Assessment of Technology Gaps for Statistically Robust Data and Integration of Monitoring of Birds and Marine Mammals into Equipment and Operations of Offshore Windfarms

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Technology Solutions to Mitigate Use Conflicts: Technology Needs for Scientifically Robust Wildlife Monitoring and Adaptive Management

Task 5.2

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Acronyms and Abbreviations

3D	3-dimensional
AUV	autonomous underwater vehicles
BRI	Biodiversity Research Institute
eDNA	environmental deoxyribonucleic acid
E-TWG	Regional Synthesis Workgroup of the Environmental Technical Working Group
Lidar	light detection and ranging
NOWRDC	National Offshore Wind Research and Development Consortium
NYSERDA	New York State Energy Research & Development Authority
OSW	offshore wind
PAB	Project Advisory Board
Radar	radio detection and ranging
ROSA	Responsible Offshore Science Alliance
ROV	remotely operated vehicle
RWSC	Regional Wildlife Science Collaborative
SME	subject matter expert
UAS	unmanned aerial system

Executive Summary

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. It can be difficult to study effects of OSW development on wildlife in a manner that is statistically robust and integrates into OSW facilities' typical operations and infrastructure. An important aspect of prioritizing resources for wildlife monitoring is understanding the technology gaps that affect robust data collection and hinder integration of monitoring systems into OSW infrastructure and operations. The National Offshore Wind Research and Development Consortium (NOWRDC) has embarked on efforts to support technology development to improve protected species monitoring. This study identified technology gaps for monitoring marine mammals and birds for fixed and floating OSW via development of a research priorities report based on the literature, three expert workshops, and development of technologies databases summarizing information on the capabilities and limitations of existing technologies. NOWRDC and a Project Advisory Board (PAB) provided input and feedback on reports and databases. Methods for developing workshops and databases are provided in detail in reports available at NOWRDC's website:

- Offshore Wind Priority Conflict Topics for Marine Mammals and Birds
- Technology Gaps for Marine Mammal Monitoring in Relation to Offshore Wind Development
- Technology Gaps for Bird Monitoring in Relation to Offshore Wind Development
- Integrating Bird and Marine Mammal Monitoring into Offshore Wind Energy Development Infrastructure and Operations
- National Offshore Wind Monitoring Technology Database - Marine Mammals
- National Offshore Wind Monitoring Technology Database - Birds

Priority research topics fell into four general 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. These include 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 on various time scales. This can include measurable changes in behavior, communication range, abilities to navigate/migrate, and/or the animal's physical condition, among other metrics; and

- Consequences: the population-level effects of 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).

The marine mammal-specific database developed as part of this study contained nine major categories of monitoring technologies, including passive acoustics, autonomous underwater vehicles (AUVs), unmanned aerial systems (UASs), camera systems, sensors, satellite tags, archival tags, surveys, and ‘other.’ Each monitoring category was further broken down into 22 technology types; for example, the passive acoustics category consisted of towed arrays, Sonobuoys, high-frequency acoustic recording packages, etc. Altogether, the marine mammal database housed individual 63 technology systems. Discussions with marine mammal experts focused on the use of visual sensors, acoustic sensors, satellite tags, environmental deoxyribonucleic acid (also known as eDNA), and software, as well as data integration and optimization.

The bird-specific database developed as part of this study contained seven major categories of monitoring technologies, including radio detection and ranging (radar), cameras, surveys, biotelemetry, habitat monitoring, passive acoustics, and ‘other.’ Each monitoring category was further broken down into a total of 30 technology types; for example, the radar category included marine radar, weather surveillance radar, and three-dimensional radar units, among others. The bird database also housed more detailed information on 46 makes/models of systems designed to be deployed on wind energy infrastructure. Discussions with bird experts focused on the use of cameras, acoustic sensors, tags and other bird-borne sensors, radar, physiological sensors, light detection and ranging (lidar) technology, population monitoring approaches, surveys at sea, and methods for habitat and prey monitoring, as well as the use of artificial intelligence and different kinds of statistical models.

Platforms on which these monitoring systems could be deployed include unoccupied aerial systems, unoccupied underwater and surface vehicles, multi-sensor tags, vessels, fixed platforms (including various areas of OSW infrastructure), and the animals themselves (e.g., with individual tracking technologies). Workshop discussions of these platforms focused on considerations for integrating wildlife monitoring technologies into OSW infrastructure and operational procedures. This included the need for physical access to OSW platforms and equipment, attachments to structures, equipment size and space requirements, power supply, safety considerations, data storage and security requirements, data quality, and the integration of monitoring plans into the broader OSW planning process. In addition, the integration workshop discussed five more specific case study questions:

- How can maintenance vessels be used in wildlife monitoring?;
- How can we develop a standardized space or platform on turbine structures for wildlife monitoring technology?;
- How can autonomous equipment connect into OSW infrastructure to transfer data and power?;
- How can we deploy a multi-technology system (e.g., radar, camera, acoustic) on turbine platforms?; and
- How can we use or modify the detection sensors on cables and mooring lines used for debris fouling detection to detect risk for secondary or tertiary marine mammal entanglements?

Based on the results of the research priority assessment, workshops, and development of the technology databases, there are some clear limitations of existing wildlife monitoring systems to collect statistically robust data and be integrated into OSW infrastructure and operations. Both bird and marine mammal technologies tend to have constraints around the following:

- Power;
- Data storage and transfer, including real-time data transfer;
- Validation of data and calibration of equipment;
- Data standardization;
- Data resolution;
- Potential to affect OSW infrastructure if mounted directly on such infrastructure;
- Safety for individuals deploying, servicing, and retrieving equipment;
- Automation of animal detection and identification;
- Interference from natural and anthropogenic sound, light, structures, etc.;
- Access to and space on structures; and
- Large-scale deployment (at windfarm and regional scales).

The key research and development needs for technology are similar for birds and marine mammals. The main exception is that bird technologies are more likely to require integration with OSW infrastructure than many marine mammal systems; the latter are more often designed to be independent (e.g., on buoys or other mooring systems). Marine mammal technologies are also more likely to be robust to harsh environmental conditions than many bird-focused technologies.

In general, improvements in technological capabilities such as improved battery life (or access to power), data storage and remote data transfer (including cybersecurity considerations and near-real-time measurements), and algorithms for identifying, localizing, and classifying animals and filtering clutter, would address many of the universal monitoring technology constraints. In particular, it is recommended that technology system and platform developments focus on the following:

- Systems
    - Increasing battery life or use of alternative power sources (e.g., solar);
    - Increasing data storage and improving remote data transfer systems;
    - Improving automation of data review and analysis;
    - Addressing field-of-view and resolution constraints;
    - Improving detection of small-bodied birds and high-frequency/small marine mammals;
    - Improving protocols for integration of datasets at different spatiotemporal scales;
    - Minimizing invasiveness of tags and increasing tag longevity;
    - Improving stabilization for technologies on moving platforms;
    - Developing commercial scale production of technologies;
    - Improving technology robustness to harsh environments; and
    - Integrating sensors, including multiple concurrent animal sensors as well as environmental data sensors.
- Platforms
    - Reducing the need for physical access to systems (e.g., remote capabilities);
    - Improving attachment mechanisms;
    - Standardizing interfaces with infrastructure, including possible dedicated space for monitoring technologies on OSW infrastructure;
    - Addressing safety concerns for deployment, maintenance, and retrieval;
    - Avoiding interference from structures (e.g., blind spots in radar);
    - Addressing cybersecurity issues; and
    - Coordinating planning processes early.

Application of the results of this study to prioritize and fund technology developments will support statistically robust data collection and practicable integration into OSW operations and equipment. While the geographic focus of this study was centered around the U.S., the findings presented in this study are also applicable to other geographic regions where OSW is being considered or implemented.

1 Introduction

To reduce carbon emissions from the generation of energy via fossil fuels, OSW energy development is expanding globally (Borowski 2022). Given this rapid and large-scale expansion, it is important to understand and mitigate the effects of OSW energy development on wildlife; however, it can be difficult to study the effects in a statistically robust manner. Current wildlife monitoring technologies are in many cases unable to collect the necessary types and amount of data required to robustly answer questions about OSW site assessment, impacts, and mitigation efficiency (Allison et al. 2019). 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 ability to place and maintain technology on and in OSW infrastructure and potentially transmit power and data through those structures, as well as 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 ultimately be scientifically robust and question-driven so that results can meaningfully inform future site assessment, impact assessments, and adaptive management (Regional Synthesis Workgroup of the Environmental Technical Working Group [E-TWG] 2023).

There has been successful deployment of technologies for monitoring (e.g., some are described in Offshore Renewables Joint Industry Programme for Offshore Wind 2022), and we have reviewed such technologies in the context of determining potential 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 (https://tethys.pnnl.gov/wind-energy-monitoring-mitigation-technologies-tool) 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 statistical robustness, nor the ability 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 farms. 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 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 assess the effects of OSW development on birds and marine mammals for fixed and floating wind projects in the U.S. Pacific, Atlantic, Gulf of Mexico, and Great Lakes regions. The technical specifications and capabilities of existing monitoring technologies, as well as limitations of data collection and integration with offshore structures, were synthesized to identify urgent technology development needs where financial resources could be directed to reduce market barriers most effectively to development.

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

2 Methods

This section provides a broad review of the methodology used for this project. Additional details of the process, tools, and references can be obtained in the individual reports provided to the NOWRDC which are listed at the end of this section.

Existing literature was synthesized into a list of potential marine mammal and bird conflict issues and research priorities to inform discussions of technology limitations. This synthesis identified key bird and marine mammal issues and data gaps that are potential barriers to OSW progress, either in the form of environmental compliance issues or stakeholder concerns for U.S. OSW.

To evaluate these conflict areas and priority topics, identify technology issues, and assess the challenges and opportunities for integration of monitoring technology into OSW infrastructure and operations, a series of three virtual workshops was undertaken with subject matter experts (SMEs) with expertise in marine mammals, birds, wildlife monitoring systems, technology R&D, and offshore wind infrastructure and operations. The workshops were designed to give participants the opportunity to discuss technology limitations, strengths, and priorities for improvement and adaptations. The first two workshops focused on input from bird and marine mammal experts. The third workshop focused on integration of monitoring into OSW infrastructure and operations, including several case studies presented for SME review. Case studies included the following:

- How can maintenance vessels be used in wildlife monitoring?;
- How can we develop a standardized space or platform on turbine structures for wildlife monitoring technology?;
- How can autonomous equipment connect into OSW infrastructure to transfer data and power?;
- How can we deploy a multi-technology system (e.g., radar, camera, acoustic) on turbine platforms?; and
- How can we use or modify the detection sensors on cables and mooring lines used for debris fouling detection to detect risk for secondary or tertiary marine mammal entanglements?

Individuals recorded their perspectives on a virtual whiteboard platform (Mural; www.mural.co). The virtual whiteboards remained open for participants to continue to provide their input after the virtual workshops. The workshops were not conducted as a formal expert elicitation process but were designed to capture a variety of stakeholder and expert opinions.

Generally, workshop discussions focused on the following:

- Identification of the technologies, methods, and study designs to answer priority questions;
- Summarization of the capabilities and limitations of existing monitoring systems;
- Identification of opportunities and limitations for operational integration of bird and marine mammal monitoring technologies (including deployment, maintenance, and data retrieval) into OSW infrastructure and operations; and
- Determination of areas where further research and development or coordination efforts could improve the capabilities of monitoring technologies to answer key research questions and better inform future mitigation and adaptive management in OSW development in the U.S.

In addition to the workshops, taxon-specific databases were developed for birds and marine mammals that contained details on monitoring systems that could be potential candidates for improvement and/or integration within OSW operations. Each technology was assessed for its overall capability and 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 points of contact for different technology systems to obtain input on the accuracy of the project team's assessment and identify additional resources from which to draw relevant information. The database products constitute a 'snapshot' of available technologies available during the project timeframe; 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 SMEs in the workshops and who conducted database review, the project incorporated input from an expert PAB. Workshop participants were identified by the project team in collaboration with the PAB and NOWRDC.

Reports submitted to the NOWRDC include more details on the development of research priorities, workshops, and the technology databases. These reports include the following, available on the NOWRDC website[1]:

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[1] https://nationaloffshorewind.org/projects/technology-development-priorities-for-scientifically-robust-and-operationally-compatible-wildlife-monitoring-and-adaptive-management/

- Offshore Wind Priority Conflict Topics for Marine Mammals and Birds
- Technology Gaps for Marine Mammal Monitoring in Relation to Offshore Wind Development
- Technology Gaps for Bird Monitoring in Relation to Offshore Wind Development
- Integrating Bird and Marine Mammal Monitoring into Offshore Wind Energy Development Infrastructure and Operations
- National Offshore Wind Monitoring Technology Database - Marine Mammals
- National Offshore Wind Monitoring Technology Database – Birds

3 Results

3.1 Research Questions

Based on the literature review, priority research needs that wildlife monitoring technologies should help to address (Table 1; Table 2) 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. Reponses 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).

In addition to these research categories, several priorities were identified focusing on research coordination, data standardization, and data access, to help ensure 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 support integration into larger research enterprises, frameworks, and modelling efforts (Kraus, Kenney, and Thomas 2019, NYSERDA 2021).

Table 1. Key research needs for birds at offshore wind farms

Category	Key Research Needs
Occurrence	Assess the distribution, abundance, and habitat use of birds in OSW areas by taxon, season, and development phase (Rijkswaterstaat 2016; Allison et al. 2019; Cook et al. 2021)
Occurrence	Inform collision risk models by improving knowledge of flight behavior, including flight height, for species of interest in relation to environmental/weather conditions such as wind speed, wind direction, visibility, and time of day (Cook et al. 2021).
Occurrence	Understand the drivers of marine bird[2] distributions and offshore migration of non-marine birds (Cook et al. 2021)

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[2] Marine birds, as defined in Cook et al. (2021), are species that use the marine environment at some point in their life cycle (including loons, grebes, sea ducks, phalaropes, and seabirds)

Conditions and Stimuli	Measure artificial light at OSW facilities during different development phases and under varying weather conditions (including light intensity, duration, and extent/directionality)
Conditions and Stimuli	Assess the effects of OSW structures on bird prey (via underwater sound, cable laying, formation of artificial reefs, or other factors) and how long these effects last (May and Perrow 2017; Allison et al. 2019)
Response	Examine changes in abundance and distributions of birds around OSW facilities (Rijkswaterstaat 2016)
Response	Investigate potential for diurnal and nocturnal collisions and flight behavior (e.g., micro-avoidance) in close proximity to OSW turbines (May and Perrow 2017; Cook et al. 2021)
Response	Examine changes in bird foraging activity and/or energetics due to OSW development and correlations with changes in prey (New York State Energy Research and Development Authority [NYSERDA] 2020; Joint Nature Conservation Commission 2021)
Consequences	Assess the demographic and/or fitness consequences of cumulative collisions/displacement at OSW facilities (Skov et al. 2018; Allison et al. 2019)
Consequences	Develop accurate demographic data for key species of concern to quantify the population-level significance of (estimated or actual) effects from OSW development and establish appropriate mitigation targets if necessary (Allison et al. 2019)

Table 2. Key research needs for marine mammals at offshore wind farms

Category	Key Research Needs
Occurrence	Estimate habitat use, distribution, and abundance in OSW development areas by season and taxon and identify dynamic environmental variables driving these patterns
Occurrence	Establish individual baseline movements and behavioral patterns (foraging, diving, reproduction) specific to OSW development areas for marine mammals (Cook et al. 2021)
Occurrence	Determine spatially and temporally explicit marine mammal species presence in OSW development areas (Cook et al. 2021)
Conditions and Stimuli	Evaluate ambient sound levels in OSW development areas prior to development activities as well as during development phases for marine mammals
Conditions and Stimuli	Evaluate changes in ecosystem and prey conditions in OSW development areas from the pre-construction to operational periods for marine mammals (May and Perrow 2017; Allison et al. 2019)
Response	Identify acoustic exposure and contextual conditions associated with potential acute response to OSW stressors to support development and refinement of risk and consequence assessment
Response	Evaluate relative threat of mortality/injury from vessel collision and entanglement (floating wind) for marine mammals associated with OSW and non-OSW activities

3.2 Considerations for Monitoring Technologies and Platforms

A list of technologies and platforms was compiled from both the subject matter expert (SME) workshops as well as the technology databases, and limitations for each technology and platform were identified for continued discussion. Technologies and limitations described for marine mammals and birds are not entirely parallel in the following sections, as SMEs brought up categories in different ways, the databases indicated different technology development and availability, and bird technologies tend to be more advanced in the context of wind studies because of significant research and effort in relation to land-based wind energy projects. The categories described for each taxon below were deemed to be most appropriate for integrating information for technology gap identification and recommendations for that taxon. For example, marine mammal SMEs discussed visual sensors together as a category, whereas bird SMEs had distinct ideas around specific sensors, such as lidar and radar. Likewise, the bird database included additional detail on technologies designed for deployment on wind energy infrastructure, while the marine mammal database was more general in focus.

While marine mammal and bird technology limitations were not entirely parallel, the following main findings were universal between marine mammal technologies and the subset of bird technologies designed to be deployed on wind energy infrastructure:

- Most technologies are designed to run day or night;
- The majority of technologies in the database are commercially available to some degree (e.g., the technology developer may need to be contacted for access, but the technology is available for purchase in some manner);
- Many operational integration parameters (system dimensions, maintenance schedule, power source) are not readily available for many technologies; cost is also not readily estimable in most cases;
- Information on performance (false positive/negative rates, sensitivity, error, etc.) is not readily available in most cases; and
- External validation by the scientific community is not always easy to find and tends to be associated with more mature technologies.

Broadly, SMEs in workshops repeatedly expressed the concern that OSW monitoring is often decoupled from research (e.g., monitoring is not designed to actually answer research questions), and that a large communication gap still exists between industry/management, the research community, and the regulatory community, making it difficult to effectively identify, test, implement and deploy technologies to address key research needs.

3.2.1 Marine Mammal Monitoring Technologies

The marine mammal-specific database contains six major categories, 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 type would 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, etc. The marine mammal database also provides information on platforms for technology (see Section 3.2.3), 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. A summary of main findings from the marine mammal database are as follows:

- The majority of the technology systems require some sort of human validation or monitoring (i.e., the technology is used to enhance human monitoring but cannot fully replace it);
- Most systems have been deployed, though some have not been tested for OSW; and
- Systems cannot be deployed on OSW structures and require deployment from a separate platform.

Table 3 summarizes six major technology categories and constraints for marine mammals.

Table 3. Summary of major technology categories and identified constraints for marine mammals

Monitoring Technology Category	**Example Technology Types**	**Examples of Identified Constraints**
Technologies for OSW Monitoring		
Visual Sensors	Infrared imaging, 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
Satellite 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
Environmental DNA		• Lack of reference data • Lack of assessment of error factors
Related Technologies and Approaches		
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
Data Integration & Optimization*	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.

3.2.2 Bird Monitoring Technologies

The bird-specific database contains nine major categories, including radar, lidar, cameras, observational surveys, acoustic sensors, biotelemetry, physiological sampling, habitat/prey monitoring, and ‘other.’ Each monitoring category was further broken down into technology types; for example, the radar category includes marine radar, weather surveillance radar, and 3-dimensional radar technologies, among others. Constraints for various technology types are identified in Table 4. In addition, several related approaches that are not standalone technologies (e.g., artificial intelligence, models) are also explored in Table 4.

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 system models often incorporate multiple technologies, including cameras, radar, passive acoustics, and other technology types. A summary of main findings from the bird database are as follows:

- Detection ranges vary widely, both within technologies (e.g., day/night and small/large birds) and among technologies;
- Technology Readiness Levels (Department of Energy 2009) range from 1 to 9 but can be difficult to assess based on available information;
- Most systems are limited by weather conditions;
- Approximately one third of systems support collision avoidance technology (16 of 46); and
- Most systems either have not been tested offshore, or in a few cases, it is not known if they have been deployed offshore (24 of 46).

The technology review (database) and workshops resulted in identification of a range of limitations for bird technologies (Table 4). The capabilities and limitations of each system are noted separately in Table 4, though as noted elsewhere in this report, many such systems can (and even should) be integrated to best answer key research questions.

Table 4. Major technology categories and identified 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-dimensional 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-dimensional tracking radar, Aircraft Detection Lighting System, Dual camera-radar systems, 2-dimensional 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
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 is challenging • Methods are sometimes invasive

		• Lack of datasets for validation of data and calibration of results • Isolating changes caused by OSW is 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
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

3.2.3 Platforms

A variety of platforms could host bird and marine mammal monitoring technologies at OSW facilities (Figure 1; Table 5). 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.

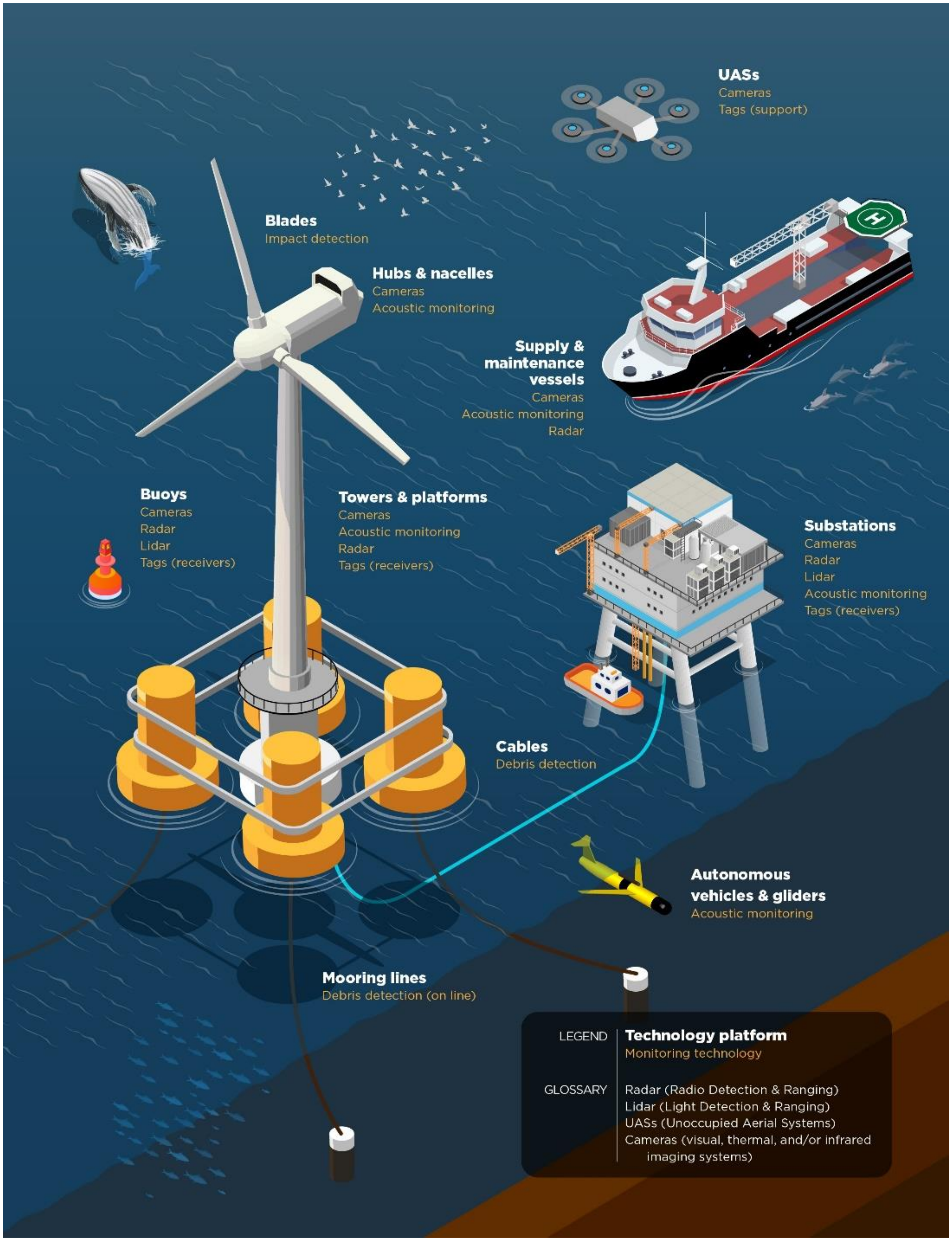

Figure 1. Main OSW monitoring platforms and examples of the technologies considered for deployment on each platform. Biotelemetry and related technologies designed for deployment on animals are not pictured.

Table 5. Types of technology platforms and identified constraints.

Platform Types*	Example Systems	Examples of Identified Constraints
Unoccupied Aerial Systems	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)

*Animals themselves can also be platforms for technology deployments, but this topic is discussed in Tables 1 and-2 and thus is not included here.

3.3 Considerations for Integration into Operations and Equipment

There are a variety of limitations associated with integrating monitoring technologies into OSW infrastructure and operations, including personnel limitations, size and space limitations, data transfer and security concerns, and limitations in the planning process (Table 6). Concerns were also raised about a lack of a pathway for technology verification, difficulty in addressing cumulative impact concerns, and open questions such as adequate sample sizes and numbers of monitoring units needed.

Table 6. 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 • OSW structures have safety issues with access in addition to logistical ones • Placement of, or regular access to, monitoring devices could affect performance of OSW equipment • Many technologies are not developed enough to conduct maintenance or download data remotely, so physical access is often required
Attachment to Structures	• Structures may need to be retrofitted to allow for installation of technologies • It is difficult or impracticable to make modifications to some structures to allow for attachment of monitoring technology. For example, drilling or otherwise compromising watertight structures would not be reasonable so attachments may be limited to magnets or adhesives • 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 and monitoring technologies may be too large for those limits • Turbines are getting higher off the surface and more complex in structure, potentially limiting what monitoring technology can be deployed on them

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, as they have confined spaces for human activities, being on them requires significant training, and there are safety and liability concerns that would be very challenging to overcome • Moving parts of turbines are particularly hazardous for humans and additional time or people on these areas would be a safety hazard • Any activity that requires physically being at sea is a human safety risk • Humans moving from vessels to offshore structures is a very hazardous activity
Data Storage and Security	• Cybersecurity of OSW data is a major risk if wildlife data are stored and transferred using OSW infrastructure (for example, if wildlife data are transferred using wind turbine fiber optic cables or Wi-Fi). Data download via manual connection to 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 or cameras
Coordination with OSW Planning Process	• Design and planning of windfarms 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

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. Many of the identified limitations for case studies were similar to the broader limitations identified in Table 6; case-specific constraints are provided in more detail in Table 7.

Table 7. 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 windfarm may not be appropriate size/scale for monitoring questions • Safety: 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 is increased 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 monitoring equipment in limited space; 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 need to be developed in different locations; some technologies have specific configurations or mounting needs; direction of attachment may not be adjustable; unobstructed views may be needed; power constraints; longevity of monitoring equipment is unclear (usually shorter lifespan than OSW infrastructure), and uncertain how 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; aerial drones launched from autonomous platforms may be a hazard to infrastructure in if close proximity • 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
Deployment of radar-camera system on turbines	• Facilitate integration of systems directly on OSW turbines	• Safety: Accessing turbine structures for deployment and maintenance; spinning units may be an added danger on turbine platforms, especially in winter with ice throw risk • Security: Data transfer has cybersecurity risks
Modification of sensors on cables and	• Facilitate detection of marine debris and potential entanglement risks using	• Operations: Unclear timeline to address a detection of potential entanglement

moorings to detect marine debris and entanglement risks	typical OSW sensors on cables and moorings	- Unclear if debris detection sensors can differentiate debris that poses risks to marine life or not 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

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 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.

4 Discussion

4.1 Synthesis of Technology Gaps

Based on the results of the research priority assessment, workshops, and development of the technology databases, there are some clear limitations of existing wildlife monitoring systems to collect statistically robust data and be integrated into OSW infrastructure and operations. Both bird and marine mammal technologies would benefit from additional R&D focused on access to the following:

- Power;
- Data storage and transfer, including real-time data transfer;
- Validation of data and calibration of equipment;
- Data standardization;
- Data resolution;
- Potential to affect OSW infrastructure if mounted directly on such infrastructure;
- Safety for individuals deploying, servicing, and retrieving equipment;
- Automation of animal detection and identification;
- Interference from natural and anthropogenic sound, light, structures, etc.;
- Access to and space on structures; and
- Large-scale deployment (at windfarm and regional scales).

With respect to platforms, both bird and marine mammal technologies tend to lack options for adequate collection of concurrent environmental data, and a range of technologies that can collect data across multiple sensors are in development. Autonomous surface, subsea, and airborne platforms are likewise being developed, but payloads and power are limited, and regulations minimize the effectiveness of airborne platforms such as UASs that are required to stay in line of sight at specific altitudes and minimize payloads. Autonomous vehicles may also pose collision risks with OSW structures and animals which need to be minimized.

Both bird and marine mammal monitoring requires R&D for effective localization and classification algorithms and artificial intelligence to detect and identify species, partially due to a lack of training datasets. Software is often not user-friendly and citizen science is difficult to obtain and integrate. It is also difficult to assess error rates for many data collection technologies and to develop correction factors for observations. Tracking technologies require additional advancement in miniaturization to be safely and effectively deployed on species of interest.

Individual sample collection and tracking is a key method for obtaining data on animal movements and behavior; however, the size of tags deployed directly on animals, and thus the capacity of tags to collect high-quality data, is strongly constrained by body size. Attaching technologies that have the potential to physically and behaviorally affect animals not only affects animal welfare, but also fails to provide useful data to answer key research questions. Thus, many tracking technologies require additional advancement in miniaturization to be safely and effectively deployed on species of interest. Systems for physiological measurements are even more nascent and tend to be at low technology readiness levels or deployment stages.

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 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 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.

There were several constraints around integration into infrastructure and operations identified during the study. One was the temporal mismatch between the design, planning, and engineering of windfarm structures and the development of wildlife monitoring plans and requirements. The potential for monitoring technologies to interfere with OSW operations and equipment and void warranties was raised by some SMEs, for example, because the technologies are typically not adequately integrated into OSW planning and design. This lack of coordination leads to a range of issues. In addition, permitting and funding were noted as constraints. Further, cybersecurity issues were a concern for data transfer, but without remote data transfer options, most technologies require physical access to OSW structures for data download and maintenance, thus introducing worker safety concerns. Also, aligning vessel operations activities with monitoring needs may be difficult; in addition to safety concerns, there are constraints on vessels with regard to space and time that can be spent at sea.

4.2 Potential Solutions and Opportunities to Improve and Implement Monitoring Technologies

In some cases, existing monitoring methods were determined to require additional technological advancement to better address the research needs identified in Section 3.1. Improved research coordination, data standardization, and data access were also identified as needs, to help ensure that data are collected in a robust and consistent manner across projects and that datasets are made publicly available to support larger research enterprises, frameworks, and modelling efforts (Kraus, Kenney, and Thomas 2019, NYSERDA 2021). As such, the below recommendations include both technological needs, as well as other identified gaps that must be addressed in order to conduct robust environmental research on taxa and effects of interest

To fill technology gaps for marine mammal and bird monitoring associated with OSW, efforts to improve and standardize specific technologies, integrate complementary monitoring technologies, and standardize the integration of wildlife monitoring capacity into OSW infrastructure designs are recommended. In addition to technology development and structure design, SMEs across workshops concluded that engaging with wind energy projects, regulators, and turbine manufacturers to plan monitoring as early as possible, preferably several years prior to construction, is critical to streamline and facilitate the operationalization of turbine-based and other platform-based monitoring at OSW sites. A combination of prioritization, cross-sector coordination and streamlining, as well as an acceleration of development and testing timelines are recommended to improve monitoring technologies. More detailed topics identified to address universal monitoring challenges consist of the following:

- Battery life improvement (or access to power);
- Replacing of batteries with solar or OSW infrastructure power sources, where possible;
- Data storage and remote data transfer improvements, including more coordination of satellite, internet, and other connectivity options for remote data transfer (including cybersecurity considerations and near-real-time measurements);

- More and better algorithms for identifying, localizing, and classifying animals and filtering clutter; making artificial intelligence and other algorithms open source as they are developed would allow for more universal application of these technologies;
- Addressing field-of-view and resolution constraints; in particular, increased data resolution and accuracy is needed to improve altitude measurements for birds, imagery resolution and field of view for birds, and localization for marine mammals;
- New technologies that can better detect small-bodied birds and high-frequency and small marine mammals at longer ranges would deepen understanding of spatiotemporal use patterns by these taxa;
- Developing protocols to better integrate datasets at different spatiotemporal scales would improve modeling and cumulative impact studies;
- Improving tags and tag deployment on animals to minimize invasiveness (e.g., smaller tags, less invasive attachment mechanisms) while maximizing tag longevity would improve tag data;
- Improving stabilization to improve data quality for technologies on moving platforms
- Commercial scale production of tags and other monitoring technologies would help standardize the quality, cost, and availability of equipment, particularly for marine mammal tags;
- Improving equipment weatherization and robustness to harsh marine environments would particularly benefit bird monitoring technologies; and
- Integrating multiple sensors into platforms, including environmental sensors.

4.2.1 Access to Power

Access to power includes improvements in battery life and reduction in battery weight for systems, such as transmitters. In other cases, efforts should focus on facilitation of access to electricity from OSW infrastructure or other sources. In addition, reducing power requirements, using alternative power sources (e.g., solar, wind), and providing redundancy in power supply would help address power constraints. Some systems could receive power directly from OSW infrastructure, but further engagement with engineers is needed to facilitate these connections.

4.2.2 Data Storage and Transfer

Many types of monitoring data, such as video and acoustic data, require substantial storage capacity, and this can be a limiting factor for some technologies. Remote data transfer would reduce the importance of on-site data storage, as well as reducing the need for physical access to systems (which, in turn, reduces other logistical hurdles, including the need for animal recapture, and human safety concerns). Remote data transfer is also very important for some types of near real-time monitoring.

4.2.3 Automation of Data Review and Analysis

Analysis of many types of wildlife monitoring data, such as photo, video, and acoustic data, is time-intensive and can require substantial manual review by human biologists. Better algorithms for detecting, identifying, localizing, and classifying animals, filtering clutter, and creating standardized data streams would allow for more timely and cost-effective analysis of monitoring data. Additional use of 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 needs to be transferred remotely).

4.2.4 Detection Improvements

There are tradeoffs between field of view and image resolution for many camera-based systems for bird monitoring that preclude either species identification at longer distances (especially for smaller-bodied species) or monitoring a large enough swath of 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 important to better understand collision and micro-avoidance behaviors at OSW facilities.

Small-bodied marine mammals are difficult to detect with thermal and visual systems because of interference and low resolution at distance, and high-frequency marine mammals are difficult to detect with passive acoustic monitoring because of attenuation of sound. Improvements to the resolution and distance of detection for these species and better localization and classification would improve data associated with baselines and OSW impacts.

4.2.5 Integration of Datasets

Methods for use of technology to collect datasets in a manner that can be integrated at different spatiotemporal scales will support synthesis of large datasets from multiple individual studies, improving outcomes of modeling efforts and cumulative impact analyses.

4.2.6 Minimize Invasiveness

Biotelemetry methods require attachment of sensors to animals while maintaining animal health and safety, and these technologies are in some cases limited by current technologies used for attachment. Attachment methods that last longer (e.g., for whales) and/or do not interfere with normal animal behaviors (e.g., for some seabirds) could improve the quality of data resulting from telemetry studies. Smaller, lighter tags may reduce the likelihood of tags to affect animal health or behavior.

4.2.7 Stabilization and Data Processing

Some types of technologies can suffer from interference or “clutter” that can greatly complicate data collection and analysis (for example, Motus marine radar). Mechanisms for minimizing interference and increasing stabilization (for systems that require stable platforms) could support broader offshore deployments.

4.2.8 Commercial Scale Production

Currently, particularly for marine mammal technologies, production of monitoring technologies, such as 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 technical support would likely make tags and other technologies more consistent in function and less expensive. It would also improve availability of technologies, particularly for large-scale deployment in regional studies.

4.2.9 Robustness of Technology

Most marine mammal technologies are robust to marine offshore environments, but bird technologies, that may be adapted from land-based technologies, need additional improvements to increase durability, capability, and longevity in harsh marine environments.

4.2.10 Integration of Sensors

Integration of multiple complementary wildlife monitoring technologies, such as cameras and radar, can help minimize the biases and limitations of each singular method and produce more useful data for understanding OSW effects than either system could individually. For example, some systems use radar to track individuals at a larger scale and estimate flux while cameras can track individuals at a micro scale and help identify individuals to species, and passive acoustics can be used to assess species presence. In conjunction with environmental data, all three technologies 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 are also important for ecosystem-based modeling and scaling studies to assess cumulative impacts.

4.2.11 Other Considerations

To improve data reliability and statistical outcomes for monitoring studies, constraints must also be addressed around understanding the error factors and correction factors inherent to current technology systems. Development of training and calibration/validation datasets, as well as the prioritization and publication of validation studies, would be important steps to improving this situation. Publishing more information on effectiveness of technologies would improve researchers’ ability to apply the best technologies for their questions and environments. Finally, 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 would improve monitoring as new technologies are developed.

In addition, 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) and Regional Wildlife Science Collaborative (RWSC) 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; Van Parijs et al. 2021). Standardizing data collection and storage will improve the ability to integrate large datasets, which will be of value to modeling, population level consequences analyses, and prey studies. Integration of surveys at different geographic scales and collaborative survey design would also improve these types of studies (Regional Synthesis Workgroup of the Environmental Technical Working Group 2023; RWSC 2023). Cost is also a factor in technology use, so commercialization at scale is important for making technology accessible.

4.3 Potential Solutions and Opportunities to Improve Integration into Operations and Equipment

To fill the gaps associated with integration of bird and marine mammal monitoring into OSW operations and equipment, it is recommended that technology system and platform developments focus on the following:

- Reducing the need for physical access to systems by developing remote access to power and capabilities for remote data transfer;
- Improving attachment mechanisms, including attachment mechanisms that are robust and reduce the need for physical access to systems;
- Standardizing interfaces with infrastructure, including possible dedicated space for monitoring technologies on OSW infrastructure;
- Addressing safety and security issues;
- Developing deployment configurations and equipment to reduce interference from structures (e.g., blind spots in radar); and
- Coordinating planning processes early.

Engagement as early as possible between researchers and OSW infrastructure designers could allow for better integration of technologies to minimize issues with space, access, cybersecurity, and safety, and avoid delays and expenses during the monitoring plan development and implementation phase of the project. To improve this communication, it is recommended that information that is important for operational integration be made more accessible. OSW development has basic parameters that need to be met for operations; 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 and could be addressed. 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 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 project.

4.3.1 Physical Access

To address physical access issues, technology development should focus on remote data access and transfer, development of versatile mobile platforms not connected to OSW infrastructure, and use of fiber optics in cables for data transmission. Minimizing the need for access by including redundant systems will also reduce access needs. Improvements to attachment mechanisms and system durability and longevity would also be helpful.

4.3.2 Standardizing Interfaces with Infrastructure

Development of a standard “plug-and-play” space for technology deployment on OSW platforms is also recommended, as it could simplify this coordination substantially. Also, reducing the size and footprint of monitoring technologies would help to address physical space constraints. Integrated systems would also reduce the number of monitoring platforms that need to be deployed.

4.3.3 Safety

Safety issues can mainly be addressed with strong safety protocols and increasing remote and long-term deployment capabilities of monitoring technologies. Minimizing the number of people at sea and near/on wind infrastructure, as well as the period of time spent offshore, will minimize safety hazards. Ideally, no or very little recurring data download or maintenance work would be needed for technologies on the turbine hub, nacelle, or blades, and such work would only be conducted by trained technology maintenance personnel. Redundancies in systems and power sources would reduce maintenance, and improvements to remote data transfer would avoid the need for direct data download. Remote data transfer is also key to resolving data storage issues, along with algorithm improvements for filtering for important data.

4.3.4 Security

There are security concerns, particularly around cybersecurity, for technologies that are attached to infrastructure or would use infrastructure, such as cables, to transfer data. Direct access to OSW turbines, substations, or other infrastructure will be strictly controlled both because of safety and security issues. Cable fiber optics may be a viable option for data transmission, but this raises cybersecurity issues that require either 1) dedicated fiber for wildlife monitoring, or 2) data to pass through developer data lakes (centralized data repositories) prior to release to researchers. Passing through data lakes will affect the speed at which data can be used, particularly for real-time monitoring. Technical solutions to improve cybersecurity while making data transfer maximally efficient will improve monitoring outcomes and minimize security risks.

4.3.5 Reduction of Interference

Data quality is affected by interference from structures, natural and anthropogenic sound and light, and stabilization issues for monitoring equipment on platforms. Improvements to filtering mechanisms, antifouling approaches, placement for minimizing interference, and stabilization technology would improve data quality.

4.3.6 Coordination of Planning Processes

There is a mismatch between the typical timing of OSW infrastructure design and the development of wildlife monitoring plans. Early communication and collaboration between engineers/designers and technology developers/researchers can reduce the challenges of integrating technology into OSW infrastructure. Engagement as early as possible between researchers, regulators, and OSW infrastructure designers could allow for better integration of technologies and avoid issues with space, access, cybersecurity, and safety up front to avoid delays and expenses during the monitoring plan development and implementation phase of the project.

4.3.7 Technology Deployment on OSW Infrastructure

Deployment on OSW infrastructure is particularly challenging for the reasons enumerated in Section 3.3. Standardization and flexibility in platforms and technologies is important, including designing systems to operate on different countries' electrical systems and a common need for front-end engineering for common scientific research needs on platforms. The incorporation of a built-in capacity designated 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 to deploy monitoring technology more efficiently and effectively on turbines is recommended. 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 would facilitate important 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 would 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).

4.3.8 Case Studies

The case studies described in Section 3.3 reinforce the recommendations provided above and identify several opportunities for integration of monitoring into OSW equipment and operations, including use of vessels, turbines, and autonomous vehicles as platforms, development of standardized spaces on turbines for bird monitoring, addressing sensor integration, and considering how to detect potential for secondary entanglement for floating wind infrastructure. It is recommended that NOWRDC continue to build on these discussions to develop operational approaches to these cases.

4.4 Study Limitations

The use of workshops to identify technology gaps and operational limitations has constraints. 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. Identification of participants was mainly based on PAB input and Worley's and BRI's 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 get time from developers and turbine engineers, 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 report to also apply to other jurisdictions.

Additionally, the databases are a snapshot of technologies at the time of publication of this report 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 are likely inaccuracies remaining in the databases regarding the specific capabilities of individual technologies, many of which are changing rapidly. Our confidence in the identification of limitations, as well as prioritization of research needs, is limited by available data. Technologies with more public information 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 is informing our understanding of both wildlife behaviors and offshore wind effects as well as the capabilities of current technologies to answer key research questions.

4.5 Conclusions

There are substantial opportunities for bird and marine mammal monitoring technologies to improve access to power, data storage and remote data transfer, cybersecurity, standardized systems and interfaces with OSW infrastructure, mechanisms for minimizing interference and increasing stabilization, improve safety and reduce access issues, reduce system size and improve attachment options, integrate sensors, and develop commercial scale production to reduce costs and improve reliability. Additional automation is also needed for filtering, localization, and classification of animals and of data streams in standardized formats, as well as transfer into 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.]). Systems that can collect environmental data concurrent with animal movement and behavior data are important for ecosystem-based modeling and scaling studies to address cumulative impacts.

Many of the research and development needs to improve existing technologies are similar for birds and marine mammals; however, bird technologies are more likely to require integration with turbines, while marine mammal technologies are more likely to be robust to harsh marine environmental conditions. While there have been substantial advances in the capabilities of bird collision and avoidance monitoring systems at offshore wind farms in recent years (e.g., Skov et al. 2018, Tjørnløv et al. 2023, Robinson Willmott 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. There is also a mismatch between the typical timing of infrastructure design and the development of monitoring plans that may include this type of monitoring system. Early communication and collaboration between engineers/designers and technology developers/researchers can reduce the challenges of integrating technology into OSW infrastructure. 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, will much more effectively inform adaptive management of the OSW industry than disjointed, poorly designed individual efforts (NYSERDA 2021; Bureau of Ocean Energy Management 2017; Wilding et al. 2017). If the OSW industry does not improve the situation regarding technologies and data issues, it may result in a situation where large datasets have been 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 developments around the major gaps that were identified will support statistically robust data collection and practicable integration into OSW operations and equipment.

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