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Answering the key stakeholder questions about the impact of offshore wind farms on marine life using hypothesis testing to inform targeted monitoring

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Abstract

Stakeholders need scientific advice on the environmental impacts of offshore wind (OW) before the facilities are installed. The utility of conventional environmental monitoring methods as a basis for forecasting OW impacts is limited because they do not explain the causes of the observed effects. We propose a multistep approach, based on process-oriented hypothesis testing, targeted monitoring and numerical modeling, to answer key stakeholder questions about planning an OW facility: **Q1**—*Where do we place future OW farms so that impacts on the ecosystem are minimized?* **Q2**—*Which species and ecosystem processes will be impacted and to what degree?* **Q3**—*Can we mitigate impacts and, if so, how?* and **Q4**—*What are the risks of placing an OW facility in one location vs. another?* Hypothesis testing can be used to assess impacts of OW facilities on target species-ecological process. This knowledge is transferable and is broadly applicable, *a priori*, to assess suitable locations for OW (Q1). Hypothesis testing can be combined with monitoring methods to guide targeted monitoring. The knowledge generated can identify the species/habitats at risk (Q2), help selecting/developing mitigation measures (Q3), and be used as input parameters for models to forecast OW impacts at a large spatial scale (Q1; Q4).

Keywords: offshore renewables; renewable energy; marine energy; offshore wind turbines; impact assessment; marine spatial planning; marine ecosystems; energy transition; offshore wind development; hypothesis testing

Introduction

The number and size of offshore wind (OW) turbines is increasing rapidly in response to the rising demand for renewable energy. OW is expected to become the main source of energy in Europe by 2042 [International Energy Agency (IEA); ICES 2022], but is also expanding rapidly elsewhere, including in the USA and China (deCastro et al. 2019). Planned OW farms will occupy thousands of square kilometer areas on continental shelves and, as such, represent the most expansive industrialization of the ocean in history. Large-scale OW farms will have a significant and semipermanent environmental footprint-impact (Degraer et al. 2020, Gill et al. 2020, Methratta 2020), with consequential societal and economic impacts (Virtanen et al. 2022). To resolve societal conflicts, and reduce OW impacts on the environment, effective marine spatial planning for a sustainable use of ocean space is needed (United Nations 2015). To guide developers and policy makers, marine spatial planning requires science-based knowledge and tools to assess how marine ecosystems and organisms will be affected by OW (Slater and Reid 2017).

During the planning phase of an OW farm, after potentially suitable areas are identified (good wind conditions, bathymetry, and so on), stakeholders need to know which species, habitats, and ecosystem processes will be impacted and if/how it is possible to mitigate the impacts. "Stakeholders" refers to all sectors/actors having a stake/interest in the development of OW or in the consequences thereof. The timing at which scientific advice is delivered to decision makers is of key importance. By providing scientific evidence of OW impacts on key species, habitats and ecosystem processes before the location of the facility is decided or the facility is designed, scientists can inform engineers about development sites, planning, and implementing solutions to mitigate impacts. For science to be useful in assisting future ecosustainable development of OW, it has to help stakeholders answer the following key questions:

Q1—Where do we place future OW farms so that impacts on the ecosystem are minimized?
Q2—Which species and processes will be impacted and to what degree?
Q3—Can we mitigate impacts and, if so, how?
Q4—What are the risks of placing an OW facility in one location vs. another?

Developing tools to answer these questions is essential to meet the ambitious goals of energy production from OW while maintaining a sustainably productive ocean. However, providing science-based answers to these questions is difficult,

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since there is a lack of knowledge about the potential effects of large-scale OW facilities on marine organisms and ecosystems. This lack of knowledge makes it challenging to assess and, at the moment, impossible to forecast the environmental footprint of future OW farms.

Expansive clusters of OW turbines modify the physical and chemical habitat of an area and, therefore, will also change the sensory world that marine animals experience on vast expanses of the continental shelf, both at the sea bottom and in the water column (Degraer et al. 2023). Turbines reduce wind forcing and modify water circulation, changing the primary productivity, oxygenation, and sedimentation rate at the sea bottom (Daewel et al. 2022). These habitat modifications, in combination with the newly introduced hard substrates from turbines, substations, cables, and moorings will affect many species of macro and mega-zooplankton, birds, marine mammals, benthic animals, and fishes (Degraer et al. 2020).

Currently, the effects of OW on the physical, chemical, and biological components of marine ecosystems are assessed using traditional approaches defined as basic monitoring (Lindeboom et al. 2015, Hutchison et al. 2020b); basic monitoring is typically conducted before, during and after the installation of OW turbines using biological sampling methods (trawls, acoustics, and so on) and arrays of sensors mounted on research vessels, autonomous vehicles, and/or monitoring platforms (Lindeboom et al. 2015, Vinagre et al. 2021, Wang et al. 2022). Basic monitoring programs are site-dependent and are usually based on 4–8 year-long sampling efforts (Methratta 2020, Livermore et al. 2023). These methods provide an overview of the biotic and abiotic characteristics of the ecosystem, and of how these evolve after the OW facilities are in place (Methratta 2020). Such monitoring is essential to assess ecosystem-wide effects of OW and to build time series of the physical, chemical, and biological status of the area throughout the lifetime of the OW facilities. However, studies that are based on this type of traditional monitoring produce data that are site-specific, are fully analyzed and interpreted only years after the OW facilities are in place, and are observational and descriptive, allowing for the formulation of hypotheses on local cause–effect relationships. Such monitoring is often unsuitable to explain the mechanisms underlying the observed effects. Importantly, it is an understanding of the mechanisms underlying the observed cause–effect relationships that are more likely to be universally applicable.

For these reasons, basic monitoring alone cannot provide knowledge, or forecasting, that is site-independent and is available to stakeholders before an OW facility is sited, designed, and constructed. Site-independent knowledge can be generated by using hypothesis testing-based research to investigate how the ecosystem processes, and the species inhabiting an area, are affected by the introduction of OW facilities. This knowledge can guide more targeted monitoring efforts, which prioritize the affected ecological processes leading to the observed impacts (Lindeboom et al. 2015, Hutchison et al. 2020b)

Forecasting OW impacts is currently performed by using complex, ecosystem-wide numerical models that include abiotic (hydrodynamic, atmospheric, and geological) components and biological components throughout the food web, from primary productivity to top predators (van der Molen et al. 2014, Pınarbaşı et al. 2019, Baulaz et al. 2023, Isaksson et al. 2023, Wang et al. 2024). Models to forecast ecosystem-wide effects of OW are only reliable and informative tools if based on high-quality data and realistic input parameters. However, there is a general lack of understanding or empirical observations of marine organism responses to the ecosystem changes caused by the introduction and operation of OW facilities (Degraer et al. 2023, Soukissian et al. 2023). Without such knowledge/observations, models to forecast OW impacts on ecosystem processes cannot be realistically parameterized. To fill this gap, experimental studies must be used to test key hypotheses on how marine organisms respond, at the scale of individuals, to the anthropogenic disturbances introduced by OW farms in marine ecosystems. These individual-level responses must then be upscaled to the population level.

We contend that by integrating basic and targeted monitoring with hypothesis testing-based methods, it is possible to achieve a paradigm shift in research on OW impact, from "reactive" to "forecasting" science. We describe how targeted monitoring and hypothesis testing can be used to assess and forecast OW impacts by species and ecosystem process, at any location, rather than by OW site. Through the integration of targeted monitoring and hypothesis testing, the scientific community can generate the globally relevant knowledge necessary for stakeholders to develop OW sustainably, and for engineers to design effective mitigation measures, *a priori*.

Step 1: answering stakeholder questions to achieve sustainable OW development

Energy produced by OW sources will increase rapidly to meet the carbon neutrality goals of the 2030 UN Agenda for Sustainable Development. To implement effective marine spatial planning and mitigation measures that minimize impacts of OW on ecosystems, stakeholders need scientific guidance before OW farms are planned, designed, and installed (Fig. 1, Step 1). Scientific advice can be delivered *a priori* only by understanding how OW turbines affect the various biotic and abiotic processes within an ecosystem. Knowledge of which marine processes and species will be impacted by OW, and the extent of that impact, will support developers and stakeholders in selecting suitable areas for OW and in designing effective and anticipatory mitigation measures. Environmental monitoring and hypothesis testing methods can provide such knowledge, *a priori*.

How OW is impacting marine ecosystems is a complex combination of a long list of cause–effect relationships (Dannheim et al. 2019). It is not possible to investigate all of them. Rather, the most pertinent ecological processes and potentially impacted species must be identified, preferably in collaboration with stakeholders (Gill et al. 2020). Such an approach to the selection of hypothesis-driven research questions greatly increases the likelihood that the scientific knowledge needed to address societal concerns will be obtained (e.g. Degraer et al. 2023).

Steps 2 and 3: environmental monitoring—hypothesis testing—targeted monitoring

Understanding how OW farms affect ecosystem processes requires knowledge of the disturbances introduced by the turbines in marine environments and of how marine organisms react to them. Environmental monitoring, including biological, chemical and geological sampling, oceanographic monitoring, and passive/active acoustics, are valuable tools to

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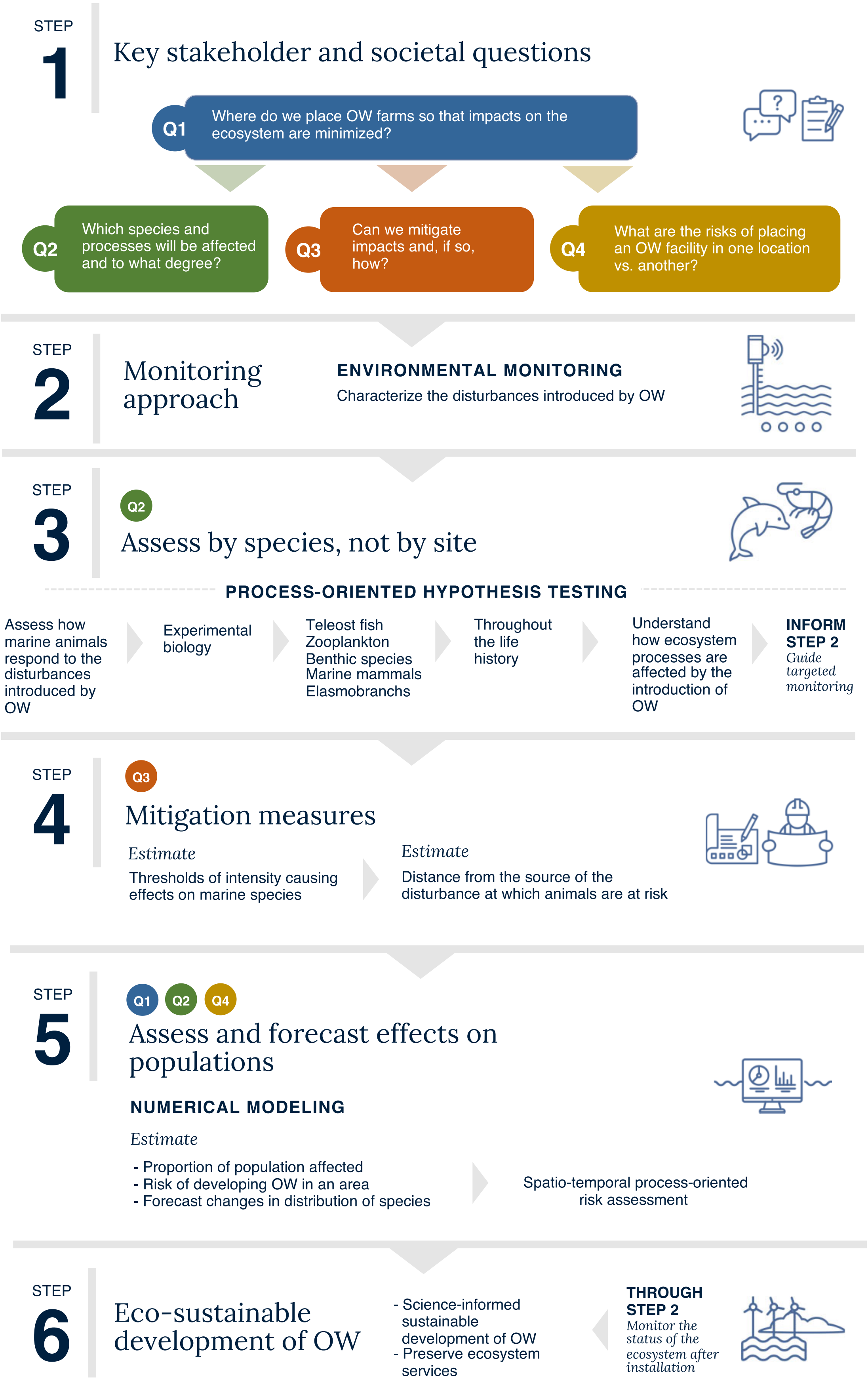

STEP
1
Key stakeholder and societal questions

Q1 Where do we place OW farms so that impacts on the ecosystem are minimized?

Q2 Which species and processes will be affected and to what degree?

Q3 Can we mitigate impacts and, if so, how?

Q4 What are the risks of placing an OW facility in one location vs. another?

STEP
2
Monitoring approach

ENVIRONMENTAL MONITORING
Characterize the disturbances introduced by OW

STEP
3
Q2
Assess by species, not by site

PROCESS-ORIENTED HYPOTHESIS TESTING

Assess how marine animals respond to the disturbances introduced by OW

Experimental biology

Teleost fish
Zooplankton
Benthic species
Marine mammals
Elasmobranchs

Throughout the life history

Understand how ecosystem processes are affected by the introduction of OW

INFORM STEP 2
Guide targeted monitoring

STEP
4
Q3
Mitigation measures

Estimate
Thresholds of intensity causing effects on marine species

Estimate
Distance from the source of the disturbance at which animals are at risk

STEP
5
Q1 Q2 Q4
Assess and forecast effects on populations

NUMERICAL MODELING

Estimate
- Proportion of population affected
- Risk of developing OW in an area
- Forecast changes in distribution of species

Spatio-temporal process-oriented risk assessment

STEP
6
Eco-sustainable development of OW

- Science-informed sustainable development of OW
- Preserve ecosystem services

THROUGH STEP 2
Monitor the status of the ecosystem after installation

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Figure 1. Conceptual diagram of a multistep framework to answer the key stakeholder questions about the impact of OW farms on marine life. **Step 1**: during the planning phase of OW facilities, stakeholders need scientific advice to answer key questions (**Q1–Q4**) to minimize impacts on marine ecosystems. Scientific advice on optimal locations for OW development, species that would be at risk, and possible mitigation measures is needed before the location is selected, and before the facilities are designed and installed. Therefore, the scientific methods used to provide such advice to stakeholders should be designed considering their main questions (**Q1–Q4**). **Step 2**: monitoring methods collect large amount of data (biological, physical/chemical, oceanographic, and acoustic) that characterize the disturbances introduced by OW farms. From these data, it is possible to quantify the exposure levels of these disturbances that marine organisms will experience within or in proximity of OW farms. **Step 3**: identify the species and ecosystem processes that would be affected by OW farms before the facility is planned/installed by using process-oriented hypothesis testing. Using the exposure levels quantified through Step 2, experimental methods can assess, which species respond (behavior, physiology, fitness, and survival), at the level of the individual, to the disturbances introduced by OW farms, and the extent of the effect. These experiments provide discrete thresholds of signal intensity causing effects, and estimations of the distance from the signal source at which effects would occur. The results from hypothesis-driven experiments would also inform targeted monitoring efforts to study OW impacts on ecosystem processes at the OW farm after the facility is in place. **Step 4**: the data from process-oriented hypothesis testing and targeted monitoring help engineers develop mitigation measures. By knowing the species at risk and the thresholds of intensity of the disturbance that elicit effects, engineers can develop mitigation measures that focus on specific harmful signals and on target sensitive species. **Step 5**: hypothesis testing and targeted monitoring provide data for the parametrization of models to assess and forecast OW impacts at large scale. With high-quality data as input variables, models can estimate the proportion of populations that would be affected by the facility and which species would be exposed to the disturbances. Therefore, through this integrative approach, models can provide recommendations for suitable locations for the construction of OW facilities where adverse effects on marine ecosystems would be reduced compared to other locations. **Step 6**: output results from targeted monitoring, process-oriented hypothesis testing, and numerical models provide the knowledge base for stakeholders to make data-informed decisions. Marine spatial planning guided by forecasting scientific advice would support the development of OW while reducing impacts on ecosystem services. The style of the infographic was designed by Erin Gallup, *Hub Ocean*.

characterize the disturbances introduced by OW farms (Lindeboom et al. 2011). Large datasets are collected at existing OW facilities to characterize changes in noise conditions during the installation and operational phases (Matuschek and Betke 2009, Tougaard et al. 2020, Wang et al. 2022), electromagnetic fields (EMFs) in proximity of the subsea cables connecting the turbines (Hutchison et al. 2021, Imperadore et al. 2023), water stratification, oxygenation and productivity (Daewel et al. 2022), hydrodynamics (van Berkel et al. 2020), and sedimentation rates (Harris et al. 2011). These data are related to specific facilities and locations and, therefore, cannot be used to assess, *a priori*, the impacts that OW farms would have at different locations. On the other hand, data from monitoring programs can be used to estimate the exposure levels (for each of the disturbances) that marine organisms will encounter at future OW facilities (Fig. 1; Step 2).

Large-scale OW turbine facilities will modify the sensory world that marine animals experience on vast portions of the continental shelf. Benthic, demersal, pelagic, and planktonic species will encounter habitat modifications, which include altered sensory cues used for predator/prey detection and migrations (Mooney et al. 2020, Hutchison et al. 2020c). By altering important spatial orientation cues, such as sound, EMFs and circulation patterns, among others, large-scale clusters of OW turbines could lead to changes in the spatial distribution of marine species that reside in or transit through the facilities.

To forecast and mitigate spatial shifts of marine species, we need to understand how OW farms modify the processes driving the spatial distribution of marine animals. This knowledge can be built using *process-oriented hypothesis testing*, which tests key hypotheses on how realistic exposure to the signals and disturbances introduced by OW farms affect the behavior, physiology, survival, and reproductive success of marine species. Data on exposure levels (noise intensity and frequency bands, EMF intensity, modified sediment characteristics, artificial reefs, turbulence, and so on) found in proximity of OW turbines can be obtained from past or current monitoring programs and used to test how individuals from any species respond to these signals (Fig. 1; Step 3). For the hypotheses to be relevant, they have to be formulated according to the sensitivity of a species to a specific signal, the movement ecology of the species, and its life history (Hutchison et al. 2020c). This is because, when transitioning from early life to adult stages, marine species can change their lifestyle dramatically (e.g. from planktonic to benthic), including their sensory capacity and movement behaviour-ecology.

Examples of a hypothesis testing-based approach can be found in the research on behavioral responses of benthic animals to disturbances introduced by OW farms. Studies on American lobster (*Homarus americanus*) and little skates (*Leucoraja erinacea*) show that these species alter their exploratory behavior when exposed to weak EMFs in the intensity range of those found in proximity of subsea power cables (Hutchison et al. 2020a). However, analogous work revealed no effect on European lobster (*Homarus gammarus*) (Taormina et al. 2020) and negligeable effects on lumpfish (*Cyclopterus lumpus*) (Durif et al. 2023). Hypothesis testing-based studies also reveal the importance of considering possible effects early in the life cycle, and how these can vary between species. Atlantic haddock (*Melanogrammus aeglefinus*) and Atlantic cod (*Gadus morhua*) larvae reduce their swimming activity when exposed to weak anthropogenic EMFs (Cresci et al. 2022b, 2023b), but this is not observed in larvae of lesser sandeel (*Ammodytes marinus*) (Cresci et al. 2022a). These laboratory-based studies provide species-specific knowledge on the effects of exposure to EMFs that is applicable to all the possible OW development areas where these species are present, and the information is available *a priori*.

Several key knowledge gaps remain about the effects of OW farms on benthic species. For example, how changes in hydrodynamics and primary production affect filter feeders, how OW will attract non-native species and how operational noise and vibration affect benthic species is largely unknown (Dannheim et al. 2019, Popper et al. 2022). These questions can be investigated by using *process-oriented hypothesis testing* to explore, for example, how filter feeders respond to changes in flow conditions and food availability, the movement behavior of non-native species, or the behavioral response of benthic animals to simulated noise and vibration from OW turbines.

Another example of *process-oriented hypothesis testing* comes from research on the response of marine animals to the noise associated with OW. The intensity and frequencies of the noise associated with the construction (pile driving) and operation of OW turbines has been measured (Burns et al.

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2022, Sigray et al. 2022, Wang et al. 2022). The noise level that will be produced by the next generation of OW turbines (larger and more powerful) can also be predicted (Stöber and Thomsen 2021, Thomsen et al. 2023). This information on the acoustic signals associated with OW provides the opportunity to test how animals respond to them before OW farms are in place. For example, this approach was taken to experimentally test the effect of noise from pile driving on cuttlefish (*Sepia officinalis*), which display damage to the statocyst sensory epithelia at the adult stage and decreased larval survival when exposed to simulated pile driving noise (Solé et al. 2022). A hypothesis-testing approach has been used to assess how operational (continuous) noise from OW turbines affects dispersing fish larvae. Experiments conducted *in situ* in a Norwegian fjord revealed that cod larvae (*G. morhua*) are attracted to the source of low-frequency (100 Hz) sound pressure and particle motion in the intensity range of that produced by operating turbines (Cresci et al. 2023a). Operational noise is one of the disturbances introduced by OW that acts at moderate to large spatial scales (Dannheim et al. 2019, 2020). Therefore, research on movement/orientation responses of marine animals to the directional component (acoustic particle motion) of OW operational noise is needed (Popper et al. 2022, Williams et al. 2023), and it would reveal how OW noise could affect the spatial distribution of marine species.

The synergistic use of targeted monitoring and process-oriented hypothesis testing described above would answer the key stakeholder question Q2–Which species and processes will be impacted and to what degree?—for any planned OW facility location, before it is installed.

While basic monitoring supports a continuous and longer-term assessment of the impacts of a specific OW farm, including unexpected impacts, it delivers only *post hoc* and site-specific knowledge (Lindeboom et al. 2015). More importantly, if not based on known cause–effect relationships, as is the case for many OW monitoring programs, it involves the collection of a large amount of data over a long period (e.g. 4–8 years) that does not necessarily address the most pertinent impacts; importantly, it may take many years before it is known that the data being collected was not fit-for-purpose. Thus, basic monitoring programs are at risk of having low effectiveness with respect to informing prompt answers to key stakeholder questions. Monitoring programs are also constrained with respect to the number of samples that can be collected and/or processed. Therefore, it is important to carefully consider how to best allocate monitoring effort.

An enhanced understanding of the cause–effect relationships behind OW-related ecological impacts, achieved via hypothesis-driven research, will help monitoring programs used for Environmental Impact Assessment (EIA) target the impacts that really matter, i.e. targeted monitoring. Such an approach would increase the effectiveness of monitoring programs (Wilding et al. 2017).

Step 4: providing knowledge for the development of effective mitigation measures

Process-oriented hypothesis testing and targeted monitoring provide insights into which signals/disturbances associated with OW animals perceive and respond to. This knowledge is essential to understand the cause–effect relationships underlying OW-driven changes in ecosystem processes; such an understanding is the basis for designing and implementing effective mitigation measures. For example, by assessing the response of marine animals to artificially simulated disturbances introduced by OW turbines, it is possible to identify the intensity threshold levels eliciting effects on them. These thresholds can be obtained for, among others, noise intensity, predator/prey abundance, sediment granulometry, deoxygenation level, flow speed, or EMF intensity, and can elicit lethal or sublethal effects in the marine species living in areas allocated for OW development. By combining data on intensity thresholds and targeted monitoring of relevant signals/processes at OW sites with models of signal propagation, we can perform realistic spatial risk assessment of OW farms for any species of interest (described below in Step 5).

The combination of these methods can quantify the extent of the area around the source where animals would detect the signal, react to the signal, and/or would be impacted by the signal. By knowing the thresholds of intensity causing effects, and the areal extent of the effect, this approach can provide the knowledge base for the development of mitigation measures that are targeted at the marine species living in planned OW farms areas (Fig. 1; Step 4). This step would answer the key stakeholder question: Q3—*Can we mitigate impacts and, if so, how?*

Step 5: assess and forecast OW impacts at the scale of populations

Results obtained through targeted environmental monitoring and hypothesis testing can supply the knowledge needed to scale up the assessment and forecasting of OW impacts to the population scale. To estimate the ability of marine species to cope with anthropogenic disturbances that act at large spatial and temporal scales (e.g. OW farms), we need to understand the spatiotemporal characteristics of the populations of the species of interest. For example, for commercially important fish species, population structure can be assessed using integrated population models (IPMs), which are typically used to provide management advice to harvest commercially valuable populations. For these spatial IPMs to be robust, they have to include the spatial dynamics of the populations. These can be movement-related variables such as the degree of population connectivity, life stage-dependent and species-specific movement behavior, or climate change-driven changes in distribution (Goethel et al. 2011, 2021). IPM-like models could be used to assess the potential impact of future OW facilities on the biomass of fish populations in areas identified for development of OW. These models can be sensitive to their input parameters, and incorrectly specified spatial and movement dynamics within the population can lead to large uncertainties in the population estimates (Bosley et al. 2022). Process-oriented hypothesis testing and targeted monitoring are valuable sources of data on fish movement behavior (which affect the spatial dynamics of fish populations), and on how movement responds to anthropogenic disturbances. By using empirical data (from tagging, field/laboratory-based experiments) and monitoring observations (e.g. from acoustic surveys) as sources of input to spatial population models, these could assess and forecast the footprint of OW farms on fish populations. The concept described above, which focuses on fish biomass, has broad applicability and could target other animals, such as invertebrates, marine birds, or marine mammals, and also to different habitats within the ecosystem (benthic, demersal, and pelagic).

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Forecasting of OW impacts can be performed for the often recruitment-determining dispersal phase of the early life history of fishes. Larval dispersal is a key process through which fish eggs and larvae disperse from the spawning areas, through pelagic waters, to reach suitable feeding and nursery areas. The success of the dispersal phase plays an important role in the survival and recruitment of fish populations (Hjort 1914). Larval dispersal depends on favourable ocean currents (passive transport) and larval movement behavior (swimming and orientation; active transport) (Houde 2016, Chaput et al. 2022), both of which will be affected by the introduction of large scale OW facilities (van Berkel et al. 2020, Cresci et al. 2023a). Process-oriented hypothesis testing can quantify the changes, caused by the disturbances introduced by OW (sound, EMFs, turbulence, and so on), in key behaviors used by fish larvae during dispersal, i.e. swimming kinematics, vertical movement, horizontal orientation, and predator/prey interactions. The data on larval behavior (both innate and affected by OW) can be incorporated as input parameters into biophysical-coupled models (Langrangian models) of larval dispersal. Biophysical models can then be used in combination with models of signal propagation from a source (e.g. acoustic propagation models) to estimate how larval fish populations will be affected by future OW facilities. This proposed combination of empirical data and numerical simulations could estimate the proportion of the population that would be exposed to harmful levels of a disturbance, and which species would be at risk.

These results would be applicable to any OW development site and can be used to inform marine spatial planning as well as for the development of mitigation measures. Therefore, implementing numerical models with variables parameterised using data provided by monitoring and hypothesis testing could answer the key stakeholder questions: Q1—Where do we place future OW farms so that impacts on the ecosystem are minimized? Q2—Which species and processes will be impacted and to what degree? and Q4—What are the risks of placing an OW facility in one location vs. another?

Step 6: supporting a rapid but ecosustainable development of OW energy

The approach described above is an interdisciplinary framework that can support EIA of OW development before the installation of the turbines. Combining targeted environmental monitoring, process-oriented hypothesis testing, and numerical modeling would generate knowledge of the species and ecosystem processes impacted by OW (Fig. 1; Step 6). After the installation of the facilities, targeted environmental monitoring, guided by hypothesis testing, could be used to assess the health of the ecosystem and the associated ecosystem services within and around OW farms throughout the life cycle of the facilities.

The proposed hypothesis testing-based approach would assess how ecosystem processes are altered at the spatial scale of the clusters of turbines. The assessment would be site-generic and, therefore, would be applicable to all areas inhabited by the species of interest, and it would be available before the turbines are in place.

Given the rapid development of the OW industry, scientific approaches that can support stakeholders in data-informed decision making at the marine spatial planning stage are urgently needed. By forecasting environmental impacts, rather than monitoring them after the turbines are in place, OW has the potential to develop rapidly in an ecosustainable manner.

Concluding remarks

The framework that we propose is ambitious. Nonetheless, we contend that it can be achieved within a realistic timeframe. Continuous dialog between government, regulators, the OW and fishing industries, scientists and the public (e.g. through NGOs) is needed to identify any potential environmental issues during the early stages of development of OW farms. Collaboration between companies developing OW farms and research institutions is essential to ensure that the data needed to inform the design and placement of OW farms is collected and is considered by OW developers and regulators in the early stages of project development and siting. Funding agencies will have to prioritize research projects—integrated combinations of field, laboratory, and modeling work—that support forecasting the impacts of OW.

Collecting more knowledge on the impacts of OW turbines on demersal, pelagic, and benthic species of vertebrates and invertebrates, throughout their life cycles, should be a focus of research. It will not be possible to investigate the impacts of OW on all species or processes. Keystone species and processes—those of greatest economic and ecological importance—will have to be targeted. Prioritization of the species targeted for researchshould also consider their relation to ecosystem functioning such as their contribution to the food web and conservation status. Such species-specific assessment of OW impacts could provide the knowledge foundation needed to plan, design, install, and operate OW farms.

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Author contributions

A.C. designed the study and wrote the paper; S.D. designed the study and wrote the paper; J.D. designed the study and wrote the paper; G.Z. designed the study and wrote the paper; H.I.B. designed the study, wrote the paper, and is the leader of the project that funded the research.

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Data availability

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References

Baulaz Y, Mouchet M, Niquil N *et al.* An integrated conceptual model to characterize the effects of offshore wind farms on ecosystem services. *Ecosyst Services* 2023;**60**:101513. https://doi.org/10.1016/j.ecoser.2023.101513.

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Bosley KM, Schueller AM, Goethel DR *et al.* Finding the perfect mismatch: evaluating misspecification of population structure within spatially explicit integrated population models. *Fish Fish* 2022;**23**:294–315. https://onlinelibrary.wiley.com/doi/full/10.1111/faf.12616 (2 October 2023, date last accessed).

Burns R, Martin S, Wood M *et al.* Hywind Scotland floating offshore wind farm: sound source characterisation of operational floating turbines. Halifax: JASCO Applied Sciences, 2022.

Chaput R, Sochala P, Miron P *et al.* Quantitative uncertainty estimation in biophysical models of fish larval connectivity in the Florida Keys. *ICES J Mar Sci* 2022;**79**:609–32. https://academic.oup.com/icesjms/article/79/3/609/6541347 (3 June 2022, date last accessed).

Cresci A, Durif CMF, Larsen T *et al.* Magnetic fields produced by subsea high-voltage direct current cables reduce swimming activity of haddock larvae (*Melanogrammus aeglefinus*). *PNAS Nexus* 2022;**1**:1–7. https://academic.oup.com/pnasnexus/article/1/4/pgac175/6678016 (3 October 2022, adte last accessed).

Cresci A, Durif MF, Larsen T *et al.* Static magnetic fields reduce swimming activity of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) larvae. *ICES J Mar Sci* 2023b;**0**:1–8. https://doi.org/10.1093/icesjms/fsad205 (11 January 2024, date last accessed).

Cresci A, Perrichon P, Durif CMF *et al.* Magnetic fields generated by the DC cables of offshore wind farms have no effect on spatial distribution or swimming behavior of lesser sandeel larvae (*Ammodytes marinus*). *Mar Environ Res* 2022;**176**:105609. https://doi.org/10.1016/j.marenvres.2022.105609.

Cresci A, Zhang G, Durif CMF *et al.* Atlantic cod (*Gadus morhua*) larvae are attracted by low-frequency noise simulating that of operating offshore wind farms. *Commun Biol* 2023a;**6**:1–10. https://www.nature.com/articles/s42003-023-04728-y (5 May 2023, date last accessed).

Daewel U, Akhtar N, Christiansen N *et al.* Offshore wind farms are projected to impact primary production and bottom water deoxygenation in the North Sea. *Commun Earth Environ* 2022;**3**:1–8. https://www.nature.com/articles/s43247-022-00625-0 (1 December 2022, date last accessed).

Dannheim J, Bergström L, Birchenough SNR *et al.* Benthic effects of offshore renewables: identification of knowledge gaps and urgently needed research. *ICES J Mar Sci* 2020;**77**:1092–108. https://doi.org/10.1093/icesjms/fsz018 (29 September 2023, date last accessed).

Dannheim J, Degraer S, Elliott M *et al.* 2019 Seabed communities. In: M Perrow (ed.), *Wildlife and Wind Farms, Conflicts and Solutions: Offshore: Potential Effects*. Vol. **3**, Exeter: Pelagic Publishing, 112–41.

deCastro M, Salvador S, Gómez-Gesteira M *et al.* Europe, China and the United States: three different approaches to the development of offshore wind energy. *Renew Sustain Energy Rev* 2019;**109**:55–70. https://doi.org/10.1016/j.rser.2019.04.025.

Degraer S, Brabant R, Vanaverbeke J EDEN 2000–Exploring options for a nature-proof development of offshore wind farms inside a Natura 2000 area. Hoisdorf: BRUSS, 2023, 440. https://mareco-odnature.naturalsciences.be/.

Degraer S, Carey DA, Coolen JWP *et al.* Offshore wind farm artificial reefs affect ecosystem structure and functioning: a synthesis. *Oceanography* 2020;**33**:48–57. https://doi.org/10.5670/oceanog.2020.405.

Durif CMF, Nyqvist D, Taormina B *et al.* Magnetic fields generated by submarine power cables have a negligible effect on the swimming behavior of Atlantic lumpfish (*Cyclopterus lumpus*) juveniles. *PeerJ* 2023;**11**:e14745. https://peerj.com/articles/14745 (5 May 2023, date last accessed).

Gill AB, Degraer S, Lipsky A *et al.* Setting the context for offshore wind development effects on fish and fisheries. *Oceanography* 2020;**33**:118–27. https://doi.org/10.5670/oceanog.2020.411.

Goethel DR, Bosley KM, Langseth BJ *et al.* Where do you think you're going? Accounting for ontogenetic and climate-induced movement in spatially stratified integrated population assessment models. *Fish Fish* 2021;**22**:141–60. https://onlinelibrary.wiley.com/doi/full/10.1111/faf.12510 (2 October 2023, date last accessed).

Goethel DR, Quinn TJ, Cadrin SX Incorporating spatial structure in stock assessment: movement modeling in marine fish population dynamics. *Rev Fish Sci* 2011;**19**:119–36. https://www.tandfonline.com/doi/abs/10.1080/10641262.2011.557451 (2 October 2023, date last accessed).

Harris JM, Whitehouse RJS, Sutherland J 2011 Marine scour and offshore wind: lessons learnt and future challenges. In: *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering—OMAE*. Vol. **5**. New York: American Society of Mechanical Engineers Digital Collection, 849–58. https://doi.org/10.1115/OMAE2011-50117 (27 September 2023, date last accessed).

Hjort J Fluctuations in the great fisheries of northern Europe viewed in the light of biological research. *Rapports et Procès-Verbaux des Réunions du Conseil Permanent International Pour L'Exploration de la Mer*, 1914;**20**:1–228. (18 June 2019, date last accessed).

Houde ED 2016 Recruitment variability. In: *Fish Reproductive Biology : Implications for Assessment and Management*. 98–187. John Wiley & Sons, Ltd, Hoboken: ISBN: 978-1-118-75274-6(18 June 2019, date last accessed).

Hutchison ZL, Bartley ML, Degraer S *et al.* Offshore wind energy and benthic habitat changes lessons from block island wind farm. *Oceanography* 2020;**33**:58–69. https://doi.org/10.5670/oceanog.2020.406.

Hutchison ZL, Gill AB, Sigray P *et al.* Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. *Sci Rep* 2020a;**10**:1–15. https://www.nature.com/articles/s41598-020-60793-x (28 September 2021, date last accessed).

Hutchison ZL, Gill AB, Sigray P *et al.* A modelling evaluation of electromagnetic fields emitted by buried subsea power cables and encountered by marine animals: considerations for marine renewable energy development. *Renew Energy* 2021;**177**:72–81, https://linkinghub.elsevier.com/retrieve/pii/S0960148121007175 (Accessed 19 May 2021).

Hutchison ZL, Secor DH, Gill AB The interaction between resource species and electromagnetic fields associated with electricity production by offshore wind farms. *Oceanography* 2020;**33**:96–107. https://doi.org/10.5670/oceanog.2020.409.

ICES. 2022 Working Group on Offshore wind development and fisheries (WGOWDF). ICES Scientific Report 4. Copenhagen. /articles/report/Working_Group_on_Offshore_Wind_Development_and_Fisheries_WGOWDF_/21750458/1 (19 December 2022, date last accessed).

Imperadore A, Amaral L, Tanguy F *et al.* Deliverable 2.2 Monitoring of Electromagnetic fields. Brussels: European Climate, Infrastructure and Environment Executive Agency, 2023, 27.

Isaksson N, Scott BE, Hunt GL *et al.* A paradigm for understanding whole ecosystem effects of offshore wind farms in shelf seas. *ICES J Mar Sci* 2023;**0**:1–12. https://doi.org/10.1093/icesjms/fsad194 (16 January 2024, date last accessed).

Lindeboom H, Degraer S, Dannheim J *et al.* Offshore wind park monitoring programmes, lessons learned and recommendations for the future. *Hydrobiologia* 2015;**756**:169–80. https://link.springer.com/article/10.1007/s10750-015-2267-4 (25 September 2023, date last accessed).

Lindeboom H, Kouwenhoven HJ, Bergman MJN *et al.* Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environ Res Lett* 2011;**6**:035101. https://iopscience.iop.org/article/10.1088/1748-9326/6/3/035101 (25 September 2023, date last accessed).

Livermore J, Truesdale C, Ransier K *et al.* Small effect sizes are achievable in offshore wind monitoring surveys. *ICES J Mar Sci* 2023;**0**:1–10. https://doi.org/10.1093/icesjms/fsad097 (13 October 2023, date last accessed).

Matuschek R, Betke K 2009 Measurements of construction noise during pile driving of offshore research platforms and wind farms. In: *Proceedings of the NAG/DAGA International Conference on Acoustics*. Washington: US Department of Energy, 262–5.

Downloaded from https://academic.oup.com/icesjms/advance-article/doi/10.1093/icesjms/fsae066/7668676 by Pacific Northwest National Laboratory user on 20 May 2024

Methratta ET Monitoring fisheries resources at offshore wind farms: BACI vs. BAG designs. *ICES J Mar Sci* 2020;**77**:890–900. https://academic.oup.com/icesjms/article/77/3/890/5802590 (1 December 2022, date last accessed).

Mooney TA, Andersson MH, Stanley J Acoustic impacts of offshore wind energy on fishery resources an evolving source and varied effects across a wind farm's lifetime. *Oceanography* 2020;**33**:82–95. https://doi.org/10.5670/oceanog.2020.408.

Pınarbaşı K, Galparsoro I, Depellegrin D *et al.* A modelling approach for offshore wind farm feasibility with respect to ecosystem-based marine spatial planning. *Sci Total Environ* 2019;**667**:306–17. https://doi.org/10.1016/j.scitotenv.2019.02.268.

Popper AN, Hice-Dunton L, Jenkins E *et al.* Offshore wind energy development: research priorities for sound and vibration effects on fishes and aquatic invertebrates. *J Acoust Soc Am* 2022;**151**:205. https://asa.scitation.org/doi/abs/10.1121/10.0009237 (8 June 2022, date last accessed).

Sigray P, Linné M, Andersson MH *et al.* Particle motion observed during offshore wind turbine piling operation. *Mar Pollut Bull* 2022;**180**:113734. https://linkinghub.elsevier.com/retrieve/pii/S0025326X22004167 (31 May 2022, date last accessed).

Slater AM, Reid G. Marine spatial planning. In: *Marine and Coastal Resource Management: Principles and Practice*. Oxfordshire: Taylor and Francis, 2017, 61–78. https://www.taylorfrancis.com/chapters/edit/10.4324/9781315666877-2/marine-spatial-planning-charles-ehler (1 December 2022, date last accessed).

Solé M, De Vreese S, Fortuno J-M *et al.* Commercial cuttlefish exposed to noise from offshore windmill construction show short-range acoustic trauma. *Environ Pollut* 2022;**312**:119853. https://doi.org/10.1016/j.envpol.2022.119853.

Soukissian T, O'Hagan AM, Azzellino A *et al.* European offshore renewable energy: towards a sustainable future. In: J. J. Heymans, P. Kellett, B. Alexander, Á. Muñiz Piniella, A. Rodriguez Perez, J. Van Elslander (eds), *Future Science Brief No. 9 of the European Marine Board*. Ostend: European Marine Board, 2023.

Stöber U, Thomsen F How could operational underwater sound from future offshore wind turbines impact marine life?. *J Acoust Soc Am* 2021;**149**:1791. https://asa.scitation.org/doi/abs/10.1121/10.0003760 (11 May 2022, date last accessed).

Taormina B, Poi CD, Agnalt A-L *et al.* Impact of magnetic fields generated by AC/DC submarine power cables on the behavior of juvenile European lobster (*Homarus gammarus*). *Aquat Toxicol* 2020;**220**:105401. https://doi.org/10.1016/j.aquatox.2019.105401 (14 August 2020, date last accessed).

Thomsen F, Stöber U, Sarnocińska-Kot J 2023 Hearing impact on marine mammals due to underwater sound from future wind farms. In: *The Effects of Noise on Aquatic Life*. Cham: Springer, 1–7. https://link.springer.com/referenceworkentry/10.1007/978-3-031-10417-6_163-1 (26 September 2023, date last accessed).

Tougaard J, Hermannsen L, Madsen PT How loud is the underwater noise from operating offshore wind turbines?. *J Acoust Soc Am* 2020;**148**:2885. https://asa.scitation.org/doi/abs/10.1121/10.0002453 (11 May 2022, date last accessed).

United Nations. Resolution adopted by the General Assembly on 25 September 2015/A/RES/70/1. United Nations General Assembly. New York. 2015. https://sustainabledevelopment.un.org/index.php?page=view&type=111&nr=8496&menu=35.

van Berkel J, Burchard H, Christensen A *et al.* The effects of offshore wind farms on hydrodynamics and implications for fishes. *Oceanography* 2020;**33**:108–17. https://doi.org/10.5670/oceanog.2020.410.

van der Molen J, Smith HCM, Lepper P *et al.* Predicting the large-scale consequences of offshore wind turbine array development on a North Sea ecosystem. *Cont Shelf Res* 2014;**85**:60–72. https://doi.org/10.1016/j.csr.2014.05.018.

Vinagre PA, Cruz E, Chainho P *et al.* Deliverable 2.1 development of environmental monitoring plans. Corporate deliverable of the Safe-WAVE Project co-funded by the European Union, Call for Proposals EMFF-2019- 1.2.1.1- Environmental monitoring of ocean energy devices. 2021. AZTI - Marine and Coastal Environmental Management, Bizkaia, Spain. https://doi.org/10.13140/RG.2.2.19708.41600/1.

Virtanen EA, Lappalainen J, Nurmi M *et al.* Balancing profitability of energy production, societal impacts and biodiversity in offshore wind farm design. *Renew Sustain Energy Rev* 2022;**158**:112087. https://doi.org/10.1016/j.rser.2022.112087.

Wang L, Wang B, Cen W *et al.* Ecological impacts of the expansion of offshore wind farms on trophic level species of marine food chain. *J Environ Sci* 2024;**139**:226–44. https://doi.org/10.1016/j.jes.2023.05.002.

Wang R, Xu X, Zou Z *et al.* Dominant frequency extraction for operational underwater sound of offshore wind turbines using adaptive stochastic resonance. *J Mar Sci Eng* 2022;**10**:1517. https://www.mdpi.com/2077-1312/10/10/1517/htm (17 August 2023, date last accessed).

Wilding TA, Gill AB, Boon A *et al.* Turning off the DRIP ('Data-rich, information-poor')—rationalising monitoring with a focus on marine renewable energy developments and the benthos. *Renew Sustain Energy Rev* 2017;**74**:848–59. https://doi.org/10.1016/j.rser.2017.03.013.

Williams KA, Popper AN, Hice-dunton L *et al.* Sound-related effects of offshore wind energy on fishes and aquatic invertebrates : research recommendations. In: *The Effects of Noise on Aquatic Life*. Cham: Springer Nature, 2023.

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