ACCELERATING OFFSHORE WIND

DEVELOPING A REGIONAL ECOSYSTEM MONITORING PROGRAMME FOR THE UK OFFSHORE WIND INDUSTRY

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EXECUTIVE SUMMARY

One of the major challenges facing the offshore renewable energy industry is how to deliver the speed and extent of the dramatic increase in offshore wind deployment needed to meet the UK's Net Zero targets.

This report introduces an alternative monitoring approach for the offshore wind industry. There is a need to take advantage of innovative technologies to better understand the functioning of the UK marine ecosystems within which large-scale offshore wind deployment is situated. There needs to be a collaborative effort to enable a transformation in data gathering driven by a regional ecosystem-based monitoring programme (REMP) supported by new technologies that can be confidently incorporated into impact assessments and future monitoring plans. By implementing a regional monitoring programme, a more coherent and cohesive approach across multiple sites can deliver targeted monitoring that enables the cumulative effects to be more accurately assessed.

A proposed framework for how a REMP might operate has been suggested, the role of innovative technology in enabling a monitoring programme at a regional scale and the importance of standardising and streamlining data management and environmental impact assessment (EIA) reporting. All have the potential to streamline the data gathering, analysis and decision-making process to accelerate consenting.

We propose a number of ambitious suggestions that will support the aim of the government's mission to make the UK a clean energy superpower:

1. Streamline monitoring requirements by shifting from project-level assessments to regional-scale monitoring.
2. Appoint a central, neutral facilitator of the REMP approach making use of existing strong links with government, industry, statutory consultees, academic institutes and SMEs. ORE Catapult is well-placed to act in such a role.
3. Remove the scoping phase from the pre-application stage. Regional advisory groups would be established to engage on environmental and engineering concerns (in collaboration with key experts from academic institutes and statutory consultees).
4. Adopt an ecosystem-based approach to monitoring driven by key indicators and monitoring priorities specific to each region.
5. Adopt an iterative framework that allows question-setting, study design, data collection, data analysis, and data interpretation to evolve and develop in response to new information or questions.
6. Transition from current monitoring methods to make use of innovative technology capable of conducting multiscale and cross-disciplinary measurements, and incorporating AI.
7. Develop a large-scale/high-resolution web portal containing EIA/monitoring data of all offshore wind farm and grid projects.
8. Transition from current EIAs to digital EIAs.
9. Datasets and model outputs generated by such tools should be open access to ensure that the information is genuinely useful and feeds into policy and management measures that promote sustainable development of the marine environment.

NOMENCLATURE

ACORD	Accelerating Consenting for Offshore Renewables Deployment
AI	Artificial Intelligence
AUV	Autonomous Underwater Vehicle
DAS	Discretionary Advice Service
DCO	Development Consent Order
EBM	Ecosystem-Based Monitoring
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EOR	Environmental Outcomes Reports
ES	Ecosystem Services
GES	Good Environmental Status
HRA	Habitats Regulations Assessment
IEA	Integrated Ecosystem Assessment
MAS	Marine autonomous systems
MCZ	Marine Conservation Zone
MDE	Marine Data Exchange
MEDIN	Marine Environmental Data and Information Network
ML	Machine Learning
MMO	Marine Maritime Organisation
MPA	Marine Protected Area
NOAA	National Oceanic and Atmospheric Administration
NSIP	Nationally Significant Infrastructure Project
OWEKH	Offshore Wind Evidence and Knowledge Hub
PAM	Passive Acoustic Monitoring
RAI	Robotics and Artificial Intelligence
REMP	Regional Ecosystem Monitoring Programme
RSMP	Regional Seabed Monitoring Plan
ROV	Remotely Operated Vehicle
SAC	Special Area of Conservation
SNCB	Statutory Nature Conservation Bodies
SPA	Special Protection Area
SEA	Strategic Environmental Assessment
TCE	The Crown Estate
UAV	Uncrewed Aerial Vehicle
USV	Uncrewed Surface Vehicle
VLOS	Visual Line of Sight

1 INTRODUCTION

Efforts to reduce carbon emissions and increase renewable energy production have led to the rapid expansion of offshore wind farms. While these offer immense potential for clean, green energy, the construction, operation and decommissioning of offshore wind farms and associated grid infrastructure causes a range of pressures on coastal and marine biodiversity which in turn leads to impacts on species and ecosystems.

It is essential that the marine fauna and flora around offshore wind farms and grids are surveyed during each phase of development and that the monitoring of species and habitats and the pressures they face is continued throughout the operational lifetime of the wind farm. While the precise environmental footprint of an offshore wind farm will depend on its location in relation to threatened species and habitats, marine mammal and bird migration routes, and other natural features, there can be several potential impacts on biodiversity. It is often the uncertainties around the assessment of impacts resulting from cumulative pressures caused by offshore wind development that can lead to substantial delays during the consenting process.

1.1. ENVIRONMENTAL IMPACTS OF OFFSHORE WIND

The main environmental impacts associated with offshore wind developments are the risk of bird collision with turbines, displacement due to disturbances such as noise, barrier effects restricting movement and habitat loss, and indirect ecosystem effects through the changes in hydrodynamics. Studies on the impact of hydrodynamics on fish caused by sediment resuspension or sedimentation, temperature change, nutrient transport, and substrate availability tend to be confined within the offshore wind farm footprint and largely neglect possible effects further afield (van Berkel et al., 2020). Positive impacts of offshore wind farms have also been noted, including the creation of new habitat, artificial reef effects and fishery reserves where marine fauna may aggregate due to the change in human activity, especially fishing. It has been suggested that, in some cases, "wind farms may even be more efficient means of conservation than ordinary marine protected areas" (Hammar et al., 2016).

Impacts are caused by a variety of pressures which vary between different phases of offshore wind development. Some pressures such as mortality caused by seabed habitat loss or underwater noise are greatest during construction; others, like bird and bat mortality from collisions, and changes in hydrodynamics are more prevalent during the operational phase.

Bennun et al. (2021) provided a detailed breakdown and identified fourteen key environmental impacts of offshore wind developments:

1. Bird and bat collision with wind turbines and onshore transmission lines
2. Seabed habitat loss, degradation and transformation
3. Hydrodynamic change
4. Habitat creation
5. Trophic cascades
6. Barrier effects or displacement effects due to the presence of wind farm
7. Bird mortality through electrocution on associated onshore distribution lines
8. Mortality, injury and behavioural effects associated with vessels
9. Mortality, injury and behavioural effects associated with underwater noise

10. Behavioural effects associated with electromagnetic fields of submarine cables
11. Pollution (e.g., dust, light, solid/liquid waste)
12. Indirect impacts offsite due to increased economic activity and displaced activities, such as fishing
13. Associated ecosystem service impacts
14. Introduction of invasive alien species

Despite our current understanding of environmental impacts, there are considerable gaps in scientific knowledge about the ecological impacts of wind turbines potentially leading to a gap between perceived and actual risk. This issue is highlighted in a paper by Rezaei et al. (2023) who reported on the proven environmental impacts of offshore wind farms gained from post-construction environmental monitoring programmes. The monitoring studies assessed showed little or only local impacts of offshore wind farms on the marine environment, during the construction or operational phases. However, Rezaei et al., (2023) stated that further research is needed to answer whether synergies of little and local impacts may determine consequences at the population level.

Rezaei et al., (2023) noted that EIAs are generally designed to understand whether habitat changes occur as a result of the presence of offshore wind farms or marine organisms change their behavioural patterns and/or avoid naturally the surrounding area affected by the construction/operation of the wind farms. Such studies are not able to detect which of the specific factors (e.g., noise, turbine presence, boat traffic or change in the prey availability) are responsible for the observed effects or how the receptor types interact with each other at the ecosystem scale.

As the number and size of offshore wind farms increase it is necessary to consider consequences at the population level as well as cumulative impacts of these activities on marine ecosystems. Isaksson et al., (2023) reported that "the cumulative ecological effects of changes from offshore wind farms may impact how ecosystems function by pushing biophysical variables and species interactions beyond natural variability" and that "understanding how these changes interact with and impact/are impacted by the wider socio-economic landscape will be critical".

To support the development of wider energy and environmental policies, we must understand the wider socio-economic, health and cultural impacts of the expanding offshore energy sector (Watson et al., 2024). The ecosystem services[1] (ES) approach for offshore energy developments sets any ecological impacts within a societal and economic context, assessing which ecological impacts may affect human well-being (Watson et al. 2024). Watson et al., (2024) found more than 86% of possible offshore wind farm impacts on ES are still unknown, suggesting that the full extent and consequences of ecological change are not being considered during decision-making processes.

Szostek et al., (2024) reviewed and synthesised UK grey literature (2012–2022) relating to the impacts of offshore wind farms and compared reported ES outcomes with those from global primary literature (2002–2021). Grey literature portrays a largely negative (71%) view of ES outcomes and fails to represent many positive ES outcomes reported in primary literature. In primary literature, 28% of reported ES outcomes are positive such as nutrient cycling, habitat condition and biodiversity, but in UK grey literature this is just 2%. Szostek et al. (2024) reported that primary literature is not currently favoured in policy decisions because of the following reasons: 1) it can be difficult or expensive to access, (2) the time between research and publication is too long, (3) developers and scientists do not regularly work together, (4) reported outcomes are too specific or not in a format suitable for policy recommendations, with grey literature generally more 'user-friendly' providing a summary of impacts and evidence. Szostek et al., (2024) recommend that evidence from both literature types is used to achieve environmentally sound decision-making and accelerate planning and consenting times.

1. Ecosystem Services (ES) are defined as "the direct and indirect contributions that ecosystems provide for human wellbeing and quality of life", for example water, construction materials, energy, food or genetic resources (Szostek et al., 2024).

1.2. MONITORING OFFSHORE WIND FARMS

Well-designed monitoring is key to maintaining a healthy, thriving marine ecosystem with the planned large-scale deployment of offshore wind. Such monitoring should detect biologically meaningful changes and provide opportunities to mitigate adverse impacts (Methratta, 2024). Monitoring plans would ideally sample meaningful biological indices, use experimental designs capable of detecting change, be hypothesis based and collect data that are comparable among projects and with regional long-term data sets, and provide open and transparent access to information for stakeholders (ROSA, 2021). Lacking these fundamental characteristics, the outcome is a scenario in which scientists, managers, and decision-makers are data-rich but information-poor (Wilding et al., 2017).

Wilding et al., (2017) reported that this data-rich but information-poor scenario should be replaced by resources addressing relevant questions that are "logically bounded in time and space" and that "efforts should target identifying metrics of change that can be linked to ecosystem function or service provision, particularly where those metrics show strongly non-linear effects in relation to the stressor". Wilding et al., (2017) recommended that "monitoring should be designed to contribute towards predictive ecosystem models and be sufficiently robust and understandable to facilitate transparent, auditable and timely decision-making".

A robust scientific monitoring plan should be designed to detect changes in the interactions between marine habitats, wildlife, and activities associated with offshore wind infrastructure and development, as well as broader ecosystem-level effects. Monitoring at each stage of offshore wind development, including planning and siting, during development activities, and throughout the lifetime of offshore wind project operations, can help support smarter siting, best management practices, and improve risk-reduction technologies. It is imperative that new information gained from monitoring is incorporated into the development process in an adaptive management cycle, and any identified risks are then proactively addressed in existing and future projects.

Current EIAs are not optimally designed for a robust and proper assessment of the present ecological and/or environmental status and assessment of pressures associated with the offshore wind sector. This leads to uncertainties regarding the prediction of adverse impacts, meaning UK regulators often take a precautionary approach to consenting new developments. The increased use of autonomous technologies for environmental monitoring could help to close critical knowledge gaps of these impacts (Isaksson et al., 2023), as long as these technologies can provide robust data to answer the key questions that are affecting consenting.

Baseline environmental data acquisition is predominantly collected from in situ survey campaigns, for example, fish trawl surveys, seabed grabs and aircraft-based bird surveys. These methods are time, carbon and cost-intensive, subject to weather disruption and inherently involve a safety risk with humans working offshore. The data is often collected ad hoc, and only covers small areas both spatially and temporally. Efficient and time-relevant monitoring methods capable of monitoring at greater temporal and spatial scales are needed to better understand the impacts. In addition, there is an increasing demand for data and transparency in decision-making, and marine data must be detailed, precise, and readily available. Recent advances in technologies, such as remote sensing (Medina-Lopez et al., 2021), machine learning (ML) techniques, acoustic monitoring, and intelligent integration of modelling and sensor measurements are revolutionising the future of marine environmental monitoring and monitoring systems (Erichsen and Middelboe, 2022).

Advanced techniques are only applied to a limited extent in the offshore wind industry and often for research purposes, such as the automated detection of bird collisions on wind turbines using cameras

and radar. There are still unresolved issues to be addressed before some of the techniques can be used in operational monitoring but different technologies can also strengthen and optimise other technologies or traditional monitoring. Marine autonomous systems (MAS) and uncrewed aerial vehicles (UAV) of increasing sophistication have been developed over the last twenty years and are now in regular use in the oceanographic community. Whilst performance and commercial availability have increased in the last decade, there are no proven systems in regular use for surveys pertinent to offshore renewable energy project consenting. This is due to a lack of commercially available MAS/UAV-based survey services and to the regulators' low confidence in such methods.

For the Statutory Nature Conservation Bodies (SNCBs) responsible for providing advice to the regulator, there is uncertainty around the use of new technology to monitor the impacts of offshore wind. There is a need to properly assess the pros and cons of novel methods, comparing them with benchmark technologies and integrating these into long-standing time series for data continuity. This requires transition periods and careful planning, which can be covered through a collaboration of current and future research projects on marine biodiversity and ecosystem health (Borja et al., 2024). It is important to demonstrate the efficacy and scientific rigour of new methods to ensure the adoption into best practice guidelines, thereby giving confidence to both the developer and the SNCBs.

1.3. CURRENT ENVIRONMENTAL IMPACT ASSESSMENT PROCESS

An Environmental Impact Assessment (EIA) and a Habitat Regulations Assessment (HRA) are required for an offshore wind project to be able to submit a Development Consent Order (DCO) application. The Habitats Regulations specifically refer to Special Areas of Conservation (SACs) and Special Protection Areas (SPAs). These sites are given legal protection because they are designated for habitats and species of importance and together form a network of protected sites known as the national site network[2]. The Regulations are used to make sure that relevant plans or projects which could impact a protected site are assessed. A plan or project can only go ahead if certain strict conditions are met to avoid adverse impacts on the special interest features of these protected sites and the process of assessing the potential effects is known as a Habitats Regulations Assessment (HRA). Any 'Competent Authority[3]' that proposes to authorise, consent, or carry out a plan or project that may affect a protected site must first carry out a HRA.

An EIA examines the environmental consequences of a proposed activity or project in advance, to better inform decision-making. EIAs are required for the whole lifecycle of a project: design, construction, operation and decommissioning stages. This needs to be done in a transparent way involving public participation to ensure that the views of key stakeholders and communities are adequately taken into consideration in the decision-making process, it is also about ensuring the quality, comprehensiveness and effectiveness of the EIA itself.

The EIA process involves four key stages: screening, scoping, undertaking the EIA, and the final application for consent. The construction of an offshore wind farm will require an EIA to be undertaken and therefore the EIA process usually jumps straight from the screening stage to scoping the project. EIA scoping is a key stage within the EIA process, and although not mandatory, it is advisable to undertake as the developer can ask the regulator for their opinion on the requirements for the EIA, providing an opportunity to present the project to regulators and stakeholders to receive initial feedback on the key environmental issues that must be addressed. For each of the topics/receptors identified in the scoping process, an EIA is undertaken. The baseline surveys required as part of the EIA include marine mammal, fish, ornithology, benthic, underwater noise, geophysical and geotechnical, metocean and onshore surveys. The developer then documents the results of the EIA in the form of an

2. https://www.thecrownestate.co.uk/media/4065/a-guide-to-hra-april-2022.pdf
3. The Crown Estate is the Competent Authority for the UK.

Environmental Statement which is then submitted with the application for consent. In addition, there will often be post-consent monitoring requirements that the developer must also adhere to.

Current EIAs attempt to assess the impacts of renewables against a supposedly stationary baseline, resulting in the consideration of only negative impacts (Scott, 2022). The ability of renewable energy to reduce CO2 production by replacing fossil fuels, needs to be considered (Scott, 2022). In terms of ecosystem services, there are more positive impacts than negative (Hooper et al., 2017). In order to make accurate assessments of positive vs negative trade-offs of locations and sizes of renewable developments, the current EIA process needs to change (Hooper et al., 2019).

1.4. UK GOVERNMENT PLANS TO REFORM THE EIA UNDER THE LEVELLING-UP AND REGENERATION ACT 2023

In March 2023, under the Levelling-up and Regeneration Bill[4], the previous government[5] sought views on a proposed new system of environmental assessment ('Environmental Outcomes Reports') to replace the current EU-derived environmental assessment processes of Strategic Environmental Assessment (SEA) and EIA. Environmental Outcomes Reports (EORs) are written reports identifying how far a relevant project or plan will impact the delivery of specific environmental outcomes. The vision is for "assessment to be more effective as a tool for managing the effects of development on the natural environment, supporting better, faster and greener delivery of the infrastructure and development we need" and to "simplify and streamline the assessment process to make it more effective as a tool to support the delivery of environmental commitments".

Part 6 of the Bill gives the Secretary of State the power to replace existing systems of environmental assessment with a new EOR regime, the details of which are to be set by secondary legislation. As with other measures projected to streamline consenting, timings are uncertain and regulations will need to be initiated to provide much of the detail needed.

Clause 138 (Power to specify environmental outcomes) gives powers for the Secretary of State to set environmental outcomes and includes a requirement that the Secretary of State must have regard to the government's Environmental Improvement Plan when setting outcomes. The safeguards under Clause 142 (Safeguards: non-regression, international obligations and public engagement) ensure the overall level of environmental protection provided by existing environmental law will not be reduced.

The previous government stated that it "intends to place environmental issues at the heart of the reformed system by introducing an outcomes-based approach, delivering a streamlined system which works for everyone and delivers better environmental outcomes". Proposed outcomes include:

- **For communities** – An easy-to-navigate system that allows for a clear understanding of how a development might impact the local environment and that instils confidence by taking a stronger approach to mitigation.
- **For developers** – Providing the certainty developers need to incorporate environmental considerations at an earlier stage of the project, therefore avoiding unnecessary costs and delays and the fear of legal challenge.
- **For decision-makers** – Clearer information to enable more robust, confident decisions to be made, aided by more robust monitoring and mitigation, concise assessment reports, and that allows decision-makers to better understand how local decisions fit with national priorities.
- **For environmental interests** – A focus on the critical environmental issues that is underpinned by transparent, robust data. A strong focus on monitoring to ensure compliance with measures identified in assessments to mitigate significant impacts and the quick delivery of remedial action if required.

4. The Levelling-up and Regeneration Bill received Royal Assent on 26 October 2023 and has since become the Levelling up and Regeneration Act 2023.
5. It is not certain whether existing plans to reform the EIA will continue with the change in UK government (July 2024).

1 INTRODUCTION
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- **For policy makers, planning and environmental professionals** – A more robust and transparent evidence base to inform future policies and assessments, that allows policy makers to continuously learn and develop their approach over time with adaptive management.

There is little doubt that a more streamlined approach to the current EIA is required, but whether the proposed EORs will prove to be a simpler and less bureaucratic option will likely depend on how the environmental outcomes are drafted. Outcomes are to be scoped out based on a desktop analysis of accessible, reliable and up-to-date information. It is suggested that the EOR approach will provide more proportionate assessment against agreed outcomes that will alleviate lengthy scoping exercises. However, any assessment to determine whether or not environmental outcomes are being met is still likely to require an assessment of the effects to understand what mitigation might be required.

1.5. DEVELOPING AN ECOSYSTEM-BASED APPROACH TO MONITORING OFFSHORE WIND FARMS

All offshore wind farms built in the UK are subject to environmental monitoring programmes to investigate the impacts of these new structures on the surrounding marine ecosystems. These previous studies have provided a large amount of data on environmental effects at the species level. However, one of the main issues linked to these environmental monitoring programmes is the focus on certain ecosystem components such as marine mammals, birds, fish, and benthos (Pezy et al., 2020).

Site assessment and characterisation, construction, and operation of offshore wind developments will affect multiple taxa and habitats, both above and below the water, resulting in potential ecosystem-level changes when built out to industrial scale. Maintaining biodiversity can also be critical for ecosystem functioning and resiliency to disturbance (Kershaw et al., 2023). It is therefore essential that a monitoring plan for offshore wind farms is designed to detect changes within the ecosystem at multiple spatial and temporal scales. Ecosystem-based monitoring (EBM) can be used to monitor the biodiversity and functioning of an ecosystem, including changes that may occur due to offshore wind development (e.g., Ruckelshaus et al. 2008; Pezy et al. 2020).

An ecosystem-based approach to monitoring can help to balance the use of natural resources with their conservation. Ecosystem-based approaches are often stakeholder-driven and tailored to regional conditions. They can help to:

- Resolve problems and address issues such as declining resources, poor quality surroundings, and increased demands on the environment.
- Resolve conflict by helping to clarify what decisions mean for different interests, and to facilitate trade-offs between stakeholder priorities.
- Provide a better understanding of how ecosystems respond to stressors, and how to forecast pressures and impacts on different components of an ecosystem.
- Help to support the conservation of biodiversity and the sustainable use of its components.

Kershaw et al., (2023) reported on the scientific principles of ecosystem-based monitoring:

"An EBM plan represents a combination of efforts to monitor specific taxa as well as the broader environment and is organised as a nested hierarchy, comprising habitat zones encompassing communities of species at the broadest level down to specific individuals within a population at the most focused level".

"Ecosystem-based principles represent a holistic view of a given ecosystem, and provide a framework that can be used to assess the health of an environment across all levels. This hierarchical framework provides a guide to determining the types of monitoring required to observe the ecological conditions in a specific region".

Kershaw et al., (2023) stated that "the goal of an EBM plan is to build a monitoring framework that effectively aids and informs decision-making with an allowable degree of uncertainty".

Environmental monitoring programmes have generally only considered the sensitivity of potential disruptions to distinct receptor groups (plankton, benthos, fish, marine mammals, and birds), in a disparate manner without considering the trophic links[6] between the groups (Raoux et al., 2017). Therefore, the environmental impacts of offshore wind construction and operation remain unclear at the ecosystem scale, particularly regarding the trophic web structure and functioning (Bailey et al., 2014; Pezy et al., 2020), contributing to critical levels of uncertainty in assessing cumulative effects (Goodale and Milman 2016). To support holistic cumulative effects assessments at large scales crucial for the sustainable deployment of offshore wind, there is a need to study the processes that drive species distributions and abundances at the spatial and temporal scales at which they occur (Isaksson et al., 2023).

Isaksson et al., (2023) outline priorities for future studies that include "determining the extent to which offshore wind farms may impact primary production; how wind energy extraction affects biophysical ecosystem drivers; whether pelagic fishes mediate changes in top predator distributions and how any effects observed at a local level will scale and interact with climate change and fisheries displacement effects".

An ecosystem monitoring approach to baseline data collection would allow an assessment of the ecosystem (functioning, structure, and resilience) after the construction of the offshore wind farm (Isaksson et al 2023). It would be necessary to maintain this ecosystem approach during operational phases to improve understanding of the behaviour of a given ecosystem, allowing the ability to anticipate potential changes in ecosystem states, and implement conservation actions in a sustainable manner (Pezy et al., 2020).

In the USA, the National Oceanic and Atmospheric Administration (NOAA) developed the integrated ecosystem assessment (IEA) as a means to conduct and deliver integrated, cross-sectoral science to support ecosystem-based management. Figure 1 shows the cyclical, iterative nature of ecosystem-based monitoring and adaptive management (adapted from the description of the NOAA IEA process in Samhouri et al., 2014).

Figure 1. The cyclical, iterative nature of ecosystem-based monitoring and adaptive management (adapted from the description of the NOAA Integrated Ecosystem Assessment process in Samhouri et al., 2014).

6. Trophic links are the feeding connections in a food web that describe the relationships between species in an ecosystem. These links represent trophic levels, which are the different feeding positions in a food chain or web.

Due to practical and resource constraints, it is not possible to monitor all components of an ecosystem. Key monitoring priorities should be selected that comprise of indicators[7] representing key components in an ecosystem that answer the most important questions about status and trends, and allow for change to be identified and measured (Kershaw et al., 2023). They provide the basis to assess the status and trends in the condition of the ecosystem or of an element within the ecosystem (Samhouri et al. 2014). As the ultimate goal is to assess the effects of offshore wind developments on wildlife, habitats, and the broader ecosystem, indicators that are expected to be affected by offshore wind development should be selected. Examples of indicators can include ambient noise levels, biological soundscape characteristics, seabed recovery rate, or taxa or habitats of conservation concern (Samhouri et al. 2014; Sparrow et al. 2020).

Once collected, ecosystem indicator data can be assessed collectively to evaluate ecosystem status and trends relative to ecosystem management goals and targets, and also offers information on an individual basis, such as highlighting underlying causes in any changes in status or trends observed (Samhouri et al. 2014). Increasing our knowledge about what indicators are best to use and what they tell us about how the ecosystem functions will lead to more strategic and integrated approaches to monitoring (Trifonova et al., 2021). It can also help to assess and evaluate trade-offs and benefits of anthropogenic impacts to enable more sustainable spatial use of our seas at whole ecosystem scales (Trifonova et al., 2021). Data collected on behalf of the offshore wind industry could also be used as evidence towards the assessment of Good Environmental Status (GES)[8] which is a qualitative description of the state of the seas. The UK Marine Strategy provides the framework for achieving GES and applies an ecosystem-based approach to the management of human activities. In doing so, it seeks to keep the collective pressure of human activities within levels compatible with the achievement of GES (Defra 2022). GES assessments, particularly in the offshore, are mainly restricted to Marine Protected Area (MPA) data sources. Currently, only a small selection of MPAs can be monitored at a reasonable frequency. Data is available from alternative sources to support GES assessments, such as those collected by Industry as part of licensing and consent procedures, however, Defra (2022) reports datasets are in different formats and the type of surveys are not always suitable for assessments of status and condition. Through an ecosystem-based monitoring approach, we have the opportunity to maximise the use of available data to support other UK policy requirements.

Models can be used to evaluate the influence of human activities (e.g., offshore wind development) and natural causes (e.g., oceanographic changes caused by climate change) on the indicators (Kershaw et al., 2023). The degree of uncertainty in each indicator's response to changes in drivers and pressures must be incorporated into a model's development (Samhouri et al. 2014). Significant progress has been made in developing models that use traditional statistical approaches to understand the relationships between a number of variables, including dynamic ecosystem models, such as Bayesian techniques (Trifonova et al., 2021). To allow for detailed local data to make predictions for regional and shelf-wide scales, ecosystem modelling approaches that include the representation of drivers of ecosystem function at all scales are needed (Isaksson et al., 2023). The outcomes of the empirical analysis and ecosystem modelling can then be used to evaluate the effectiveness of management strategies and inform adaptive management (Samhouri et al. 2014).

Stephenson (2021) made several recommendations on the need to develop a more integrated, multi-species, multi-method approach to biodiversity monitoring in the offshore wind sector. The approach would allow flexibility in the methods being used but in a more standardised way to monitor common indicators, allowing for comparisons between sites, data aggregation and sharing across regions, the study of cumulative impacts, and more informed results-based decision-making (Stephenson, 2021).

7. An indicator is a physical and/or biological ecosystem component, that could be described as an environmental predictor, a response, or a pressure.
8. GES is defined as the environmental status of marine waters where they constitute ecologically diverse and dynamic ocean and seas which are clean, healthy and productive within their intrinsic conditions, and the use of the marine environment is at a level that is sustainable, thus safeguarding the potential for uses and activities by current and future generations (Defra, 2022).

1 INTRODUCTION

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There is a need to adopt a set of principles and practices to ensure effective monitoring which include (Stephenson, 2021):

- Choosing methods based on indicators and monitoring questions
- Defining the appropriate spatial and temporal scale
- Engaging key stakeholders in monitoring design and implementation
- Designing fit-for-purpose monitoring programmes
- Collating data in standard formats to facilitate data sharing

In addition, there is a need for monitoring that facilitates more persistent, comprehensive coverage in time and space, with more temporal and spatial resolution. This is a natural fit with the evolving autonomous system capabilities. The next section will explore how a regional approach to ecosystem monitoring programmes in the offshore wind industry could help to address the many uncertainties and issues that currently impede the UK consenting process.

2 REGIONAL ECOSYSTEM MONITORING PROGRAMME

Unlike site-specific monitoring that tends to focus on one narrowly defined area of interest, regional monitoring can holistically examine the condition of a marine ecosystem across time and space, with the ability to address cumulative impacts relative to meaningful spatial and temporal baselines, to fill knowledge gaps and inform effective, adaptive, and proportionate decision-making.

A Regional Ecosystem Monitoring Programme (REMP) is an innovative approach to compliance monitoring for the offshore wind industry, addressing the need for regional research and monitoring of marine and coastal resources during offshore wind development, construction, operation and decommissioning.

The following sections discuss a potential framework for how a REMP might operate in the UK. The framework is comprised of lessons learned from mature monitoring programmes that have been summarised in Part 3 to help guide an approach for the UK.

2.1. WHAT IS MEANT BY 'REGIONAL'?

Firstly, it is important to understand what is meant by the term 'regional' for the purpose of establishing a REMP. In the UK, the Crown Estate (TCE) identifies areas of seabed around the UK that offer the least constrained (most technically favourable) areas for offshore wind development. For each of these regions identified as potential leasing areas for offshore wind such as the Celtic Sea, the spatial opportunity is then refined by TCE to Project Development Areas (PDAs). 'Regional' refers to the collective PDAs as well as the wider zone of influence, which includes impacts outside of the development footprint. For most species, the zone of influence will extend to 4 km beyond the development footprint, however, there are exceptions for more sensitive species (in particular if red-throated divers are likely to be present, a buffer of 10 km will be required; NatureScot, no date). The regional area would also include proposed cable route corridors and grid connections.

2.2. OVERVIEW OF A REGIONAL ECOSYSTEM MONITORING PROGRAMME

The purpose of a REMP is to collaboratively and effectively conduct and coordinate relevant, credible, and efficient regional monitoring and research of marine flora, fauna and ecosystems that support the advancement of environmentally responsible and cost-efficient offshore wind development activities in the UK. For the REMP to be effective it will be necessary to:

- Ensure monitoring plans are effectively designed to provide information that can be used to understand and minimise adverse impacts on marine resources from offshore wind development consistent with the best scientific advice and in line with the data needs of decision-makers and developers.
- Contribute to the greater regional research effort by ensuring that existing and ongoing research is not duplicated, data gaps are addressed, and long-term monitoring needs are met.
- Promote the use of standardised methods to collect and analyse biological and environmental data.
- Support the integration of monitoring efforts across multiple spatial and temporal scales (site-specific to regional/ecosystem and before/after construction).
- Focus monitoring efforts on important species and habitats of concern, commercial and recreational species, and other resources that may be impacted by or vulnerable to offshore wind development.

- Conduct rigorous, hypothesis-based, and scientifically defensible monitoring and research with results that are reproducible and statistically robust.
- Adopt an ecosystem-based approach to monitoring.
- Encourage proactive engagement, collaboration, and involvement among government departments, SNCBs, local councils, wind developers, research institutions, and environmental stakeholders to identify research priorities and timelines for products.
- Identify and inform actions for adaptive management to avoid, minimise, and/or mitigate impacts, including cumulative impacts, from offshore wind on coastal and marine resources, including habitat, biota, and recreational and commercial fisheries.
- Make products readily available to stakeholders and the public in a user-friendly accessible format.
- Establish an adaptable framework for future offshore wind monitoring efforts, including goals, objectives, protocols, criteria for prioritisation of projects, roles and responsibilities, and timeframes.

2.3. FRAMEWORK FOR A REGIONAL ECOSYSTEM MONITORING PROGRAMME

First, monitoring priorities for each region need to be identified, ranging from ecosystem-level questions such as changes in hydrodynamics and underwater noise levels, to species or habitat-specific questions such as changes in the distribution or behaviour of marine mammals and birds, to questions related to specific potential impact factors such as the effects of electromagnetic fields on sensitive species.

At this stage, the study design, standardised methods, and operational protocols that will help to ensure the proposed monitoring can collect the information necessary to assess the impacts (both positive and negative) of offshore wind development projects and associated mitigation measures on marine resources are determined.

Every region will have unique priorities and considerations that are not necessarily transferable across other regions. Monitoring priorities and key indicators for each region would be developed through the engagement and collaboration of SNCBs, relevant environmental stakeholders and experts. Figure 2 illustrates the development process for establishing a REMP.

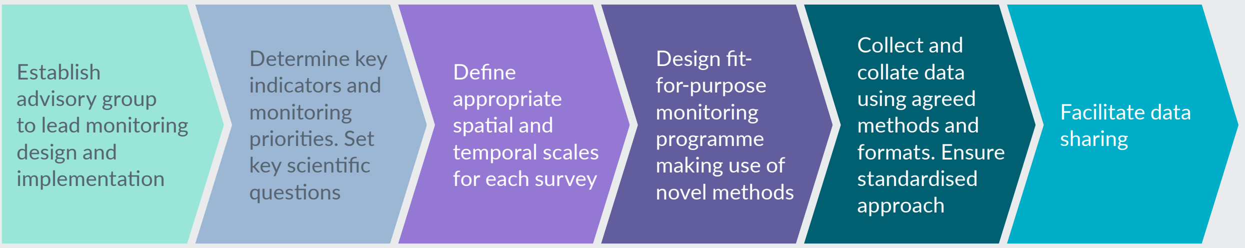

Figure 2. Regional Ecosystem Monitoring Development Process

It is important to be adaptive throughout the process to reflect that different or expanded research and monitoring needs may arise to accommodate unforeseen circumstances and new scientific information as future offshore wind projects are developed.

The REMP may be government- and/or industry-funded depending on the preferred approach and delivery models for each option are shown in Figure 3 which is described in more detail below:

1. Whether funded by government or industry, the programme could be managed by a relevant existing government department or by an independent facilitator, such as ORE Catapult to coordinate and deliver the monitoring programme.
2. The coordinators of the REMP would then engage with the wind developers, relevant experts, both environmental and engineering, the SNCBs, and regulatory stakeholders. From these individuals, two groups would be convened; the Cross-Receptor (Ecosystem) Advisory Group, responsible for planning and developing the monitoring studies, identifying data gaps and developing key scientific questions to address those gaps (as outlined in Figure 2), and the Offshore Wind Technology Advisory Group that would be responsible for providing the technological input relating to wind farm infrastructure.
3. Following a process of detailed planning, coordinators of the REMP would contract specialists in environmental monitoring and data processing.
4. Data collection would follow as stipulated in the monitoring protocol.
5. Datasets would be quality-approved and published in an existing or new data portal.
6. The data portal's web apps would process the data, analyse and perform ecosystem modelling to produce outputs required for the EIA. The portal would host a standardised EIA template applicable to the offshore wind industry DCO process.
7. The EIA template with relevant data outputs would be available to individual wind developers and their chosen consultants for completion.
8. The completed Environmental Statement along with the application for the DCO will be submitted by developers to the Planning Inspectorate.
9. Throughout the process, there will be ongoing engagement and feedback between the coordinator of the REMP and industry.

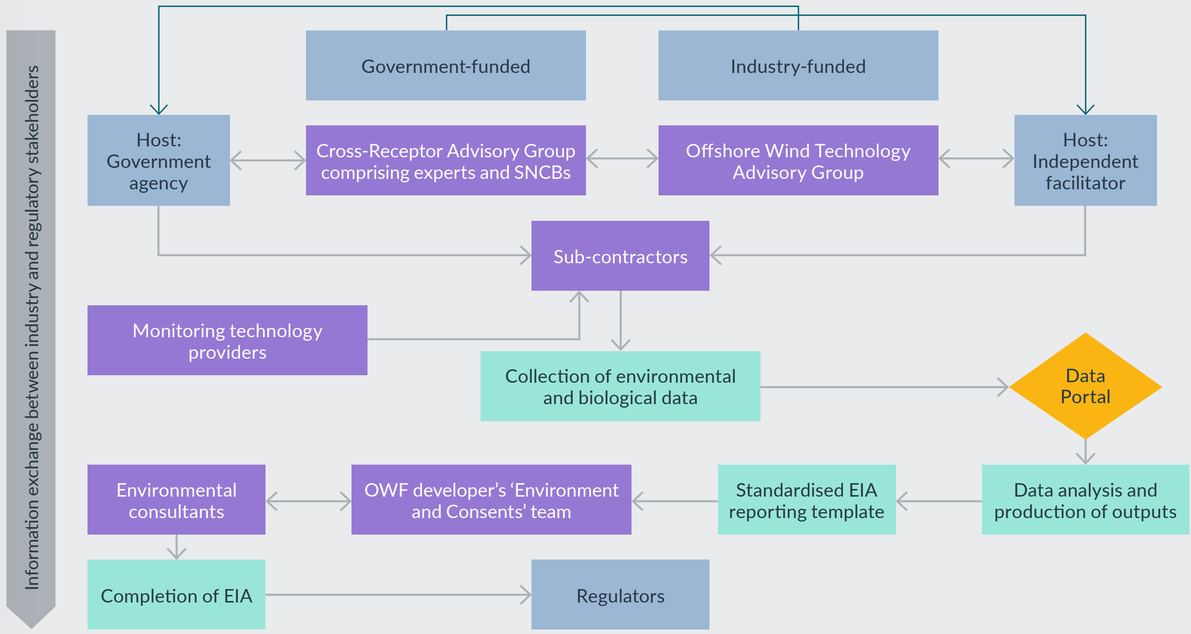

Figure 3. Proposed Government and Industry-funded delivery models for a Regional Ecosystem Monitoring Programme

If the REMP was entirely industry-funded, a phased approach to funding the monitoring programme could be adopted, creating a pro-active, collaborative, industry-led approach to environmental baseline surveys and post-consent monitoring. It is imperative that the wind farm developers taking part in the programme feel empowered to make effective decisions concerning data collection and that the framework supports efficient and fair collaboration among those companies.

Figure 4 shows a framework for how the industry-led and -funded REMP might operate. This approach has been successfully used in Australia, coordinated by RPS in collaboration with offshore wind developers.

- **Phase One:** design of the delivery framework and early baseline study scoping utilising a range of subject matter experts across academia, consultancy, and government.
- **Phase Two:** detailed planning and preparation of marine baseline studies to inform project environmental assessment across the specific region including finalising the study scopes and delivery framework to suit all participants, with detailed design, contracting, and safety planning.
- **Phase Three:** provision of datasets, analysis and standardised EIA reporting template.

Phases One and Three would involve a single cost model where developers pay a single fee and in Phase Two, during data collection, developers could decide which monitoring they wish to pay for, funding specific surveys and therefore choosing to opt-in or -out of particular aspects of the broader monitoring programme.

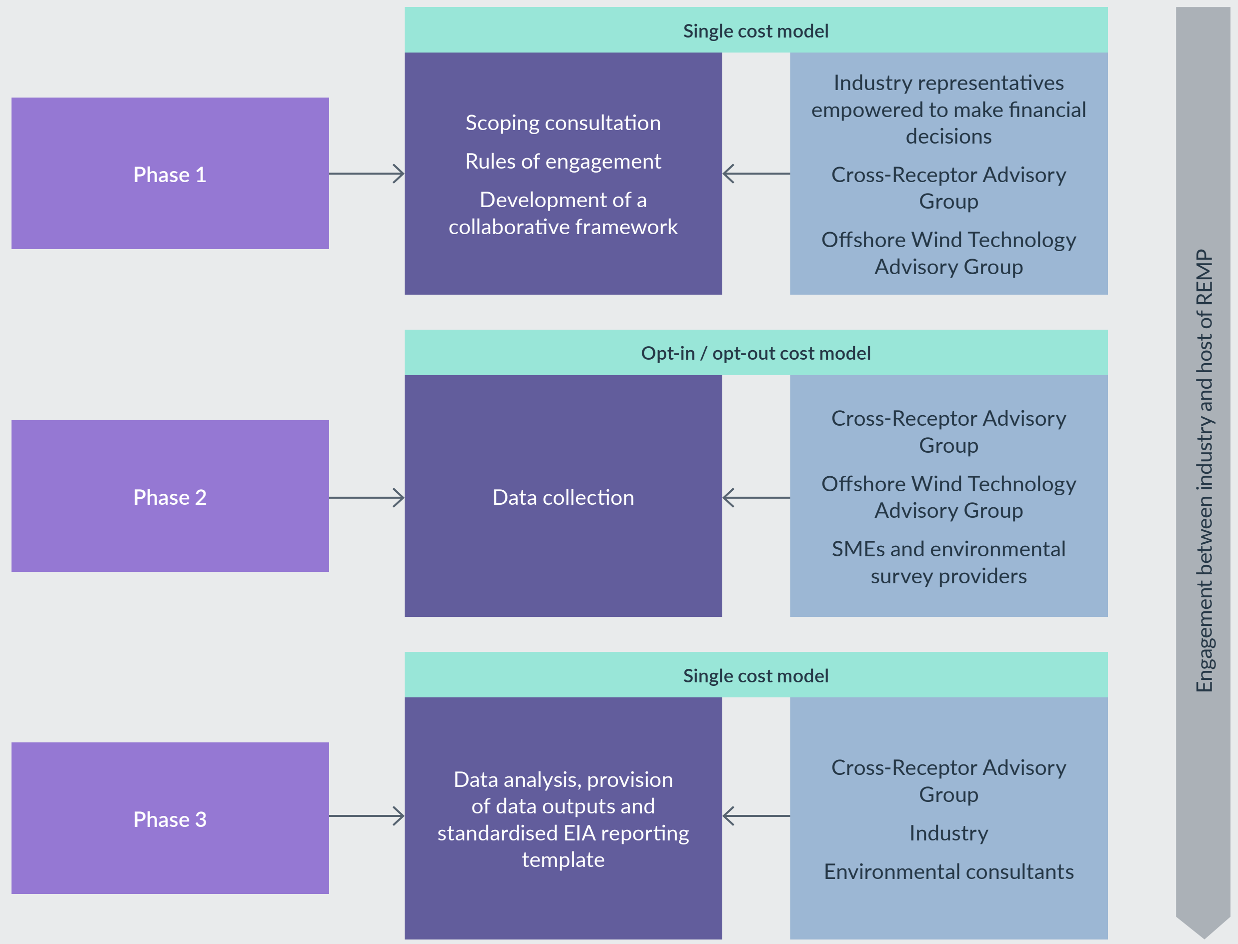

Figure 4. A phased approach to Industry funding a Regional Ecosystem Monitoring Programme

2 REGIONAL ECOSYSTEM MONITORING PROGRAMME
CONTINUED

2.4. CHALLENGES AND OPPORTUNITIES

The development of a REMP to detect and quantify environmental impacts from offshore wind farms presents a number of opportunities that could address the current challenges with monitoring development sites. Table 1 identifies some of the challenges and attempts to set out the potential opportunities of establishing a regional monitoring programme.

Table 1. Examples of challenges and opportunities presented by the planning and application of a Regional Ecosystem Monitoring Programme

CHALLENGES	OPPORTUNITIES
BASELINE SURVEYS	
Overlap in areas surveyed by different developers	– Avoid duplication by more strategic and regionally consistent approaches to baseline environmental surveys
The extent of the required baseline	– Collaborative and partnership arrangements can streamline the monitoring effort and reduce costs to individual developers – Innovative monitoring technology can monitor over a greater spatial and temporal scale providing data that would include the wind farm development site, buffer zone and the wider region, crucial to understanding cumulative impacts
Different survey techniques between developers impact the utility of data	– Improve data consistency and utility through development of appropriate standards for data collection
DATASETS AND ANALYSIS	
Concern about providing a competitive advantage to other developers	– OneBenthic data portal adapted and replicated for other receptors is a potential resource for facilitating data discovery and access. Where commercial constraints exist, the metadata can be uploaded to the data portal to make the data discoverable, with caveats on accessibility
SCIENTIFIC UNCERTAINTY	
Conservative approaches to monitoring are resource-intensive and costly	– Establish strategic initiatives to identify and address key sources of uncertainty – Develop key indicators and monitoring priorities to simplify and focus monitoring efforts – Ensure monitoring is capable of answering key questions for the region – with an adaptive pathway
SOCIAL LICENCE TO OPERATE	
Public concern/scrutiny about environmental and social effects of offshore wind	– Demonstrate appropriate planning and preparedness through the development of a fit-for-purpose monitoring program – Highlight the monitoring programme provisions during the stakeholder consultation process
DESIGNING FIT-FOR-PURPOSE MONITORING PROGRAMMES	
Opportunities for less prescriptive monitoring requirements	– Create more flexibility to develop a fit-for-purpose ecosystem-based monitoring programme that can be practically and efficiently implemented and deliver high-quality environmental outcomes

2.5. BENEFITS OF A REGIONAL ECOSYSTEM MONITORING PROGRAMME

The adoption of a REMP approach could offer a range of benefits for both the offshore wind industry and the regulator. For the industry, the approach will reduce the complexity and costs of monitoring. Cost and time savings will arise from using autonomous and uncrewed vehicles and avoiding duplication from a regional approach. For the regulator, a more streamlined approach to the EIA process would help to reduce the administrative burden, more robust data collection and agreement on analysis would reduce the uncertainty in environmental impacts and an ecosystem-based approach to monitoring would answer the pertinent questions of concern relating to each region. In addition, the data generated by industry, whilst serving its specific requirements, could help fulfil other government objectives concerning monitoring e.g. progress towards GES and monitoring MPAs. Table 2 summarises some of the main issues associated with the current consenting process for offshore wind as well as the benefits that may result from a regional monitoring approach.

Table 2. Issues and benefits of a Regional Ecosystem Monitoring Programme for key stakeholders

STAKEHOLDER GROUP	ISSUES	BENEFITS
Offshore wind industry	Uncertainty in consenting timelines	– Streamlined EIA process – More certainty for the regulator from an ecosystem-based monitoring approach – Potential for removal of the scoping phase with regional advisory groups established to engage on environmental and engineering concerns
	Uncertainty in the quality of data	– Smarter, innovative technology and AI data processing to collect more scientifically robust data
	Competition between developers	– Regional monitoring would reduce competition for resources – Transparency in data sharing, standardisation of analysis and output products would benefit developers
	Availability of resources for monitoring and analysis	– Flexibility in the monitoring methods and streamlined EIA reporting requirements will address resourcing issues
	High costs	– Reduced expenditure on project management, consultancy fees, discretionary advice, and expensive monitoring methods
Regulator/SNCB	Resourcing	– Reduced regulatory burden due to streamlined pre-application process
	Workload	– Reduced administrative burden from standardised EIAs – Greater consistency in quantity and quality of data and analysis – More targeted and effective licence conditions
	Uncertainty in environmental impacts	– Improved understanding of the effects and their significance
Academic community	Lack of useable, readily available datasets	– Timely datasets freely available for research
		– Ability to address evidence gaps
Business community		– Build regional and UK-wide supply chain
		– Global export opportunity

Many additional benefits come from establishing a regional approach to meeting the monitoring requirements of the offshore wind industry. A regional monitoring programme would address the specific needs of monitoring required at all stages of a wind farm, and would represent a very substantial contribution to scientific literature for the region as well as future marine spatial planning. Understanding the effects of offshore wind farms at the right scales underpins the determination of impacts resulting from the interactions between offshore wind farms and other marine industries, such as fisheries and is therefore essential for sustainable coexistence. A regional monitoring approach will provide a much more accurate understanding of environmental activity and can be used by The Crown Estate and Crown Estate Scotland to inform advanced seabed lease planning.

2.6. REGIONAL MONITORING AND CUMULATIVE IMPACT ASSESSMENT

Under UK legislation, there is a requirement to consider the extent of cumulative impacts, defined in the Welsh National Marine Plan as:

"those effects that result from incremental changes caused by two or more past, present and/or reasonably foreseeable actions. These can be economic, social or environmental in nature. Cumulative effects could arise from single or multiple responses (environmental, economic or social) to single or multiple pressures from single or multiple activities. The term "cumulative" is extended to include the term "in combination" effects as used in some legislation."

Successful collaborative efforts to develop baseline regional data-sharing, at a minimum, can increase the chances that scientists will be better able to assess the cumulative environmental impacts of offshore wind installations in the future.

A major challenge of offshore wind farm environmental monitoring programmes is to assess cumulative impacts and to upscale locally observed impacts to a larger scale at which different ecological processes take place (Rezaei et al., 2023). The rapid increase in the number and size of offshore wind farms means that the cumulative contribution from the many turbines may be considerable. Offshore wind farms should not be considered in isolation because the significance of environmental impacts depends on the full spectra of human activities in each area.

Although the majority of monitoring efforts that have been done so far are concentrated on the environmental effects of a single wind farm and certain receptors, the overall impacts of offshore wind farms and other anthropogenic activities on certain receptors should be the focus. Ecologists advise expanding the scope of the impact investigation to account for the population level of the impacted species and the species that span over wider territories (Rezaei et a., 2023). For example, seabirds attracted to wind farms have an increased risk of collision with the wind turbine blades and the number of collisions may put the sustainability of certain bird populations at risk. However, it can only be reliably assessed by considering the multitude of wind farms throughout the range of the bird's spatial distribution (Lindeboom et al., 2015). According to van Berkel et al. (2020) wind farms can result in wind distortion over a radius of 5–20 km. Some studies suggest that offshore wind farms can have an impact on primary production decline (Daewel et al., 2023) and fish behaviour up to 10 and 15 km, respectively, while wind farm development can have an impact on bird and mammal behaviour up to 16 and 50 km, respectively (Haelters et al., 2015; Mendel et al., 2019). As more wind farms are developed, there may be a need to assess impacts at a broader scale than what has been suggested in the proposed framework to ensure that no essential information is lacking.

2 REGIONAL ECOSYSTEM MONITORING PROGRAMME

CONTINUED

2.7. RESOURCING ISSUES IN THE INDUSTRY

There are several skills gaps and shortages that need to be addressed across the industry. The Offshore Wind Industry Council's 'Offshore Wind Skills Intelligence Report' in 2023, highlighted the shortage of people with consenting skills, particularly amongst SNCBs and regulators. These are critical skills gaps and shortages that will inhibit the delivery of projects in the immediate future (OWIC, 2023). There is a shortfall in the required volume and range of skilled resources within the SNCBs and regulatory bodies to meet the demand in casework to deliver offshore wind 2030 and net zero targets, which is made worse by the turnover of experienced staff within regulators during the time it takes to secure consent.

Developers are encouraged to take advantage of the Discretionary Advice Service (DAS) which is offered by the SNCBs to provide non-statutory advice related to development proposals. However, the labour shortage affecting the SNCBs can affect a developer's access to this service. By implementing a regional-scale monitoring programme and removing project-level assessments, the need for this advice is less important. The creation of expert advisory groups could remove the need for discretionary advice upfront. Each region will have its own set of monitoring priorities that could be discussed through the engagement and collaboration of SNCBs, regulators and subject-matter experts that would set the key indicators and requirements for monitoring.

Another option to address the resource shortage is to reduce the administrative burden and ensure there is standardisation in data collection and reporting for Environmental Statements (discussed in Part 5).

3 REGIONAL MONITORING: A GLOBAL PERSPECTIVE

Consenting is still regarded as a non-technological barrier to progress in the offshore renewables industry, generally caused by the complexity of the processes and the lack of dedicated legal frameworks.

The legal and regulatory frameworks surrounding environmental impacts are clearly a priority area. Although how EIAs are conducted differs by country, most governments typically require the environmental and social impacts of a proposed offshore wind project to be assessed and mitigated and/or compensated for, if impacts cannot be avoided. This chapter provides examples of regional monitoring approaches to the EIA for offshore wind developments in other countries. Also highlighted is a regional monitoring programme that already exists in the UK.

3.1. UK

An example of a regional monitoring approach within a UK sector that has already been successfully adopted is the Regional Seabed Monitoring Plan (RSMP) developed by the aggregates industry, an approach based on monitoring the long-term impacts of aggregate dredging on the seabed. The UK marine aggregates industry adopted the RSMP in the main English dredging regions (Humber Anglian Thames East Channel and South Coast) in 2013. In 2015, the Welsh Government and Natural Resources Wales adopted the RSMP in its waters (Bristol Channel/ Severn Estuary and North-West dredging regions). Each licensed area for the study and secondary impact zone is covered by an array of grab sampling stations. The nature of the seabed animal communities (i.e. assemblage type) at each station is identified at the baseline usually at the EIA stage. Sampling stations are then revisited during subsequent RSMP monitoring rounds (once every five years) to check whether sediment composition remains favourable for the return of the original assemblage type after dredging. In 2014, the British Marine Aggregate Producers Association estimated that monitoring costs from a regional approach may be reduced by 50 percent[9]. It was also reported that industry operators, regulators and advisors benefited from significant savings in time, effort and resources from the more coordinated approach to compliance monitoring delivered through the RSMP programme.

3.2. USA

In New Jersey, USA, the Research and Monitoring Initiative (RMI) is administered by the Department of Environmental Protection (DEP) in collaboration with partners at the Board of Public Utilities (BPU). The RMI coordinates regional research and monitoring of marine and coastal resources during offshore wind development, construction, operation and decommissioning as recommended in the New Jersey Offshore Wind Strategic Plan. Initial funding is provided by developers through New Jersey's Offshore Wind Solicitation 2. The New Jersey interagency effort is funded by wind developers Atlantic Shores Offshore Wind, LLC, and Ørsted's Ocean Wind II project with each reported to have committed $10,000 per megawatt of planned project capacity – about $26 million in all for long-term research and ecological monitoring[10]. The DEP and BPU collaborates with research institutions, industry, regional monitoring organisations and members of the New Jersey Offshore Wind Environmental Resources Working Group to identify and prioritise research and monitoring needs.

3.3. AUSTRALIA

In Australia, baseline environmental monitoring is being led by consultancy and engineering firm RPS, with specialist subcontractors and developers (Flotation Energy, Corio Generation, Ocean Winds, Vena Energy, RWE, and Alinta Energy) to deliver the Regional Marine Environmental Baseline Studies programme (RMEBS) in Victoria. The multi-phased

9. Reported in the "Marine-Aggregate Regional Seabed Monitoring Plans: Cost/Benefit Statement on Behalf of the Marine Aggregate Sector. https://assets.publishing.service.gov.uk/media/5a81d6dce5274a2e87dbfc13/BIT_assessment_-_Improvements_to_marine_licensing_-_Regional_seabed_monitoring_plan.pdf
10. https://www.workboat.com/wind/new-jersey-sets-3-3-million-for-offshore-wind-environment-studies

programme is aimed at creating a pro-active, collaborative, industry-led approach to environmental baseline surveys, in support of regulatory approvals, across the emerging offshore wind industry in Victoria. Key features of the program are to collect data at regional scales, which reflects the movements and behaviours of protected marine species and to reduce costs for individual developers by sharing resources[11], realising synergies, and eliminating the duplication of survey effort by developers.

3.4. THE NETHERLANDS

In the Netherlands, the government commissions a series of local site studies including meteorological and oceanographic surveys, soil surveys, archaeological and UXO surveys as well as the EIA. Project developers do not have to conduct an EIA, nor perform individual site studies (or bear the associated costs) before deciding whether a project may be viable or not. Costs for the surveys are borne by the State and not the competing project developers. An EIA starts with a Range and Detail Memorandum (NRD) which gives insight into how the environmental impact is studied and assessed. The memorandum follows a public consultation and offers a solid basis for the EIA. This ensures all important matters are given appropriate consideration, and helps to limit the range of assessments. The NRD is based on current relevant developments in both scientific and legal fields. The substance of both the NRD and the EIA is reviewed by the independent Environmental Impact Assessment Committee. The recommendations of the committee are not binding, but are often followed in practice. The Netherlands Enterprise Agency (RVO) commissions and publishes the resulting datasets and all studies and investigations are officially and independently certified and quality-approved.

3.5. BELGIUM

Prior to installing a wind farm, a developer in Belgium must obtain a domain concession and an environmental permit. When a project developer applies for an environmental permit, the procedure has several steps, including a public consultation during which the public and other stakeholders can express any comments or objections based on the environmental impact study (EIS) that is set up by the project developer. The Management Unit of the North Sea Mathematical Models (MUMM), a department of the Royal Belgian Institute for Natural Sciences advises on the acceptability of expected environmental impacts of the future project to the Minister responsible for the marine environment. MUMM's advice includes an EIA based on the EIS. The EIA is led by the MUMM who coordinates the monitoring which specifically covers underwater noise, hard substrate epifauna and fish, radar detection of seabirds, marine mammals and hydrodynamics. To cover all necessary scientific expertise MUMM collaborates with several institutes: the Research Institute for Nature and Forest (INBO), the Institute for Agricultural and Fisheries Research (ILVO-Bio-Environmental research group), Ghent University (Marine Biology Research Group and INTEC), International Marine and Dredging Consultants (IMDC) and Grontmij Belgium NV. Where the MUMM deems it appropriate, project developers are required to conduct some of the monitoring. The Minister then grants or denies the environmental permit in a duly motivated Decree. The environmental permit includes several terms and conditions intended to minimise and/or mitigate the impact of the project on the marine ecosystem. Furthermore, as required by law, the permit imposes a monitoring programme to assess the effects of the project on the marine environment.

11. Estimated cost savings to developers of 50 percent (pers. comms, Dr Christine Lamont, Technical Director, RPS Australia).

3 REGIONAL MONITORING: A GLOBAL PERSPECTIVE
CONTINUED

3.6. GERMANY

The German consenting system consists of several steps, primarily conducted by the Federal Maritime and Hydrographic Agency (BSH) including the strategic level assessments (SEAs) and EIAs. Initially, there is an assessment of the German Exclusive Economic Zone (EEZ)'s marine spatial planning to ensure that economic and social interests are balanced with protecting the environment. After the marine spatial plan is approved, baseline surveys are conducted, that include the marine and reference environments (species community analysis), subsoils, and wind and oceanographic conditions (BSH, 2020). The BSH determines the survey area, monitoring programme and reference area for individual conservation interests. The site investigation is completed in partnership with the Federal Network Agency (BNetzA) and in consultation with the Federal Agency for Nature Conservation (BfN), the Directorate General for Navigation and Waterways (GDWS), and the federal states that contain the wind farm. The cost for conducting the surveys is borne by the BSH, but eventually recovered indirectly in the tender from the winning bidder. The biologists at the BSH examine the results of the site investigations and assess the impacts of the windfarms on the marine environment. They use the web application MARLIN (Marine Life Investigator)[12] developed by the BSH, to use biological data and information from offshore projects more efficiently for environmental assessments. It supports users, such as offshore wind farm operators, in delivering marine biological data and analysis.

3.7. SWEDEN

In Sweden, the County Administrative Board in Västra Götaland has recommended developers jointly pay for a study into the impact of offshore wind farms on marine life off the west coast[13]. The article in reNEWS Issue 530 stated "the review would assess the cumulative impacts of projects planned for the region on porpoises, birds, fish and other marine life. "It is not enough that each park examines and monitors the impact from their own facility," the authority said. "The introduction of some form of joint funds to pay for monitoring of the total impact should be considered. If several wind farms come into being in the area in question this may entail a significant impact risk."

12. MARLIN: https://www.bsh.de/EN/TOPICS/Offshore/Environmental_assessments/Biology/biology_node.html
13. reNEWS Issue 530 20th June 2024.

The role innovative technology could play and the different types of sensors and platforms available in helping to shorten consenting times were discussed in the report by ORE Catapult (2023). The following sections discuss how innovative technology can support the shift from project-level assessments to regional ecosystem monitoring.

4.1. SPATIAL AND TEMPORAL COVERAGE

Autonomous solutions now exist for many of the relevant monitoring challenges, and they already offer the potential to streamline some operations. Data of direct relevance to environmental monitoring for offshore wind can be collected using acoustic, visual, and oceanographic sensors deployed on marine autonomous systems. There is considerable potential for both cost savings and a substantial improvement in the temporal and spatial resolution of environmental monitoring (Jones et al., 2019).

Compared with traditional in situ observations by ships and moorings, the greatest strength of autonomous platform networks is their capacity to conduct multiscale and cross-disciplinary measurements. Such resolution is critical for a regional-scale monitoring programme. The appropriate scale of sampling (both spatial and temporal) will depend on the variables and species of interest, the methods being used and the overall objectives of the monitoring program (Booth et al., 2020). The benefits of concurrent data collection methods utilising mobile and static platforms, with multi-parameter instruments, can greatly increase the information needed to explain variations in seabird, fish and marine mammal distributions (Chapman et al., 2024) and provide robust, informative outputs that can help to reduce uncertainties.

Advances in in-situ measurement techniques over the past decade have made it possible to study environmental drivers of marine ecosystem processes at fine-scale resolutions and capture any (predictable) variation (Isaksson et al., 2023). The sensors capable of continuous multi-day and concurrent bio-physical parameter measurements relevant to offshore wind farms and the autonomous and uncrewed platforms capable of hosting multiple sensors for studies offshore are listed in Appendix 1 (taken from Isaksson et al., 2023). These include active and passive acoustic techniques that can measure the spatio-temporal distribution and abundance of organisms and also track their movements (Williamson et al. 2021, Gillespie et al. 2022), whilst combining acoustic sensors with concurrent environmental measurements allows for multitrophic monitoring (Chapman et al., 2024). Autonomous platforms can fill some of the important temporal continuity gaps inherent with traditional platforms, improving observation frequency in the open ocean from monthly or seasonal to daily and weekly timescales (Chai et al., 2020). Recent advances have led to the use of swarm autonomous underwater vehicles (AUVs) where multiple vehicles work together to achieve a common objective, offering advantages such as greater spatio-temporal resolution, enhanced robustness to sensor errors and reduced survey time (Lin et al., 2017). With the deployment of wind farms into deeper waters, the need for similar multi-sensor floating platforms and sensor integration with turbine structures will become increasingly valuable (Isaksson et al., 2023). The major perceived limitation of autonomy in monitoring is the general inability to collect physical samples, particularly in the case of the seabed sediments. This necessarily limits the use of particular current standard practices. Jones et al., (2019) reported that these issues may well be surmountable through careful re-evaluation of appropriate indicators and/or by rapid technological advances.

Monitoring offshore, energy-related activities have long been spatially and temporally limited, and the range of mitigation options is narrow, most commonly consisting of pausing or delaying activities when marine mammals are detected close to operations. The incorporation of risk assessment and risk management in the procedures is extremely limited to non-existent, resulting in an approach that is highly precautionary (Macrander et al., 2022). By contrast, risk-based monitoring and mitigation approaches for marine mammals is growing, for example, Whale Safe, which manages the risk of vessel strikes. Risk is estimated through the collection of data and modelling to allow decision-makers to establish and address mitigation priorities. The risk profile of an area containing multiple species and subject to constantly changing ecological profiles and industrial development is extremely dynamic, requiring near real-time data and projection capacities (Macrander et al., 2022). Given the potential large-scale movements of marine mammals, together with the high spatial coverage of future offshore wind activities, a regional approach is needed. However, for the regional approach to be successful and to benefit all stakeholders, there needs to be an emphasis on coordination, data sharing, standardisation and transparency.

The rapid advancement of ocean observation technologies has enabled the collection of increasing amounts of data at higher spatial and temporal resolutions than was previously possible (Qian et al., 2021). Added to this, developments in high performance computing, big data analytics and artificial intelligence can make processing and analysis of large datasets more manageable and less time consuming (Ditria et al., 2022). Despite the increasing technological ability to collect and process large volumes of data, it is imperative that monitoring avoids the ‘a ‘data-rich, information poor’ situation (Wilding et al., 2017) and consideration is given to the statistical power of surveys to detect change.

4.2. ARTIFICIAL INTELLIGENCE FOR DATA PROCESSING

Autonomous monitoring platforms facilitated by artificial intelligence (AI) can provide a cost-effective solution for monitoring impacted and restored ecosystems over more relevant spatial and temporal scales. Automation is defined as the use of technology to replace or reduce human intervention (Ditria et al., 2022). Machine learning (ML), a subset of AI, has been fundamental to automation (Ditria et al., 2022). ML algorithms use experience through exposure to data to improve model performance and, as a result, can make accurate predictions from large volumes of data obtained in an automated framework (Mohri et al., 2018). After implementation, automated systems should require minimal input to report on the state of an ecosystem and are potentially more cost-effective. Novel monitoring approaches using automation and AI have consequently shown a marked decrease in running costs after implementing automated systems (e.g. Chen et al., 2015). González-Rivero et al. (2020) reported, for example, on the use of ML technologies for image-based data from coral reefs that resulted in a 99% cost reduction compared to traditional methods, and 200 times the speed (Ditria et al., 2022). Automated monitoring therefore has the potential to have high short-term costs but low ongoing costs.

In addition to the reduction in cost and time, incorporating automation and AI into monitoring programmes can enhance the ability to manage impacts on ecosystems by providing data at the appropriate resolution to address management needs and inform policy (Ditria et al., 2022). ML techniques have been used to analyse ecosystem effects and to predict critically important factors for ecosystem functioning (e.g. stratification, primary production, temperature) and how they change across contrasting spatial regions within UK waters. The additional data collected across greater temporal and spatial scales, and processed via automated monitoring methods, provides more information on the state of an ecosystem, which in turn allows for a better understanding of the environmental processes operating within the system (Ditria et al., 2022).

Figure 5 shows how integrating AI-facilitated, automated methods to collect and process data can increase the scope, resolution, and breadth of monitoring studies and provide greater capacity to share and build knowledge about the target ecosystem (Ditria et al., 2022). This capability is vital to the success of a regional monitoring approach. Removal of the processing bottleneck can increase the speed at which data is transferred and translated into useful information, thereby reducing costs and enabling management decisions to be delivered in a timely manner.

4.3. ECOSYSTEM MODELLING

Ecosystem models will need to play a much more prominent role in assessing and more accurately predicting the effects of offshore wind developments (Declerck et al., 2023). Ecosystem modelling approaches that represent the drivers of ecosystem function at all scales are needed. Declerck et al., (2023) suggest an ecosystem modelling framework that can enable the assessment of near, mid and far-field effects, including climate change. The recommended approach can predict cumulative impact assessment risks by 2050 under climate scenarios and predict changes in species distributions.

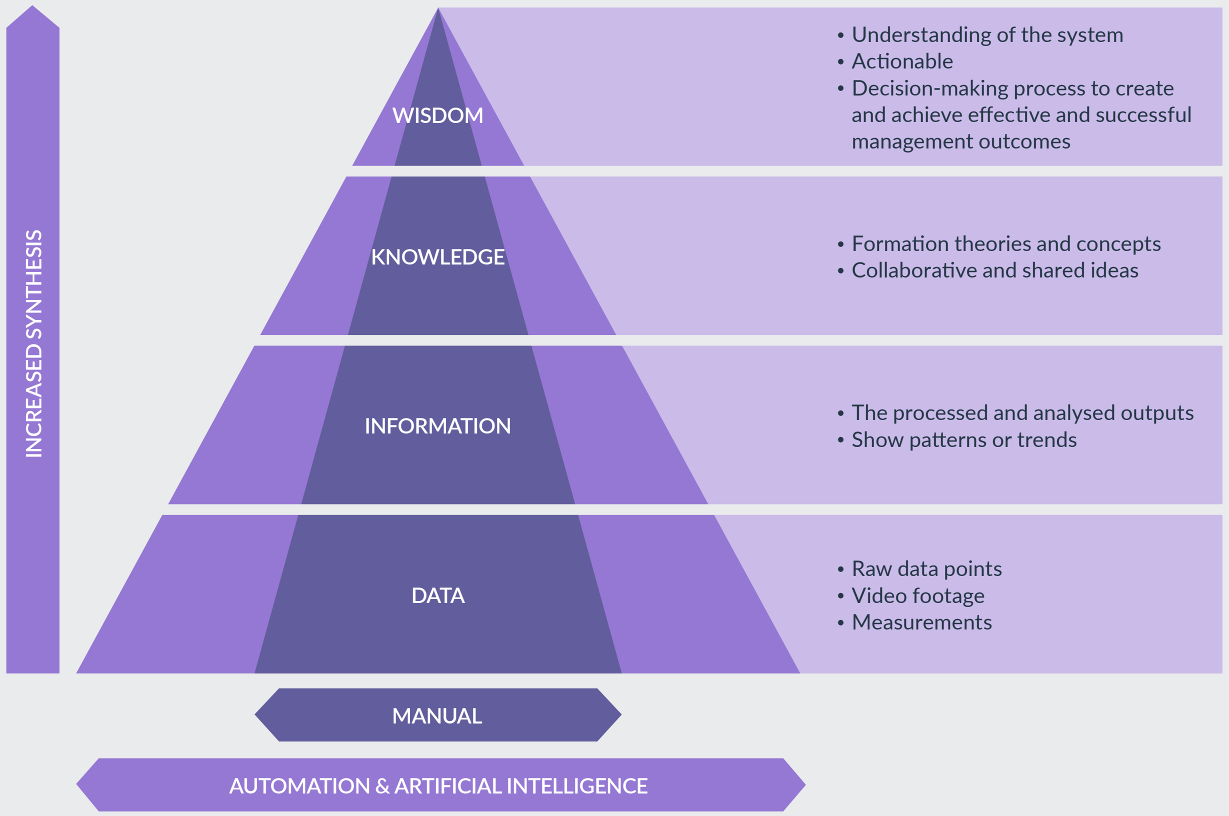

Figure 5. Data-information-knowledge-wisdom pyramid (Ditria et al., 2022)

4 THE ROLE OF INNOVATIVE TECHNOLOGIES IN SUPPORTING REGIONAL MONITORING INITIATIVES
CONTINUED

4.4. TRANSITIONING FROM TRADITIONAL METHODS TO NOVEL TECHNIQUES

With a growing need to better understand the functioning of the UK marine ecosystems within which large-scale offshore wind deployment is situated, it is critical to take advantage of innovative technologies, such as the use of robotics and artificial intelligence that will support the need for highly efficient survey and environmental monitoring procedures that limits potential costs and that fit with needs of the regulators.

Although the adoption of emerging and novel monitoring techniques can improve data collection, it is important to continue data collection in a coherent manner (McGeady et al., 2023). For this reason, many monitoring programmes have retained traditional methods, such as trawls and towed nets. Where a transition in monitoring technique is proposed, a long period of temporal overlap will normally be required to allow inter-calibration of the methods. However, in some cases it may be possible to supplement the older technology with modern instrumentation whilst retaining the essential original sampling characteristics (Reid et al., 2003). Where new monitoring programmes are proposed then maintaining historical consistency may be less critical, although it may still be desirable to be able to compare new data with results from surrounding locations.

Industry demand and regulatory support could help to increase the pace of technology transfer. There seems little doubt that uncrewed and autonomous vessels will be a transformative technology for environmental monitoring, only the rate of change is uncertain.

MEDIN (Marine Environmental Data and Information Network) data portal is a UK initiative that allows users to find information on over 18,000 marine datasets[14].

It has stringent data guidelines and a discovery metadata standard to ensure quality assurance and discoverability in the available data. Much of the data that is collected by the offshore wind industry for EIAs is stored in TCE's Marine Data Exchange which is linked to MEDIN via the MEDIN metadata discovery standard. Historically, however, there has been little standardisation of data limiting its utility (Pick, 2023). The former UK Offshore Wind Champion, Tim Pick's report published in March 2023 pointed to the results of a gap analysis performed as part of the Planning Offshore Wind Strategic Environmental Data and Information Network (POSEIDON) project. It discovered several technical issues associated with standardisation of environmental data and that the Marine Data Exchange lacked some aspects of functionality. TCE recently added a spatial search interface tool to the Marine Data Exchange which allows users to search for industry data via an interactive map, making data more discoverable and accessible. One of Tim Pick's recommendations on data was for TCE to "consider the opportunity for greater input from the academic sector's marine ecology and data science specialisms to facilitate development of the Marine Data Exchange". At the end of 2023, TCE launched the Offshore Wind Evidence and Knowledge Hub (OWEKH). The digital knowledge hub was created to help streamline the consenting process and support wider efforts to develop digital strategy, whilst providing a collaborative space where experts from across industry and academia can engage.

An example of best practice for data management is the portal developed in Germany (Section 3.6). MARLIN is a large-scale/high-resolution web portal containing EIA/monitoring data of all offshore wind farm and grid projects. Web apps incorporated into the portal enable data to be uploaded, shared, and analysed and outputs exported. MARLIN and MEDIN share similar objectives but due to commercial data sensitivity, there is resistance to uploading data onto MEDIN (Wolf et al., 2022). Neither data portal yet contains outputs from ecosystem models (Wolf et al., 2022).

5.1. ONEBENTHIC DATABASE

Data hosted on the Marine Data Exchange also feeds into other initiatives and tools that support in the sustainable development of the seabed. For example, data collected by the aggregates industry is hosted on the Marine Data Exchange and then fed into the OneBenthic[15] database, an initiative set up and maintained by Cefas. OneBenthic brings together disparate benthic datasets (e.g. seabed macrofauna, sediment particle size) in one cloud-based platform. The resulting high quality, standardised dataset is used to generate new science, and new innovative and collaborative ways of working. Outputs are shared via open-access publications and a suite of interactive web apps. Data can be harvested and the software allows for manipulation, analysis and presentation of data. The Marine Data Exchange is one of the primary sources of data for OneBenthic. This big data approach creates an opportunity to realise the concept of 'collect once, use many times' by finding ways to add value to marine data.

In the offshore wind industry, data standards for collecting, presenting and storing data are often inconsistent. Where data is available online, it is often inaccessible for a lengthy period of time due to ownership and commercial sensitivity, and access to the underlying data itself is rarely provided. Low searchability discourages stakeholders from using the data that already exists and prompts the need for further primary data to be gathered. The functionality and capability of OneBenthic represents an opportunity for a similar data portal to be developed for the offshore wind industry. Therefore one option to improve data sharing and transparency in the industry is to develop, operate and maintain a flexible online central data portal to hold datasets specific to offshore wind.

Another benefit for the aggregates industry from OneBenthic is its ability to assist with marine licence applications and compliance monitoring. Navigating current Environmental Statements can be difficult. An Environmental Statement is a report on the EIA for a defined development project and identifies the significant environmental effects of the scheme in the aspects set out in the EIA Regulations. The level of unnecessary information in the document makes recommendations and impacts hard to find and users often have to cross-reference and consult several versions of a document, making them impenetrable. The language of the Environmental Statement is often technical and full of acronyms, which can be challenging and inaccessible to the general public, making it difficult for local communities to understand the real impact of a development.

14. https://medin.org.uk/
15. https://rconnect.cefas.co.uk/onebenthic_portal/

5.2. DIGITAL EIAS

Digital EIAs are seen as the next natural step in EIA progression and can offer optimisation in the timeline for consenting. The Digital EIA project was a collaboration between Connected Places Catapult, Quod, Temple, ODI Leeds and Liquorice Marketing and explored how the EIA process could be transformed[16]. The project, delivered in 2020, identified a number of opportunity areas for transformation:

- **Data digitisation:** The process needs to "systematically collect, feed, store and access data in a standardised machine readable format, to allow recouping and recycling within and across assessments".
- **Streamlined processes:** The EIA needs to be a streamlined, iterative process.
- **Real-time collaboration:** A digital EIA would allow "multiple stakeholders to write, collate, model, and assess impacts simultaneously while managing, visualising and tracking overall progression".
- **Improved communication:** The "Environmental Statement needs to explore new technologies and visualisation to communicate the impacts in an accessible, interactive, transparent and personalised way".
- **Feedback-based iterative evolution:** The whole assessment needs to incorporate post-consent monitoring to re-assess mitigation, environmental baseline and methodologies.

16. https://digitaleia.co.uk/wp-content/uploads/Digital-EIA-Report.pdf

5 DATA MANAGEMENT

CONTINUED

5.3. ONE PORTAL FOR FASTER DATA COLLECTION AND MORE ACCURATE ASSESSMENTS

As public attention to the environmental impact of offshore wind farms increases, the offshore wind industry needs a more efficient and dynamic approach to collecting data and reporting for the EIA. By establishing an environmental digital portal for the offshore wind industry, wind farm operators can access one portal for all digital data relevant to the proposed development site. Currently, a major constraint for fast-tracking the EIA process for offshore wind projects is the restricted access to all the environmental baseline data collected in the past. DHI (2024) reported that "a unifying data portal would provide easy access to all data sets relevant for the EIA process, such as meteorological data, waves, currents and water levels, environmental parameters (marine life such as seabirds, fish and marine mammals). But existing activities in the area can also be included, e.g. existing commercial activities and cultural heritage of importance for the approval process". The portal could also facilitate modelling of the data including "analyses for aspects such as noise impacts or disruption of habitats for marine mammals and collision risks for seabirds".

DHI (2024) argues that "with a unifying database based on data and modelling, the wind farm developer would be able to complete the mandatory EIAs more quickly and cheaper". In addition, it would enable "a more accurate assessment of the impact of the new offshore wind farms because the modelling data would enable more comprehensive descriptions of the occurrence of sensitive species and habitats, for example by describing the distribution over longer periods (multiple years)". This would also benefit the regulator who could make decisions based on more informed and accurate data, thereby minimising the risk of potential negative environmental impacts once construction starts.

Datasets and model outputs generated by such tools should be open access to ensure that the information is genuinely useful and feeds into policy and management measures that promote sustainable development of the marine environment.

6 RECOMMENDATIONS AND NEXT STEPS

The goal of meeting the UK Government's ambitions for offshore wind deployment is a major challenge and streamlining the consenting process is essential to help achieve this goal. Chris Stark, head of the government's new Mission Control for clean energy stated "Tackling the climate crisis and accelerating the transition to clean power is the country's biggest challenge, and its greatest opportunity. By taking action now, we can put the UK at the forefront of the global race to net zero[17]."

The current consenting process is inefficient and cumbersome resulting in significantly delayed approvals which delay the start and completion of projects. There is a need to overhaul how offshore wind development sites are monitored shifting from project-level EIA assessments to a regional ecosystem-based monitoring programme.

This report has provided a framework for how the REMP might be developed and operated. A collaborative and multi-disciplinary approach with scientific experts, developers, academics, researchers, regulators and technical specialists, focused on knowledge gaps at regional scales, could deliver independent and rigorous scientific outcomes, allowing consistency in environmental assessments. Robotics, AI and smart/autonomous technologies will help to improve data gathering and speed up processes for consenting and environmental monitoring and such data must be made available at the earliest opportunity.

The development of a REMP for the UK offshore wind industry has numerous benefits including:

- Reduced costs for the developers
- Reduced carbon footprint by using autonomous and uncrewed monitoring vessels
- Greater certainty in the data collection and standardisation of methods and datasets
- Streamlined EIA reporting requirements
- Transparency in the data; benefiting wider monitoring initiatives such as GES assessments and research opportunities
- Address the resourcing issues that hinder the organisations responsible for regulatory decision-making
- Reduction in overall consenting timelines
- A new national and global supply chain in innovative marine monitoring technologies.

Funding such monitoring/research is challenging and following a combination of existing frameworks from other countries is recommended. An approach that is government-funded but hosted by an independent facilitator would be the most effective and efficient way to support basic, multi-sector, ecosystem-scale research, thereby offering the best opportunity to understand and accelerate the sustainable future of the offshore wind industry.

6.1. THE ROLE OF ORE CATAPULT AND GOING FORWARD

The release of the report by ORE Catapult (2023), resulted in the development and launch of the 'Accelerating Consenting for Offshore Renewables Deployment' (ACORD) project which aims to accelerate the deployment of major offshore renewable energy infrastructure projects, minimise the damage to the environment and maximise the potential to reach net zero. ORE Catapult has developed an expert-led, systematic, open and consultative approach to the issues surrounding the existing consenting process and the areas for significant improvement in quality, time and cost.

The key elements of ACORD are:

- The development of an ecosystem-based approach to regional monitoring
- The adoption of smart technologies, appropriately developed, tested and demonstrated to enhance environmental data collection and monitoring
- Drive the development of a flexible online central data portal to hold offshore wind datasets
- The creation of a significant market sector with potential for global exportation for the UK supply chain.

17. https://www.theguardian.com/environment/article/2024/jul/09/climate-expert-chris-stark-appointed-to-lead-uk-clean-energy-taskforce

6 RECOMMENDATIONS AND NEXT STEPS

CONTINUED

The project will involve a series of work packages including technology audits for platforms and sensors, regulatory landscape review, demonstrations and counterfactuals at pre-consented sites to compare innovative technology with traditional methods. As part of the ACORD project, ORE Catapult will build and support a collaborative and effective network of innovative companies involved in marine environmental monitoring to enable rapid improvement and cost reduction in monitoring the marine environment and facilitate their collaboration with industry. In addition, with its strong relationships with government, industry, the SNCBs, and academic community, ORE Catapult is well-placed to coordinate and deliver a regional monitoring programme for the offshore wind industry.

Given the imperative to deploy offshore wind rapidly at scale, but in a highly responsible and sustainable manner, we have identified a series of ambitious suggestions to transform the way we consent wind farms and characterise the marine environment for offshore wind:

1. Remove developer-led project-level assessments and move to a regional monitoring programme that is funded by government (but potentially recovered indirectly in the tender from the winning bidder(s)).
2. Appoint a central, neutral facilitator of the REMP approach making use of existing strong links with government, industry, statutory consultees, academic institutes and SMEs. ORE Catapult is well-placed to act in such a role.
3. Remove the scoping phase from the pre-application stage. Regional advisory groups would be established to engage on environmental and engineering concerns (in collaboration with key experts from academic institutes and statutory consultees).
4. Adopt an ecosystem-based approach to monitoring driven by key indicators and monitoring priorities specific to each region.
5. Transition from current monitoring methods to use innovative technology capable of conducting multiscale and cross-disciplinary measurements, incorporating AI.
6. Develop a large-scale/high-resolution web portal containing EIA/monitoring data of all offshore wind farm and grid projects. Web apps incorporated into the portal enable data to be uploaded, shared, and analysed and outputs exported. Create a unifying database based on data and modelling to allow the wind farm developer to complete the mandatory EIAs more quickly and cheaply (in collaboration with Digital Catapult, Cefas and MEDIN).
7. Datasets and model outputs generated by such tools should be open access to ensure that the information is genuinely useful and feeds into policy and management measures that promote sustainable development of the marine environment.
8. Transition from current EIAs to digital EIAs.

On a final note, it is time we developed the governance and cooperative mechanisms to harness new technology in order to deliver on the goal of generating the information and knowledge that is required to sustain oceans into the future and ensure the sustainable deployment of offshore wind farms.

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APPENDIX 1

Table 1A. Sensors capable of continuous multi-day and concurrent bio-physical parameter measurements relevant to offshore windfarm impacts, including coverage and/or range *Diving seabirds only (taken from Isaksson et al., 2023).

SENSOR TYPE AND INSTRUMENT	PARAMETER(S) OF INTEREST				TYPICAL COVERAGE/RANGE
	FISH	SEABIRDS	MARINE MAMMALS	ENVIRONMENTAL	
ACOUSTICS - ACTIVE					
Multi-frequency split-beam echosounder	✓	✓*	✓	– Zooplankton	7°, 100's of metres
Multibeam echosounder (imaging sonar)	✓	✓*	✓		120°, 10s to 100s of metres
ADCP with echosounder as centre beam	✓	✓*	✓	– Hydrodynamics – Zooplankton	3°, 10s to 100s of metres
ACOUSTICS - PASSIVE					
Hydrophone	✓	–	✓	– Noise	50 Hz – 150 kHz, 10's to 100's of m, species & environment dependent
VISUAL					
Underwater camera	✓	✓*	✓	–	10's of m
Aerial camera	✓	✓	✓	– Sea surface features (i.e. wake)	1000's of m
Photographic systems	–	–	–	– Phytoplankton/ Zooplankton	Point measurement
OCEANOGRAPHIC					
eDNA sensor	✓	✓	✓	– Nuclear or mitochondrial DNA	Point measurement
CTD (conductivity, temperature and depth)	–	–	–	– Salinity – Temperature – Depth	Point measurement
Fluorometer	–	–	–	– Phytoplankton – Chlorophyll	Point measurement
Macro- and micro nutrient sensors	–	–	–	– Dissolved inorganic nitrate, nitrite, phosphate, iron, silicate	Point measurement
Microstructure profiler	–	–	–	– Turbulence and diapycnal mixing, flux; – Flux rates (when combined with nutrient profiles)	Point measurement
Optical / galvanic dissolved oxygen probe	–	–	–	– Oxygen	Point measurement
Optical or backscatter of suspended sediment	–	–	–	– Suspended material; – Dissolved organic matter	Point measurement
PAR sensor	–	–	–	– Photosynthetically – Active Radiation (PAR)	Point measurement
pH sensor	–	–	–	– pH	Point measurement

APPENDIX 1

CONTINUED

Table 1B. Comparison of autonomous and/or uncrewed platforms capable of hosting multiple sensors for multitrophic marine studies in shelf and coastal waters, including coverage, advantages and limitations (taken from Isaksson et al., 2023).

MOORING TYPE AND PLATFORM	COVERAGE			ADVANTAGES	LIMITATIONS
	WATER COLUMN	SPATIAL	TEMPORAL		
STATIC					
Lander	From the seabed to instrument max range	Fixed point	Weeks to months (limited by power)	– Robust	– Large vessel required for deployment – Limited by power unless cabled
Floating buoy	Surface, down to instrument max range	Fixed point	Weeks to months, longer with solar panels	– Easy deployment, flexible payload, real time summary data	– Wind/wave induced movement affects data quality – Requires navigational awareness
Fixed to existing structure	Structure dependent	Fixed point	Months, years possible with power integrated or obtained from structure	– Robust	– Requires structure integration
MOBILE					
Ship	Surface less keel, down to instrument max range	~km transects	Days	– No instrument recovery required, real time data (reactive survey possible)	– Vessel availability, cost
Uncrewed Surface Vehicles (USV)	Surface down to instrument max range	~km transects	Days/months	– Easy deployment, embedded instrumentation options, real time summary data	– Survey duration, power against currents, data quality in high wave conditions, requires pilot
Autonomous Surface Vehicles (ASV)	Surface	~km transects	Days/months	– No pilot, easy deployment, embedded instrumentation options	– Survey duration, power against currents, data quality in high wave conditions
Autonomous Underwater Vehicle (AUV)	Entire water column	~km transects	Days/weeks	– No pilot, easy deployment, embedded instrumentation options	– Survey duration, power against currents, limited sensor payload
Remotely Operated Vehicle (ROV)	Entire water column (dependent on positioning)	~100-300 m dependent on umbilical	Hours/days	– Real time data so points of interest can be investigated further	– Requires pilot and deployment ship
Glider	Entire water column (dependent on positioning)	~km transects	Weeks/months (depending on sensor load and sampling strategy)	– Autonomous and web-based piloting tools, easy deployment, embedded instrumentation options – Near real-time data collection – High vertical data resolution	– Glider 'sawtooth' profiles can complicate acoustic data collection, presently unsuitable in high current conditions
Drifter	Surface	~km transects	Months	– Low cost, survey – Survey duration	– Limited positional control
Uncrewed Aerial Vehicle (UAV)	Surface	~500 m transects unless beyond visual line of site (BVLOS)	Hours/days	– Low cost	– Limited by Visual Line Of Sight (VLOS), weather conditions, battery duration, take-off locations and need for piloting, – On or at-surface measurements only – Post-processing of imagery datasets challenging to fully automate

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