "drowning out" of sounds of interest to animals. Detection, discrimination, and recognition are all crucial for meaningful auditory perception. Research indicates that marine organisms can discern sound source directionality from particle motion (micro-vibrations) transmitted through water, use sound to communicate, confirm, and avoid predator locations, and gain cognitive awareness of their surroundings [126]. Underwater noise generated by human activities masks biologically significant acoustic information for marine organisms, causing behavioral changes and even resulting in injury or mortality.
(2) Physiological Stress and Chronic Effects: Exposure to underwater noise pollution is linked to significant behavioral shifts in numerous marine animals. For example, in high-noise environments, marine populations may exhibit reduced social cohesion, abandonment of preferred habitats, decreased offspring numbers and increased mortality rates, altered patterns of surfacing and diving, changes in vocalization patterns, volume, and rhythm, mass strandings, and increased vessel collisions [18,124,127]. Simultaneously, noise impacts individual behavior, physiology, anatomy, and development, leading to reduced growth rates, weakened immunity, and lower reproductive success [128]. Anatomically, noise impacts may manifest as developmental abnormalities or deformities, hearing loss, or injury to vital organs—all potentially leading to strandings, disorientation, and death. While some animals may recover from behavioral or physiological effects, others suffer irreversible consequences, such as altered DNA or genetic material, or damage to critical organs [129].
(3) Temporary or Permanent Hearing Damage: Underwater noise can cause severe impacts in areas immediately adjacent to high-level sources [122]. As the distance from the sound source increases, noise levels decrease and their effects diminish. Noise impacts are classified as follows: primary effects (direct or delayed lethal injuries to animals near powerful sound sources [130], such as casualties caused by underwater explosions); secondary effects (e.g., tissue damage or hearing loss, which may adversely affect an individual's long-term survival and adaptive capacity [131]) and behavioral impacts (e.g., animals avoiding associated areas due to noise). When anthropogenic noise sources are located near breeding grounds, migration routes, or areas of congregational activity [132], such behavioral changes may lead to significant ecological consequences at the population level.

4.2. Detailed Analysis

Before delving into specific taxa, it is essential to acknowledge a pronounced geographical bias in the extant literature. The vast majority of studies have been conducted in Europe and North America, leaving a significant research gap in the extensive marine regions of Asia, Africa, and South America. Furthermore, some investigations into the mechanisms of underwater noise impacts draw upon experimental results from freshwater species, necessitating careful consideration of the applicability of such findings when extrapolating to marine species. In addition, quantitative values reported in the literature (e.g., source levels, detection distances, and effect thresholds) are often site- and method-dependent. We, therefore, report ranges and indicate when evidence is based on modeling, laboratory exposures, or field observations. Transferability across regions is not guaranteed because exposure depends on bathymetry, sediment properties, and oceanographic conditions;

species assemblages differ and regulatory baselines vary. This underscores the need for region-specific baselines and locally relevant studies.

4.2.1. Effects on Fish

Research on the Effects of Offshore Wind Turbine Noise on Fish. First, it is essential to determine the detectable threshold range of wind turbine noise for fish. Second, studies should investigate the behavioral and physiological responses of fish to wind turbine noise.

The auditory range of fish varies significantly across species, generally spanning 30 to 1000 Hz, with optimal hearing occurring between 100 and 400 Hz [133,134]. Based on auditory sensitivity, fish can be classified as either auditory-sensitive or non-auditory-sensitive, with different species detecting wind turbine operational noise over varying ranges. Across studies, estimated detection ranges span 0.5 to 25 km [135,136], but these values are strongly dependent on turbine type/operational state, propagation, ambient noise and masking, and how 'detection' is defined. These estimates should be interpreted as indicative ranges and field validation remains limited. Auditory-sensitive species such as Atlantic cod (*Gadus morhua*) and herring (*Clupea harengus*) detect turbine operational noise at distances of 4.6 to 13 km, while non-auditory-sensitive species like halibut (*Limanda limanda*) and Atlantic salmon (*Salmo salar*) detect noise at 0.5 to 1 km. When noise sources fall within the audible range of fish, behavioral or physiological responses may occur [137,138].

Studies on fish behavioral responses primarily utilize ultrasonic remote sensing to observe swimming patterns and compare catch per unit effort (CPUE) between operational and non-operational conditions inside and outside wind farms to assess avoidance behavior [133,139,140]. Studies indicate that fish swimming near turbines during operation do not exhibit significant changes in swimming behavior. Furthermore, fish catch rates within operational wind farms are lower than during shutdown periods or outside the wind farm. Conversely, catch rates within operational wind farms exceed those outside during turbine shutdowns. Overall, operational turbine noise can influence fish behavior and spatial distribution; however, the direction and magnitude of responses (avoidance, attraction, or neutral effects) remain context-dependent and sometimes contradictory across studies. Differences likely arise from species-specific hearing sensitivity, habitat and bathymetry, background noise levels, acoustic metrics used (pressure vs. particle motion), and confounding factors such as habitat modification/artificial reef effects and fishing restrictions. Therefore, the current evidence does not yet support a universal avoidance pattern for all sites and species, highlighting the need for standardized metrics and long-term in situ validation [116,141]. Simultaneously, the artificial reef effect increases food availability within the wind farm, attracting fish to approach the area when turbines are not operating.

Research into the physiological responses of fish is relatively scarce. Among existing studies, only Smith exposed goldfish to continuous noise levels of 160–170 dB for short durations (less than 24 h) and measured blood glucose and cortisol levels. The findings revealed a transient surge in cortisol levels while glucose levels remained unchanged [142]. Additionally, auditory damage in fish falls under physiological responses. Noise-induced hearing impairment is assessed by observing damage or microperforations in the hair cells within fish ears [96]. Current research indicates that the sound pressure levels of operational wind turbine noise fall far below thresholds capable of inducing acute physiological damage or hearing impairment [133,134,139].

Furthermore, de Jong et al. [143] conducted aquarium experiments to test the effects of low-frequency continuous noise on the courtship behavior of two marine fish species (*Gobioides bicolor* and *Gobiidae*). Following noise introduction, males of both species exhibited reduced vocal courtship behavior. Furthermore, the zebra goby exhibited reduced visual courtship. Female zebra gobies were less likely to spawn during noise exposure. Neither species appeared to compensate for noise by increasing visual signals. Noise may have suppressed spawning because females likely require hearing males' song characteristics to assess male quality and identify the correct species. Interestingly, the 20–30 dB increase in noise levels—comparable to vessel noise in UK coastal waters—did not affect the overall activity or nesting of the zebra goby. This finding is significant: it suggests that even without acute injury, chronic sublethal noise exposure can lead to reduced reproductive success, impacting population viability. Noise could also alter a population's genetic makeup if females prefer different male traits in the presence of noise [143].

Limitations and field validation needs: A substantial fraction of evidence for fish and invertebrates is derived from laboratory exposures, playback studies, or simplified models. Extrapolation to natural conditions should be made cautiously because tank acoustics may not reproduce realistic propagation and particle-motion fields, and behavioral responses can be influenced by confinement, handling stress, and the absence of ecological context (predation risk, foraging, habitat complexity). Field observations, in turn, can be confounded by habitat modification, artificial reef effects, and fishing restrictions around wind farms. Therefore, future studies should prioritize long-term in situ monitoring designs that pair co-located acoustic measurements (including particle motion where relevant) with robust ecological endpoints and appropriate controls.

4.2.2. Impact on Marine Mammals

For marine mammals, sound is fundamental to communication, navigation, and foraging; acoustic signals are, therefore, vital for social cohesion, reproduction, and survival. The increasing prevalence of underwater noise pollution masks these vital acoustic signals, significantly reducing the effective communication range of marine mammals. This diminished communication range disrupts important social behaviors and negatively impacts reproductive success [144]. Studies on the impact of offshore wind turbine noise on marine mammals aim to determine the detection range of marine mammals for turbine noise, followed by an examination of the behavioral responses of marine mammals to turbine noise within that range.

The hearing thresholds of marine mammals span a wider range than those of fish, with significant interspecies variation. Given that current offshore wind farm studies primarily focus on nearshore waters, research has concentrated on the spotted seal (*Phoca largha*) and harbor porpoise (*Phocoena phocoena*) as representative species in many European marine areas. The spotted seal, with its highly sensitive hearing, is particularly representative. Existing research provides hearing thresholds for harbor seals and harbor porpoises across different frequencies. Harbor seals detect noise over ranges exceeding 1 km, while porpoises detect noise within 50 to 500 m [145]. Reported detection ranges (e.g., >1 km for seals; 50–500 m for porpoise) are representative examples from nearshore European settings and may vary with background noise, behavior state, and propagation conditions.

Studies on behavioral responses of marine mammals primarily employ methods such as marine observations, aerial surveys, theodolite tracking, and sonar monitoring to investigate whether they flee the noise source or increase echolocation frequency [146]. Studies indicate that during turbine operation, spotted seals exhibit noticeable minor avoidance behavior away from noise sources [147], with acute, high-intensity pile-driving noise during construction having a well-documented and severe impact. In contrast, the response to chronic operational noise is more subtle. For example, finless porpoises may not alter their swimming paths but instead shorten echolocation intervals. This compensatory behavior, while not an acute injury, implies a chronic stressor that could increase energy expenditure and reduce foraging efficiency over the long term. Beyond communication masking, noise also disrupts navigation and foraging [148]. For example, noise reduces the efficiency of toothed whales using echolocation to detect prey or perceive their environment. More critically, exposure to high-intensity noise can directly damage their auditory systems, causing temporary threshold shift (TTS) or permanent hearing loss (PTS) [149].

4.2.3. Effects on Benthic Organisms and Invertebrates

As a vital component of marine ecosystems, the response of invertebrates—particularly benthic organisms—to underwater noise has emerged as a critical—and largely overlooked—research area. Reviewing the development of offshore wind power over the past few decades, the potential impacts of offshore wind farm construction on benthic organisms have gradually drawn researchers' attention. From the installation of turbine foundations, construction of associated facilities, laying of subsea cables, and turbine operation, to the eventual decommissioning of the wind farm, the impacts on marine invertebrates (especially benthic organisms) from the entire process can be categorized into five types: noise and vibration, temperature, electromagnetic fields, pollutants, and disturbance [147,150].

Benthic organisms inhabiting the seafloor and associated habitats are also susceptible to underwater noise impacts [151]. Although less studied than fish and marine mammals, evidence indicates noise disrupts their behavior and may affect their habitats [152]. For instance, low-frequency noise from pile-driving activities impairs burrowing behavior in marine benthic invertebrates, which play a vital role in sediment dynamics and nutrient cycling. Noise also disrupts the ecological services these animals provide, such as water filtration and mixing of sediment layers. Concurrently, physical disturbance from pile-driving directly impacts benthic habitats [138]. Therefore, further research is needed to clarify the adverse effects of operational turbine noise on benthic organisms.

Although historically overlooked, a growing body of evidence indicates that many marine invertebrates possess sophisticated sensory systems capable of detecting sound and vibration. An increasing number of studies demonstrate that invertebrates are also highly sensitive to underwater sounds and vibrations [153]. Studies reveal that noise exposure can exert multifaceted effects, including inducing physiological stress, disrupting anti-predator behaviors, impacting feeding and reproductive activities, and even causing developmental abnormalities and increased mortality in juveniles [154]. For instance, research has confirmed that turbine noise masks critical acoustic cues used by crab larvae for habitat selection, potentially delaying their metamorphosis [155]. These findings suggest that chronic, low-intensity noise may disrupt fundamental ecological processes (e.g., larval settlement and metamorphosis). Nevertheless, many available results are derived from laboratory or simplified exposure designs, and translating these effects to complex natural soundscapes requires caution. Robust field studies combining co-located acoustic measurements (including particle motion where relevant) with ecological endpoints are needed to confirm population- and community-level consequences. Given the growing recognition of invertebrate sensitivity to underwater noise, increasing attention and research are being directed toward better understanding the potential cumulative impacts of wind farm noise on invertebrate communities [156], highlighting their significance in marine ecosystem studies.

4.3. The Missing Monitoring Dimension: Particle Motion and Horizontal Ecological Comparison

In assessing wind farm noise ecological impacts, one must consider that underwater sound propagation contains two physical components: Sound Pressure and Particle Motion. In this review, 'particle motion' refers to particle displacement, velocity, or acceleration (a vector quantity) that is often more relevant to fish and invertebrates than scalar pressure metrics. Current monitoring standards and equipment (e.g., standard hydrophones) mainly focus on sound pressure. However, vast marine biological research indicates that almost all fish and invertebrates (e.g., benthic shellfish, crustaceans) acquire environmental information primarily by sensing particle motion (oscillation displacement, velocity, or acceleration of water molecules) rather than sound pressure [131,157,158]. Particularly in shallow water environments, the relationship between sound pressure and particle velocity is very complex, and simple plane wave approximations no longer apply [157,159,160]. Therefore, measuring sound pressure alone may severely underestimate the potential impact of wind farm noise on benthic organisms [131,157–159,161]. To bridge this gap, future monitoring systems must integrate vector sensors or accelerometers. From a measurement perspective, particle motion can be quantified as particle displacement, particle velocity, or particle acceleration. Practical approaches include the following: (i) direct vector sensors (acoustic particle velocity sensors/vector hydrophones) that measure the directional particle-velocity field; (ii) triaxial accelerometers, often used to capture substrate vibration or local acceleration (with attention to sensor orientation and coupling) and (iii) pressure-gradient-based estimation using closely spaced hydrophone pairs/arrays to approximate particle velocity, although this approach becomes less reliable in shallow-water, near-field, or highly complex propagation environments where plane-wave assumptions break down. Key implementation challenges include sensor calibration (magnitude and phase), orientation control, flow-noise contamination, and cross-platform comparability—factors that currently limit routine inclusion of particle motion in standard monitoring practice. While pressure-based SPL/SEL metrics remain the dominant regulatory reporting format in most jurisdictions, particle-motion requirements are not yet consistently standardized, which motivates the need for community-agreed protocols and reporting practices for ecological assessments of OWFs.

This mismatch between monitoring metrics and biological perception mechanisms leads to significant blind spots in current ecological risk assessments. For example, in areas where sound pressure levels have not yet reached thresholds causing auditory damage, high-intensity particle motion may have already caused behavioral interference or physiological stress to benthic organisms [161–164]. Table 3 outlines the sensitive parameters and potential impacts for different taxa, highlighting the urgency of introducing vector sensors [157,158,165,166].

Table 3. Potential acoustic impacts and sensitive parameters of offshore wind farm noise on key marine biological taxa.

Biological Taxon	Primary Perception Mechanism	Sensitive Acoustic Parameter	Construction Phase Potential Impact (Acute)	Operation Phase Potential Impact (Chronic/Cumulative)	Ref.
Marine Mammals (e.g., Harbor Seal, Porpoise)	Cochlear hearing (High frequency sensitive)	Sound Pressure, High-frequency pulses	TTS/PTS, Auditory masking, Avoidance behavior	Long-term communication space compression, Habitat utilization decline	[143–148]
Fish (e.g., Cod, Herring)	Otoliths and Swim bladder	Particle Motion and Sound Pressure	Tissue damage, Startle response, Elevated cortisol (stress)	Reproductive disruption (e.g., courtship masking), Distribution shifts	[116,132–135]
Invertebrates (e.g., Scallop, Squid)	Statocysts/Sensory hairs	Particle Motion	Larval metamorphosis delay, Burrowing/feeding interruption, Physical injury	Increased physiological stress, Growth rate decline, Ecosystem service function weakening	[151–155]

4.3.1. Physical and Practical Challenges in Monitoring

While the biological necessity of monitoring particle motion is clear, its implementation faces significant physical and engineering hurdles: (i) Vector Nature and Orientation: Unlike sound pressure, which is a scalar quantity, particle motion is a vector quantity requiring measurement in three dimensions (x, y, z). This introduces complexity regarding sensor orientation; if the sensor rotates or tilts during deployment, the directional data become difficult to interpret without precise attitude correction. (ii) Platform Coupling and Flow Noise: Particle motion sensors are highly sensitive to physical movement. In offshore environments, "platform coupling"—where the motion of the buoy or cable is transferred to the sensor—can generate high-amplitude, non-acoustic noise. Additionally, "flow noise" generated by water currents moving past the sensor body can mask low-frequency biological signals, creating a signal-to-noise ratio challenge that is far more severe than in pressure hydrophones [167]. (iii) Shallow Water Propagation Physics: In deep water, a predictable relationship (plane wave assumption) exists between sound pressure and particle velocity. However, offshore wind farms are typically located in shallow waters where the seabed and surface interact complexly. Here, the simple plane wave approximations no longer apply. Consequently, attempting to mathematically derive particle motion from pressure measurements is unreliable; it should be measured directly.

4.3.2. Current Measurement Approaches and Technical Limitations

To bridge this gap, future monitoring systems must integrate specialized instrumentation, though current technologies exhibit distinct limitations: (i) Sensor Architectures: The primary approaches include triaxial vector sensors (which measure particle velocity directly) and collocated hydrophone–accelerometer setups (which derive motion from pressure gradients). (ii) MEMS and Noise Floors: While Micro-Electro-Mechanical Systems (MEMS) offer a pathway to miniaturized, low-cost vector sensors, they currently suffer from high "self-noise" levels [168]. This intrinsic noise often exceeds the ambient background noise of quiet marine environments, limiting their utility for detecting subtle biological signals or long-distance wind farm noise. (iii) Calibration and Stability: There is a lack of standardized calibration facilities for low-frequency particle motion sensors compared with the mature standards for hydrophones. Furthermore, maintaining the mechanical stability required to measure minute particle displacements in a high-energy ocean environment remains an unresolved engineering challenge.

4.3.3. A Pathway Toward Regulatory Integration

Given the immaturity of particle motion monitoring relative to pressure monitoring, we advocate for a phased "pragmatic pathway" to integrate this dimension into OWE governance: (i) Phase 1: Dual Reporting (Near-Term): Regulations should not immediately mandate strict particle motion thresholds, which do not yet exist. Instead, baseline and construction monitoring protocols should require the reporting of particle motion metrics alongside standard pressure metrics. This "data accumulation" phase is critical for validating propagation models and understanding the real-world ratio between p and u in wind farm environments. (ii) Phase 2: Standardization and Thresholds (Long-Term): As data accumulate, the industry must move toward standardized measurement protocols (defining specific frequency bandwidths and integration times for particle motion). This will eventually support the development of taxa-specific dose-response thresholds—specifically for invertebrates and shellfish —enabling the transition from pressure-based "noise maps" to biologically relevant "impact risk maps."

5. Long-Term Monitoring and Adaptive Governance

With the intensification of marine development activities such as offshore wind power construction, underwater noise pollution has become increasingly prominent. To effectively manage this environmental pressure, establishing scientific long-term noise assessment methods and sustainable mitigation strategies has become an urgent global issue. Systematic underwater noise monitoring is fundamental not only to evaluating ecological impacts but also to formulating effective management policies and achieving sustainable governance objectives [155,169,170].

5.1. Underwater Noise Assessment Methods

Underwater noise assessment is a vital component of modern marine ecological research and forms the foundation for understanding the impact of sound waves on marine life and their habitats. Effective assessment methods not only accurately quantify noise levels but also evaluate their potential effects on ecosystems. To gain deeper insights into the characteristics of underwater noise and its ecological impacts, researchers employ a range of advanced techniques and methodologies. The following are several key assessment methods and technologies:

5.1.1. In Situ Acoustic Measurements and Passive Acoustic Monitoring (PAM)

In situ measurements are the core method for directly collecting acoustic data by deploying hydrophones in target sea areas. Passive Acoustic Monitoring (PAM) serves as the foundational technology for achieving long-term, continuous observation. It captures anthropogenic noise and biological acoustic signals by continuously recording the ambient acoustic environment. PAM systems can be deployed on diverse platforms, categorized into mobile platforms (e.g., autonomous underwater vehicles (AUVs), underwater gliders) and fixed platforms (e.g., surface buoys, seabed observation networks, or tethered hydrophone arrays). Mobile platforms excel at large-scale spatial mapping, while fixed platforms provide indispensable continuous data streams for long-term trend analysis in specific areas [68,171–173]. In recent years, the integration of artificial intelligence (AI) and machine learning algorithms has significantly enhanced the efficiency and accuracy of automated processing for PAM's massive datasets, enabling automatic identification and classification of specific sound sources [174,175]. However, the widespread implementation of PAM faces challenges, including interference from ambient noise and the high costs associated with deployment and maintenance.

This assessment method has seen widespread application. In a cetacean conservation study in a specific marine area, researchers employed this approach during the breeding season to monitor noise levels and cetacean communication behavior within the region. They observed that when noise levels significantly increased, whale communication frequency decreased by up to 80% [176]. Conversely, during periods of reduced noise levels, whale communication frequency notably increased, indicating that noise reduction contributes to improved communication behavior [177]. This real-time, long-term monitoring not only reveals the short-term impacts of human activities on whales but also provides a scientific basis for long-term conservation measures. Frisk (2012) further noted that this method enables the monitoring of acoustic transmission among fish and marine mammals across different ecological zones, yielding rich ecological data crucial for assessing noise impacts on multiple species [178].

5.1.2. Underwater Acoustic Modeling and Simulation

Acoustic modeling uses numerical calculations to predict how sound waves propagate in complex marine environments, thereby assessing the potential impact zones of specific sound sources (such as offshore wind farms) across varying spatial and temporal scales. However, the application of acoustic modeling faces two major challenges: First, most models predict sound pressure levels while neglecting particle motion, which serves as a critical sensory cue for fish and invertebrates. This represents a critical governance failure, as policy decisions (based on these models) are systemically blind to the impacts on key ecological groups. Second, model accuracy heavily relies on detailed environmental parameters (e.g., water depth, seabed substrate, thermohaline profiles) and must be validated through field measurements. In practice, however, the predictive accuracy of such models in environmental impact assessments is often limited by data scarcity and oversimplification [38].

By analyzing global noise datasets, researchers simulated noise propagation during wind farm construction and found noise levels in surrounding areas increased by 15 to 20 dB. Notably, this amplified noise may significantly disrupt marine mammal behavior, particularly during breeding seasons [87]. Furthermore, research by Merchant et al. indicates that commercial shipping and offshore engineering activities globally contribute to noise levels exceeding 40% in certain regions. These data underscore the critical role of acoustic modeling in noise management [179]. However, a particular challenge in assessing impacts on fish and invertebrates is that propagation modeling is typically based on sound pressure rather than particle motion. Moreover, modeling sound propagation—especially in relatively shallow waters (shore, reefs, rivers)—must account for the frequency range, temporal structure, water depth (bathymetry), properties of adjacent media (including seabed sediment characteristics), and water temperature and salinity profiles. When considering fish and invertebrates, it should simultaneously address both sound pressure and particle motion. Such models do exist, but remain underutilized in many cases. To ensure accurate predictions, models must be validated through field measurements of sound pressure and particle motion levels at various locations. In practice, acoustic modeling for environmental impact assessments often relies on simplified models, constrained by limited environmental data and lacking field measurements to simulate realistic model predictions [38].

5.2. Sustainable Governance Strategies and Measures

To address the increasingly severe challenges of underwater noise, it is crucial to establish a multidimensional, systematic governance framework encompassing policy regulations, technological innovation, spatial planning, and public participation. At the core of sustainable governance is the creation of an adaptive management framework based on a continuous feedback loop of scientific evidence, with long-term, reliable underwater noise monitoring serving as the cornerstone that drives this closed-loop system.

5.2.1. Policy and Regulatory Framework Based on Long-Term Monitoring Data

Comprehensive policies and regulations form the foundation for sustainable underwater noise governance. However, to ensure their effectiveness and adaptability, their formulation, evaluation, and revision must be grounded in scientific data derived from long-term monitoring. Static, one-off regulations struggle to address the dynamic changes in marine environments and the continuous evolution of human activities. Therefore, sustainable governance models require integrating long-term acoustic monitoring as an integral part of the policy lifecycle. For instance, through continuous monitoring data, policymakers can evaluate the effectiveness of existing noise thresholds, identify hot spots and critical periods of noise pollution, and dynamically adjust regulations accordingly—such as establishing seasonal construction windows to protect species during breeding periods. This evidence-based, iterative approach to policy optimization transforms governance from a static compliance-checking exercise into a dynamic, proactive process oriented toward continuous ecosystem health improvement.

5.2.2. Technological Innovations for Long-Term Monitoring and Source Control

Technological innovation serves as a dual driver for achieving sustainable underwater noise management. It encompasses both technologies that reduce noise emissions at the source and equipment technologies that ensure long-term effective monitoring.

First, source-level mitigation. Controlling noise at its source is the most direct and efficient mitigation strategy. This includes improving ship propeller designs to reduce cavitation noise, developing acoustically more benign pile-driving techniques (such as replacing impact pile-driving with vibratory methods or employing noise attenuation systems like bubble curtains), and optimizing wind turbine structures to minimize vibration and noise radiation during operation. The application of these technologies is fundamental to achieving preventive noise pollution management.

Second, long-term monitoring equipment enhancement. To support sustainable governance, the in situ acoustic monitoring systems themselves must possess the capability for long-term, stable, and autonomous operation. This necessitates targeted optimizations at the equipment level: Reliability and durability: Monitoring devices (e.g., hydrophones, data loggers) require corrosion-resistant, biofouling-resistant materials and robust encapsulation designs to withstand prolonged exposure to harsh marine environments, ensuring continuous data acquisition.

Third, low-power design. Given that equipment is typically deployed in remote offshore areas far from land, minimizing system energy consumption is critical. Utilizing low-power microprocessors and sensors, coupled with optimized data acquisition and sleep strategies, is key to extending the equipment's autonomous operational cycle.

Fourth, autonomous energy supply. To achieve long-term unattended monitoring, reliance on disposable batteries must be eliminated. Integrating renewable energy solutions—such as solar panels or wave energy converters—to provide continuous, stable power for monitoring systems is the core technology ensuring sustainable operation.

Fifth, data transmission reliability. As offshore wind farms expand into deeper and more distant waters, efficient and reliable data transmission faces significant challenges. Developing multi-mode telemetry systems that integrate satellite communications, hydroacoustic communications, and wireless radio frequency technologies ensures the real-time or near-real-time transmission of massive monitoring data to shore-based data centers under varying ocean conditions. This capability is fundamental to effective remote monitoring and early warning systems.

5.2.3. Dynamic Ecosystem-Based Spatial Planning

Implementing ecosystem-based spatial planning is a key strategy for preventing and mitigating noise impacts. This involves not only establishing Marine Protected Areas (MPAs) or designating "acoustic quiet zones" in known critical habitats, breeding grounds, or migration corridors, but more importantly, ensuring such planning is dynamic and adaptive. Combining long-term acoustic monitoring with biodiversity surveys reveals seasonal and interannual patterns of marine species' use of the acoustic environment. This provides a scientific basis for dynamically adjusting protected area boundaries or management measures. For instance, long-term monitoring can identify new critical acoustic habitats or evaluate the effectiveness of existing "quiet zones." Integrating such monitoring data into marine spatial planning decisions makes conservation measures more targeted and forward-looking, achieving a sustainable balance between renewable energy development and biodiversity protection.

5.2.4. Data-Driven Closed-Loop Adaptive Management Framework

Traditional static management (fixed thresholds) cannot cope with dynamic marine environments. We suggest a "Monitor-Assess-Decide-Respond" loop. When DAQ & DSP/PAM systems detect cumulative noise (SEL_{cum}) approaching thresholds or identify endangered species via AI, the system automatically warns control centers to trigger responses (e.g., adjusting pile hammer energy, activating bubble curtains). This shift from "post-event compliance" to "real-time active intervention" is key.

5.2.5. Stakeholder Acceptance and Implementation

The effectiveness of long-term noise governance depends not only on technical monitoring capacity but also on stakeholder acceptance and implementability. Transparency of monitoring methods, open reporting of uncertainty, and clearly defined adaptive decision triggers (monitor–assess–decide–respond) can improve legitimacy and reduce disputes. Where appropriate, participatory mechanisms (e.g., shared data portals, independent audits, and community-informed monitoring priorities) may increase trust and facilitate sustained implementation, particularly for multi-decadal operational monitoring.

5.3. Closed-Loop Adaptive Management Based on Long-Term Data

Building an adaptive management framework is the core mechanism. Traditional static models may be insufficient to capture long-term variability and cumulative change. We, therefore, propose an integrated monitoring network (Figure 7) concept:

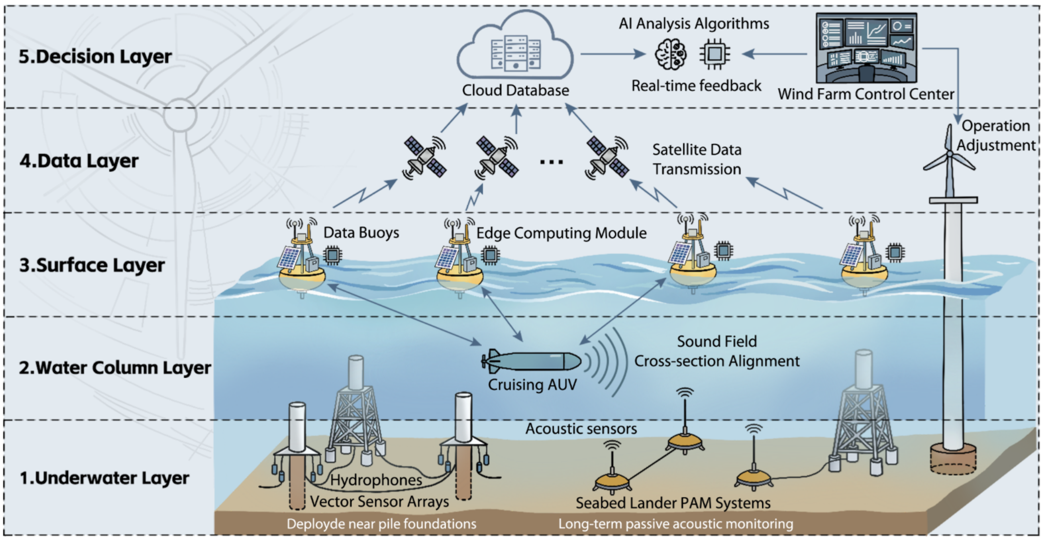

Figure 7. Integrated offshore wind farm underwater noise long-term monitoring & management network architecture.

(1) Baseline Establishment: Use long-term PAM to establish baselines and identify biological critical periods.
(2) Real-time Warning: Edge computing identifies high-risk events.
(3) Dynamic Adjustment: Adjust construction windows/strategies based on biological avoidance or cumulative levels.
(4) Model Correction: Calibrate models with measured data to reduce EIA uncertainty.

5.4. Case Study

The following case studies demonstrate the practical application of the adaptive management cycle (Monitor → Assess → Decide → Respond) proposed in this paper.

These examples illustrate how long-term monitoring data are not merely archived but actively used to validate mitigation efficacy and drive iterative policy refinement.

- Case Study 1: The Collaborative Governance Model of the European Marine Observation and Data Network (EMODnet)

EMODnet exemplifies data sharing and collaborative governance. By integrating marine noise monitoring data from European nations, this platform pioneered the first comprehensive soundscape map of European waters, providing critical scientific support for implementing the Marine Strategy Framework Directive (MSFD). This transnational data-sharing mechanism enables assessment of cumulative impacts from transboundary noise sources like shipping, promotes unified noise monitoring and reporting standards, and forms the foundation for regional adaptive management [131]. Critically, this initiative supports a cyclical policy feedback loop. The soundscape baselines generated by EMODnet allow member states to periodically assess whether current noise levels meet 'Good Environmental Status' (GES) targets under the MSFD. This assessment drives the iterative adjustment of monitoring standards and mitigation thresholds in subsequent 6-year management cycles, ensuring governance evolves alongside changing marine acoustic environments.

- Case Study 2: New Zealand's Marine Noise Management

New Zealand's approach demonstrates an integrated governance framework combining policy, technology, and spatial planning. The country not only imposes strict legislative limits on vessel noise [180] but also adopts risk-based preventive measures for specific projects like offshore wind farms. For instance, construction windows are regulated during critical biological breeding seasons, and the use of low-noise equipment is mandated. This "prevention-first, multi-pronged" strategy effectively balances economic development with ecological conservation needs. Furthermore, New Zealand's approach reflects broader adaptive principles applied beyond wind energy, such as in the management of commercial shipping noise. By monitoring the acoustic signature of vessels post-regulation, authorities can verify the efficacy of source-control measures (e.g., quieter propeller designs) and dynamically update vessel speed limits or exclusion zones if noise reduction targets are not met. This parallel demonstrates the universality of the monitor-assess-respond framework.

- Case Study 3: Long-Term Marine Biodiversity Monitoring at Bohai Sea Wind Farms

As a key demonstration project for China's offshore wind development, the Bohai Sea wind farms implement systematic long-term monitoring measures to safeguard ecological balance and sustainable development [180]. The project employs a combination of passive acoustic monitoring (PAM), remote sensing technology, and routine biodiversity surveys to dynamically track the impacts of wind farm construction and operation on surrounding ecosystems. Additionally, regular biodiversity surveys are conducted, recording changes in the species and abundance of marine life such as fish and shellfish through underwater sampling to ensure a comprehensive assessment of ecological conditions. Through these monitoring methods, the Bohai Offshore Wind Farm has achieved significant ecological outcomes. The monitoring results not only provide a scientific basis for the project's adaptive management (such as optimizing construction plans) but also accumulate valuable data and practical experience for China's coordinated development of renewable energy and ecological conservation in similar environments. This project operationalizes the 'real-time intervention' aspect of adaptive management. When real-time PAM systems detect noise levels exceeding cumulative thresholds or identify the acoustic presence of key species, the system triggers immediate operational adjustments—such as pausing pile driving or extending soft-start durations. This creates a closed-loop mechanism where monitoring data directly dictates construction pacing to minimize ecological risks.

5.5. Practical Feasibility: Tiered Deployment and Indicative Cost Framing

We provide an implementable feasibility framing that clarifies (i) a tiered monitoring architecture, (ii) a deployment workflow aligned with OWF lifecycle phases, and (iii) Cost-effectiveness framing.

- Tiered architecture

A pragmatic scalable design is a tiered network that combines the following: (a) a limited number of high-capability real-time nodes (cabled or buoy-based with telemetry/edge processing) to support compliance and adaptive triggers, and (b) a larger number of low-cost archival nodes (self-contained recorders) to expand spatial coverage and characterize long-term soundscape variability. This hybrid approach balances data timeliness, coverage, and cost.

- Deployment workflow

We recommend a phase-aligned workflow: (1) baseline (≥6–12 months) to quantify seasonal variability and shipping background; (2) construction monitoring emphasizing impulsive metrics (SEL/peak SPL) and near-field validation; (3) operation monitoring emphasizing chronic exposure indicators (e.g., long-term SPL distributions, tonal components, SEL_cum) with periodic model re-calibration and (4) adaptive review cycles where monitoring outputs inform threshold refinement, mitigation selection, and spatial planning.

- Cost-effectiveness framing

Because mitigation measures differ in both acoustic performance and operational constraints, comparative evaluation benefits from simple quantitative metrics such as (i) cost per achieved reduction in SEL or peak SPL at ecologically relevant ranges, (ii) reduction in probability of threshold exceedance during sensitive periods, or (iii) reduction in modeled cumulative exposure (e.g., SEL_cum footprint) at the wind-farm scale. Such metrics should be reported with site-specific uncertainty bounds and paired with monitoring data to verify real-world performance.

6. Challenges and Future Research Directions

Offshore wind power holds immense potential as a key pathway to replacing fossil fuels. However, the accompanying underwater noise pollution has become an ecological bottleneck constraining its sustainable development, particularly as it expands into ecologically more sensitive deep-sea areas. This review indicates that despite progress in existing monitoring technologies and impact assessments, several critical challenges must be addressed to ensure the effective protection of marine ecosystems. Consequently, future research on underwater noise monitoring for offshore wind farms and sustainable governance practices has challenges as follows:

(1) How can we build a long-term monitoring network that is both cost-effective and scalable? Currently, high equipment and maintenance costs are major barriers to achieving large-scale, long-term underwater noise monitoring, particularly limiting the capacity of developing countries and regions to participate in global ocean governance. Future technological innovations should focus on developing low-power consumption, highly durable, and miniaturized monitoring devices. These should integrate renewable energy supply solutions, such as solar and wave power, to enable long-term autonomous system operation. Most commercial monitoring system solutions currently range from $5000 to $30,000, which can limit large-scale deployments. Exploring open-source hardware and software solutions could reduce monitoring system costs from tens of thousands to hundreds of dollars [181,182]. Our objective is to control costs around $500, thereby driving the widespread adoption of monitoring technology and enabling

equitable access to global ocean soundscape data. Importantly, 'cost' has multiple layers: node-level hardware (sensor/logger/power/housing), network infrastructure (telemetry, synchronization), and program-level costs (moorings, vessel time, calibration, QA/QC, and long-term data stewardship). Therefore, cost-reduction strategies should differentiate between (i) lowering BOM for archival nodes and (ii) reducing operational costs through modular designs, extended service intervals, and standardized calibration/metadata practices. Here, the $500 figure is presented as an aspirational target for a baseline node (sensor + logger + storage + power + housing), while acknowledging that moorings, deployment/retrieval, calibration, and telemetry can dominate total program costs. We, therefore, emphasize tiered monitoring designs that combine a small number of higher-end real-time nodes with a larger number of low-cost archival nodes as a pragmatic pathway toward scalable long-term monitoring. This will lay the foundation for comparative ecological research and collaborative governance on a global scale.

(2) How to enhance the processing efficiency and information extraction accuracy of massive data? With the deployment of long-term, large-scale monitoring networks, offshore wind farms will generate unprecedented volumes of data, posing severe challenges to traditional methods in terms of processing efficiency and information extraction accuracy. Future research must focus on intelligent frameworks (e.g., AI/ML) to drive the transition from "manual analysis" to "intelligent processing," thereby enabling real-time adaptive governance. Advanced algorithms based on artificial intelligence and machine learning can achieve automatic identification, classification, and quantification of different noise sources and key bioacoustic signals within complex acoustic environments, thereby enhancing efficiency and reducing human bias. To support this shift, standardized, open-access big data platforms should be established to integrate multi-source acoustic, environmental, and biological information, providing a foundation for uncovering relationships between noise exposure and ecological responses. Concurrently, rigorous data quality control and reliability assessment mechanisms must be implemented, including unified data standards, automated validation, and ongoing verification of new equipment to ensure the integrity and comparability of analytical results. Finally, as wind farms expand into deep offshore waters, data transmission bottlenecks will need to be addressed. This requires optimizing traditional strategies while integrating emerging technologies like satellite and hydroacoustic communications, combined with data compression and edge computing. Such measures will ensure real-time, complete transmission of monitoring data to data centers, thereby providing efficient support for online monitoring and safety assessment systems.

(3) How can acoustic data be converted into precise ecological risk assessment indicators? Current noise assessments primarily focus on physical metrics such as sound pressure level (SPL) and sound exposure level (SEL), which mismatch the actual perception mechanisms of marine organisms (especially fish and invertebrates), such as particle motion. As argued in Section 5, this is not just a technical shortcoming but a systemic governance failure: policies built on SPL-only models are systemically blind to the risks posed to entire ecological guilds. Future research must prioritize developing assessment frameworks that better reflect biological significance. On one hand, fundamental studies on species-specific auditory thresholds, behavioral responses, and physiological tolerance—particularly regarding cumulative effects and sublethal impacts from prolonged, low-intensity noise—need strengthening. On the other hand, integrated risk assessment tools should be developed that couple acoustic field propagation models with biological distribution and behavioral models. This will enable

the transition from physical "noise maps" to ecological "impact risk maps," providing managers with truly actionable decision-making support.

(4) How to robustly scale from single-turbine measurements to wind-farm cluster and regional cumulative exposure, and link this exposure to ecological consequences? Key challenges include multi-source superposition, spatiotemporal variability driven by wind/sea-state and turbine operating modes, and validation of propagation models with long-term field measurements. Addressing this requires integrated monitoring–modeling frameworks and study designs that couple cumulative acoustic metrics with biological distribution, behavior, and population-relevant endpoints.

(5) How can adaptive governance based on long-term underwater noise monitoring be effectively implemented? Effective sustainable governance is not static management but an adaptive process of continuous learning and dynamic adjustment. However, current noise monitoring at offshore wind farms often remains confined to short-term compliance checks (e.g., for pile driving), lacking the long-term predictive and verification role required for adaptive governance. With the widespread application of emerging technologies like big data, cloud computing, and the Internet of Things, future governance frameworks must mandate long-term acoustic monitoring as a binding legal and procedural requirement. This monitoring should be integrated throughout the entire process—from project environmental impact assessments to post-construction oversight—and leverage emerging technologies to design fully automated, intelligent monitoring systems requiring no human intervention. Such systems would not only enhance noise signal capture and data storage capabilities but also integrate functions like data collection, fault diagnosis, real-time weather tracking, and power forecasting, providing managers with powerful decision-making tools. Through continuous real-time data feedback, managers can dynamically evaluate the effectiveness of existing noise thresholds, identify critical ecologically sensitive zones and time windows (such as breeding seasons and migration periods) to implement refined marine spatial planning, and promptly adjust management strategies when unexpected ecological impacts occur. This technology-enabled "monitor-assess-manage-adapt" feedback loop is the fundamental guarantee for achieving a win-win outcome between offshore wind development and marine ecological conservation.

7. Conclusions

This paper has reviewed the existing technologies for underwater noise monitoring, identified the noise profiles of offshore wind farms across their lifecycle, and synthesized the current understanding of noise impacts on marine life. Furthermore, it has discussed critical challenges and future directions for long-term monitoring. The main conclusions are as follows:

(1) Comprehensive technical approaches are essential for monitoring underwater noise from offshore wind farms. No single monitoring technology can fully address the complex acoustic challenges posed by these facilities. Establishing an integrated monitoring network that combines the strengths of buoys, DASP, and PAM systems is crucial for future development. Such a network enables precise, long-term assessment of wind farm noise and its ecological impacts, providing core scientific evidence for sustainable offshore wind energy development and refined environmental management.

(2) OWE constitutes a significant noise source across its lifecycle. We differentiate between acute, high-intensity pulsed noise (construction) and chronic, low-intensity continuous noise (operation). We find the ecological threat from the latter, via cumulative effects, remains critically misunderstood and under-regulated. We contend that environmental

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impact analyses should be expanded to encompass the full spectrum of construction noise, not be limited to pile driving alone.

(3) Existing research confirms that underwater noise exerts widespread negative impacts on fish, marine mammals, and invertebrates through mechanisms such as communication masking, physiological stress, and auditory damage. However, current research remains limited by insufficient attention to benthic communities and an unclear understanding of long-term cumulative effects, constituting key uncertainties in ecological risk assessment.

(4) Passive acoustic monitoring (PAM) and acoustic modeling are core tools for assessing underwater noise. The central argument of this review is that the current management paradigm—focused on mitigating acute, high-intensity events—is insufficient. We suggest that complementing event-based mitigation with proactive long-term monitoring and adaptive governance may improve the ability to address chronic operational noise and cumulative soundscape change.

Looking ahead, long-term underwater noise monitoring for offshore wind farms is poised to become smarter and more cost-efficient. The integration of cost-effective, open-source technologies (IoT) with intelligent data frameworks (AI) is key. This will not only furnish managers with tools for adaptive governance but will foster the collaborative, transnational, and data-transparent governance models required to balance global energy transition with marine biodiversity

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