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Developing an integrated monitoring approach for marine net gain at offshore wind farms

Joint US and NL white paper on minimizing ecological impact of offshore wind

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1. Background

Offshore wind (OSW) energy has become a key pillar of global decarbonization strategies, with installed capacity expanding rapidly over the past two decades. From just over 3 GW in 2010, global OSW capacity has reached approximately 83 GW in 2025, and is projected to exceed 230 GW by 2030, despite recent industry setbacks such as inflationary pressures and supply chain disruptions[1].

Europe continues to be a leader in the sector, accounting for nearly half of global capacity. The region has over 37 GW installed by 2025 and is expected to reach 84 GW by 2030[2,3]. The Netherlands is a key contributor to this growth, having commissioned a total of nearly 5 GW by 2025 and targeting 21 GW by the end of the decade[4].

In the United States, OSW development has progressed more slowly. Total installed capacity stands at 174 MW in 2025, with forecasts suggesting growth to 14 GW by 2030 – well below the federal target of 30 GW, set by the Biden Administration in 2021[2]. There is a significant opportunity for growth in the US as waters have a technical resource potential of 1,476 GW from fixed-bottom offshore wind power and 2,773 GW from floating offshore wind power.[5]

1.1. Offshore wind brings both ecological risks and opportunities

The growth of OSW has led to closer examination of its environmental impacts and the policies that regulate them. As a low-carbon energy source, OSW plays a critical role in mitigating climate change by displacing fossil fuel-based electricity generation and reducing greenhouse gas emissions. However, OSW deployment also introduces environmental pressures. Construction and operation have the potential to disturb seabed habitats, generate underwater noise that may affect marine

mammals and fish, and pose displacement and collision risks to birds. At the same time, OSW turbine foundations and associated scour protection (e.g. rocks or concrete mats) can enhance biodiversity by acting as artificial reefs. These hard structures can provide surfaces for colonisation by sessile and mobile benthic fauna, increasing habitat complexity and attracting higher trophic levels such as fish, seabirds, and marine mammals.

These impacts (both positive and negative) are increasingly better understood and well-documented through numerous research programmes and projects. Examples include the likes of Offshore Renewables Joint Industry Programme (ORJIP) for Offshore Wind, Regional Wildlife Science Collaborative (RWSC) in the US, and the Wozep Offshore Wind Ecological Programme in the Netherlands, with cross-cutting initiatives such as the Offshore Wind Evidence and Knowledge Hub (OWEKH) and Plymouth Marine Laboratory's (PML) Offshore Renewables Impacts and Ecosystem Services (ORIES) database helping to consolidate findings across studies. However, despite growing knowledge and evidence base, further research is needed to fully quantify and understand long-term and cumulative ecological effects, particularly in dynamic and relatively data-poor marine environments.

1.2. From mitigation to enhancement

Governments are increasingly responding to the environmental implications of OSW with policy mechanisms that go beyond mitigation, and there is recognition that more proactive enhancement strategies could be achievable. Central to this is the emerging concept of Marine Net Gain (MNG)– the principle that OSW development should leave the marine environment in a measurably better state than before. Here we clarify some of the terminology that will be used in this paper as there is significant overlap in the objectives and research around terms such as Net Positive Impact, MNG, and Nature Inclusive Design. In broad terms, a Net Positive Impact refers to a specific impact measured (focusing on positive outcomes after other impacts are addressed and/or mitigated), whereas MNG is a marine specific approach aimed at measurable improvement in marine biodiversity and habitats to leave the marine environment in a substantially better state than before development. Nature Inclusive design is a project design philosophy to include nature within design principles and utilize supporting technology). Each of these areas will require investment and research, however, the primary focus of this paper is on MNG. MNG encourages developers to go beyond avoiding harm, by actively contributing to ecosystem restoration, biodiversity enhancement, and the delivery of key ecosystem services. A recent stakeholder study led by PML found broad consensus on the need to integrate ecosystem services into MNG, particularly fisheries productivity, nursery habitats, and climate regulation[6]. Restoration of shellfish beds, invertebrate habitats, and plankton communities were identified as high-value actions. The study also emphasized the importance of considering MNG for addressing fishing pressures and those arising from physical structures, as well as during project decommissioning.

In the UK, central to ecological impact assessment is the concept of the mitigation hierarchy, encompassing avoidance, mitigation, compensation and enhancement measures. Compensation can be required in those instances where Imperative Reasons of Overriding Public Interest (IROPI) are

identified as part of the habitats regulations assessment (HRA); to this end, the Department for Environment, Food & Rural Affairs (Defra) is establishing the Marine Recovery Fund (MRF) that will enable the OSW industry to contribute to strategic, compensatory measures for impacts on Marine Protected Areas, using options from a library of strategic compensation measures. The MRF will aim to streamline the consenting process by offering a coordinated approach across projects. Expected to launch by late 2025, the MRF supports ecological recovery while accelerating OSW deployment. The UK Government has also taken significant steps toward embedding MNG into OSW policy. Following Defra's 2022 consultation on the principles of MNG, the government confirmed support for a "nature first" framework that assesses impacts on both habitats and species, and may incorporate wider environmental benefits. A contributions-based delivery model is under consideration, with the MRF potentially playing a role in managing financial contributions, subject to future legislation. The next phase of policy development will focus on refining the assessment framework and engaging stakeholders to ensure MNG aligns with existing environmental standards and planning regimes.

The Dutch government has adopted a centralized and proactive regulatory model since 2013, taking responsibility for site selection, permitting, and environmental assessments. While MNG is not yet a formal policy requirement, nature-inclusive design is embedded in OSW development, and biodiversity enhancement is increasingly integrated into tender procedures. For example, recent tenders for IJmuiden Ver Alpha and Beta projects were based on a comparative assessment where the vast majority of ranking points (85%) were to be awarded to a predefined set of standard non-price criteria and site-specific non-price priorities – including ecological enhancement. The winning bid for Ijmuiden Ver Alpha included turbine and wind farm designs that contribute to the protection of birds, as well as a plan for the design of the wind farm as a "living laboratory" in which more than 75% of the turbines will have artificial reefs for mussels and other maritime animals.

Other practical measures include innovations such as habitat restoration pilots, fish refuges, eco-friendly scour protection, and low-noise installation techniques, supported through initiatives like the Rich North Sea programme, which has implemented nature enhancement projects such as oyster broodstock structures at Borssele III/IV and experimental reef-building installations at Belwind OWF, aimed at restoring native shellfish populations and improving habitat complexity. Such efforts are supported by collaborative research and monitoring frameworks and are designed to align OSW deployment with broader marine ecosystem recovery goals. Together, they lay the groundwork for potential MNG implementation in the future.

In the US, OSW projects are reviewed under the National Environmental Policy Act (NEPA) and other federal statutes. As part of its regulatory responsibilities, BOEM has undertaken extensive baseline ecological studies to better understand marine environments and inform OSW development. One key area of focus has been fisheries coordination, which is overseen by BOEM and the National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NOAA Fisheries). Recent efforts include BOEM's national fisheries mitigation guidance and NOAA's survey integrity strategy, both aimed at balancing OSW development with sustainable fisheries management through ecological monitoring, stakeholder engagement, and adaptive planning.

As the US continues to develop its OSW sector, emerging approaches around strategic compensation, nature-inclusive design, and biodiversity-focused tender requirements in the UK and the Netherlands may offer useful reference points for developing future efforts to support MNG and ecological enhancement.

1.3. Robust, integrated metrics are essential to demonstrate MNG

To demonstrate that MNG has been achieved, positive impacts on marine ecosystems must be quantifiable. Quantification typically draws on adapted biodiversity assessment metrics which typically encompass two domains: species-level indicators, and habitat and ecosystem function. Species-level metrics track species richness and diversity, changes in community composition, and changes in abundance and biomass of key taxa through space and time. Evaluating trophic interactions can further enhance understanding of how improvements in prey availability translate into benefits for marine predators. Similarly, habitat and ecosystem function metrics assess factors such as the quality and extent of marine habitats, and the presence of significant biodiversity hotspots. Collectively, these metrics support the assessment of structural habitat improvements and functional ecosystem gains. Novel approaches to MNG assessment have also incorporated ecosystem services considerations, such as fish nursery habitat function, fisheries productivity and climate regulation. To complement these biological metrics, environmental variables such as temperature, salinity, ambient noise levels and water quality can provide the contextual information which is necessary to distinguish anthropogenic effects from natural variation.

To integrate these metrics into a coherent assessment, several frameworks have been developed which provide structured approaches for evaluating MNG. MNG assessment frameworks are constantly evolving; evidence-based, holistic and adaptive frameworks incorporate a wide range of biological, ecological and social metrics. One example of a structured approach for MNG quantification is the adoption of a state-pressure-response (SPR) model[7]. This framework recognizes that marine ecosystems (i.e. state) are influenced by multiple pressures, both anthropogenic and natural, and that targeted management actions can result in positive ecological responses over time.

In isolation, single metrics (e.g. carrying capacity, the ability of an ecosystem to support a population) only partially reflect the complex interactions among species, habitats and many environmental variables present in marine ecosystems, and their inherent dynamism. A robust MNG framework should move beyond single-metric approaches to better capture the diversity of ecological and functional changes that occur. Recognizing this complexity, current MNG frameworks advocate for comprehensive, integrated metrics to capture ecological changes, and robust monitoring systems are required to collect the data which underpin them.

1.4. Long-term integrated monitoring is needed to establish baseline conditions and observe changes

Monitoring is fundamental to the effective application of MNG frameworks. Robust, high-resolution, long-term data are essential for quantifying ecological change and validating enhancement outcomes. Evidence-based compensatory measures require information across trophic levels and time scales, making integrated monitoring systems essential to the success of MNG strategies. Monitoring serves a dual role: primarily, it can provide direct evidence of positive ecological change, and secondarily, long-term monitoring establishes a baseline against which compensatory measures can be assessed. If monitoring indicates that intended net gains are not being achieved, or that unforeseen negative impacts are occurring, this provides the OSW industry and regulators with data which can be used to develop corrective measures and adaptive management responses. In this context, integrated monitoring technologies are a powerful and necessary tool for collecting the evidence needed to demonstrate MNG.

2. Monitoring for MNG

A diverse array of established and emerging monitoring technologies has been employed to survey the marine environment. These range from traditional methods like sensor-equipped buoys and ship-based surveys to innovative tools such as environmental DNA (eDNA) analysis, autonomous vehicles, and artificial intelligence-driven data processing.

Given the emerging concept of MNG, established technologies offer clear advantages for monitoring MNG, including proven reliability, regulatory acceptance, and a wealth of baseline data that underpin effective short-term monitoring and management. However, the urgent need to address challenges like biodiversity loss and climate change is prompting growing interest in newer, cutting-edge monitoring approaches that can enhance spatial and temporal coverage, reduce costs, and uncover deeper ecological insights.

Despite this excitement, caution is warranted before fully embracing novel methods; emerging technologies often require further validation, standardization, and integration into regulatory frameworks. They may involve high initial costs, technical complexity, or gaps in interpretability that limit immediate application. In the near term, a balanced strategy that leverages the robustness of established tools while gradually incorporating promising innovations is essential. This approach ensures ongoing data reliability while enabling innovation to mature, ultimately enabling more comprehensive and cost-effective MNG monitoring that keeps pace with evolving scientific and policy needs.

Below we describe two paths to monitoring for MNG, which can run concurrently. In combination, these provide a powerful roadmap to understanding MNG, as well as fostering trust and knowledge development in this emerging topic. This is critical, especially while concepts of MNG and strategic compensation are in development.

2.1. Established technologies offer a reliable foundation for MNG monitoring

An integrated monitoring approach that combines complementary sensor technologies could give a robust, evidence-driven method to quantify MNG metrics and demonstrate that MNG has been achieved.

Commonly used technology for monitoring in the context of OSW includes multibeam sonar, passive acoustic monitoring (PAM), and remote underwater video (RUV). Multibeam sonar maps habitat structure and fish aggregations, diving birds and marine mammals; PAM allows monitoring of noise levels, detects and tracks vocal species and their activity patterns; and RUV documents behaviour and species presence (Figure 1). Other environmental sensors can also be integrated to provide contextual information to aid interpretation of biological data, an essential aspect for understanding ecosystem-scale responses. Examples of environmental sensors include conductivity-temperature-depth (CTD) profilers, Acoustic Doppler Current Profiles (ADCP), and fluorometers. These measure key physical and chemical parameters such as temperature, salinity, turbidity, ocean currents, and chlorophyll a concentration (a proxy for primary productivity). Incorporating environmental measurements alongside biological data can help to distinguish between natural variability and anthropogenic effects and improves the quantification of MNG metrics across spatial and temporal scales.

Each of these sensor systems have different detection and range capabilities, and in isolation, none of these systems can provide sufficient information to assess whether an OSW development is achieving MNG. However, in combination, they can build a more confident view of the functioning of the entire ecosystem surrounding an offshore wind development.
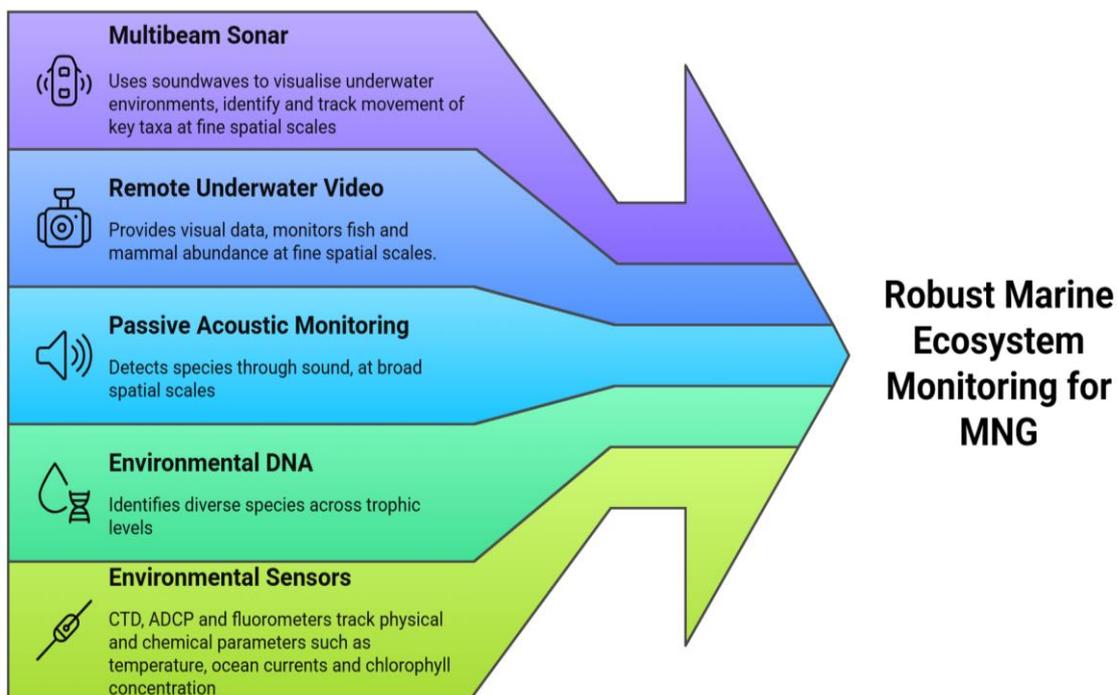
Figure 1. Integration of five complementary technologies for robust marine ecosystem monitoring to support Marine Net Gain quantification: multibeam sonar, remote underwater video, passive acoustic monitoring, environmental DNA and environmental sensors.

2.1.1. Passive Acoustic Monitoring (PAM)

PAM is widely used in the offshore wind industry to establish baseline levels of marine mammal presence, measure underwater noise levels during construction and operations, and track ecological change[8]. A typical PAM system includes a hydrophone capable of recording a specific frequency range, a data logger, and power supply mounted to a mooring. PAM systems are highly customizable and can be configured in multiple ways to meet monitoring goals. For example, long-term deployments can extend battery life by adjusting duty cycles and sampling rates, or battery changes can be eliminated by cabling the system to a shoreside power source. The mooring design can also be adapted: archival systems without surface buoys minimize entanglement risk, whereas surface buoys enable real-time or periodic data transmission (to reduce HSE and cost burden associated with retrieval and maintenance trips). When PAM systems are assembled in an array with multiple hydrophones or multiple synchronised units, it becomes possible to triangulate sound sources and track the direction of animal movement. PAM arrays can also provide robust estimates of the number of individuals vocalizing in a certain area and are therefore indicative of changes in abundance over time. PAM systems are also capable of measuring underwater noise levels in different frequency bands, providing key indicator information on the occurrence and scale of potential stressors.

2.1.2. High resolution imaging sonar

Multi-beam imaging sonar technology is a survey technique capable of providing reliable marine species detection and tracking data under a broad range of conditions. A multibeam imaging sonar system uses a 2D array of transmitters and receivers to emit acoustic energy and generate detailed images from the returning echoes. This tool is particularly useful for monitoring key species at very close range to turbine foundations, where trawl surveys are not possible due to the risk of gear entanglement. The high frequency of the acoustic signals used limit the range at which multibeam sonar can operate to within 100 m, which makes this tool most relevant for monitoring marine mammals and fish at very close range to turbine foundations[9]. Unlike visual methods, multibeam sonar can operate continuously under all visibility conditions to provide valuable data on the size, behaviour and occurrence of marine species. In one of the first applications at an offshore wave power farm, a team of scientists used this technique to distinguish seal species based on body size, identify an orca from dorsal fin morphology, and inferred fish species by combining size classes with behavioural patterns[10]. This highlights the potential of multibeam sonar to provide valuable ecological insights across multiple trophic levels. The feasibility of using multibeam imaging sonar from a seabed-mounted platform to monitor seal movements has been demonstrated, reliably detecting individuals at tens of metres and tracking their paths with high spatial and temporal resolution[11]. Classification algorithms based on size, shape and movement effectively distinguished seals from other moving targets, and accuracy is expected to improve when combined with additional complementary sensors.

A good example of this and of the integration of PAM and imaging sonars is the successful deployment of the 'High Current Underwater Platform (HiCUP)', which integrated two high-frequency multibeam imaging sonars and a high frequency hydrophones hydrophone array (i.e. PAM system) to track an array of species[12]. Multibeam sonar is a powerful tool for obtaining preliminary information on the presence of marine mammals and fish, their size, and predator-prey interactions. However, the question of species identity and indicators of MNG (species diversity and richness, prey availability) can best be resolved by integrating multibeam sonar with additional technologies such as RUV and PAM.

2.1.3. Remote Underwater Video (RUV)

Remote underwater video (RUV) is highly complementary to multibeam sonar imaging, as video recordings provide species identification, abundance and size distributions of fish and marine mammals at offshore wind farm foundations. The recordings can also be used to support the development of automated species classifiers used to process multibeam sonar imagery. Deployments have been carried out successfully using baited and unbaited systems. Baited remote underwater video systems (BRUVs) were first introduced in the mid-1990s and are now widely used to study marine communities throughout diverse habitats, such as reefs, seagrass beds, deep-water and intertidal zones[13]. A typical BRUV configuration consists of a seafloor-mounted frame, an underwater video camera mounted on this frame and enclosed in pressure-resistant housing, and a bait arm, holding a bait canister, that extends 1 – 1.5 m in front of the camera. The canister contains prey to attract scavenging and predatory species. When configured as a stereo system with dual cameras, BRUVs can also provide accurate and precise measurements of individuals[14].

BRUV systems offer several advantages over traditional surveys: they are non-destructive, non-invasive, reduce observer bias, and can operate at unrestricted depth and in close proximity to foundations. Fish ecologists deployed BRUVs at two operational North Sea wind farms and demonstrated higher abundance, biomass and size of haddock and flatfish closer to turbine foundations, with a stronger positive effect on abundance, biomass and size at the older windfarm with more complex jacket foundation structures (i.e. 'complex' referring to surface area and structures available for settlement)[15]. These results highlight the potential for established wind farms to generate MNG and importantly, the suitability of remote underwater video as an established monitoring tool.

2.1.4. Additional Technologies

Several other well-established technologies are available for monitoring species in and around OSW sites. When selecting technologies for measuring MNG, it is important that they are proportionate, non-invasive and provide an appropriate level of spatial and temporal resolution. For example, traditional sampling methods such as deploying nets or pots are invasive and remove individuals from the ecosystem. Therefore, these techniques are less suitable for measuring MNG, where non-invasive alternatives such as multibeam sonar, PAM and RUV exist.

Physical, non-destructive photographic monitoring techniques, such as Sediment Profile Imaging (SPI), can be advantageous for visualizing seabed sediments and benthic habitats. They help to assess whether there have been any disturbance effects caused by OSW installations, and monitor recolonization of OSW foundations and the surrounding seabed. Satellite monitoring, eDNA sampling and environmental RNA (eRNA) sampling, discussed further in Section 2.2, have unique limitations. While satellite monitoring is a well-established technique widely used in marine ecosystem research, improvements in imagery resolution are still emerging. Local weather conditions and turbidity can also affect the accuracy of observations (for example, measuring chlorophyll *a* in turbid environments remains challenging). For eDNA, in the context of monitoring around specific foundations (i.e. fine scale monitoring), a key limitation is distinguishing whether detected species are resident in the OSW area or simply genetic material passing through via currents. Additionally, another consideration is distinguishing whether detected species represent live or recently dead abundance of biomass resident at the OSW. This can be overcome by the use of eRNA for detection of biodiversity, as it sheds and degrades rapidly, thus outperforming eDNA in sensitivity of live biological communities. Both tools are considered new and emerging relative to other typically visual and acoustic technologies for monitoring biological communities, and this could both limit adoption of these tools and add costs in addition to the use of established technologies.

Above-water monitoring techniques provide additional non-invasive, high-resolution options which are complementary to below-water techniques such as multibeam sonar, PAM and RUV. These include high-frequency radar for measuring bird and bat abundance, above water-video for quantifying species including birds and bats, and thermal imaging for monitoring birds, bats and surface-level marine mammals. Studies at OSW farms in the Netherlands and the US have shown that these approaches can reveal temporal patterns in bird abundance and behaviour, as well as insights into flight heights, movement speed and interactions with turbine structures.[16,17]

Guidance has been published on available monitoring technologies for flying birds and bats at OSW farms, particularly in relation to the risk of collision. In Europe, birds and bats that breed within EU Special Protection Areas (SPAs) and EU Special Areas of Conservation (SACs) are legally protected under the Birds and Habitats Directives, and OSW developments near these areas are required to carefully monitor interactions between the wind farm and these species[18]. In the US, BOEM recommends technologies such as radar, thermal imaging and acoustic sensors for post-construction monitoring of birds and bats around OSW farms.

2.2. Emerging technologies are expanding the frontier of marine monitoring

There are a variety of novel monitoring methods, at various stages of development and testing. These include eDNA and RNA, use of autonomous platforms and drones, satellite remote sensing and 'omics' methodologies. Many or all of these can play a valuable role in the future monitoring of MNG. We describe some of the emerging technologies below.

2.2.1. Environmental DNA and RNA

In the marine environment, the use of environmental DNA (eDNA) methods for monitoring species and ecosystems is an emerging tool. Past studies have used this technique to explore species presence, diversity and relative indices for abundance and biomass (though these later metrics require detailed calibration). Additionally, eDNA can be used to assess within species genetic diversity, with emerging potential for monitoring population and individual health metrics. Water samples containing trace genetic material shed by organisms can be analyzed with polymerase chain reactions (PCR) or metabarcoding to identify species without visual or acoustic observations. Like multibeam sonar, RUV and PAM, eDNA is particularly valuable in areas where traditional trawl surveys are impractical or unsafe, such as near turbine foundations. At Blyth Offshore Demonstrator, eDNA outperformed traditional trawls in species detection (54 vs. 26 species detected), capturing small, migratory and bottom-dwelling taxa that trawls missed[19]. The most abundant species identified were consistent across trawl data and eDNA, highlighting the potential for eDNA to cross-validate trawl survey data. Furthermore, eDNA allowed the expansion of monitoring into areas which were inaccessible to trawling, such as within close proximity to turbines. Detection of reef-associated species near turbines at higher relative densities compared to stations outside of the turbine area suggested the artificial habitat created by the turbines could be attracting fish and generating MNG.

Emerging research indicates that environmental RNA (eRNA) can offer further advantages[20]. Unlike eDNA, where genetic material from living or deceased organisms may persist in the environment, eRNA degrades rapidly and therefore provides a more accurate real-time snapshot of living organisms. Studies which compare eRNA and eDNA in marine communities have found that eRNA reveals higher species richness, and clearer signals of active community composition.

New autonomous eDNA/eRNA samplers, such as those developed by Dartmouth Ocean Technologies and the Monterey Bay Aquarium Research Institute (MBARI), can collect eDNA/eRNA samples via preconfigured missions without the need for human presence. MBARI's Environmental Sample Processor, for example, offers *in situ* sample analysis and real-time transmission of results. In the context of measuring marine net gain, this type of autonomous real-time eDNA sampling could send alerts when target species return to an area and also provide a method of tracking overall ecosystem DNA richness over time. Integrated with sonar, RUV and PAM, these systems enable near real-time biodiversity tracking and can provide early warnings of ecological change, providing robust data to quantify MNG.

Of course, it is important to consider the challenges of using emerging methods, before they are validated. eDNA applications have grown enormously in recent years – providing a means to assess the strengths and limitations of such approaches and to identify critical considerations that need to be taken into account before using the approach[21]. Currently, eDNA challenges to be addressed include improving understanding of detectability of different species (including false positives and negatives), scaling from detection to meaningful MNG metrics (e.g. abundance), understanding the spatial and temporal scale that an eDNA sample monitors (which may be species-specific and a function of oceanographic conditions). Additionally, as the field continues to develop, more work will

be done on drawing inference from eDNA sampling and translating that to ecological status and MNG.

2.2.2. 'Omics' Methods

The fields of genomics, transcriptomics, proteomics, epigenomics and metabolomics all can be used to explore health, stress levels, and adaptive responses of marine organisms at a molecular level. As monitoring approaches, these can contribute to powerful ecosystem diagnostics. Use of this in the marine environment is dependent on collection of samples to be processed using techniques in these domains. Sampling typically involves collecting environmental samples such as seawater, sediments, and biological material from different marine habitats at specific time intervals using standardized protocols. These samples are then processed for molecular analyses including DNA, RNA, and other 'omics' data. eDNA and omics methods could be powerfully integrated to advance marine monitoring by combining the non-invasive detection of species from environmental samples with detailed molecular insights into organism health and ecosystem functions. Building on the current state of eDNA and RNA, omics approaches help us go beyond assessing species inventories but also develop a deeper understanding of population connectivity, adaptation, and resilience across marine protected areas. This integration supports dynamic, efficient, and comprehensive MNGmonitoring that links biodiversity presence with ecosystem health and capability for recovery. As with eDNA and eRNA methods, the use of omics in the marine domain is comparatively limited and often expensive. Furthermore, interpretation of omics data in relation to ecological outcomes is still in development.

2.2.3. Integration of Artificial Intelligence (AI)

Many of the survey methods described are evolving and improving with advances in AI, and the data outputs from one of these technologies can be used to cross-validate data from the other.

AI has the potential to transform ecological monitoring at offshore wind farms by improving data quality, speeding up processing, and enabling integration across technologies. In multibeam sonar, AI-powered algorithms can enhance image resolution, filter out noise from static structures and track animal movement patterns to distinguish biological activity from that of anthropogenic structures or static objects. For remote underwater video, machine learning algorithms can automate species classification, restore poor-quality footage, and reduce the need for manual review of video footage. Likewise, PAM systems can benefit from AI through more reliable automated detection, as well as recognition of patterns in acoustic signals linked to behaviours such as foraging or reproduction.

In an integrated system, AI could simultaneously analyze movement patterns in multibeam sonar data, species counts and measurements obtained by remote underwater video recording, and acoustic signatures collected by PAM to provide a complete picture of the marine ecosystem. This type of data fusion can increase species identification certainty and reduce false positives and allows behaviours and trends to be tracked over time and across spatial scales. Of course, as AI develops, it is critical to ensure that the performance of AI is carefully assessed to ensure the outcomes are robust and equivalent to a human analyst. In general, planning for a human-in-the-loop is a key need

for the short term, until the performance of AI systems is at the required level for robust science. In the absence of this, there is a risk of spurious outcomes akin to poorly trained scientists delivering the work. This will set MNG monitoring (and other domains) back, by reducing stakeholder confidence. Therefore, adequate investment must be made in extensive training datasets to minimise bias (e.g. caused if training data are misrepresentative or incomplete), algorithm transparency (to help build confidence), and the understanding of AI performance in complex ecological scenarios.

However, even with these concerns in mind, it is likely that because AI models are continuously improving, the incorporation of AI into integrated systems will enable more detailed, cost-effective and scalable assessments of MNG around offshore wind developments.

2.2.4. Satellite Remote Sensing

Use of satellites globally is increasing and when appropriately instrumented, they can provide broad-scale insights into habitat changes and measurements of oceanographic variables (e.g. sea surface temperatures, chlorophyll concentrations, pollutants etc.). These are likely a complementary measure as they are often limited in resolution for fine scale habitat features which would be required for OSW MNG monitoring. Additionally, cloud cover and atmospheric conditions can impact data quality, and ground-truthing of data is required to improve confidence in remotely sensed data products.

2.2.5. Validation and Stakeholder Acceptance of Monitoring Technologies

It is critical that emerging technologies, such as those described in this section, are statistically robust and accepted by marine stakeholders. The validation of these methods should occur alongside traditional, established monitoring methods. The integration of novel and traditional monitoring approaches enhances scientific rigor and provides an opportunity to cultivate trust among stakeholders (e.g. eNGOs, policy makers and government representatives). Without validation and appropriate stakeholder engagement, buy-in on MNG initiatives and their outcomes may lag.

To strengthen validation and stakeholder engagement, projects should prioritize transparent, comparative deployments of established and emerging monitoring tools, and ensure key stakeholders are consulted iteratively throughout the process. Protocols which address technical and stakeholder concerns should be established. These practices, in combination with open communication and opportunities for stakeholder feedback, will ensure new technologies are viewed as scientifically robust and relevant. Ultimately, this will lead to broader trust and lasting support for MNG in offshore wind projects.

2.3. Monitoring systems must be tailored to site conditions and operational constraints

There are several practical considerations which must be taken into account when implementing MNG monitoring technologies either in isolation or as an integrated system. These considerations reflect the technical limitations of each technology as well as the maintenance requirements. As systems are deployed underwater, biofouling may accumulate reducing the sensitivity of the hydrophone in PAM monitoring or the recording quality of RUVs. Additionally, water turbidity can obscure RUV recording. Biofouling and sediment build-up may require manual removal, or the addition of features such as 'wipers' to keep visual and acoustic sensors clean.

A common theme across the technologies is the need for a power source, which can be provided either through a cable connection for continuous monitoring or by using batteries. Another variable is how quickly storage fills up will depend on the type of data (whether it is acoustic, visual, sonar) and whether real-time or onboard analysis and transmission of data is utilised.

If battery power is used, there is a question of how much capacity can be installed, how often the batteries will need to be exchanged, or whether the duty cycle of the equipment should be reduced to extend the battery life. There is a trade-off between extending the battery life and reducing the amount of information captured when implementing duty cycling, and the appropriate duty cycle will differ depending on the characteristics of the location and the species of interest (which collectively dictate sampling strategy). A species that vocalizes infrequently or is rarely present at a site will have a lower likelihood of being detected by systems with a duty cycle that has long periods of 'off' recording time.

A further variable are the characteristics of the site. At locations with a high density of marine mammals, fish activity, or anthropogenic noise, storage may fill more quickly as devices are triggered to turn on and need to store higher loads of information. The strength of water currents, vessel traffic in the area, and bathymetric features will all affect the mooring design, and technologies deployed in areas with high tidal activity or extreme weather may require more frequent maintenance. All of these considerations need to be incorporated when designing a MNG monitoring system, and the types of components chosen as well as the maintenance schedule, power, storage and mooring design must be customized to match the features of the site and the questions being studied.

3. Next steps

3.1. Defining metrics and methodologies is key to operational MNG assessments

A clear requirement in the assessment of MNG is a framework against which monitoring of marine habitats can be framed – to facilitate a roadmap for assessments and consideration for strategic

compensation. Such frameworks have been developed in recent years but no widely accepted framework exists. Constructing considerations of MNG around a structured, principles-based approach can assist in assessments of whether marine developments like OSW result in a net positive impact on marine habitats, species, and/or ecological functions. Such principles might include measurement of impacts on both species and habitats; establish and prioritize environmental benefits that are genuinely biodiversity underpinned; takes a 'nature first' approach and ensures proportionality, ensuring that net gain requirements align with the scale of any development. Frameworks will need to be adaptable and scalable, applied strategically and at the project levels.

Any framework will likely require multiple metrics to help quantify the diversity of ecological and functional changes that occur. Such integrated metrics will help capture ecological changes, and robust monitoring systems are required to collect the data which underpin them. Whilst establishing clear MNG metrics could be considered premature at this time, there has been sufficient discussion around this topic to highlight broad areas summarising different kinds of metrics to be monitored. These include habitat area and condition, functional metrics like measurements of nursery or foraging habitat, pressure reduction contributions (e.g. reduced vessel disturbance or fishing impacts), and/or specific population or biodiversity indices (e.g. density of individuals, detection rates, biomass estimates, carrying capacity).

Demonstrations of MNG are likely to require standardized, repeatable methodologies, with clear justification of chosen metrics and transparent methods for aggregating results. To further the needs of OSW, this will need to be demonstrated by MNG monitoring on OSW sites. A robust demonstration would likely require key steps: baseline quantification (i.e. assessing pre-development ecological state of relevant features or MNG metrics), residual impact calculations (both positive and negative), quantification of gains (e.g. changes in detection rates or estimates of improved ecosystem functions) and a net gain statement (i.e. demonstration of the MNG 'balance sheet').

3.1.1. A multi-sensor approach is essential for demonstrating Marine Net Gain

As highlighted above, robustly quantifying MNG requires an understanding of baseline conditions, the scale of nature-positive gains from the introduction of structures, and an understanding of the improvement of habitat achieved. To achieve this, we require trusted, scalable monitoring packages which can be deployed across meaningful temporal and spatial scales in and around offshore wind farms. Given the current state of technology and the base needs to inform MNG, monitoring can commence whilst frameworks are developed.

Section 2.1 and 2.2 detail the many well-established and emerging technologies available to deliver a roadmap for monitoring for MNG. However, none of these systems in isolation are fit for purpose to monitor MNG metrics alone. PAM extends monitoring capability beyond the fine-scale range of RUVs and multibeam sonar, detecting acoustic signals from several kilometres away depending on frequency and background noise. Past research efforts combined PAM with time-lapse video at recently deployed artificial reefs and demonstrated that PAM detected reef colonization by demersal fish within two weeks of reef deployment, whereas the video monitoring indicated that demersal fish species did not colonize the newly deployed reef until five months later[22]. This highlights the

importance of using complementary approaches to monitoring. In North America, BOEM's Proposed Mitigations for Offshore Wind Energy Development recommend that wind farms should conduct long-term PAM for 1 year before construction through at least 10 years of operations[23]. This long-term PAM monitoring can reveal trends and patterns in species population dynamics which could provide evidence of MNG occurring in the vicinity off offshore wind farms. Deployments like the HiCUP demonstrate how imaging sonars offset and the multi-hydrophone array complement one another and allow detection and tracking of a variety of higher trophic levels[24]. Where such systems are cabled to shore for power, data transfer, and communications using subsea infrastructure, the challenges above are minimised. This allows for continuous operation over many months or years, which will be required to capture what may be rare interactions. Shorter term deployments (e.g. weeks) are capable using established systems.

In the future, there will be an increased need to move beyond 'co-deployment' (i.e. utilising multiple modalities managed and analysed separately/independently) to true integration. The benefits of integration are clear: firstly, they provide improved efficiencies via streamlined workshops and minimise duplicative tasks, saving time and money; secondly, integration provides better data and insights via consolidated datasets to support informed (and potentially real-time) decision-making. Finally, integrated systems are more adaptable and can grow and expand more easily than siloed monitoring – meaning systems can scale to meet the monitoring needs of MNG.

Each technology contributes complementary insights, across trophic levels: multibeam sonar and remote underwater video track fish and marine mammal movement and abundance at finer spatial scales (50m and <3m respectively), listening with PAM extends monitoring to broader spatial scales and provides information on species identity, presence and behaviour, as well as the soundscape. Environmental sensors such as CTDs, ADCPs, and fluorometers complement biological data by tracking physical and chemical parameters that influence ecosystem dynamics.

At a minimum co-deployment of such established technologies and independent analyses of data streams can be achieved. PAM and imaging sonar data analyses have already been successfully integrated into a common analysis platform (which can be done in near real-time if required) and this provides a model for how future integration should be done[25]. Harmonising and standardising via a single platform can provide efficiencies across sampling. Careful development of new detectors and classifiers, potentially using AI, but certainly with a human in the loop, would likely enhance and streamline monitoring capabilities.

Together, these tools could deliver a comprehensive dataset spanning multiple trophic levels. This integrated, multi-sensor approach not only enables cross-validation across technologies but may also capture both structural and functional ecosystem changes, helping to ensure that any claims of MNG are robust, evidence-driven and defensible. In the future, novel and emerging technologies like monitoring for eDNA, leveraging the development of AI and 'omics' methods may provide powerful tools to expand species identification capabilities beyond fish and marine mammals to include invertebrates, phytoplankton and algae, offering insights across multiple trophic levels – quantifying net gain as the key metrics become clearer.

3.2. Policy should strive to support innovation and alignment in MNG monitoring

In parallel with discussions around the scientific and technical aspects of MNG monitoring and integrated monitoring frameworks, it is important to consider how policy can support the uptake and further development of MNG monitoring and, in turn, effective ecological enhancement as part of OSW development. While integrating MNG monitoring into specific policy requirements may be premature at this stage given the uncertainties around the metrics and frameworks for integrated MNG monitoring, some enabling policy mechanisms could be introduced to encourage uptake and continued development. At this stage, any regulatory frameworks and interventions should be adaptive and evolve with scientific understanding and technological capabilities.

In the Netherlands, this could mean placing more emphasis specifically on MNG monitoring as part of existing nature-inclusive development requirements in OSW tenders, rewarding bids that propose approaches for advancing and implementing MNG monitoring techniques. In the US, this could take the form of integrating MNG monitoring considerations into NEPA reviews, alongside regularly updated guidance on the status of MNG monitoring approaches and technology development, highlighting opportunities for early-stage implementation. This should focus on standardized and repeatable methodologies for MNG monitoring to build a comparable evidence base across different jurisdictions.

To support these developments, a valuable next step could be the establishment of cross-government working groups, which could be used to share learnings from existing and future research initiatives, as well as to help identify opportunities for standardization of definitions and metrics and identify potential regulatory changes. Such collaboration should take into account geographical and ecological differences across relevant geographies to ensure that MNG approaches remain context appropriate. Bilateral collaboration between the Netherlands and Massachusetts could facilitate the adoption of shared standards, build datasets that are larger in size and representative across different species groups to support research in both jurisdictions, potentially enabling cross-validation of ecological data, improving interoperability of monitoring systems, and supporting evidence-based policy development across jurisdictions. Ultimately, this alignment could help expedite the development of integrated MNG frameworks that are both scientifically robust and scalable.

To accelerate the development and adoption of effective MNG monitoring, governments should also actively support innovation in this space. This could include providing guidance and supporting recognition of existing technologies or directly supporting pilot projects demonstrating integrated monitoring systems. Although the required MNG metrics are currently unclear, there is a clear need to utilise proven and established technology and demonstrate what is possible with integrated systems. Collaborative R&D focused on practical implementation and testing of integrated sensor platforms, along with generation of robust data would be particularly beneficial at this stage; this could also provide a platform for engaging stakeholders to support alignment of approaches and

metrics, with the ultimate aim of developing consistent, scalable, and evidence-based solutions for integrated MNG monitoring at offshore wind farms.

Finally, to support the uptake of MNG, it will be important to assess the economic implications of implementing MNG in OSW projects. There is a potential concern that a focus on MNG could drive costs up for OSW developers. While ecological enhancement measures may involve additional upfront costs, they can also deliver long-term value through faster permitting and improved stakeholder support, especially as expectations around environmental impacts continue to grow. To better understand these dynamics, it is recommended that government and industry stakeholders commission targeted research into the costs and benefits of adopting MNG measures, including their potential to reduce project risk and enhance long-term value. Given the cost pressures currently experienced by OSW projects, there is a need to ensure strategic and efficient monitoring of MNG on OSW projects. Demonstration of MNG potential and technology would be paramount to achieving developer acceptance, and the initial investment in research and development will be offset by the long-term benefits MNG achieves for OSW developers, stakeholders, and the marine environment.

4. Conclusions

A principles-based framework for Marine Net Gain (MNG) is essential, with adaptability and scalability at its core to meet evolving scientific and industry needs. Clearly defined and integrated metrics are needed to quantify ecological change and gauge the success of MNG measures, facilitating robust, evidence-driven assessments. Policy mechanisms should be developed or refined to incentivize and support the adoption of MNG monitoring across OSW projects, ideally through adaptive regulatory pathways that promote practical innovation.

Monitoring can commence immediately using established, proven technologies—such as sonar, acoustic monitoring, and remote video—while frameworks, metrics, and broader technological integration continue to mature. Looking ahead, promising tools like artificial intelligence, environmental DNA (eDNA), and novel omics-based approaches offer potential to transform monitoring, but further validation and coordination are necessary before wide-scale adoption. As the field advances, a balanced, stepwise approach is necessary: building on current capabilities, embracing innovation in a measured way, and ensuring that progress towards MNG is robust and truly beneficial for marine ecosystems.

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