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CARBON TRUST

Roadmap to accelerate the commercial acceptance of seabird collision detection systems for offshore use

Prevalence of Seabird Species and Collision Events in Offshore Wind (PrediCtOr) project

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Lead Participant:	**The Carbon Trust,** PM: Bethany White, Bethany.White@carbontrust.com

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Project information

The PrediCtOr project was initiated and set up within the Offshore Renewables Joint Industry Programme (ORJIP) for Offshore Wind. The project is jointly delivered by the Carbon Trust, British Trust for Ornithology (BTO), and Waardenburg Ecology.

PrediCtOr project partners include: Equinor Energy AS; Ørsted Wind Power A/S; Rijkswaterstaat Water; Verkeer en Leefomgeving; RWE Offshore Wind GmbH; Shell Global Solutions International B.V.; The Scottish Ministers; TotalEnergies OneTech; and ScottishPower Renewables (UK) Limited.

The project forms part of the Offshore Wind Evidence and Change Programme (OWEC), led by The Crown Estate, in partnership with the Department for Energy Security and Net Zero and the Department for Environment, Food and Rural Affairs. The Offshore Wind Evidence and Change programme is an ambitious strategic research and data-led programme. Its aim is to facilitate the sustainable and coordinated expansion of offshore wind to help meet the UK's commitments to low carbon energy transition whilst supporting clean, healthy, productive and biologically diverse seas.



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Who we are

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Executive summary

Currently, seabird collision assessments rely heavily on modelling approaches that contain substantial uncertainty due to limited empirical validation. Automated collision monitoring technologies offer a potential solution but face challenges in achieving regulatory and commercial acceptance. The **PrediCtOr Roadmap to Accelerate the Commercial Acceptance of Seabird Collision Detection Systems for Offshore Use** sets out a framework to accelerate the commercial acceptance of offshore seabird collision monitoring systems capable of generating reliable empirical data.

The Roadmap was developed through a review of existing monitoring technologies, regulatory requirements and industry experience, alongside engagement with monitoring equipment suppliers, regulators, environmental authorities, offshore wind developers and researchers. Lessons from previous offshore deployments and findings from the PrediCtOr best practice guidance documents were used to identify the challenges limiting adoption and to define a framework for technology acceptance.

The assessment identified two overarching barriers to commercial acceptance: confidence in the quality and interpretability of data collected by monitoring systems, and confidence in the technical feasibility of deploying and operating these systems in offshore environments. Stakeholder engagement confirmed that both challenges must be addressed if monitoring systems are to support regulatory decision-making and inform future collision risk assessment approaches.

The Roadmap finds that industry confidence is currently constrained by the absence of recognised validation approaches, common performance expectations and consistent methods for communicating system capabilities. Stakeholders consistently emphasised the importance of transparency regarding system performance, limitations and operational requirements.

To address these challenges, the Roadmap establishes a set of six core performance indicators: spatial coverage, temporal availability, concurrency of target tracking, detection rates, target identification capability, and target localisation accuracy. Together these indicators provide a common language for describing performance and uncertainty across different technology types and deployment contexts.

The Roadmap sets out three maturity stages and the performance indicators required to meet them:

1. At the **baseline stage**, a system has been proven in onshore or nearshore settings and has generated evidence on core functionality, detection capability and operational limitations.
2. At the **pre-commercial stage**, the system has been demonstrated in an offshore wind farm environment, allowing its performance boundaries, data limitations and technical feasibility to be assessed under more representative conditions.
3. At the **commercial stage**, the system has shown reliable performance across multiple offshore deployments, with well-characterised limitations and sufficient evidence to support routine use in offshore monitoring programmes.

This framework shifts the focus from technology readiness alone to demonstrated performance readiness, recognising that commercial acceptance depends on both data quality and practical deployment success.

The Roadmap also highlights the potential for misalignment between developers and monitoring suppliers, and practical tools to support this. This includes a technical specification template to

consistently communicate system capabilities, and roles and responsibilities for each stage of the development process.

Overall, the Roadmap concludes that accelerated commercial acceptance will require greater transparency, improved offshore validation, shared performance metrics and stronger collaboration across the sector. By providing a common framework for evaluating and communicating monitoring system capability, the Roadmap offers a practical pathway towards routine deployment of offshore collision monitoring technologies and the generation of the empirical evidence needed to improve future seabird collision assessments.

List of acronyms and abbreviations

Acronym / abbreviation	Meaning
3D	Three-dimensional
AI	Artificial intelligence
Bft	Beaufort scale
BSH	Bundesamt für Seeschifffahrt und Hydrographie / German Federal Maritime and Hydrographic Agency
BTO	British Trust for Ornithology
CRM	Collision risk (rate) model
EIA	Environmental Impact Assessment
HSE	Health, safety and environment / health, safety and environmental requirements
IEC	International Electrotechnical Commission
ImpUDis	Improving understanding of distributional change for relevant seabird species
IP-rating	Ingress Protection rating
JNCC	Joint Nature Conservation Committee
KNE	Kompetenzzentrum Naturschutz und Energiewende
LiDAR	Light Detection and Ranging
OEM	Original equipment manufacturer
ORJIP	Offshore Renewables Joint Industry Programme
PCM	Post-construction collision monitoring
PrediCtOr	Prevalence of Seabird Species and Collision Events at Offshore Wind Farms
PTZ	Pan-tilt-zoom
QA	Quality assurance
RSZ	Rotor-swept zone
SCADA	Supervisory Control and Data Acquisition
SNCB	Statutory Nature Conservation Body
TRL	Technology Readiness Level
UK	United Kingdom

UPS	Uninterruptible power supply

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1. Introduction

The expansion of offshore wind (OSW) has intensified scrutiny of its potential effects on seabird populations, particularly the risk of collision-related mortality. Onshore, it is possible to gather empirical evidence on fatal collisions – such as the number of carcasses, species involved, and the circumstances of impact – through systematic carcass search studies. Offshore, however, this is more challenging. Carcass search studies are not feasible, and visual observation by human observers is similarly impractical. As a result, collision estimates must rely on modelling approaches that inevitably draw on generalisations and expert judgement, and which are at present difficult to verify or calibrate with empirical data. This introduces considerable uncertainty into the resulting assessments.

Automated collision detection systems offer a potential solution for collecting empirical data on bird collisions at offshore wind turbines. Regulatory bodies, environmental agencies, researchers and offshore wind developers have all shown increasing interest in the potential of such systems. Yet, as with any emerging technology, the reliability and robustness of the data they produce remain key concerns. Establishing confidence in automated monitoring outputs is therefore essential if these systems are to support offshore monitoring programmes and inform regulatory decision-making.

Camera- and sensor-based systems have been deployed at onshore wind farms for several decades, primarily for deterrence or turbine shutdown, rather than for direct collision counting. These systems rely on automated detection to record bird activity around the turbine, which underpins any subsequent action. The underlying detection capabilities have been assessed and, in some cases, validated through evaluations of system effectiveness for mitigation.

Recent advancements in sensor technologies, data-processing automation, and the growing need for empirical offshore collision data are driving the development of offshore-ready systems. However, early adoption of insufficiently validated technologies risks undermining confidence across the sector and could slow progress if regulators and developers cannot rely on the data collected. A clear understanding of system capabilities, limitations, and validation requirements are therefore crucial to ensuring these technologies are accepted and used effectively.

With an increasing number of system suppliers and a wider range of automated monitoring systems on the market, reducing uncertainty and validating systems' functionality and outputs are becoming increasingly important. This Roadmap sets out a common framework for evaluating and communicating monitoring system capability, offering a practical pathway towards commercial acceptance and routine deployment of offshore collision monitoring technologies.

1.1. Purpose and scope of the Roadmap

The **Prevalence of Seabird Species and Collision Events at Offshore Wind Farms (PrediCtOr)** project was established to develop a coordinated approach to reduce uncertainty about seabird collision risk and to improve post-construction collision monitoring (PCM) at offshore wind farms.

This PrediCtOr **Roadmap to accelerate the commercial acceptance of seabird collision detection systems for offshore use** identifies current technical and operational challenges, highlights key areas of uncertainty, and sets out the performance indicators required for each of the stages towards commercial acceptance. It also promotes alignment among developers, regulators, equipment suppliers, and environmental stakeholders on what constitutes robust, reliable collision-detection systems for offshore use.

We outline the performance indicators providing the technical basis for assessing system readiness, and translate these into a staged maturity framework, showing how evidence requirements increase from baseline testing to pre-commercial offshore demonstration and, ultimately, commercial deployment. This approach allows system maturity to be assessed in terms of demonstrated performance and documented limitations, rather than technology readiness alone.

Ultimately, this Roadmap seeks to provide clear expectations for monitoring equipment suppliers, offshore wind developers, regulators and other stakeholders, while encouraging open dialogue on the strengths and limitations of automated systems. By doing so, it aims to support faster, more confident adoption of technologies that generate robust empirical evidence to inform future assessments and policy. For industry, this also means better informed decisions about monitoring equipment, increasing the value of monitoring investments and the utility of the data collected.

The focus of the Roadmap is on monitoring systems capable of detecting bird collisions to generate empirical data. Many points we develop also apply to automated monitoring systems offshore that have a different objective, e.g. collecting data on flight activity close to turbines and where relevant, the Roadmap also discusses automated systems that provide other learnings, but the focus is ultimately on systems that aim to count collisions.

While the broader offshore environment affects many bird species, the PrediCtOr project scope focuses specifically on **seabirds** and **daytime monitoring**. Migratory landbirds are acknowledged as collision susceptible, but because their migration primarily occurs at night and over broad spatial corridors, they require different detection capabilities and system configurations.

This Roadmap sits alongside the PrediCtOr best practice guidance documents on data and monitoring system deployment (Carbon Trust, 2026a; Carbon Trust, 2026b). Those documents provide detailed guidance on the collection, management and analysis of monitoring data, and on the design, installation and operation of monitoring systems offshore. This Roadmap does not seek to replicate that guidance and focuses on the broader challenge of gaining commercial acceptance of collision monitoring systems. Where data and design considerations are referenced in this Roadmap, readers should refer to the PrediCtOr best practice guidance documents for detailed recommendations.

1.2. Aims of the Roadmap

This Roadmap seeks to accelerate the commercial acceptance of automated seabird collision monitoring technology for offshore wind farms by:

- Identifying steps to increase confidence in the quality and reliability of collected data by setting out stages for commercial acceptance of monitoring technology.
- Supporting the development of shared industry expectations and requirements for offshore collision monitoring technologies.

1.3. Methodology

To develop the Roadmap, the PrediCtOr project undertook a review of existing offshore and onshore collision monitoring approaches, assessed current regulatory requirements across key offshore wind markets, and carried out multiple rounds of engagement with monitoring equipment suppliers, regulators, environmental authorities, offshore wind developers, and researchers. The findings were

supplemented by lessons from previous offshore monitoring deployments. This evidence base was used to identify the principal barriers to commercial acceptance, define common performance indicators, and develop a maturity framework describing the progression from baseline testing to commercial deployment.

1.4. The need for empirical data

The current lack of empirical data on bird collisions with offshore wind turbines has led to heavy reliance on collision rate models (CRMs; also called collision risk models). CRMs are used in assessments of prospective wind farms to estimate the potential number of collisions within Environmental Impact Assessments (EIAs). These models require a range of input data specific to the species and wind farm in question, from empirical data to broader estimates based largely on expert opinion. It is these less well-known parameters that have the most influence on the model results, leading to uncertainty in the actual numbers of collisions. This uncertainty can be further amplified by the variability of these parameters (Table 1).

Table 1: Overview of input parameters commonly used in collision rate models and their associated availability and variability, and influence on the model outcomes.

Parameter	Availability and variability of data	Influence on outcome
Bird length, wingspan **Rotor diameter, width, hub height (air gap)**	Good data, low variability	Low
Operational time	Good data, low variability	Medium
Rotation speed, pitch **Flight speed** **Proportion at collision height (flight height)** **Nocturnal activity**	*Quality of data varies depending on species, location and methods used* Relatively good data for fair weather conditions, relatively high variability	Medium
Bird density **Avoidance**	*Quality of data can vary depending on species, location and methods used. Generally good data on densities for fair weather conditions* Limited or no data on avoidance rates, high variability	High

Many monitoring programmes have focused on improving the data fed into these models to improve future assessments. While this is highly valuable and adds to understanding, uncertainty about the occurrence of collision events is likely to remain, particularly given the influence and variability in avoidance rates (where fractional changes can have great impacts on the model results), and because fundamentally the correctness of the model structures (that aim to estimate frequency of collisions based on a number of other factors) cannot be evaluated by assessing input parameters alone. To overcome this, the **direct recording of collision events is crucial and will provide unique insights into their frequency and occurrence.** Considering the expected infrequency of seabird collisions with offshore wind turbines and the remote locations, automated monitoring systems provide the best opportunity for this.

Within this Roadmap, we focus on collecting empirical data on collisions using automated collision-detection systems, as this approach has the greatest potential to accelerate understanding of seabird collisions with offshore wind turbines. Nevertheless, many of the learnings and stages outlined to achieve acceptability apply to other automated monitoring systems.

1.5. Regulatory requirements

Regulatory requirements for bird collision monitoring at offshore wind farms are most developed in Europe, particularly in North Sea markets, though current rules and recommendations remain relatively non-specific.

Table 2: Regulatory requirements for offshore seabird collision monitoring.

Country	Regulatory requirements for seabird collision monitoring
The United Kingdom	PCM conditions are typically determined on a case-by-case basis through discussions between regulators, Statutory Nature Conservation Bodies (SNCBs), and developers; there are generally no fixed monitoring equipment requirements. Requirements may vary substantially between projects depending on perceived risk, species sensitivities, and development-specific considerations.
The Netherlands	Dutch regulators do not prescribe rigid equipment requirements. However, certain Ministerial Orders include qualitative expectations, such as the need to reduce collision casualties or employ monitoring methods that can identify species, document turbine shutdown decisions, or capture key metrics such as flight altitude and speed. These orders may refer to particular combinations of technologies (e.g. cameras, radar, or sensors) and may specify the number of turbines to be monitored or the level of species-level identification required.
Denmark	Danish construction licences may include general environmental monitoring obligations but historically have not included specific requirements for collision detection systems or detailed equipment specifications.
Germany	Germany has the most explicit regulatory framework. Under BSH requirements for migratory bird monitoring, developers are required to undertake combined surveys of site-related migration activity, the number of birds flying through the rotor area, and collisions of birds, as well as accompanying data on weather and the operational status of the turbines using various systems (e.g. calibrated radar, camera and weather sensors)[1]. Methods must be suitable in terms of a continuous and automated survey (day and night) at least during the main migration periods. The number and position of the monitoring systems need to ensure a representative survey of the wind farm. Specialised bird radars for survey of migration intensity and phenology must be used, provided they are the latest technical standard.[2] There are no specific requirements for seabird monitoring.

[1] For further information on systems, please see Section 2.1.
[2] Further requirements exist under the German planning approval process stipulated by the Offshore Wind Energy Act (WindSeeG), to cover activities during the construction period aimed specifically at reducing the risk of bird collisions (e.g. light management for vessel crews when birds are present, monitoring of weather conditions with a particular focus on those that may lead to higher risk of bird attraction, radar-monitoring of bird migration intensity (Feb-May and July-Nov), and warning procedures for offshore vessels concerning the risk of attraction under specific conditions).

Although many jurisdictions do not mandate specific equipment types, regulators commonly require some form of PCM, creating opportunities for automated systems – particularly when they can demonstrate reliability, species discrimination capability, and appropriate spatial coverage. In the UK, SNCBs have expressed support for combined system approaches, such as integrating 3D radar with high-definition cameras or thermal imagery, which improve collision-detection confidence and species-identification accuracy.

2. Technical foundation for collision monitoring systems

Throughout this Roadmap, the term “automated monitoring systems” refers to complete end-to-end monitoring solutions. This includes monitoring technologies (e.g. cameras and sensors), power and communication infrastructure, on- and off-turbine control hardware, data storage, and software for detecting and recording collisions. Components such as cables, mounts, and other installation elements are included because, while they do not directly influence data accuracy, they must withstand the environmental and operational demands of offshore deployment.

Automated monitoring systems cover a range of different systems, with varying aims as pictured in Figure 1. While this Roadmap focuses specifically on offshore collision monitoring systems, certain challenges they face are also encountered by other types of automated monitoring systems, particularly when transitioning to an offshore environment. As such, throughout this Roadmap we may refer to learnings that can be made from other automated monitoring systems, and its applicability to collision monitoring systems in an offshore environment.

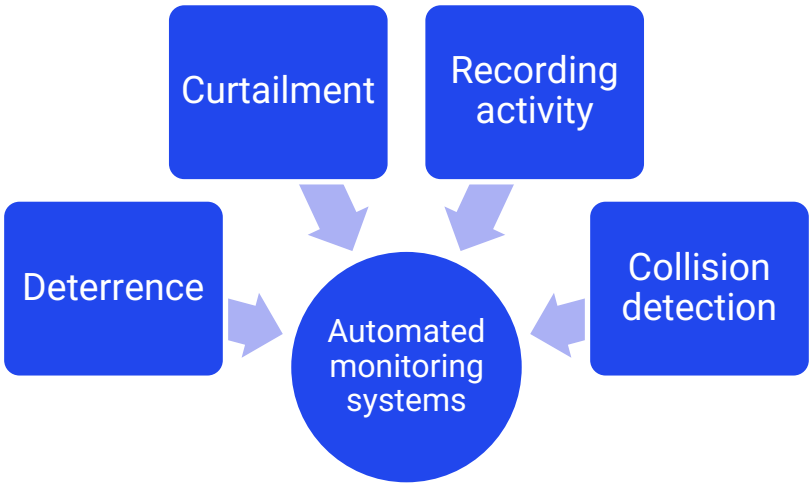


Figure 1: Types of automated monitoring systems.

2.1. Types of monitoring technologies

The range of automated monitoring systems currently available on the market includes technologies such as cameras and blade-mounted vibration or acoustic sensors. Some systems also incorporate thermal imaging, light detection and ranging (LiDAR), or radar, although these technologies can be considered less suited for species identification and/or for detecting birds close to the rotors and therefore for collision detection monitoring (Table 3). Nevertheless, these technologies can be used in combination with other technologies to provide additional benefits for a complete system, such as the longer detection range of radars or night-time detection capabilities by thermal cameras.

Table 3: Overview of monitoring technologies used in automated monitoring systems and their suitability within collision detection systems.

Monitoring Technology	Description	Benefits and limitations	Suitable for collision detection monitoring?
Camera (daylight)	Visual imaging device that captures pictures or video using visible light.	- Provides species identification - To combine with image recognition/AI software - Limited to daytime/good visibility	Yes
Thermal imaging	Detects infrared radiation (heat) and translates into visible images.	- Works at night - No species identification - Limited range - To combine with daylight cameras for species identification	Yes in combination with (daylight) camera
Vibration sensor /accelerometers	Measures the change in motion or vibration.	- Can act as trigger of collision event - To combine with cameras for verification (e.g. specifically daylight camera for species identification)	Yes in combination with (daylight) camera
Acoustic sensors	Detects sound waves by converting pressure into electrical signals.	- Can act as trigger of collision event - To combine with cameras for verification (e.g. specifically daylight camera for species identification)	Yes in combination with (daylight) camera
LiDAR	Uses multiple short-duration laser pulses to create a 3d map of the sampled area, including any airborne objects.	- Limited or no detection close to turbines (susceptible to clutter/shadow effect) - Works during day and night - No species identification - To combine with (daylight) camera for species identification	No
Radar	Uses radio waves to determine distances of detected airborne objects.	- Large range (several kms) - Works during day and night - Limited or no detection close to turbines (susceptible to clutter/shadow effect), or during rain/periods with high waves - Performance may be constrained above certain wind-speed thresholds - No species identification - To combine with (daylight) camera for species identification	Only in combination with (daylight) camera (which have greater range and allow species recognition cf. thermal cameras)

The exact set-up of the system, including the types, specifications and numbers of each of the component sensors will depend on a range of variables. Importantly, these sensors must be integrated into a complete system that includes suitable power, storage and communication components as well as software to ensure the functionality of the entire system.

A final consideration is the deployment of collision detection systems within a monitoring campaign, including numbers of turbines monitored, locations within the wind farm, and timing and length of the study. This is outside of the scope of this Roadmap and independent of the acceptance of automated monitoring systems. Any monitoring campaign will likely be developed as part of licensing requirements or a larger study in which the monitoring set-up is developed.

2.2. Existing use of automated monitoring systems

Onshore, a variety of automated monitoring systems are in operation. Most of these focus on deterrence and/or shutdown triggered by real-time detection and identification of target species using automated processing of camera images (e.g. Fric, Tzen & Tzali, 2018). Some camera-based systems focus solely on collecting data on bird activity, using software to detect and identify species; other systems aim to record collisions using acoustic or vibration sensors, and/or cameras. Collisions at onshore wind farms are more commonly monitored using carcass searches, with cost and practical aspects likely factors in this choice, along with uncertainty around the accuracy of estimates based on data collected by collision detection systems onshore.

Automated monitoring systems developed for used within onshore wind farms generally focus on diurnal birds of prey, particularly those relating to shutdown. Nevertheless, identification software can be trained and systems tuned for particular study species and locations.

Onshore systems cannot be directly transferred offshore, where turbine specifications, target species, and environmental and regulatory conditions differ substantially. As a result, onshore performance metrics may not translate to offshore environments; application of monitoring systems offshore may also be limited by project-specific technical considerations, such as power availability and data access, implications of mounting systems on turbine structures, and developer-specific practices or ways of working. Many of these factors are inherently project specific and will therefore require tailored, site-specific solutions.

Several automated monitoring systems have been deployed at offshore wind farms with the focus mainly being to collect data on bird activity (Carbon Trust, 2026a). Many use integrated, multi-sensor configurations, combining cameras, radar, and visual observations to capture bird movements across spatial scales (e.g. meso- and micro-avoidance). Additional technologies such as acoustic sensors, LiDAR, and bird-borne telemetry have been used in supporting roles where relevant to study objectives. Experimental approaches, including blade-mounted acoustic or vibration sensors, have seen limited offshore application but are of growing interest as potential tools for detecting collision events.

2.3. Comparing automated monitoring systems

Automated monitoring systems are customised within each project. Whether it is the number or specifications of components, or the software settings, automated monitoring systems are tailored for the species, wind turbine, location, and desired monitoring outcome. This makes direct comparisons between systems challenging.

Similarly, systems cannot be compared by their technical sensor specifications alone. For example, higher resolution cameras provide clearer images for human interpretation, but this may be less important when processing images with software, which may benefit from the smaller file sizes of lower resolution images.

3. Challenges for the commercial acceptance of collision monitoring systems offshore

Currently, there are no recognised standards or widely accepted guidelines for the use of collision monitoring systems offshore, such as those that exist for automated shutdown systems onshore (Wulfert *et al.* 2022; Smallie *et al.* 2024). Guidelines of this type help set out clear aims and targets against which systems can be measured. This is also important for determining when an automated system has reached an acceptable level of maturity. The initial step towards agreeing on these stages is identifying the challenges.

Based on discussions with regulators, system suppliers, offshore wind developers, and researchers, two key challenges exist for the acceptance of automated collision detection systems[3] offshore, namely:

1. ensuring confidence in the data collected, including understanding its limitations in functionality; and
2. the technical feasibility of the systems being deployed and operated in offshore wind farms.

These challenges mirror those identified for onshore systems, where functionality, integration, and validation remain key barriers (Gottlieb *et al.*, 2025). However, offshore systems introduce additional complexities that require distinct assessment pathways.

These two challenges can be addressed separately, to enable stakeholders to focus on the unique requirements of data reliability and hence suitability to produce information that satisfies regulatory demands versus technical and practical deployment considerations. The challenge of data confidence will be a key question for developers and regulatory and environmental authorities, particularly in relation to the collection and interpretation of data to satisfy research aims and any regulatory requirements. The second, relating to the technical and practical aspects, will be the focus of developers and system suppliers.

3.1. Confidence in the collected data

The most significant challenge in using automated monitoring systems offshore is achieving confidence in the accuracy, reliability, and interpretability of the collected data. Understanding both system capabilities and limitations is essential for accurate analysis and meaningful conclusions.

3.1.1. Validation of data performance

Onshore validation typically involves combining automated detection assessments with observer comparisons and carcass searches, often conducted during periods of high bird activity. These conditions are rarely representative of offshore species, behaviours, or visibility challenges.

Validation offshore is constrained by practical, logistical, and financial factors. Offshore work requires certified personnel, is governed by strict health and safety regulations, and is limited by weather and accessibility. The cost of offshore fieldwork is also substantially higher than onshore.

[3] This also applies to automated monitoring systems offshore irrespective of the exact focus, whether direct monitoring of collisions or collecting data on flight activity close to turbines.

Additionally, collision carcass searches cannot be conducted, and field observations – whether from vessels, platforms, or turbines – are limited to specific locations and conditions. Collision events themselves are presumed to be rare, further extending the timeframe and spatial scale required for effective validation.

3.1.2. Improving confidence in the collected data

Confidence in collision monitoring outputs depends on a clear understanding of system performance and its limitations. These considerations are essential when selecting a system, designing a research programme, and assessing a system's fitness to meet regulatory standards.

Given the constraints around offshore validation, lessons from comparable scenarios are particularly valuable, helping to identify strategies for achieving commercial acceptance. Understanding when and why false negatives (i.e. the lack of detecting a collision event or near miss) occur is especially important, as systems may fail to detect an event or may stop operating altogether without obvious indicators. Understanding and quantifying the incidence of false negative detections is an outstanding challenge, given that carcass searches, which form an important component of ground truthing in onshore applications, are impossible in the offshore environment. A robust understanding of how systems observe bird transits, near misses and collisions is crucial to draw inferences about what might be missed by a system, and the performance indicators developed in this Roadmap are intended to provide a framework for this.

3.2. Confidence in the technical feasibility of deployment and operation

The second major challenge relates to the practical deployment and long-term operation of automated monitoring systems offshore. This affects all types of offshore monitoring technologies and includes issues such as hardware attachment, cable routing, secondary equipment placement, cybersecurity, and maintenance requirements that must withstand harsher offshore environments. These challenges differ markedly from onshore environments due to regulatory differences, developer requirements, and the physical realities of working in remote offshore settings.

The PrediCtOr project's Design best practice guidance provides guidance on mounting camera and radar systems (Carbon Trust, 2026b), but system-specific and site-specific challenges will continue to require bespoke solutions. Previous offshore deployments provide useful insights, yet early and open dialogue between suppliers and developers remains the most effective strategy for identifying feasible approaches. Nevertheless, developers highlighted differences in the technical information provided by different suppliers often makes comparisons difficult and increases the time and costs of the orientation stage early in the process.

To facilitate early-stage communication between suppliers and developers, **we have developed a technical specification sheet (Appendix 1)**, which is intended as a template for suppliers when providing initial technical information of systems to developers; relevant sections may also be shared with regulatory and environmental authorities to support transparency. The list of attributes has been developed following input from developers and aims to cover key information for assessing the technical suitability of systems and potential considerations for deployment. This list is not exhaustive but rather aims to provide a standardised overview in the initial stages of system selection.

This is relevant to all automated monitoring systems, but challenges arise when transferring systems that have been used onshore to offshore situations. In particular, onshore deployments will not be

representative of the offshore environment or the seabird species present. Onshore performance metrics, such as detection range or classification accuracy, may not translate to offshore environments because of:

- Limited options for system placements, generally either at the focal turbine (requiring wide sensor field of view) or at neighbouring turbines (requiring large sensor range);
- Larger turbines and greater distances between them (potentially limiting the relative coverage of sensors);
- Sensor types varying in coverage and detection;
- Sensor and housing types or different environmental conditions affecting periods of operation;
- Bespoke target identification classifiers that are optimised for the specifics of the original deployment context (taxonomic, environmental);
- Sea clutter within radar traces affecting (i) detectability of seabirds flying close to the sea surface, where wave crests may obscure birds and increase the level of background noise and (ii) tracking performance of automated tracking algorithms when acquiring and maintaining targets.

These factors may limit the application of detection and identification rates and ranges recorded at onshore deployments. In some instances, monitoring systems with a specific purpose onshore, such as automated shutdown, may be repurposed to purely detect collisions offshore. In this instance, the performance thresholds for an automated shutdown may be different than those for purely detecting collisions.

In addition to the environmental challenges, there are several project-specific technical challenges that may limit confidence in the system:

- Power availability and data access, particularly with confidentiality issues
- High cybersecurity requirements which can limit remote access to a secure gateway connection
- Mounting of the system onto the wind turbine and the impact on design
- Developer-specific issues or ways of working

Many of these challenges are project-specific and will require tailored solutions. As outlined further in Chapter 5, challenges may arise at any stage of the technology's lifecycle, and early engagement between suppliers and developers provides the best opportunity for resolving them.

3.2.1. Validation of system technology

Validation of collision monitoring systems is part of each system's internal research and development process. Accordingly, most validation is conducted in-house during testing and development. Despite these processes, questions often remain about the collected data and the technical and practical aspects of long-term deployment. Increased transparency around validation methods, results and associated evidence may help address some of these uncertainties and improve stakeholder confidence in monitoring systems.

The Technology Readiness Level (TRL) framework is a commonly used indicator to assess the technology maturity within a specific environment. Although TRLs are used within the offshore

renewables sector, the levels assessed are not fully interchangeable between suppliers and technologies. Where a supplier may have assigned a specific level to their technology, a developer may often re-assess this in line with their own requirements. It must also be noted that the TRL framework does not take into account the overall maturity of the system, but rather the technology itself, and additional factors may need to be considered to assess full commercial viability and readiness for deployment (Carbon Trust, 2016).

Definitions of TRL can vary, so it is recommended that projects agree on a common interpretation at the outset, such as the European Commission's TRL definitions (Table 4).

Table 4: Technology readiness level (TRL) definitions (European Commission, 2014).

Research	1. Basic principles observed
	2. Technology concept formulated
	3. Experimental proof of concept
	4. Technology validated in a lab
Development	5. Technology validated in a relevant environment
	6. Technology demonstrated in a relevant environment
Deployment	7. System prototype demonstration in operational environment
	8. System complete and qualified
	9. The actual system proved in the operational environment

3.2.2. Improving confidence in the technical feasibility

Improving confidence in the technical feasibility of offshore collision monitoring systems requires a clear understanding of the operational demands of offshore wind farms and the minimum standards that systems must meet to perform reliably in this environment. Confidence in technical feasibility is built not only on system robustness, but also on clarity around operational expectations, maintenance needs, and long-term reliability.

At a minimum, systems deployed offshore must fulfil offshore engineering standards and windfarm operational regulations, including:

- weather- and marine-proof housings
- cables and components capable of withstanding corrosive and high-energy marine conditions
- safe electrical integration,
- cybersecurity protocols governing data transfer and network connectivity

Independence of system power and communication pathways may be preferred in some cases, both to avoid interference with turbine operations and to increase operational resilience during adverse conditions.

Confidence also increases when system performance is documented systematically across deployments. Adhering to offshore standards such as IEC 60529 to detail ingress protection/ weatherproofing of the technology is key.

3.3. Improving confidence in offshore collision monitoring systems

Validating systems offshore is a critical gap hindering the commercial deployment of collision monitoring systems, compounded by the absence of a standardised validation framework. Although approaches differ among suppliers, developers, and regulators, several principles are widely shared:

- Transparency about development and testing,
- Offshore validation as the highest standard, and
- Use of TRLs as a benchmark for maturity.

Strengthening validation protocols is essential to building regulatory and industry confidence. The case study below shows a potential framework for accepting collision monitoring technologies.

Case study: framework for acceptance of land-based automated detection and shutdown systems in Germany

In Germany, automated detection and shutdown systems that are proposed as a mitigation measure onshore must be approved within a framework under German environmental law and include details of how they will prevent bird mortality. Suggested prerequisites that approved systems need to achieve include: 1) pre-construction evaluation of system parameters; 2) post-construction validation of system parameters; 3) assurance of full technical operability, including back-up mitigation measures; 4) documentation of curtailment events; 5) allowances for subsequent technical improvements (KNE 2019). Brun *et al.* (2021) outline recommendations for automated shutdown systems on land and including minimum requirement thresholds for coverage, detection and identification. These recommendations specifically refer to automated shutdown (e.g. coverage needs to consider flight corridors and system/turbine reaction times) and are generally aimed at protecting birds of prey, so their specifics will differ from systems aimed solely at collision detection of offshore species without a shutdown component where different species, ecological situations and required outcomes are expected. As such, the specific requirements and performance thresholds might not be directly transferable to offshore collision monitoring applications. Nonetheless the general principles about system maturity and reliability hold, and were used to inform this Roadmap.

A further barrier to progress is the limited sharing of data from offshore deployments. Restricted access to system outputs inhibits a supplier's ability to demonstrate consistent performance and constrains collective learning within the sector. This barrier is not a property of any particular system per se, but highlights that these monitoring systems need to operate in a context where suppliers, developers and regulators ensure that performance metrics and to some extent the monitoring data are available to relevant stakeholders. Without improved collaboration and data exchange, opportunities for cross-validation and the development of best-practice guidance will remain limited. Regulatory and environmental authorities have also emphasised that any performance standards adopted for offshore contexts must reflect ecological relevance, particularly the need for accurate identification of seabird species.

In addition, the establishment of a certification scheme, perhaps through use of independent auditing, could be a mechanism to achieve proof of performance for the industry against the framework specified in the Roadmap. Achieving full commercial readiness for offshore collision monitoring systems therefore requires greater consistency across the industry and a shared understanding of performance expectations. However, the variety of collision monitoring systems means using fixed benchmarks is complex.

To support this aim, stakeholders representing offshore wind developers, equipment suppliers, and regulatory and environmental authorities were engaged in developing this Roadmap. The following solutions have been identified as essential to build confidence in offshore collision monitoring systems, while also supporting innovation and supplier openness and enabling users to make well-informed decisions:

- Improve transparency and understanding of the system limitations. **This is addressed in Chapter 3 of this Roadmap.**
- Develop stages for acceptance for the two challenges of i) data confidence and ii) technical feasibility. **This is addressed in Chapter 4 of this Roadmap**.
- Identify performance indicators that collision monitoring technologies would be expected to meet, for example:
    - Deployment and operation aspects (e.g. maintenance schedules and expected downtime)
    - Data limitations (e.g. conditions when data can be collected as expected; periods when no data is collected)

  This is addressed through the performance indicators and maturity framework **presented in Chapter 4**.
- Agree performance indicators with regulators, to include in monitoring requirements. **While this is considered outside of the scope of this Roadmap**, until more systems have been deployed, **the embedding of more prescriptive survey and metadata standards in consent conditions is likely a useful pathway to ensure that future monitoring data are considered fit for collision risk quantification by regulators from the outset.**
- Outline guidelines based on the stakeholder roles and responsibilities and operational steps to indicate performance readiness. **This is addressed in Chapter 5 of this Roadmap.**
- Outline the expectations of key information needed from suppliers to make well informed choices and streamline decision making. **The technical specification sheet in Appendix 1 addresses this.**

Through the establishment of transparent performance stages, clearer expectations, and improved documentation practices, the sector can move towards a more consistent and evidence-based approach to accepting collision monitoring systems for commercial offshore use.

3.4. Performance indicators for monitoring systems

The lack of consistent effort data, poor metadata standards and ambiguous species identification have been highlighted as fundamental challenges to the robust analysis of post-consent monitoring data

(Carbon Trust, 2026c). Similar challenges are a risk in collision monitoring and point to a common need: stakeholders must be able to describe system performance in a clear, measurable and comparable way. Without this, claims about data quality, reliability or commercial readiness remain difficult to assess. A shared set of performance indicators is therefore needed to describe what a system observes, when it is operational, how reliably it detects and identifies relevant targets, and how well its outputs can support collision-risk interpretation.

These indicators are not intended to prescribe a single technology configuration or fixed performance threshold for all use cases. Instead, they provide a common language for describing system capability and uncertainty across different sensor types, deployment contexts and monitoring objectives. They also provide the basis for assessing whether evidence from experimental testing, onshore trials, offshore demonstrations or operational deployments is sufficient to support increasing levels of confidence. Well-documented observations of collisions at offshore turbines remain scarce, and therefore there is no reliable evidence base for defining an explicit indicator that measures whether or not a collision is detected by a system. Rather, the following section proposes a set of performance indicators that can be used to describe the fundamental capabilities and limitations of collision monitoring systems to observe bird movements at or near the rotor across different technologies and deployment contexts.

Spatial coverage: the sampled volume

Quantifying effort across space and time requires accurate knowledge of the **sampled volume**, i.e. airspace that is reliably observed by the monitoring system. This governs which collisions and/or movements of birds near the rotor-swept zone are available to be observed. Geometric constraints of the sampled volume arise from the field of view of the employed sensors, e.g. the field of view angles and sensor resolution of a camera system, the beam shape of a radar, or the coverage of blades with impact sensors. The geometry of the sampled volume may take a complex shape, particularly in multi-sensor systems where the overlap of different sensor fields-of-view determines the effective sampled volume and/or when objects such as turbines or other structures obscure the sensor's field of view. The shape of the sampled volume may further change with environmental conditions, e.g. as the detection range changes (see below).

Temporal availability: system uptime

Temporal availability of the monitoring system is shaped both by planned (e.g. for maintenance) and unplanned system downtime, as well as by the integrity of the data stream, e.g. a system may have been monitoring but data is lost or corrupted on storage or transfer. System uptime adds a temporal constraint on the collisions and/or movements of birds that are available to be observed.

The reasons for and duration of planned and unplanned downtime should be clearly documented, including outages affecting individual sensors. Monitoring systems should not be expected to achieve 100% availability; therefore, this information is important for understanding the completeness of the resulting monitoring data.

Concurrency of target tracking

In addition to temporal and geometric constraints there may be further system characteristics that limit which birds can be observed, notably system limits on the simultaneous monitoring of concurrent

targets. This may be a particular issue for systems using cameras that are not using triangulation (such as stereographic cameras and PTZ cameras) to identify targets and/or reconstruct their movement trajectories.

Detection rates within the sampled volume

Within the sampled volume, detection is almost always imperfect, i.e. not all birds that are available to be observed in the monitored airspace are registered by the monitoring system. In general detectability decreases away from the sensor or observer, e.g. because the radar energy and therefore magnitude of an echo declines with range, or because the image resolution relative to target size declines in a digital image. Detection rates for many sensor types are not only range dependent, but also sensitive to environmental conditions. For example, noise from waves under inclement at-sea conditions (e.g. Douglas sea state 3 and above) may obscure targets and prevent tracking, and heavy precipitation may increase noise in radar data and reduce the visibility.

A robust understanding of detection rates across the sampled volume and across the full range of operational conditions is critical to understand target detection rates in the collision risk zone and/or to get an unbiased understanding of spatial variation in target densities around wind turbines. This may also be informed by understanding detection ranges for different sized targets, for instance under different sea states, e.g. using computer-aided radar performance evaluation tools, and would enable comparisons among systems.

Target identification

Only detected targets are available for identification, and identification, typically achieved using human review and/or machine learning classifiers, can vary in taxonomic resolution (size class, species group, species) and accuracy (correctness of classification) depending not only on sensor technology and system skill (e.g. radar and vibration sensors are fundamentally unable to identify biological species, but may be able to distinguish size classes of targets), but also the composition and diversity of the species assemblage encountered at a given site (e.g. discrimination between species of similar appearance typically requires higher classifier skill). Training of machine learning classifiers / AI systems to identify species from site-specific sensor data is typically part of the system deployment process.

In assessing a system's capability it is important to distinguish resolution and accuracy of the identification process. Unresolved targets (e.g. those with ambiguous labels such as "Gull species") reduce the efficiency of monitoring with respect to target species of regulatory concern, as events observed with an ambiguous target label may need to be treated in a precautionary manner. In contrast, misidentified targets (i.e. false positive/negative identifications that result in the wrong label being attached to a target) reduce the accuracy of a monitoring system potentially leading to false positive or false negative assignments of events to target species of regulatory concern.

Accuracy and precision of target localisation

Many currently available collision monitoring systems rely on indirect evidence from changes in target trajectories to assess whether or not a collision has taken place. Such methods are likely to be affected by measurement error in the target localisation, i.e. when a bird is available and detected, but the measured location relative to the focal turbine is inaccurate. Knowledge of the accuracy of target localisation is crucial for the interpretation of such indirect evidence, which is likely to remain a key

source of collision monitoring data. Similarly, target localisation is also in principle of interest for direct collision detection through impact sensors, so that the location of the collision relative to the focal turbine can be established.

3.5. From challenges to commercial acceptance

Chapter 3 identified key challenges limiting commercial acceptance of collision-risk monitoring technologies and proposes measures to improve confidence in system performance and deployment readiness. The performance indicators described above provide the technical basis for assessing system readiness. Chapter 4 translates these indicators into a staged maturity framework, showing how evidence requirements increase from baseline testing to pre-commercial offshore demonstration and, ultimately, commercial deployment. This approach allows system maturity to be assessed in terms of demonstrated performance and documented limitations, rather than technology readiness alone. However, overcoming these barriers will also require coordinated action by technology suppliers, developers, regulators, researchers and industry bodies. Chapter 5 outlines stakeholder roles and responsibilities to achieve greater regulatory and commercial acceptance of these technologies.

4. Maturity stages for collision monitoring systems

The performance indicators described in Chapter 3 provide the technical basis for assessing system readiness. This chapter translates these indicators into a staged maturity framework, showing how evidence requirements increase from **baseline** testing to **pre-commercial** offshore demonstration and, ultimately, **commercial** deployment. This approach allows system maturity to be assessed in terms of demonstrated performance and documented limitations, rather than technology readiness alone.

The three maturity stages defined in this Roadmap are:

1. At the baseline stage, a system has been proven in onshore or nearshore settings and has generated evidence on core functionality, detection capability and operational limitations.
2. At the pre-commercial stage, the system has been demonstrated in an offshore wind farm environment, allowing its performance boundaries, data limitations and technical feasibility to be assessed under more representative conditions.
3. At the commercial stage, the system has shown reliable performance across multiple offshore deployments, with well-characterised limitations and sufficient evidence to support routine use in offshore monitoring programmes.

These stages are intended to reflect **performance readiness**, rather than simply technology readiness. Technology Readiness Levels can provide useful context for understanding whether a technology has progressed from concept to deployment, but they do not fully capture whether a complete monitoring system can provide reliable, interpretable and decision-relevant data in offshore conditions. For collision monitoring systems, commercial confidence depends on both the quality of the data produced and the practical reliability of the system throughout deployment and operation.

The staged approach therefore helps stakeholders understand what evidence is expected at each point in the development pathway. It also clarifies what limitations remain, how these should be documented, and how confidence in both data quality and system reliability can increase over time. This avoids the use of simplistic labels such as “trialled” or “validated”, which may obscure important differences in the type, quality and relevance of supporting evidence.

By linking the maturity stages to measurable performance indicators, the framework also supports clearer and more transparent expectations for monitoring requirements. It provides a basis for identifying the evidence needed to assess consent conditions, compare system capabilities, and determine whether a system is suitable for a particular monitoring objective or offshore deployment context. The following sections describe each maturity stage in turn and outline the types of evidence, limitations and outcomes associated with progression from baseline testing to commercial deployment.

4.1. Baseline stage

The baseline stage establishes whether a system has a credible technical and evidential foundation for further development. Evidence at this stage may demonstrate that the underlying sensing technologies, triggering mechanisms and data-processing workflows function under controlled, onshore or nearshore conditions. It can also provide an initial understanding of expected detection capability, identification potential and operational constraints.

However, baseline evidence should not be interpreted as evidence of offshore readiness. Performance observed onshore or in nearshore settings may not transfer directly to offshore wind farms because of differences in target species, turbine scale, sensor placement, weather exposure, background clutter, access constraints and data connectivity. The baseline stage should therefore be used to identify the system's known limitations and to define the additional evidence needed before deployment in representative offshore conditions. The relevant performance indicators and evidence expectations are set out in Section 4.4.

Table 5: Definition and criteria for the baseline stage.

Baseline stage		
Definition		Technology proven in onshore or nearshore environments, with documented performance but **not yet demonstrated in offshore conditions**.
Objectives		• Establish system functionality, reliability, and detection capability under controlled/accessible conditions.
Evidence expected	**Data**	• Supplier document fundamental performance indicators and limitations as detailed in section 4.4.
	Technology	• System has undergone onshore "tuning" and optimisation. • Technical feasibility for offshore deployment considered but **not yet proven** (e.g. housings, power, networking, cybersecurity).
Limitations		• Onshore validation **does not directly translate** offshore (different species, turbine scale, metocean, clutter effects). • No evidence of long-term reliability in offshore conditions
What this stage can achieve		• Confidence in the underlying sensing technologies. • Early indication of likely detection performance. • Clear baseline for the next stage.

4.2. Pre-commercial stage

The pre-commercial stage provides the first opportunity to test whether baseline system performance remains credible in representative offshore conditions. Evidence from offshore demonstrations can show whether the system can be installed, powered, maintained and operated within the practical constraints of an offshore wind farm, and whether data can be collected reliably across relevant environmental and operational conditions.

Nevertheless, evidence from a pre-commercial deployment should be interpreted with caution. A single demonstration site may not be representative of other offshore wind farms and their operational procedures and requirements, turbine designs, layouts or metocean conditions. Demonstrations may involve too few turbines to characterise variation across an array, may be too short to assess long-term reliability, and may not capture the full range of seasonal, circadian or weather-related variation relevant

to seabird collision monitoring. Offshore trials may also require ongoing tuning and adjustment as baseline data on system performance in offshore settings are developed.

For this reason, the pre-commercial stage should be treated as evidence of offshore feasibility rather than full commercial readiness. It can support decisions about whether a system is a viable candidate for scaled deployment, but the remaining limitations should be clearly documented against the performance indicators in Section 4.4.

Table 6: Definition and criteria for the pre-commercial stage.

Pre-commercial stage		
Definition		System deployed at least once within an offshore wind farm environment.
Objectives		• Demonstrate offshore feasibility. • Collect offshore data to understand performance characteristics.
Evidence expected	**Data**	• Supplier documents performance indicators and limitations as detailed in Section 4.4 under representative offshore environmental conditions (e.g. spray, low light, vibrations, variable target density) and across the relevant seasonal and/or circadian cycles.
	Technology	• Evidence of functional deployment during realistic offshore operation (i.e. at least one maintenance cycle and a representative range of environmental conditions for the site; generally ≥1 year recommended to meet both of these criteria). • Compliance with offshore requirements (power, network, HSE, cybersecurity). • Evidence of successful installation, maintenance access and uptime.
Limitations		• A single deployment rarely covers aspects required for extrapolating system performance to other sites (with different turbine sizes, layouts, or metocean conditions). Therefore, results may not be transferable between sites. • Still insufficient evidence for large-scale commercial roll-out.
What this stage can achieve		• Demonstrates offshore feasibility. • Provides early reliability evidence. • Enables developers/regulators to judge whether the system is a viable candidate for scaled deployment.

4.3. Commercial stage

The commercial stage indicates that a system has generated sufficient evidence to support routine use in offshore monitoring programmes. At this stage, performance should be reliable, repeatable and sufficiently well characterised across multiple offshore deployments, with limitations clearly documented and, where appropriate, independently validated and potentially certified by a third party with demonstrated technical expertise and no commercial conflict of interest in the matter. Evidence should demonstrate not only that the system can collect useful data, but that it can do so consistently under the operational, environmental and logistical constraints of commercial offshore wind farms.

Suppliers should provide evidence that system performance is fundamentally transferable beyond a single deployment context and that a system can be expected to operate reliably under the range of conditions for which deployment is intended. Commercial readiness should be supported by sufficient deployment evidence to demonstrate that system performance is not dependent on site-specific circumstances, and through testing and evaluation that captures an appropriate range of operating conditions relevant to the intended monitoring objectives. The breadth of evidence should cover parameters that could reasonably influence system performance such as environmental and meteorological conditions, turbine models and configurations, wind farm layouts and scales, operational and maintenance practices, as well as species assemblages and patterns of bird activity. While no fixed minimum number/duration of deployments is prescribed in this roadmap, it is anticipated that such a breadth of evidence is typically only achieved through deployments at more than one offshore windfarm over the duration of more than one full annual cycle.

Suppliers should clearly document the context in which performance has been demonstrated, together with any known limitations, assumptions, or constraints on deployment. The objective is not to demonstrate universal transferability, but to provide evidence that performance can be expected to be robust and repeatable across operational environments. System outputs remain dependent on the monitoring objective, target species, turbine design, sensor configuration, site conditions and data requirements agreed for a given project.

The commercial stage should therefore be understood as a high-confidence maturity stage rather than a guarantee of universal and immediate applicability. It supports routine procurement and deployment where the system's capabilities align with the monitoring objective, but project-specific feasibility and performance expectations should still be checked against the indicators in Section 4.4 and the deployment considerations in Chapter 5, particularly where systems must be retrofitted to existing turbines or integrated with site-specific power, connectivity, cybersecurity and maintenance arrangements. Variability between nearshore fixed-bottom sites and more remote or floating wind developments may also require further design adaptation. In terms of immediacy, even a mature system may need a certain run-in time after installation to adapt and/or tune the system to local conditions, and ensure the detection and identification procedures are adequately trained for the deployment location, but at the commercial stage there would be an expectation that the duration and requirements of any necessary run-in and/or tuning period are evidenced from prior deployments.

Finally, the commercial stage should not be interpreted as an endpoint in the system evolution, but that an expectation remains that systems generate performance statistics and validation evidence throughout their operational lifetime to allow continuous improvement.

Table 7: Definition and criteria for the commercial stage.

Commercial stage		
Definition		System reliably deployed at multiple offshore wind farms, with **proven long-term performance** and well characterised data limitations.
Objectives		• Demonstrate system reliability across diverse offshore environments. • Provide transparent, validated evidence of detection capability and data quality.
Evidence expected	**Data**	• Performance indicators and limitations as detailed in section 4.4 are publicly documented and independently validated over sufficiently long-term offshore deployments (indicatively >2-3 years, depending on the deployment context and evidence generated) to demonstrate performance across representative operational and environmental conditions. • Evidence that data is useful for regulatory/compliance needs.
	Technology	• Reliable operation and data transmission with minimal downtime and/or data loss across multiple sites. • Proven ability to integrate with differing developer requirements. • Demonstrated ability to scale deployments and maintain functionality at commercial volumes.
Limitations		• Site-specific variation will always exist; performance is never fully generalisable. • Continuous improvement will still be required as technologies evolve.
What this stage can achieve		• Confidence for developers, SNCBs and regulators that the system is mature for routine deployment. • Clear expectations for performance and maintenance, including expected duration of post-installation tuning/training phase. • Continued collection of validation evidence. • Enables procurement at scale.

4.4. Mapping monitoring performance indicators onto maturity stages

The stage descriptions above summarise the type of evidence expected at baseline, pre-commercial and commercial maturity. They are intentionally broad, because each stage must account for both data confidence and technical feasibility. To avoid repeating detailed criteria within each stage description, the specific monitoring performance indicators are mapped separately in Table 8.

Table 8 provides a more detailed performance-evidence matrix for the maturity framework. The rows define the indicators that should be documented for any collision monitoring system, while the columns describe how the expected quality, representativeness and independence of evidence increases from

baseline testing through offshore demonstration to commercial deployment, with the general expectation that all indicator requirements in a column are met before the system can be considered to have achieved the relevant stage.

Threshold values for particular indicators are based on recommendations developed for terrestrial shutdown systems (Bruns et al. 2021; KNE, 2021), which differ in their scope and technical constraints from offshore collision detection systems – largely because shutdown systems need to take reaction times of the shutdown procedure into account, but share the same fundamental requirements for assessing system maturity and reliability. These thresholds should therefore be interpreted as provisional benchmarks only, not as prescriptive acceptance criteria. Offshore thresholds should be adapted to the monitoring objective of the relevant regulator, as necessary for each target species, sensor configuration and deployment context.

Table 8: Performance-evidence matrix for the maturity framework of collision monitoring systems. Rows define monitoring performance indicators, columns describe maturity stages, with the general expectation that all indicator requirements in a column are met before the system can be considered to have achieved the relevant stage. Specific thresholds are provisional benchmarks only, not prescriptive acceptance criteria, and should be adapted to the monitoring objective of the relevant regulator, as necessary for each target species, sensor configuration and deployment context.

Performance indicator	Baseline	Pre-commercial	Commercial
Spatial coverage / Geometry of sampled volume	The system manufacturer's specifications of the observed volume are available from sensor specifications and/or quantified with artificial targets.	The system covers a defined portion of the rotor-swept zone of one or more turbines, and the system manufacturer's specifications of the realised sampled volume are available and have been assessed with detected biological targets. Variation of the observed volume under the full range of operational conditions can be quantified in post-processing.	The system covers a defined portion of the rotor-swept zone that is fully representative of the expected airspace utilisation of targets of regulatory interest on one or more turbines, and information about the realised sampled volume is based on measurements of biological targets in several case studies, which have been validated by an independent third party. Variation of the observed volume under the full range of operational conditions is well understood and can be quantified in near-real time.
Temporal availability	No information is available.	The system manufacturer's specifications about system uptime and data integrity are available.	The system has a high level of system uptime and data integrity (e.g. >95% each)*. The information is based on long-term deployments in several cases, which have been validated by an independent third party.
Concurrency of target tracking	The system manufacturer's specifications of the maximum number of concurrent targets is available.	Target saturation is documented in the system outputs when it occurs and/or can be assessed in post-processing	The ratio of tracked to untracked targets under real-word operational conditions is known from auxiliary sensors and can be quantified in near-real time. Preferential target selection (or lack thereof) is quantifiable.
Detection rate	No information is available or available information does not allow discrimination between target classes of regulatory interest.	The information is target class-specific, including false positive detections, and based on initial investigation results. Variation of the detection rate across the sampled volume under the full range of operational conditions can be quantified in post-processing.	The information is based on robust investigation results and has been validated by independent third party, and detection rates are sufficiently high to satisfy regulatory targets (e.g. >75%, preferably >85%)*. Variation of the detection and false-positive rates for relevant target classes, across the sampled volume under the full range of operational conditions is well understood and can be quantified in near-real time.

Target identification **(can vary by target class and/or environmental condition)**	Quality of identification is known (e.g. size classes, species groups, species). No or limited information is available on the detection success rate.	The identification success rate of target classes containing the species of regulatory concern is known, and moderate to high across the sampled volume (e.g. >75%)*. Variation of the identification rate by target class and/or environmental condition under the full range of operational conditions can be quantified in post-processing	Well quantified and high identification success rate in the detection volume. Validation by independent third party (e.g. >90%)*. Ideally differentiates species of regulatory concern as such. Variation of the identification rate by target class and/or environmental condition under the full range of operational conditions is well understood and can be quantified in near-real time.
Localisation of detected targets **(can vary by target class and/or environmental condition)**	No or limited information on target localisation accuracy. Quantification with artificial targets and/or complementary measurement approaches.	Target localisation accuracy quantified for relevant biological targets using complementary measurement approaches. Accuracy sufficient to identify behaviour in meso-avoidance zone.	Well quantified and independently validated location accuracy for relevant biological targets. Biological Targets can be localised with sufficient accuracy to identify micro-avoidance behaviour (i.e. typically 3D spatial accuracy <5-10m at the edge of the rotor-swept zone).

** Indicative benchmarks only; not prescriptive offshore acceptance criteria.*

4.5. Performance indicators and maturity stages as common ground among stakeholders

The performance indicators outlined in this section provide a practical basis for aligning expectations among regulators, developers and monitoring equipment suppliers. Regulators and environmental authorities can use them to frame clearer monitoring requirements, review evidence consistently, and identify where further validation is needed. Developers can use them to compare systems, define procurement requirements, and assess whether proposed monitoring approaches are proportionate to project-specific risks and consent conditions. Monitoring equipment suppliers can use the same indicators to present system capabilities and limitations transparently, supported by evidence appropriate to the relevant maturity stage.

Applied together, the maturity stages as defined by the indicators should support more transparent decision-making, reduce uncertainty in system selection and acceptance, and help build a shared evidence base for future offshore collision monitoring requirements.

5. Delivering commercial acceptance

Providing clarity on system expectations is critical because it establishes a shared understanding of what monitoring technologies can deliver, increases confidence from regulatory and environmental authorities, and reduces uncertainty for developers making investment decisions. Clear expectations also help suppliers align product development with industry needs and regulatory requirements, ensuring that deployments are efficient and effective. Regulatory requirements are one of the most important drivers for the deployment of monitoring systems. A more explicit approach to using systems to monitor collisions at offshore wind farms from regulators could provide clarity for developers and suppliers, as well as provide opportunities for collaborations between projects. This approach may also ultimately encourage the roll out of systems that may in isolation be unable to satisfy the monitoring requirements of individual locations. In the shorter term this may speed up the understanding of system effectiveness and where limitations need to be overcome.

Currently, the lack of confidence in the data collected can be an obstacle to having specific collision monitoring requirements. Stakeholder feedback indicated that regulatory and environmental authorities prioritised confidence in data suitable for future assessments over simply having more data (with higher uncertainty). Likewise, OSW developers preferred systems with clearly defined and transparently communicated limitations, ensuring confidence that outputs would meet consent conditions and licence requirements.

Equipment suppliers also noted that transparency fosters collaboration and increases willingness among developers and regulators to engage in trials and deployment. However, deployments have occasionally been delayed by technical integration challenges, such as access to the Supervisory Control and Data Acquisition (SCADA) networks or power.

Stakeholders agreed that a recognised validation and certification framework would be beneficial for scaling up monitoring system deployment. Such a framework would define performance expectations, ensure data quality, and streamline regulatory acceptance, while also encouraging innovation. Collaborative approaches to validation, combined with a strong emphasis on transparency, were highlighted as essential for building confidence and accelerating commercial acceptance.

All stakeholder groups stressed the need for clear disclosure of system limitations, operational challenges, and pathways for future improvement. Transparency was considered more valuable than overpromising capabilities, as selecting a system that fails to deliver on stated performance can undermine trust and delay progress across the sector. For developers, this may also have implications for compliance with consent requirements, particularly where monitoring systems are unable to deliver on the monitoring requirements.

5.1. Stakeholder roles and responsibilities

The barriers to commercial acceptance identified in Chapter 3 cannot be addressed by any single stakeholder group acting independently. Building confidence in monitoring data, demonstrating offshore feasibility, improving transparency, establishing consistent performance expectations and supporting future regulatory acceptance all require coordinated action by regulators, developers, monitoring equipment suppliers and the wider research community. Defining roles and responsibilities at the outset of a project is therefore essential for ensuring clarity, accountability, and effective collaboration among

all parties involved in offshore wind farm development. Clear delineation of responsibilities helps avoid misunderstandings, streamlines decision-making, and supports compliance with regulatory requirements throughout the project lifecycle.

This section outlines indicative roles for three key stakeholder groups: regulatory and environmental authorities, offshore wind developers or operators, and bird monitoring equipment suppliers, with the aim of outlining a practical implementation pathway to progressively address the barriers identified in Chapter 3. Regulatory and environmental authorities include all governmental or statutory bodies responsible for environmental protection, biodiversity conservation, and regulatory compliance throughout the offshore wind farm lifecycle. Their roles broadly cover setting and/or interpreting monitoring requirements, reviewing and approving environmental assessments, ensuring compliance with national and international legislation, and providing guidance on environmental considerations. In particular, regulators often have a fundamental role in deciding whether a monitoring campaign will fulfil regulatory requirements.

For the purpose of outlining the roles and responsibilities, we provide a brief overview of the typical offshore wind farm development stages and their expected durations in Table 9.

Table 9: Definitions and typical durations of offshore wind farm development stages.

Development stage	Definition	Typical duration
Early-stage planning	Initial site selection, feasibility studies, stakeholder engagement, early environmental scoping	~1-2 years
Development	Detailed wind farm design, environmental impact assessments, consenting processes	~2-4 years
Procurement	Selection and contracting of suppliers for turbines, monitoring equipment, and services	~1-2 years
Manufacturing	Production of turbines, foundations, cables, and monitoring system integration	~1-2 years
Construction and installation	Offshore installation of infrastructure and monitoring systems	~1-2 years
Operations and maintenance	Long-term operation of the wind farm	~20-30 years
Decommissioning	Removal of infrastructure and monitoring equipment, final environmental reporting	~1-2 years

In Table 10, we list the expected roles and responsibilities for the three stakeholder groups across all project development stages. It is important to note that the roles presented here are not fixed and may not be equally applicable across different jurisdictions. Specific roles and responsibilities should be agreed and refined at the start of and throughout each project engagement to reflect contractual arrangements, site-specific conditions, evolving best practices, and regulatory changes.

Table 10: Indicative roles and responsibilities for regulatory and environmental authorities, wind farm developers/operators, and bird monitoring equipment suppliers for bird collision monitoring studies across different offshore wind farm development stages.

Development stage	Regulatory and environmental authorities	Developers/operators	Monitoring equipment suppliers	Contribution to commercial acceptance
Early-stage planning	➢ Define monitoring requirements informed by state-of-the-art in science and monitoring technology development (including through stakeholder consultation, where appropriate) ➢ Provide clearly defined measurable quantities (e.g. coverage, detection rates, identification rates) that systems have to fulfil in validation and operation ➢ Identify special considerations (if any) for the identified project area, where there could be different/additional requirements (e.g. around protected species, sensitive habitats) ➢ Provide early guidance on any cumulative impact considerations (important for ornithology and multi-project areas)	➢ Understand consenting requirements, undertake initial engagement with regulators/SNCBs to discuss expectations around collision monitoring	➢ Share up to date information on equipment capabilities, relevant case studies, etc.	➢ Reduces uncertainty around monitoring requirements ➢ Establishes common performance expectations
Development	➢ Review and approve environmental assessments, including seabird collision risk components ➢ Confirm detailed monitoring objectives and plan with the developer	➢ Confirm detailed monitoring objectives and plan with regulators and environmental authorities ➢ Ensure monitoring plan aligns with international standards and best practice guidance ➢ Engage with monitoring equipment suppliers to share monitoring objectives, project site and wind farm design	➢ Share detailed information on equipment specifications, requirements, capabilities, limitations, etc., particularly in relation to the monitoring objectives specified by wind farm developers	➢ Aligns monitoring objectives with evidence requirements ➢ Improves confidence in future data outputs

<table>
<tr><td></td><td>➢ Confirm that monitoring plan aligns with international standards and best practice guidance
➢ Review information provided by developers or monitoring equipment suppliers on monitoring system performance indicators, limitations and maturity stage when assessing the suitability of proposed monitoring plans.</td><td>information, and to understand monitoring equipment specifications, requirements, capabilities, limitations, etc.</td><td></td><td></td></tr>
<tr><td rowspan="2">Procurement</td><td rowspan="2">➢ Review and provide feedback on the monitoring plan, particularly regarding expected data outputs and ecological relevance</td><td>➢ Contract a monitoring equipment supplier to run collision monitoring post-construction
➢ Assign responsibilities and ownership (between developer and monitoring equipment supplier, including aspects such as installation, maintenance, data transmission and storage, decommissioning, etc.)
➢ Share detailed wind farm design information with monitoring equipment supplier
➢ Identify potential data confidentiality and cybersecurity obstacles and work with the monitoring equipment supplier to find solutions
➢ Keep regulatory and environmental authorities updated on monitoring plan development/implementation, particularly in case of any delays and potential changes to the monitoring plan</td><td>➢ Specify the full monitoring equipment setup and installation and commissioning requirements, including any anticipated calibration, tuning, adjustment or training period and its expected duration</td><td rowspan="2">➢ Resolves technical integration barriers
➢ Supports deployment feasibility</td></tr>
<tr><td colspan="2">➢ Agree on data ownership, confidentiality, and cybersecurity protocols upfront</td></tr>
<tr><td colspan="5">After the procurement stage, roles and responsibilities between developers and monitoring equipment suppliers become highly contract specific. Detailed obligations around installation, maintenance, data handling, cybersecurity, and decommissioning are typically defined within the contractual agreements rather than at a general framework level.</td></tr>
<tr><td>Manufacturing</td><td>N/A</td><td colspan="2">➢ Where possible, ensure integration of monitoring equipment during manufacturing of relevant wind farm components</td><td>➢ Resolves technical integration barriers</td></tr>
</table>

		➢ Consider constraints posed by turbine OEMs and certification standards when planning integration; confirm compatibility of monitoring equipment with turbine certification and OEM constraints early in the process ➢ Keep regulatory and environmental authorities updated on monitoring plan development/implementation, particularly in case of any delays and potential changes to the monitoring plan	➢ Supports deployment feasibility
Construction and installation	➢ Regulatory compliance checks	➢ Coordinate installation and commissioning; ensure communication between operations team and installation contractor ➢ Verify correct setup and functionality of monitoring systems **(see Section 5.2. Considerations for successful deployment)** ➢ Keep regulatory and environmental authorities updated on monitoring plan development/implementation, particularly in case of any delays and potential changes to the monitoring plan	
Operations and maintenance	➢ Regulatory compliance checks ➢ Verify initial monitoring outputs; may assess the need for adaptive changes to monitoring based on initial findings ➢ Evaluate and approve monitoring outputs	➢ Data analysis and QA; reporting to regulators on meeting regulatory requirements ➢ Define and carry out maintenance schedules and troubleshooting protocols ➢ Keep regulatory and environmental authorities updated on monitoring plan development/implementation, particularly in case of any delays and potential changes to the monitoring plan	➢ Generates offshore validation evidence ➢ Builds confidence in system performance
Decommissioning	➢ Review and approve decommissioning plans ➢ Review and approve any final environmental monitoring outputs	➢ Plan and execute safe removal of monitoring equipment ➢ Ensure final data reporting and compliance with environmental requirements, and plan for data archiving and transfer to authorities or research bodies before equipment removal	

5.2. Considerations for successful deployment

The previous section outlines the expected roles and responsibilities throughout the lifecycle of the system deployment. To ensure successful implementation, it is essential that all parties proactively address key considerations and reach an agreement on critical aspects at the outset. This alignment will help streamline processes and reduce the risk of delays.

As part of developing this Roadmap, we engaged a range of stakeholders to capture lessons learnt from previous offshore deployments of collision monitoring systems. These discussions identified several potential points of conflict that, if unresolved, could hinder progress during the system deployment timeline. Figure 2 highlights these conflict areas, with further detail provided in Table 11.

Addressing these risks early in the project lifecycle is vital to avoid unnecessary delays and ensure smooth execution.

1. Unclear species monitoring responsibilities and disagreement on acceptable detection accuracy.
2. Misalignment of expectations of system downtime and accessibility could impact regulatory compliance. The system expects scheduled downtime for updates; the site expects continuous availability without clear coordination.
3. Unclear accessibility requirements. The system may require SCADA access for data; the site may not anticipate or allow this level of integration.
4. Misalignment on power availability at the site. The system assumes dedicated or backup power; the site provides limited or shared power without a clear agreement.
5. Unclear data connectivity requirements. The system expects high-bandwidth, real-time connectivity; the site may only provide intermittent or basic links. Additional disputes could occur over data ownership and sharing responsibilities if not predefined.
6. Unclear design considerations and collaboration. The technical specification detailed in Appendix 1 could provide a solution to mitigate conflict.
7. Misalignment on installation responsibilities and scheduling conflicts.
8. Conflicts over maintenance scheduling and increased downtime due to poor coordination. The system requires planned maintenance windows; the site operations may prioritise turbine uptime over system access.

Figure 2: Potential areas of misalignment for deployment of monitoring systems that must be clarified between relevant parties.

Table 11: Key factors for successful deployment with expectations for stakeholder groups.

Category		Expectations of the system	Expectations of the site	Expected guidance and regulation	Successful deployment consideration
Technical	*Species monitoring*	• Ability to monitor the required species for the applicable environmental conditions.	• Provide baseline environmental data to train the AI model. • Allow site access for calibration and testing.	• Clarification on the required species to monitor to help train the AI model. • Compliance with environmental protection laws.	**1**
	Resolution	• Resolution should be defined based on the monitoring objective, target species and applicable regulatory requirements.	• Resolution should be defined based on the monitoring objective, target species and applicable regulatory requirements.	• Clarification on the resolution requirements to determine the system.	
	Software & hardware updates	• System must support remote software updates and modular hardware upgrades with minimum downtime.	• Site should allow scheduled downtime for updates and provide secure access for technicians.	*Oversight of existing standards and compliance requirements.*	**2**
	Insurance/ security	• System must include cybersecurity measures.	• Site should provide secure access to monitoring data where feasible and consistent with the project's/developer's cybersecurity requirements.	*Oversight of existing standards and compliance requirements.*	**3**
Infrastructure	*Power*	• The system must demonstrate **electrical independence** from the turbine system.	• The site will provide defined **power availability** and integration needs.	*Oversight of existing standards and compliance requirements.*	**4**
	Data access and connectivity	• Reliable data storage and transfer protocols to prevent loss or corruption. • Preference for minimum manual data retrieval and it should be automatic.	• Clear provisions of data links and transfer protocols.	*Oversight of existing standards and compliance requirements.*	**5**
Operational	*Design*	• The system can adapt to different project designs and locations.	• Access to the site and design details would aid system integration. Dedicated space for the system.	*Oversight of existing standards and compliance requirements.*	**6**
	Installation	• Equipment suppliers must provide clear plans for updates, service and end-of-life management. • Suppliers must conduct the installation process and comply with relevant HSE standards (e.g. IEC 61400), as well as relevant technical and cybersecurity standards (e.g. IEC 62443).	• **Installation support** should be available from the site developer.	*Oversight of existing standards and compliance requirements.*	**7**
	Maintenance	• Remote diagnostics capability. Scheduled servicing aligned with site operations.	• Coordination for maintenance windows. Provide access for technicians.	*Oversight of existing standards and compliance requirements.*	**8**

6. Conclusion

This Roadmap set out to outline the stages to commercial acceptance for offshore wind collision monitoring systems. For the purposes of this Roadmap, collision monitoring systems are assumed to include camera-based capability to enable species recognition, which has been highlighted as a key need from regulatory and environmental authorities; systems may also incorporate additional sensor technologies.

The Roadmap identifies two key challenges to the commercial acceptance of offshore seabird collision monitoring systems: confidence in the data collected and confidence in the technical feasibility of deployment and operation offshore. Addressing both challenges is essential if monitoring systems are to generate evidence that can support regulatory decision-making and improve understanding of seabird collision risk.

To help address these challenges, the Roadmap sets out a framework based on:

- Greater transparency around system development, testing, performance and limitations;
- A common set of performance indicators to describe system capabilities, data quality, and performance uncertainties;
- A staged maturity framework, comprising baseline, pre-commercial and commercial stages;
- Clearer expectations for system deployment, including stakeholder roles and responsibilities, and practical deployment considerations.

These elements provide a consistent basis for describing, evaluating, and comparing collision monitoring systems. They are intended to support more transparent decision-making, enable users to make well-informed choices, and help regulators, developers and monitoring equipment suppliers align expectations regarding system performance and evidence requirements. The proposed maturity stages focus on performance readiness rather than technology readiness alone, recognising that commercial acceptance depends on both data quality and technical feasibility

The Roadmap does not seek to prescribe specific technologies or fixed performance thresholds, but provides a structured approach for documenting system capabilities, limitations and evidence requirements, while supporting continued innovation and technology development. As additional offshore deployments are completed and more evidence becomes available, the proposed framework can be refined to reflect evolving industry experience and regulatory needs.

Failure to thoroughly and confidently assess collision monitoring system performance risks premature deployment driven by cost pressures, which could undermine ecological objectives and regulatory compliance. Continued collaboration between regulators, developers and monitoring equipment suppliers, as well as the wider research community, will be essential to accelerate learning and build confidence in offshore collision monitoring systems.

References

Ballester C., Dupont S.M., Corbeau A., Chambert T., Duriez O., Besnard A. 2024. A standardized protocol for assessing the performance of automatic detection systems used in onshore wind power plants to reduce avian mortality. Journal of Environmental Management. 354: 120437.

Boersch-Supan, P.H., Brighton, C.H., Thaxter, C.B. *et al.* Natural body size variation in seabirds provides a fundamental challenge for flight height determination by single-camera photogrammetry: a comment on Humphries et al. (2023). *Mar Biol* 171, 122 (2024). Accessed at: link.

Brighton, C.H., Clarke, J.A. and Boersch-Supan, P.H. 2025. Scientific support to the trial of Spoor AI at the European Offshore Wind Deployment Centre. British Trust for Ornithology, Thetford, UK. Accessed at link.

Bruns, E., Schuster, E. & Streiffeler, J. 2021. Anforderungen an technische Überwachungs- und Abschaltsysteme an Windenergieanlagen Abschlussbericht der Workshopreihe „Technische Systeme“. BfN Skripten 610.

Carbon Trust, 2017. Assessing the commercial maturity of renewable energy technologies: Moving beyond technology readiness. https://www.carbontrust.com/sites/default/files/documents/resource/public/Assessing%20The%20Commercial%20Maturity%20Of%20Renewable%20Energy%20Technologies%20-%20Moving%20Beyond%20Technology%20Readiness%20-%20REPORT.pdf

Carbon Trust, 2026a. Best practice guidance for the collection, management and analysis of data to support post-construction seabird collision monitoring at offshore wind farms. The Carbon Trust Report for Prevalence of Seabird Species and Collision Events in Offshore Wind (PrediCtOr) project D4.3.

Carbon Trust, 2026b. Best practice guidance for the installation of monitoring equipment to support post-construction seabird collision monitoring at offshore wind farms. The Carbon Trust Report for Prevalence of Seabird Species and Collision Events in Offshore Wind (PrediCtOr) project D5.1.

Carbon Trust, 2026c. Improving understanding of distributional change for relevant seabird species (ImpUDis). Offshore Renewables Joint Industry Programme (ORJIP) for Offshore Wind.

Corbeau A., Dupont S., Besnard A. 2021. Detection-reaction systems in onshore windfarms, a mitigation solution to reduce bird fatalities: Principles for a relevant assessment of their performances. Reduction of Avian Mortalities in Operating Windfarms (MAPE) Research Project, France.

European Commission. 2014. Horizon 2020 – Work Programme 2014-2015: Annex G – Technology Readiness Levels (TRL). https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

Feather A.P., Burton N.H.K., Johnston D.T. & Boersch-Supan P.H. 2025. A review of existing methods to collect data on seabird flight height distributions and their use in offshore wind farm impact assessments. BTO Research Report 780: British Trust for Ornithology, Thetford, UK.

Fric J., Tzen E. & Tzali M. 2018. Modern technologies for the mitigation of impacts of wind farms on biodiversity. Technical Brochure. www.windfarms-wildlife.gr

Gottlieb, I., C. Hein, P. Field, and T. Allison. 2025. Accelerating technology development to monitor and minimize effects from land-based wind energy on birds and bats. *Journal of Wildlife Management* 89:e70107.

JNCC, Natural England, Natural Resources Wales, NatureScot. 2024. Joint advice note from the Statutory Nature Conservation Bodies (SNCBs) regarding bird collision risk modelling for offshore wind developments. JNCC, Peterborough. https://hub.jncc.gov.uk/f7892820-0f84-4e96-9eff-168f93bd343d.

KNE, 2019. Minimizing bird collisions with wind turbines: Can detection systems facilitate an environmentally sound wind energy development? PROCEEDINGS OF THE KNE CONFERENCE ON MAY 15–16, 2019 IN KASSEL.

KNE, 2021. Anforderungen an Antikollisionssysteme zum Schutz von Vögeln an Windenergieanlagen – Checkliste für eine qualifizierte Entscheidung über die Anwendbarkeit von Antikollisionssystemen.

Skov, H., Heinänen, S., Norman, T., Ward, R.M., Méndez-Roldán, S. & Ellis, I. 2018. ORJIP Bird Collision and Avoidance Study. Final report – April 2018. The Carbon Trust. United Kingdom. 247 pp.

Smallie J., Froneman A., Smith D.L., Mulvaney J.M. 2024. Shutdown on Demand for the mitigation of bird collision risk at onshore wind farms in South Africa. BirdLife South Africa, Johannesburg, South Africa.

Wulfert, K., Köstermeyer, H., Lau, M., Fischer, S., Kostelnik, I., Schöne-Warnefeld, J., Weber, J. (2022): Vögel und Windenergienutzung: Best Practice-Beispiele und planerische Ansätze zur Konfliktlösung. BfN-Schriften 634: 203 Seiten.

APPENDIX

Appendix 1: Technical specification sheet

Attribute	Specification/description	Response
Physical		
Primary hardware	Type of sensor	
	Number of sensors	
	Size	
	Weight	
	Location(s)	
	Attachment type	
	Operating temperatures [°C]	
	Ingress Protection standards [IP-rating]	
	Power supply [voltage/type/source]	
	Power consumption [W]	
Additional hardware	Type	
	Size	
	Weight	
	Location	
	Attachment type	
	Power supply [voltage/type/source]	
	Power consumption [W]	
General	Number of cables	
	Types of cables	
	Diameter of cables [mm]	
	Location of server rack	
	Need for backup power [within number of hours]	

	Type of power backup [UPS]	
	Drilling in structure required? [where]	
	Operating wind speeds [m/s/Bft]	
Monitoring characteristics		
Sampled volume (by target class and/or environmental condition)*	[3D geometry]	
Detection rates across sampled volume (by target class and/or environmental condition)*	[% / Detection function]	
Temporal availability*	[% uptime * % data integrity]	
Identification rate (by target class and/or environmental condition)*	[False positive/false negative rates]	
Localisation accuracy of detected targets*	[absolute accuracy in m and/or range-relative error]	
**Connection*		
Internet	[bandwidth/source]	
SCADA access required	[Y/N]	
Cybersecurity	[protocols/encryption/standards]	
Data		
Types of raw data	[type and formats]	
Processed data available	[type and formats]	
Dashboard type	[i.e. web-based]	
Dashboard data fields		
Accessibility	[local/online]	
If online, type of connection	[physical cable/mobile network]	
If local, frequency of site visit		
number of people		
Data storage needed	[volume and time]	

**Please include sources of figures and whether these are from suppliers' own testing or independent validation studies onshore and/or offshore. Where possible please supply supporting reports and/or papers.*

Volume of data generated	[average MB per day/week] [peak MB per day/week]	
Frequency of data retrieval/back-up	[hours/days]	
Delivery and installation		
Timeframe	[months]	
Number of personnel	[total]	
from equipment supplier		
from wind farm operator		
from third party		
Specialist equipment		
Responsible for installation?	[company name]	
Maintenance		
Expected lifetime	[years]	
Number of personnel		
Schedule/frequency (on location)		
Specialist equipment		
Activities for maintenance	[list of activities]	
Calibration		
Test period	[months]	
Responsible for maintenance?	[company name]	
Costs		
Equipment		
Installation costs	[per turbine/system]	
Subscription charge	[per month/year]	
Additional service/maintenance charge	[per hour/month/year]	
Minimum contract period	[months/year]	

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+44 (0) 20 7170 7000

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