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Technology Gaps for Monitoring Birds and Marine Mammals at Offshore Wind Facilities

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ABSTRACT

With increased focus on offshore wind (OSW) as a renewable energy resource in the United States and elsewhere, there are concerns about OSW impacts to wildlife, particularly birds and marine mammals. This study identifies technology gaps and technological research and development (R&D) priorities for monitoring marine mammals and birds for fixed and floating OSW. A synthesis of current monitoring technologies generated two databases (with over 100 technologies) that can be integrated in current technology repositories for renewable energy projects. Generally, the key technology R&D needs are similar for birds and marine mammals. The main exception is that some types of bird technologies are more likely to require direct integration with OSW infrastructure, whereas marine mammal systems tend to operate independently. Priorities to advance wildlife monitoring include improved early communication, harmonization of technologies and data collection for monitoring systems on OSW structures, battery/power access improvements, remote data transfer improvements, and advancements in automated collection and analysis of data. The successful integration of wildlife monitoring systems into OSW infrastructure and operations is dependent on remote access mechanisms for data collection, system maintenance, and data transfer, in order to minimize risks to worker safety in the offshore environment, as well as minimizing costs and disruption to normal operational activities. Application of the results of this study to prioritize and fund technology R&D will help to support statistically robust data collection and practicable integration of monitoring systems into OSW operations and infrastructure.
Keywords: offshore wind, marine mammals, birds, technology, monitoring

Introduction

Climate change represents a substantial threat to wildlife populations, including birds and marine mammals worldwide. To reduce carbon emissions from the generation of energy via fossil fuels, offshore wind (OSW) energy development is expanding globally (Borowski, 2022); however, OSW energy development has the potential to negatively affect many of these same wildlife populations via mechanisms including behavioral change (e.g., attraction or avoidance), collisions with vessels or OSW infrastructure, and changes to habitats and prey populations (Allison et al., 2019; Williams et al., 2024).

Current wildlife monitoring technologies are in many cases unable to collect the necessary types and amount of data required to robustly address questions about OSW site assessment, impacts, and mitigation efficacy (Allison et al., 2019). These limitations include species-level identification, duration or range of sampling, resolution of datasets, and lack of real-time monitoring capabilities. Additionally, technologies are seldom integrated into OSW infrastructure and operational procedures (Carlson et al., 2012), which can both limit the effectiveness of data collection and increase deployment costs. Integration, in this context, includes both the ability to place and maintain technology on and in OSW infrastructure and potentially transmit power and data through those structures, as well as the ability to use operations platforms (e.g., vessels for OSW maintenance), to reduce time at sea, cost, and other constraints that arise when wildlife and OSW monitoring activities are independent of each other. Wildlife data collection should be scientifically robust and question-driven so that results can meaningfully inform future site assessments, impact assessments, and adaptive management (Regional Synthesis Workgroup of the Environmental Technical Working Group, 2023).

There has been successful deployment of a range of technologies for OSW monitoring (e.g., as described in Offshore Renewables Joint Industry Programme for Offshore Wind, 2022), which can provide helpful context for identifying further adaptations to improve data collection and ease of access and use. Resources such as the open access "Wind Energy Monitoring and Mitigation Technologies Tool" database (Working Together to Resolve Environmental Effects of Wind Energy, 2023) list existing monitoring tools for energy projects for a variety of wildlife and habitats; however, to date, there has been no comprehensive assessment of the capabilities of wildlife monitoring technologies in the context of obtaining statistically robust datasets to address key research needs and data gaps. In addition, analyses to date have not evaluated the capacity for integration of monitoring technologies into the normal operations and maintenance of OSW facilities. Such integration can require substantial coordination and planning but is essential to deploy monitoring technologies efficiently and effectively.

This study integrates information from a comprehensive literature review, including the scientific literature, technical and government reports, and other information on existing monitoring technologies, with expert workshops to 1) identify technology gaps for wildlife monitoring, and 2) identify key technology research and development (R&D) priorities to better achieve statistically robust data collection and successful integration of monitoring technologies into OSW farm infrastructure and operations. Technologies that can be used for a variety of purposes (e.g., to inform site characterization and risk assessment, as well as to enact mitigation and assess short- or long-term impacts) were examined, with a focus on methods that address questions related to birds and marine mammals for fixed and floating wind projects in the U.S. Pacific, Atlantic, Gulf of Mexico, and Great Lakes regions. Technologies used for minimization/mitigation, while not our primary focus, are included in the review when such systems also provided wildlife monitoring data (e.g., passive acoustic monitoring). The technical specifications and capabilities of existing monitoring technologies, as well as limitations of data collection and integration with offshore structures, are synthesized to identify urgent technology development needs where financial resources could be directed to reduce market barriers.

Monitoring should be question-driven and support statistically robust research and regulatory decisions. The recommendations that emerge from this study aim to support improvement of monitoring technology capabilities to answer key research questions to better inform future mitigation and adaptive management of OSW development.

Methods

This section provides a broad review of the methodology used for this project. Additional details can be obtained in project reports provided to the National Offshore Wind Research and Development Consortium (NOWRDC, n.d.).

Existing literature was synthesized into a list of key bird and marine mammal issues and data gaps that were identified as potential barriers to OSW progress, either in the form of environmental compliance issues or stakeholder concerns about OSW (Courbis et al., 2022).

To evaluate these priority topics, identify technology limitations, and assess the challenges and opportunities for integration of monitoring technology into OSW infrastructure and operations, three virtual workshops were conducted in 2022–2023 with subject matter experts (SMEs) with expertise in marine mammals, birds, wildlife monitoring systems, technology R&D, and offshore wind infrastructure and operations. A total of 69 SMEs from academia, state and federal agencies, non-government organizations, and industry participated in the three workshops. The workshops were not conducted as a formal expert elicitation process but were designed to capture a variety of expert opinions via facilitated discussion and informal elicitation. The workshops gave participants the opportunity to discuss technology limitations, strengths, and priorities for improvement and adaptation. The first two workshops focused on input from bird and marine mammal experts regarding existing technologies (Courbis, Pacini, et al., 2023a; Williams et al., 2023). The third workshop focused on integration of monitoring into OSW infrastructure and operations, including several case studies presented for SME review (Courbis, Williams, et al., 2023b). Case studies included topics such as the use of maintenance vessels as platforms for wildlife monitoring, the development of dedicated standardized space on turbine structures for wildlife monitoring, the transfer of power and data between autonomous systems and OSW infrastructure, and the deployment of multi-technology/sensor systems. In addition to group discussions, individuals recorded their perspectives on a virtual whiteboard platform (Mural; https://www.mural.co), which remained open for participants to continue to provide their input after each workshop.

In addition to the workshops, technology databases were compiled for birds and marine mammals that contained details on monitoring systems that could be candidates for improvement and/or integration with OSW operations. Each technology was assessed for its overall capability, current deployment stage and/or Technology Readiness Level (Department of Energy, 2009), limitations in scientific robustness, and potential to integrate with equipment and operations. Information was drawn from a range of sources, including scientific literature, technical reports, company websites, and expert review. Draft database summaries were also shared with technology developers to obtain input on the accuracy of the assessment and identify additional resources. Given the speed with which many technologies are changing, the database products constitute a "snapshot" of available technologies available during the project timeframe (Pacini et al., 2023; Stepanuk et al., 2023). However, databases were shared with other existing technology databases that continue to be updated by organizations such as the National Renewable Energy Laboratory and Renewable Energy Wildlife Institute.

In addition to the workshop and database SMEs, an expert Project Advisory Board also provided guidance on project implementation, reviewed reports, and contributed to the workshops. As with workshop SMEs, the advisory board included representatives from offshore wind energy developers, state and federal agencies, and environmental stakeholder groups.

Results

Priority Research Questions

- Based on the literature review, priority research needs that wildlife monitoring technologies should help to address were grouped into four categories:
- Occurrence: basic information on species' distribution, abundance, and temporal habitat use;
- Conditions and Stimuli: OSW activities and their characteristics that may affect marine mammal and bird taxa of interest, specifically modifications of baseline environmental conditions such as sound, vessel activity, and electromagnetic fields, as well as potential changes in food web structure;
- Response: how animals may react to external stressors posed by OSW at multiple spatial and temporal scales; responses may include measurable changes in behavior, communication range, abilities to navigate/migrate, and/or the individual physical condition; and
- Consequences: the population-level effects of individual exposures and responses to OSW stressors, including cumulative impacts, defined "as interacting or compounding effects across spatiotemporal scales, caused by anthropogenic activities relating to the development and operation of multiple OSW energy facilities, that collectively affect wildlife populations or ecosystems" (Southall et al., 2021). Cumulative impacts may also include the effects of other stressors (e.g., offshore oil and gas development, fishing, and other anthropogenic activities); however, these additional stressors were not explicitly considered with regard to the capabilities of wildlife monitoring systems.

In addition to these research categories, several priorities were identified for research coordination, data standardization, and data access, to help ensure that that there are standardized pathways for technology verification, that data are collected in a consistent manner across projects, and that datasets are made publicly available to ensure easy integration into larger research enterprises, frameworks, and modeling efforts (Courbis et al., 2022).

Monitoring Technologies and Platforms

Marine Mammal Monitoring Technologies

Six major categories of marine mammal monitoring systems were identified, including visual sensors, acoustic sensors, satellite and radio tags, environmental DNA sampling technology, software, and data and integration and optimization technologies. Active acoustic systems were not considered, as this technology introduces additional anthropogenic sound that could potentially affect animals and their behavior. Each monitoring category was further broken down into technology types; for example, the acoustic sensor category included towed arrays, Sonobuoys, high-frequency acoustic recording packages, and so forth. The marine mammal database also provides information on platforms for technology, such as autonomous underwater vehicles (AUVs; inclusive of sea surface and underwater gliders and remotely operated vehicles [ROVs]) and unoccupied aerial systems (UASs). Altogether, the marine mammal database houses 63 technology systems. Table 1 summarizes technology categories and constraints for marine mammals (Pacini et al., 2023). The full database for marine mammal technology is freely available on the NOWRDC website.

TABLE 1

Summary of technology categories and constraints for marine mammals.

Monitoring Technology Category	Example Technology Types	Examples of Identified Constraints
Sensors		
Visual sensors	Infrared imaging, light detection and ranging (lidar), satellite imaging, cameras, thermal sensors	Environmental conditions affect efficacy of visual sensors Requires animals to surface Image resolution insufficient for some analyses Correction and availability factors are not known or estimated Lack of data storage space for archiving Lack of access to computer power for processing large datasets Lack of data standardization
Acoustic sensors	Passive acoustic monitoring systems (hydrophones—fixed or mobile)	Species-level classification can be problematic Localization may require multiple systems and requires more robust internal clocks Lack of data on cue rates and other biological information necessary to extrapolate population and group parameters from acoustic monitoring Access to data from archival tools or streaming is generally difficult Reliability issues due to battery life and electrical leakage Lack of commercial production of sensors and/or systems Lack of standards and annotated database for training artificial intelligence algorithms
Biotelemetry (satellite and radio tags)	Low-impact minimally percutaneous electronic transmitter, smart position and temperature tags	Battery life and tag size leads to short deployments Attachment improvements are needed to minimize impacts on animals Data access via satellites is challenging because of limited bandwidth or access to cellular networks Data compression loses resolution Satellite coverage can be poor Data provides only a snapshot in time, with no fine-scale behavioral information Lack of safe, low impact, and effective long-term tag attachments Permitting and animal safety restrictions Logistical challenges with accessing animals Invasive nature of deploying technology directly on animals Biases in which individuals are accessible and appropriate for tagging
Other technologies		
Environmental DNA technologies		Lack of reference data Lack of assessment of error factors
Software	Data processing and management, classification, and filtering algorithms	Many parallel efforts without a cohesive approach and standardization Training datasets for developing algorithms are not available Lack of user-friendly interfaces and customization capabilities Lack of effective classification and filtering algorithms for many species or in some environmental conditions Lack of integration of citizen science to maximize overlap between researchers' effort and general public accompanied by lack of apps that are accessible, transferrable, and relatable to encourage maximum buy-in from the public

continued

TABLE 1

Continued

Monitoring Technology Category	Example Technology Types	Examples of Identified Constraints
Data integration & optimization technologies*	Large-scale integration of multiple data streams	Lack of comparable methodologies for data collection and recording Differences in temporal and geographic scales Lack of robust datasets for modeling Lack of environmental datasets at appropriate temporal and geographic scales Lack of data standardization Lack of integration across disciplines (e.g., biology and oceanography) Data access and storage are limited Mainly record surface conditions and not subsea conditions Quality of data dependent on environmental factors like cloud coverage, glare, and Beaufort sea state

*Although not a specific technology, data integration and optimization call for development of targeted software and standardization.

Bird Monitoring Technologies

Nine major categories of bird monitoring systems were identified, including radio detection and ranging (radar), light detection and ranging (lidar), cameras, observational surveys, acoustic sensors, biotelemetry, physiological sampling, habitat/prey monitoring, and "other" (Table 2). Each monitoring category was further broken down into technology types; for example, the radar category included marine radar, weather surveillance radar, and 3-D radar units, among others. Constraints for various technology types are identified in Table 2. In addition, several related approaches that are not standalone technologies (e.g., artificial intelligence, models) are also explored in Table 2.

The bird database houses additional detailed equipment specifications and other information on 46 specific technology systems that are designed to be deployed on wind energy infrastructure. Individual models often incorporate multiple technologies, including cameras, radar, passive acoustics, and other technology types (Stepanuk et al., 2023). The full database for bird technology is available on the NOWRDC website.

Monitoring Platforms and Operational Integration

A variety of platforms could host bird and marine mammal monitoring technologies at OSW facilities (Figure 1, Table 3). Some of these platforms were technologies in and of themselves, with their own constraints and technological limitations (e.g., UASs). For instance, unmanned systems such as drones and ROVs had permitting restrictions as well as limitations due to battery life and noise. Other platforms represented opportunities and limitations related to operational integration of monitoring into OSW facilities. Fixed OSW platforms such as turbines, buoys, and substations presented challenges associated with access, data transfer, power sources, and physical space availability for wildlife technology deployment (Table 3). Animals themselves can also be platforms for sensors (e.g., via biotelemetry); however, constraints associated with these types of technology deployments are already addressed in previous sections and are not repeated here.

There were a variety of limitations associated with integrating monitoring technologies into OSW infrastructure and operations, including personnel needs, size and space, data transfer and security concerns, and planning processes (Courbis, Williams, et al., 2023b; Table 4).

As part of the expert workshops, case studies were presented to SMEs to assess the utility of potential technology integration solutions for addressing the above limitations (Courbis, Pacini, et al., 2023a; Williams et al., 2023). Many of the identified limitations for case studies were similar to the broader limitations identified in Tables 1–2; case-specific constraints are provided in Table 5.

Information Constraints

There were several common themes across the range of marine mammal and bird technologies and their platforms when examining the available information on specific systems. For example, while the majority of identified technologies and

TABLE 2

Summary of technology categories and constraints for birds.

Monitoring Technology Category	Example Technology Types	Examples of Identified Constraints
Technologies for OSW monitoring		
Camera systems	Red/green/blue, thermal, and infrared cameras	Image resolution and range insufficient in many cases for robust analyses Effort needed for sufficient sample sizes is high Lack of validation of detection capabilities in most cases; correction and availability factors are often not known or estimated No public database for archiving Limited capability to access data remotely in most cases Manual review is very effort intensive Environmental conditions affect efficacy of visual sensors
Acoustic sensors	Passive acoustics	Interference from other sources of sound Detection range is typically limited Lack of data on cue rates and other biological information necessary to extrapolate densities from acoustic monitoring Species identification limited for some taxa and call types
Biotelemetry (tags and other bird-borne sensors)	Accelerometers, bird-borne cameras, geolocators, global positioning system proximity sensors and tags, heart rate monitors, Motus tags (automated radio telemetry), passive integrated transponder tags, pressure sensors, satellite tags, time-depth recorders	Tag size/weight and battery life are often limited by size/weight of the bird Size of technology affects power and data storage Poor precision in 3-D locations and transmission limitations for many tag types, particularly those appropriate for smaller-bodied birds Biases in which individuals are accessible, appropriate for tagging, and may be captured/recaptured Potential effects to animal behavior and movement because of attached device Problems with waterproofing and ruggedization for marine environments Permitting and animal safety restrictions Invasive nature of deploying technology directly on animals
Radar	3-D tracking radar, Aircraft Detection Lighting System, Dual camera-radar systems, 2-D navigational (marine) radar, weather surveillance radar	Very limited or no species identification ability Environmental factors (e.g., weather) affect performance Blind spots and shadows from turbines or other structures Detection of bird targets is still hypothetical for some systems (e.g., Aircraft Detection Lighting Systems) Orientation of birds and masking by insects affects detection No set standards for data processing Requires a stable platform for deployment, and installation can be difficult Problems with waterproofing and ruggedization for marine environments Calibration among multiple systems is difficult

continued

TABLE 2

Continued

Monitoring Technology Category	Example Technology Types	Examples of Identified Constraints
Physiological sampling		Time and effort needed for sufficient sample sizes is high Data can be time sensitive Logistical and bird safety constraints for deployment Training and permitting are challenging Methods are sometimes invasive Lack of datasets for validation of data and calibration of results Isolating changes caused by OSW are difficult
Lidar	Lidar	Similar limitations to radar Deployment for estimating bird flight heights (from buoy or aircraft) is still in pilot phase
Observational surveys at sea	Visual, digital aerial, ornithodolite	Weather and other environmental conditions affect data quality, safety, and survey feasibility Inter-observer variability can be a challenge Digital surveys require substantial effort for data processing and analysis Field of view, image resolution, and safety tradeoffs for altitude of digital aerial surveys Manual review of imagery is very effort intensive
Habitat and prey monitoring	Active acoustics (echosounders), ambient acoustic sensors below water, mid-/bottom trawls, remote sensing	Identification of prey taxa is challenging Underwater biomass is not always correlated to surface biomass Benthic and burrowing species are poorly sampled by most methods Data are often not at temporal and spatial scales at which birds make foraging decisions Although correlations exist among prey species and remotely sensed data, validation of model predictions has been challenging The dynamic nature of the environment requires data intensive models across long time scales
Other	Blade impact detection; observation of carcasses	Blade impact detection: requires in-blade deployment; may affect turbine operations; has not been deployed offshore. Observation of carcasses: very limited areas around offshore turbines on which carcasses can be collected; requires physical presence of personnel on offshore platforms; relies on consistent data collection by OSW personnel whose primary jobs lie elsewhere
Related technologies and approaches		
Artificial intelligence		Training datasets for developing algorithms are not readily available Difficult to quantify error Lack of effective classification and filtering algorithms for many species or in some environmental conditions

continued

TABLE 2

Continued

Monitoring Technology Category	Example Technology Types	Examples of Identified Constraints
Population monitoring	Productivity monitoring, colony-based monitoring (of metrics such as nesting activity, survival, and population size), mark-recapture approaches, genetic approaches	Isolating changes caused by OSW is difficult Logistical and bird safety constraints, including accessibility of research sites and limits on time spent in colonies; lack of remote imaging data at colonies Methods are sometimes invasive Some methods are limited by ability to re-capture birds Lack of data on population dynamics hinders modeling
Models	Collision models, vulnerability models, movement models, energetics models, population models	Lack of review and standardization of data used in some models Models generally require large amounts of data that can be difficult to obtain in sufficient spatial and temporal scales Lack of demographic data about populations to inform models Combining different types of data (e.g., tracking and observational survey data) into singular models is difficult

platforms were commercially available to some degree (e.g., the technology developer may have needed to be contacted for access, but the technology was available for purchase), many operational integration parameters (e.g., system dimensions, maintenance schedule, power source) were not readily available for many technologies and platforms. Cost was also not readily estimable in most cases. Likewise, information on performance (false positive/negative rates, sensitivity, error, etc.) was not readily available in most cases; external validation by the scientific community was not common and tended to be associated with more mature technologies.

Discussion

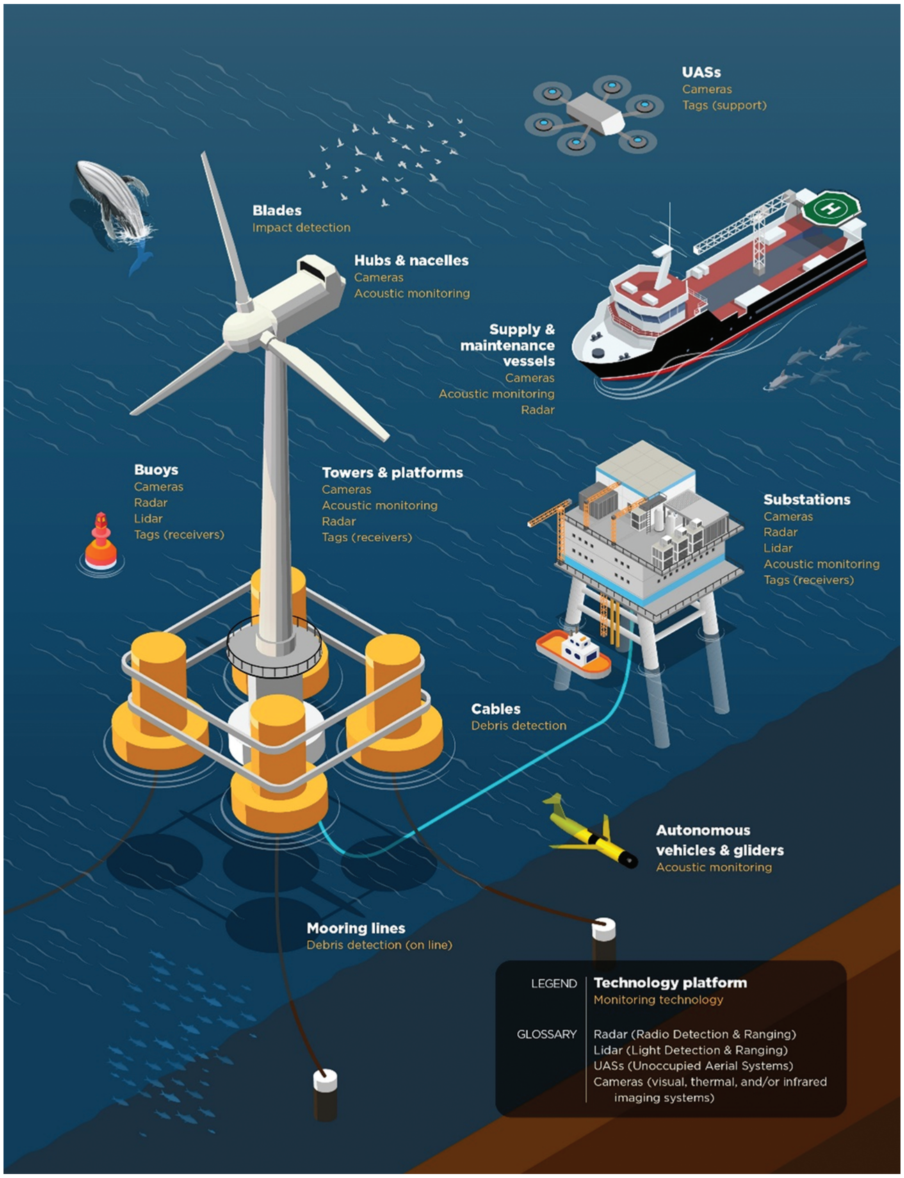
Synthesis of Technology Gaps

Based on the results of the research priority assessment, workshops, and technology databases, there were some clear limitations of existing wildlife monitoring systems to collect statistically robust data that can be integrated into OSW infrastructure and operations (Courbis et al., 2024). Both bird and marine mammal technologies would benefit from additional R&D focused on access to power, data resolution, data storage and transfer, equipment validation and calibration, automated detection and classification, interference from natural and man-made sources (light, sound, vibration, structures), physical access and worker safety, and safe and reliable attachment mechanisms. Additionally, both bird and marine mammal technologies tend to lack options for adequate collection of concurrent environmental data, which can be important to ensure studies have sufficient statistical power to detect changes due to OSW energy development (e.g., by being able to better tease apart OSW effects from other sources of change). Autonomous surface, subsea, and airborne platforms are currently being developed that can efficiently collect such data, but payloads and power are limited, and regulations minimize the effectiveness of airborne platforms such as UASs, which are required to stay in line of sight at specific altitudes. Some technologies for both bird and marine mammal monitoring requires additional R&D for effective localization and classification algorithms and artificial intelligence to detect and identify species, partially due to a lack of available training datasets. It is also difficult to assess error rates for many data collection technologies and to develop correction factors for observations. Tracking technologies required additional advancement in miniaturization to be safely and effectively deployed on species of interest.

There were also some important differences in constraints for bird and marine mammal technologies. Lack of physical space and access limitations are substantive issues for installation of systems on OSW structures and are highly relevant for bird monitoring technologies, many of which are meant to be installed on or around turbines. Deployments on OSW infrastructure can also introduce cybersecurity concerns. In contrast, marine mammal technologies generally do not require deployment directly on OSW infrastructure and are thus less impacted by such platform constraints, though scheduling

FIGURE 1

Main OSW monitoring platforms and examples of the technologies considered for deployment on each platform. Biotelemetry and related technologies designed for deployment on animals are not pictured.



of vessel operations to allow for technology servicing remains a challenge for many systems. The stabilization of deployed technologies on moving infrastructure, such as buoys and vessels, tends to be more relevant to bird technologies than marine mammal technologies. Generally, bird technologies tended to be more commercially developed, as some types of technologies have been deployed to address land-based wind impact questions. Technologies, such as archival tags, for marine mammal studies tend to be developed at very small scales, often making them inconsistent in reliability, even within a single make and model; however, marine mammal technologies have been developed to be more robust to marine environments than many bird technologies.

In addition to the above technology and platform limitations, wildlife monitoring at offshore wind facilities is substantially hampered by the temporal mismatch between the design, planning, and engineering of structures and the development of wildlife monitoring plans and requirements. Wildlife monitoring plans for OSW facilities in the United States are typically developed years after design and engineering plans have been made. Some SMEs mentioned concerns with the potential for monitoring technologies to interfere with OSW operations and equipment, in part because the technologies are typically not adequately integrated into OSW planning and design.

Potential Solutions and Opportunities

Coordination

SMEs in multiple workshops concluded that engagement between scientists, wind energy projects, regulators, and turbine manufacturers to plan monitoring as early as possible, preferably several years prior to construction, is critical to streamline the operationalization of turbine-based and other platform-based monitoring at OSW sites. A combination of cross-sector coordination and an acceleration of development and testing timelines are recommended to improve monitoring technologies. Engagement as early as possible between researchers, regulators, and OSW infrastructure designers could allow for better integration of technologies to minimize issues with space, access, cybersecurity, and safety, and to avoid delays and expenses during the monitoring plan development and implementation phases of the project. To improve this communication, it is recommended that

TABLE 3

Types of technology platforms, examples and constraints.

Platform Types	Example Systems	Examples of Identified Constraints
UASs	Drones	Bottlenecks related to permitting new technologies Often non-US-based systems, which prevents researchers from using them when applying with federal funding Flight duration can be limited by battery life Altitude and "line of sight" regulations affect usefulness for some types of data collection Battery, payload limitations Environmental conditions affect deployment and data collection Lack of data standardization/sharing protocols Can affect behaviors of birds or marine mammals
Unoccupied underwater and surface vehicles	ROVs, AUVs, autonomous surface vehicles	Bottlenecks related to permitting new technologies Propulsion noise interference with data collection Lack of maneuverability Often financially inaccessible to the research community Battery, payload limitations Environmental conditions affect deployment and data collection
Multi-sensor tags	Integrated sensors for location estimation, physiological monitoring, barometric pressure, video, accelerometry, acoustic, etc.)	Limitations on battery life Data access/offloading is difficult and may require recapture Attachment longevity issues Data storage limits on archival tags Lack of validation/ground truthing for physiological measurement devices Deployment can be intrusive
Vessels	Survey, construction, supply, and maintenance vessels	Space limitations for equipment and crew Safety issues Lack of adequate platform stability for some types of sensors Sound, electromagnetic interference, and presence of line-of-sight objects may inhibit data collection Irregular schedules and weather limitations may limit effectiveness of data collection
Fixed platforms	Buoys, substations, foundations, cables, moorings, turbines	Space limitations Lack of standardized holes or ports or dedicated space for monitoring technologies Potential interference with primary purpose of platform Data storage and security issues Physical access and safety issues Power access limitations Data transmission and manual retrieval limitations Potential to void warranties with post hoc technology deployment Sound, electromagnetic interference, and presence of line-of-sight objects may inhibit data collection Lack of platform stability (e.g., buoys, moorings, cables) Technologies deployed on substations may not be sufficient to understand impacts near turbines Deployment for only part of the lifetime of the project (e.g., buoys)

TABLE 4

Major considerations for technology integration into OSW infrastructure and/or operations.

Integration Need	Identified Constraints
Physical access to OSW platforms and equipment	System maintenance and data download may be hindered by inability to access monitoring equipment regularly. Access is difficult and expensive in remote locations. Many technologies do not allow users to conduct maintenance or download data remotely, so physical access is often required, which presents safety issues.
Attachment to structures	Structures may need to be retrofitted to allow for installation of technologies. It is difficult or impracticable to make some types of modifications to allow for attachment of monitoring technology (e.g., drilling or otherwise compromising watertight structures). Inaccessibility for maintenance in some locations Damage to systems could occur from weather, fishing, or marine debris.
Physical space	Space on most platforms is limited Turbines are taller and more complex in structure over time, potentially limiting what monitoring technology can be deployed on them and consistency over time.
Power supply	Power supply directly from turbines or cables can be challenging to connect and maintain. Autonomous power for technology systems, such as solar power, introduces additional safety, engineering, and maintenance requirements. AUVs, UASs, and drones have limited power, though some may use solar or other non-battery power sources. Docking of vessels or ROVs on structures to access power has logistical issues and may affect OSW equipment performance and stability.
Worker safety	Scientists are unlikely to be given physical access to turbine structures due to safety and liability concerns. Any activity that requires physically being at sea is a human safety risk. Humans moving from vessels to offshore structures, in particular, is a very hazardous activity. Likewise, moving parts of turbines are particularly hazardous for humans and additional person-time to deploy or maintain technologies in these locations would be a safety hazard.
Data storage and security	Cybersecurity of OSW data is a major risk if wildlife data are stored and transferred using OSW infrastructure (e.g., if wildlife data are transferred using wind turbine fiber optic cables or Wi-Fi). Data download via manual connection to monitoring equipment introduces safety risks (above). Use of cellular networks for data is limited at sea. Data transmission by satellite requires additional equipment on offshore infrastructure and can be costly. Local data storage can be limited by equipment size and power constraints, as well as size of data files. Developers may be able to address some security concerns by transferring data to their internal “data lakes” (centralized data repositories), but that may slow transfer of data to researchers, which is particularly problematic for real-time data needs (e.g., for mitigation actions).
Data quality	Acoustic, visual, and other interference for monitoring equipment deployed on OSW structures and vessels Some OSW platforms are not physically stable, which is a problem for some types of monitoring equipment like radar
Coordination with OSW planning process	Design and planning of wind facilities usually happen prior to development of wildlife monitoring plans. Monitoring requirements from regulators are typically not clear until late in the design and planning process, at which time modifying structures and designs is very difficult and expensive. Some platforms have limited deployment durations (e.g., some metocean buoys), limiting their value as platforms for monitoring.

TABLE 5

Case studies for technological integration.

Case Study	Purpose	Identified Constraints
Integration of monitoring activities with maintenance vessels	Facilitate the use of vessels already performing OSW operations activities to deploy, retrieve, and maintain wildlife monitoring platforms/ technologies without significant impact to typical operations	Operational: lack of early communication; lack of priority for monitoring tasks versus operational tasks; access constraints to data from ship's instruments (e.g., global positioning system) Engineering: storage, deck, and crew space limitations; lack of appropriate lifting gear for monitoring equipment or platforms; layout of a wind facilities may not be appropriate size/scale for monitoring questions Safety: availability of training for personnel supporting monitoring equipment deployment and minimizing risks to crew and researchers; transfer from vessels to OSW structures is very hazardous; increased numbers of people at sea and hours at sea increase risk; risks around use of monitoring equipment near OSW infrastructure (e.g., towed passive acoustic monitoring arrays)
Standardized and dedicated space on turbines for monitoring technology	Facilitate incorporation of wildlife monitoring capacity into the OSW design process; create dedicated spaces on turbines with standardized capacity and resources (such as power, data transfer, and physical space) so that these specifications can be incorporated into early OSW design processes even if wildlife monitoring plans have not yet been finalized, and monitoring technologies can then be designed to meet these specifications	Operational: need to prioritize dedicated space for monitoring equipment; need adaptive situation as monitoring equipment and platforms change over time; potential interference from electrical signals; unclear processes for data storage and transfer Engineering: multiple standardized platforms may be needed in different locations; some technologies have specific configurations or mounting needs; direction of attachment may not be adjustable; unobstructed views are needed for some systems; power constraints; longevity of monitoring equipment is usually shorter than lifespan of OSW infrastructure, and uncertainty regarding how best to remove or replace; corrosion control and wind loading issues; physical access issues Safety: need safe access to monitoring equipment on turbines; equipment must be easy to install and maintain (plug-and-play); railings may need to be designed for both safety and gear mounting; a dedicated space may create an area for birds or pinnipeds to perch/haul out Security: direct contact with turbine structures creates potential for security issues; connections for power or data transfer increase cybersecurity risks
Connection of autonomous monitoring platforms to OSW infrastructure for data and power transfer	Address limitations associated with data power, storage, and transfer using typical OSW infrastructure	Operations: docking an external platform could affect operations or create liability issues Engineering: Some autonomous platforms would potentially be a collision hazard in proximity to OSW structures; lack of standardization in autonomous platform brands. Security: Wireless systems could be a cyber security risk

continued

TABLE 5

Continued

Case Study	Purpose	Identified Constraints
Modification of sensors on cables and moorings to detect marine debris and entanglement risks	Facilitate detection of marine debris and potential entanglement risks using typical OSW sensors on cables and moorings	Operations: unclear timeline to address a detection of potential entanglement Engineering: unclear if debris detection sensors can differentiate debris that poses risks to marine life or differentiate between an entanglement and general debris; possibly need adaptation of fiber optics in cables to transmit data in near-real-time Security: Data transfer could be a cybersecurity risk.

information that is important for operational integration be made more accessible. OSW development has basic parameters that need to be met for operations (e.g., expected timing and types of routine maintenance activities, engineering constraints); however, there is a lack of transparency about these parameters, which may lead to inefficient integration of monitoring technology. In general, a lack of publicly available information on monitoring systems likely also limits deployment opportunities. In addition to the databases developed for the current study, the international collaboration Working Together to Resolve Environmental Effects of Wind Energy (2023) and the Renewable Energy Wildlife Institute (2023) have developed databases of wildlife monitoring technologies that continue to be updated. Continuing to incorporate new technologies into the established databases and to update existing entries will increase accessibility and, thus, likely lead to the utilization of a wider variety of technologies that better fit the needs of specific projects.

System Size and Attachment Methods

Biotelemetry methods require attachment of sensors to animals while maintaining animal health and safety, and these technologies are sometimes limited by current methods of attachment. Attachment methods that last longer (e.g., for whales and some seabirds) and/or are less likely to interfere with normal animal behaviors could improve the quality of data resulting from telemetry studies. Smaller, lighter tags could reduce the likelihood of tags affecting animal health and behavior and enable tag deployment on a wider range of smaller-bodied bird and marine mammal species. For monitoring technologies designed to be deployed on OSW infrastructure, reducing the size and footprint of the systems would likewise help to address common physical space constraints.

Technology Standardization and Data Quality

Some types of technologies can suffer from interference or “clutter” that can greatly complicate data collection and analysis (e.g., automated radio telemetry and marine radar). Data quality is affected by interference from structures, natural and anthropogenic sound and light, and stabilization issues for monitoring equipment on platforms. Mechanisms to minimize interference (including filtering mechanisms and antifouling approaches) and increase stabilization could support broader offshore deployments and improve data quality.

Production of some monitoring technologies, such as marine mammal tags and some bird tags, tends to be at small scale with inconsistency in tag longevity, cost, capability, and durability, even within a given model of tag. Commercial-scale production of technology with improved technical support would likely improve the function of tags and other technologies and reduce their cost, as well as improving technology availability, particularly for large-scale deployment in regional studies.

Sensor Integration

There are tradeoffs between the field of view and image resolution for many camera-based systems for bird and marine mammal monitoring that can preclude either species identification at longer distances (especially for smaller-bodied species) or monitoring a large enough swath of water/airspace to develop sufficient sample sizes. Additional technological development of such systems and further integration of cameras with other technologies, such as radar, could be useful in learning more about the cumulative effects of bird collision and to more reliably measure micro-avoidance behaviors at OSW facilities. Integrating multiple complementary wildlife monitoring technologies, such as cameras and radar, helps to minimize the biases and limitations of each singular method and produce more useful data for understanding OSW effects than individual systems. For example, some systems use radar to track individuals at a larger scale and estimate flux while cameras track individuals at a micro-scale and help identify individuals to species. In conjunction with environmental data, these sensors can be used to assess patterns of offshore habitat use and movements in relation to site conditions. Systems that can collect environmental data concurrently with animal movement and behavior data could also inform ecosystem-based modeling and help interpret results across studies to assess cumulative impacts.

Access to Power

Access to power can be improved for many systems, including improvements in battery life and reduction in battery weight for systems such as transmitters. Reducing power requirements, using alternative power sources (e.g., solar, wind), and providing redundancy in power supply could also help to address power constraints. Some systems could receive power directly from OSW infrastructure, but further engagement with engineers may be needed to facilitate these connections.

"Plug and play" Configurations on OSW Platforms

The development of a standard "plug-and-play" space for technology deployment on OSW platforms was strongly recommended by SMEs. It could simplify access to power and reduce physical space constraints for monitoring technology on OSW structures. Incorporating designated capacity for wildlife monitoring systems (including power, internet/data transfer, and physical space) into turbine designs would facilitate the ability of OSW developers to meet environmental monitoring requirements, which are typically finalized much later in the development process than infrastructure engineering. The development of a universal science "platform" with standardized capacity/resources would allow for more efficient and effective deployments of monitoring technology on turbines. Standardized technology deployment areas could be engineered into turbine designs and include standardized electrical and network connections, including a parallel network to accommodate wildlife monitoring and maintain data separation from the turbine Supervisory Control and Data Acquisition system. This could facilitate important wildlife monitoring system capabilities such as remote system checks and data streaming. By standardizing the location (or set of locations) and built-in capacity for monitoring technologies on turbines, technology developers could design monitoring technologies to meet a common set of specifications, and it could be easier to make monitoring decisions on a different timeline from turbine engineering decisions.

To further streamline data collection, maintenance, and data download requirements, it is recommended that complementary technologies be spatially concentrated within each wind facility (with numbers of systems to be informed by power analyses).

Data Storage and Remote Data Transfer

Many types of monitoring data, such as video and acoustic data, require substantial storage capacity. Remote data transfer would reduce the importance of on-site data storage, as well as the need for physical access to systems (which, in turn, reduces other logistical hurdles, including the need for animal recapture and human safety concerns). Cable fiber optics are a viable option for data transmission, but this raises cybersecurity issues that require either 1) dedicated fiber for wildlife monitoring, or 2) passing data through developers' secure, but inaccessible, "data lakes" prior to release to researchers. Passing data through data lakes (centralized data repositories) adds an additional burden to OSW facilities operations staff and affects the speed at which data can be used, particularly for real-time monitoring. Technical solutions to improve cybersecurity while making data transfer maximally efficient could improve monitoring outcomes and minimize security risks.

Data Standardization and Transparency

Improved research coordination, data standardization, and data access were identified as needs to help ensure that data are collected in a robust and consistent manner across projects and regions and that datasets are made publicly available to support larger research enterprises, frameworks, and modeling efforts (Kraus et al., 2019; New York State Energy Research & Development Authority [NYSERDA], 2021). Limited data access and standardization (including a lack of dedicated databases and portals) could be addressed through collaborative science organizations and government agency policies. Organizations like the Responsible Offshore Science Alliance (ROSA), Regional Wildlife Science Collaborative (RWSC), and the NYSERDA

Offshore Wind Environmental Technical Working Group have put forward recommendations on data standards and research planning that continue to evolve as the OSW industry grows in the United States (e.g., ROSA, 2021; RWSC, 2023; Regional Synthesis Workgroup of the Environmental Technical Working Group, 2023; Van Parijs et al., 2021).

Standardizing data collection and long-term storage could improve the ability to integrate large datasets and conduct robust analyses of population-level consequences from OSW effects. Integration of surveys at different geographic scales and collaborative survey design could also improve these types of studies (Regional Synthesis Workgroup of the Environmental Technical Working Group, 2023; RWSC, 2023).

Automation

The analysis of many types of wildlife monitoring data, such as photo, video, and acoustic data, is time-intensive and can require substantial manual review. Improved algorithms for detecting, identifying, localizing, and classifying animals; filtering clutter; and creating standardized data streams could allow for more timely and cost-effective analysis of monitoring data. Incorporating artificial intelligence into on-site systems could also help with data storage and data transfer processes (e.g., if some data analysis can happen on-site such that only a proportion of the raw imagery or other data need to be transferred remotely). The development of training and calibration/validation datasets, as well as the prioritization and publication of validation studies, would also be important steps to addressing this bottleneck.

Technology Verification and Adoption

The development of clear pathways to technology verification by regulatory agencies and the adaptation of permitting processes to allow greater flexibility (e.g., more wide-ranging drone use) and more efficient approvals for technology use in monitoring studies could improve both the quality of monitoring and ease of implementation as new technologies are developed.

Study Limitations

The workshops undertaken in this study were conducted via video conference, which increased the breadth and number of people who could attend but decreased the direct interaction potential among participants. The Mural whiteboard platform allowed a shared written mode of participation in the virtual setting, but use of a virtual instead of an in-person workshop approach may have affected outcomes. Standardized expert elicitation approaches were not employed, although discussions were carefully designed and facilitated to elicit targeted knowledge and opinions from SMEs.

The identification of participants was mainly based on input from project advisors and the authors' knowledge of researchers engaged in the fields of marine mammal and bird studies. For the workshop focused on integration of monitoring technologies with OSW infrastructure and operations, it was difficult to meaningfully engage turbine engineers and other OSW contractors involved with designing monitoring capacity at OSW facilities, so future discussions would benefit from more active engagement with those groups. Most participants were also based in the United States, particularly the East Coast. Priority gaps in other countries may not be identical to those identified here, though the authors expect most of the recommendations in this paper to also apply to other jurisdictions.

The databases are considered a snapshot of the capabilities of monitoring technologies at the time of database publication and cannot reflect future technologies or unforeseen challenges to technology development. Substantial gaps in available information also exist for many monitoring systems. Databases were shared with technology developers and other points of contact to try to ensure accuracy in assessments, but there may be inaccuracies remaining in the databases regarding the specific capabilities of individual technologies, many of which are changing rapidly. Technologies with more public information available have been prioritized for discussion to some degree, though they may not be the best suited technologies to meet the identified research needs.

Additional advancements in monitoring technologies have been made even during this study, and verification of system capabilities is likewise ongoing for a wide range of systems. Several recent tests of turbine-based monitoring systems in offshore environments (e.g., Tjørnløv et al., 2023; Robinson Willmott et al., 2023) have provided valuable additional information on collision and micro-avoidance rates, species presence and foraging behavior, and other data that are informing our understanding of both wildlife behaviors and offshore wind effects, as well as the capabilities of current technologies to answer key research questions.

Conclusions

There are substantial opportunities for the developers of bird and marine mammal monitoring technologies to pursue targeted improvements to better access electrical power, increase data storage and facilitate remote data transfer, improve cybersecurity, standardize interfaces with OSW infrastructure, prioritize worker safety, improve system size and attachment options, integrate multiple sensors, collect concurrent environmental data, and improve reliability. Additional automation is also a need for filtering, localization, and classification of animals. The creation of standardized data streams, as well as long-term storage of data in publicly accessible databases (modeled after examples such as the Motus Wildlife Tracking System [Taylor et al., 2017], National Ecological Observatory Network [National Science Foundation, 2023], and the Integrated Ocean Observing System [National Oceanic and Atmospheric Administration, n.d.]), could greatly improve the utility of existing and new datasets for ecosystem-based modeling and studies of cumulative impacts.

Many of the R&D needs to improve existing technologies are similar for birds and marine mammals; however, bird technologies are more likely to require integration with turbines, which introduces additional challenges. While there have been substantial advances in the capabilities of bird collision and avoidance monitoring systems at offshore wind facilities in recent years (e.g., Robinson Willmott et al., 2023; Skov et al., 2018; Tjørnløv et al., 2023), there remain challenges with cost-effective, safe, scalable offshore deployment of these systems, as well as with the collection of statistically robust datasets. For marine mammals, advances in passive acoustic monitoring methods (Van Parijs et al., 2023) have allowed researchers to obtain real-time information about the presence of certain species but direct interactions with OSW facilities still remain difficult to quantify and will likely require the integration of multiple robust and long-term datasets.

There is a mismatch between the typical timing of infrastructure design and the development of monitoring plans that may hinder monitoring technology integration into infrastructure and operations. Early communication and collaboration between engineers/designers and technology developers/researchers can reduce these challenges. Development of a standard "plug-and-play" space for technology deployment on OSW platforms is particularly recommended, but in general, more collaborative development of monitoring plans could help to optimize monitoring so data are collected in a manner that can answer questions, reduce uncertainty, and support regulatory compliance.

Availability of long-term, high-quality datasets, collected using robust methodologies within cohesive, transparent, and collaborative research efforts, could much more effectively inform adaptive management of the OSW industry than disjointed, poorly designed individual efforts (Bureau of Ocean Energy Management, 2017; NYSERDA, 2021; Wilding et al., 2017). Improvements in monitoring technologies and related coordination and data analysis/management workstreams are needed to avoid a situation where large datasets are gathered, but they do not actually improve the understanding of OSW effects. Application of the results of the current study to prioritize and fund technology R&D could help to support more statistically robust data collection and practicable integration into OSW operations and infrastructure.

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