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WORKSHOP TO COMPILE EVIDENCE ON THE IMPACTS OF OFFSHORE RENEWABLE ENERGY ON FISHERIES AND MARINE ECOSYSTEMS (WKCOMPORE)

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Contents

i Executive summary

This report provides a comprehensive analysis and evaluation of the current state-of-the art in available evidence and science concerning the economic, social, and ecological impacts of offshore wind farms (OWF) and floating offshore wind farms (FLOW) on fisheries in the Baltic Sea, Celtic Seas, and Greater North Sea. It describes the observed and potential economic, social, ecological and cumulative impacts of OWF and FLOW, with a focus on the scope of the existing evidence base, data and methods to assess impacts, and mitigation options to avoid or reduce unwanted impacts. Overall, the workshop to compile evidence on the impacts of offshore renewable energy on fisheries and marine ecosystems (WKCOMPORE) highlights the need for additional high-resolution data, comprehensive assessments, and stakeholder involvement to better understand and mitigate the impacts of OWF and FLOW on fisheries and marine ecosystems. Specific 'key findings' arising from WKCOMPORE include:

Economic and Social Impacts:

- The assessment of economic and social impacts of OWF and FLOW requires high-resolution data on vessel positions, fisheries catch and effort, fisheries economics, and social data. However, existing data are often insufficiently detailed and not well-linked, making comprehensive impact assessments a challenge.
- Both ex-ante (before) and ex-post (after) methods are used to assess these impacts. Studies have shown that OWF and FLOW can negatively affect income, fishing grounds, catching opportunities, and operating costs. It was concluded there are generally more studies reporting on negative impacts than positive benefits.
- Context factors such as the type of OWF and FLOW, development phase, and adaptive capacity of fisheries influence the nature and magnitude of impacts. No studies were found on trade-offs between economic impacts on fisheries and OWF and FLOW.

Ecological Impacts (benthos and higher trophic levels):

- OWF and FLOW development phases have known or predicted local impacts on commercially fished species, but no population-level assessments were identified. The requirements for such analyses are, however, described.
- Assessing the potential impact of offshore wind farms (OWF) (fixed and floating) on commercial species requires a detailed understanding on how related human operations and the pressures they exert cause environmental effects leading to population-level impacts across spatial and temporal scales.
- Combined pressures caused by OWFs, climate change and other human pressures give rise to cumulative risks, demanding integrated environmental assessments such as cumulative effects assessments (CEA) and multi-scale management strategies.
- The trait-based framework (TAFOW) applied in the current study links OWF-induced state changes to population characteristics and response traits, enabled species vulnerabilities to all phases of OWF life cycle to be assessed.
- A total of 34 commercial species were assessed in the North Sea, Celtic Sea, and Baltic Sea, using the TAFOW framework, which identified that sediment resuspension was likely to be the most impactful state change, with highest vulnerabilities noted in the Celtic Sea driven by changes in larval dispersal and predator-prey interactions.

- The present study revealed that from the 34 commercially most important fisheries resources assessed; herring, great scallop, and monkfish are the most vulnerable species across the three regions.
- Trophic interactions and recruitment survival of fisheries resources are particularly vulnerable to pressures that are exerted by operational OWF.
- It was concluded there is insufficient evidence to directly assess and quantify the effects of OWF and FLOW on the Western Baltic herring stock, although there is no direct specific evidence to suggest existing OWF sites are impacting Western Baltic herring stocks.
- Baltic Proper harbour porpoise will likely be directly affected during all stages of offshore renewable energy development, and especially by the introduction of underwater noise. Given the aforementioned critically low population size, even moderate impacts are to be avoided.

Cumulative Impacts:

- WKCOMPORE evaluated existing methods and models with the potential to assess cumulative impacts of OWF and FLOW. Some models and tools were deemed suitable or had potential through further development to quantify cumulative impacts and test mitigation options.
- An important distinction is made between CEA models/ tools based on risk assessment framework approaches which are useful in identifying ecosystem components in areas at highest risk, from ecosystem models which can quantitatively assess the interactions between specific aspects of windfarm developments and fisheries in support of operational management advice.
- The models/ tools evaluated in the present study (in terms of their operational utility), classified as ecosystem models, offering the greatest utility to support operationally CEAs were; VMStools, FishSET, Community Profiling Tools. DISPLACE, OSMOSE and EwE/ Ecospace.
- The importance of developing case studies to demonstrate the practical application of available strategic risk-based assessment frameworks (such as BowTie, FEISA, ODEMM and SCAIRM) should be linked explicitly with the outputs of quantitative (mechanistic) ecosystem models where possible.
- It was concluded there is no single CEA or ecosystem model/ tool available to provide a comprehensive assessment of all component interactions at a social, economic and ecological level, between windfarm developments and fisheries. The application of a combination of CEA and ecosystem models/ tools is therefore recommended for assessment purposes.
- The current study concluded the need to increase focus on exploring long time-series fisheries and environmental data (>10 years) to better describe and understand the spatial/temporal dynamics of core fishing areas and climate effects in response to offshore windfarms.

Hydrodynamic and Pelagic Ecological Effects: (foodweb, productivity and lower trophic levels):

- Most commercial species with a pelagic life stage within an ecoregion will overlap in spatial distribution with dynamic cables associated with OWF and FLOW throughout the time that the cables are in the water column (construction, operation and decommissioning).
- Interactions between species and cables leading to responses will relate to either direct energy emissions, physical effects and/or indirect ecological effects.
- Only during OWF and FLOW operations will dynamic power cables create energy emissions sufficient to represent potential stressors to commercial pelagic fisheries species.

- The timing of exposure to energy emissions will be determined by the operational characteristics of the cables and the length of time that species use the pelagic environment around dynamic power cables.
- An approach to assess the impacts of dynamic power cables on commercial fish species is proposed.
- Turbines create atmospheric wakes, and underwater structures modify currents and stratification. These changes affect primary production and support communities of filter feeders.
- Offshore wind farms (OWFs) provide stepping stones for species dispersal across unsuitable environments, benefiting both indigenous and non-indigenous species (NIS), especially benthic species with long larval pelagic phases. However, the relative influence of OWFs compared to other artificial substrates remains unclear. All NIS observations in OWFs had previously been reported from the region.
- Floating OWFs are likely to harbour non-indigenous species (NIS) and facilitate their spread through turbine transport between ports and wind farms. Evidence from similar structures supports this, but direct studies on floating OWFs are lacking.
- Impressed Current Cathodic Protection (ICCP) may enhance calcifying organism growth in biofouling communities, with potential regional variations due to environmental factors. Confidence in this effect is however low, as it lacks robust empirical support.
- Galvanic Anode Cathodic protection (GACP) may impact biofouling communities through metal toxicity effects, but confidence is low due to limited studies.
- Elevated temperatures on cooling water pipes and dynamic cables in OWFs might influence biofouling community composition and growth rates. However, evidence remains inconclusive, and further studies of this pressure is required.
- OWF sound pollution may impact biofouling organism behaviour, with variability across species. The relationship between sound and invertebrate behaviour in OWFs is poorly understood, and its ecological significance remains uncertain.
- Underwater structures can directly affect ocean dynamics by causing friction and flow obstruction. This increases turbulence, reduces current speed, and weakens water stratification up to 400 meters behind the structures. Enhanced mixing induced by OWFs may increase nutrient availability in the euphotic zone, promoting local phytoplankton production in the near-field of the structures. This effect applies primarily to fixed-bottom foundations.
- Reduced wind speeds within atmospheric wakes decrease wind-driven currents and ocean mixing, strengthening water stratification on scales up to 100 km away from the OWFs. Large wind farms create vertical circulation patterns (upwelling and downwelling). This can increase primary production around and decrease it inside wind farm areas.
- The currently planned OWF installation in the North Sea can induce changes in hydrographic conditions that might alter spatial and temporal dynamics in the marine ecosystems. In a published model scenario considering the installation of 120GW in the North Sea, local ecosystem changes could reach up to 10% not only at the OWF side but on a regional scale.

Mitigation measures Maritime Spatial Planning (MSP):

- Maritime (or Marine) Spatial Planning (MSP) provides a way to allocate areas to OWF & FLOW and other human activities, and through subordinate planning processes, instruments and supporting procedures contribute to the identification and implementation of management measures, including mitigation options.

- Multi-use and co-use approaches seek to enable co-existence between users and activities.
- Stakeholder involvement, engagement and co-design help enable development of mitigation options that are technically, economically, politically, socially and ecologically feasible, and supported, or at least accepted, by stakeholders.

ii Expert group information

Expert group name	Workshop to compile evidence on the impacts of offshore renewable energy on fisheries and marine ecosystems (WKCOMPORE)
Expert group cycle	Annual
Year cycle started	2023
Reporting year in cycle	1/1
Chairs	Katell Hamon, (Netherlands)
	Andreas Kannen (Germany)
	Jan Vanaverbeke (Belgium)
Meeting venue and dates	3-7 February 2025, Copenhagen, Denmark (83 participants)

1 Summary

1.1 Introduction to the special request from the European Commission, DGMARE

Offshore wind energy has become one of the main energy sources in Europe, helping to achieve greenhouse gas emissions reduction ambitions and to reduce the regions dependency on imported fossil fuels. In 2023, nine European countries (e.g. Belgium, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands, Norway and the United Kingdom) signed the Ostend declaration. This declaration made a commitment to achieving offshore wind capacity targets of 120 GW in 2030 and 300 GW in 2050. The intention of achieving the 2030 target requires an accelerated speed of building offshore wind farm developments approximately 6 times greater than those undertaken to date (about 13 GW/year compared to 2.2 GW/year)[1]. The importance of advancing this energy commitment, whilst balancing the ecological integrity and carrying capacity of the seas with the adoption of "*no significant harm*", requires an increased understanding of – cumulative – environmental, and socio-economic impacts of offshore wind. In the *EU Offshore Renewable Energy Strategy*[2], the EC acknowledges the need for a long-term framework that promotes a sound coexistence between offshore renewable energy installations and other uses of the sea space while contributing to the protection of the environment and biodiversity.

The workshop to compile evidence on the impacts of offshore renewable energy on fisheries and marine ecosystems (WKCOMPORE) was set in response to a request to ICES on the socio-economic impacts of Offshore Renewable Energy (ORE) on fisheries and methodologies to model (cumulative) impacts in the Celtic Sea, Greater North Sea and Baltic Sea (ICES ecoregions).

The main objective of the request to ICES is to understand better the socio-economic impacts of large-scale ORE developments on the fisheries sector. The focus of the advice is on bottom-fixed offshore wind devices but evidence from floating wind and ocean energy (tidal, wave, etc.) can be considered where necessary.

More specifically, the request aims to address the following questions:

a) Assess data and resources available for the analysis of the economic[3] and social[4] impacts of ORE developments on the fisheries sector. On that basis:
b) Summarise the known and projected economic and social impacts of existing and planned offshore renewable developments (on fisheries, at métier and fleet levels). Trade-offs between negative economic impacts on fisheries and positive economic impacts of the ORE sector should be considered.
c) Describe sources of information available, methods that may be applied, and further data and information required, to address the economic and social impacts of ORE on fishers.

[1] IEA Wind 2023, iea-wind.org/wp-content/uploads/2024/11/EC_WE_2023.pdf and WindEurope 2024 Latest wind energy data for Europe: Autumn 2024 | WindEurope

[2] EU Offshore Renewable Energy Strategy, https://ec.europa.eu/commission/presscorner/detail/en/ip_20_2096

[3] Focusing on economic impacts on fishers

[4] Identify priority impacts, but focus the assessment on employment of fishers

d) Summarize the known ecological impacts of ORE developments and their intensity (severe, medium, limited, unknown) on main commercial fish species[5] for the areas listed above and at population levels (positive and negative impacts) looking at the different phases of ORE development (survey, construction, operation, decommissioning). A specific case study on the effects on recruitment of western Baltic herring and of the effects on harbour porpoises should be developed.
e) Provide recommendations for next steps to define methodologies to model cumulative impacts of offshore wind on commercial fisheries (temporary, permanent) and the possibility to adopt mitigation measures.
f) Provide a review, based on the most recent literature, to describe how changes on hydrodynamic conditions produced by ORE may change the food availability to filter-feeders and influence phytoplankton primary production.
g) Provide a review, based on the most recent literature, of the ways artificial structures could influence the colonization of new areas by species, both indigenous and non-indigenous species. Based on data available for other structures (e.g. oil & gas), also from other locations (e.g. US), extrapolate how this colonization will affect ORE developments.
h) Provide a review, based on the most recent literature, of the ways in which pelagic species (especially commercial fish species) may react to dynamic cables suspended in the water column (floating wind).
i) List options for mitigation measures, good practices, and spatial planning for ORE developments and assess their strengths, weaknesses, implications and uncertainties. List priorities for research and monitoring related to these options.

1.2 Process to address the special request and structure of the WKCOMPORE report

The process to coordinate ICES expert group and scientist input to address these questions required organising the request into three parts, namely:

Part 1: Economic and social impacts of ORE on fisheries (questions a, b, & c of the request, ToR a.i.i and a.i.ii of WKCOMPORE)

Part 2: Cumulative impacts assessment methods of ORE and mitigation measures (questions e & i of the request and ToRs a.v.i. and a.vii of WKCOMPORE)

Part 3: Review of the ecological, hydrographic, fisheries and select species impacts of ORE developments (questions d, f, g, & h of the request and ToR a.ii, a.iii, a.iv, a.v of WKCOMPORE).

For each part, the ICES Working Groups with expertise to address each term of reference (ToR) were identified and a number of intersessional meetings and/or workshops were held to address the various questions of the request.

WKCOMPORE was established to review, merge and consolidate the work undertaken by the three sub-groups addressing each part of the request, and to compile the present report. The report is therefore organised into three major parts (as defined above), with the response to each ToR forming a major section within each part. Most of the sections addressing the ToRs start with short statements and summaries of (i) confidence in the response/ evidence, (ii). key findings/ conclusions, (iii) data gaps and research needs, and (iv) recommendations.

[5] species included in the ICES advice on list of Descriptor 3 species to support reporting by EU Member States under MSFD Article 17 (https://doi.org/10.17895/ices.advice.21332967

1.3 Terms of Reference for WKCOMPORE

WKCOMPORE met and prepared this report under the following terms of reference:

WKCOMPORE – Workshop to compile evidence on the impacts of offshore renewable energy on fisheries and marine ecosystems.

The workshop to compile evidence on the impacts of offshore renewable energy on fisheries and marine ecosystems (WKCOMPORE), chaired by Andreas Kannen (Germany), Jan Vanaverbeke (Belgium), Katell Hamon (Netherlands), will meet in Copenhagen, Denmark, 3- 7 February 2025. WKCOMPORE will use the outputs of the ICES ORE Part One, Part Two and Part Three groups[6] as the primary sources of material to address the following:

a. To review, summarise and compile evidence on the impacts of offshore renewable energy (ORE) on fisheries and marine ecosystems[7] to address the following topics (Science Plan codes: 2.1, 2.2, 2.7, 7.3):
    i. The data and resources available for the analysis of the economic and social impacts of ORE developments on the fisheries sector, and on that basis:
        i. Summarise the known and projected economic and social impacts of existing and planned offshore renewable developments (on fisheries, at métier and fleet levels). Potential trade-offs between negative economic impacts on fisheries and positive economic impacts of the ORE sector should be considered;
        ii. Summarise the sources of information available, methods that may be applied, and further data and information required, to address the economic and social impacts of ORE on fishers;
    ii. The known ecological impacts of ORE developments and their intensity (severe, medium, limited, unknown) on main commercial fish species for the areas listed above and at population levels (positive and negative impacts) looking at the different phases of ORE development (survey, construction, operation, decommissioning). A specific case study on the effects on recruitment of western Baltic herring and of the effects on harbour porpoises should be developed;
    iii. How changes on hydrodynamic conditions produced by ORE may change the food availability to filter-feeders and influence phytoplankton primary production;
    iv. The ways artificial structures could influence the colonization of new areas by species, both indigenous and non-indigenous species. Based on data available for other structures (e.g. oil & gas), and from other locations (e.g. US);
    v. The ways in which pelagic species (especially commercial fish species) may react to dynamic cables suspended in the water column (floating wind);
    vi. Recommendations for next steps to define methodologies to model cumulative impacts of offshore wind on commercial fisheries (temporary, permanent) and the possibility to adopt mitigation measures;
    vii. Options for mitigation measures, good practices, and spatial planning for ORE developments and their strengths, weaknesses, implications and uncertainties. Priorities for research and monitoring related to these options.

[6] The 'Part' groups developed expert reviews and analyses of the impacts of offshore renewable energy on fisheries and marine ecosystems in 2024 and 2025. The Part One group addressed ToR 'a' i, the Part Two group addressed ToR 'a' vi & vii, and the Part Three group addressed ToR 'a' ii, iii, iv, and v.

[7] With a focus on the Celtic Sea, Greater North Sea and Baltic Sea ecoregions.

b. To ensure, in the compilation to evidence described in ToR 'a', that the level of detail presented, data used, approaches taken, treatment of knowledge gaps and uncertainty, conclusions drawn, and references to evidence are, as far as possible, consistent.
c. To identify and report on recommendations and future work required to help address areas of uncertainty, data quality/ availability and the implementation of ORE applicable assessment methods.

1.4 Acknowledgements

WKCOMPORE would like to acknowledge the contributions of the following experts to the literature review in part 1; Samuel Arfwedson, Cecilia Axelsson, Helene Buchholzer, Gisela Costa, Richard Curtin, Geret DePiper, Sophie Leonardi, Karyn Morrissey, Bård Misund, Emily Ogier, Hans van Oostenbrugg, Lisa Pfeiffer, Steven Rust, Andrew Scheld, Olivier Thebaud, Eric Thunberg, and Xiurou Wu.

The authors acknowledge ChatGPT was utilised while writing the summary page (3.4.1-4). All other chapters were written solely by the authors.

2 PART 1

Economic and social impacts of ORE on fisheries

This section addresses WKCOMPORE ToRs a.i and a.i.ii (see Section 1.3) that provide the scientific basis to answer request questions a), b) and c) (see Section 1.1):

a) Assess data and resources available for the analysis of the economic and social impacts of ORE developments on the fisheries sector and on that basis.

b) Summarise the known and projected economic impacts of existing and planned offshore renewable developments (on fisheries, at metier and fleet levels)

c) Describe sources of information available, methods that may be applied, and further data and information required, to address the social impacts of ORE on fishers.

2.1 ToR a.i.i. Summarise the known and projected economic and social impacts of existing and planned offshore renewable developments (on fisheries, at métier and fleet levels). Trade-offs between negative economic impacts on fisheries and positive economic impacts of the ORE sector should be considered.

2.1.1 Confidence in the evidence and assessment

Assessing the socioeconomic impacts of ORE on fisheries is challenging because of the interconnectedness of the fishery system components and drivers of change (see figures 2.1 and 2.2). To date not a lot of research has been done on impacts of ORE on fisheries (N=139, of which 47 were empirical studies and kept for analysis). From these, 12 impacts were identified, 5 direct and 7 indirect, most of them resulting in a deterioration of the situation for fisheries. Full details of literature review are available in section 2.3.

Changes in the productivity of fishing might result from changes in fish resources (which will be difficult to track, given that both traditional data collection methods will change, and that ORE infrastructure may affect fish resources) and from changes in fishing practices in response to the constraints imposed on fishing activities by ORE exploitation. These changes may affect both the costs and the earnings of fishing, leading to changes in profits and wages in the fishing industry. Additional costs may also be incurred by fishing companies, such as higher insurance costs for fishing in/close to ORE areas. The changes will have downstream effects on the supply chain, including first sale of fish and processing industry.

Additional resources will be required to survey the fishing sector directly to better understand how fishing operations are impacted, leading to changes in fishing practices and/or fishing location, and the associated changes in costs, landings and revenues. Additional information will also be required on how fishery responses are managed at local and regional levels (e.g. what access regulations favour or hamper adaptation), as well as on the fisheries monitoring, evaluation and management costs, changes in local infrastructure (e.g., processing plants) and port competition. Risks associated to changed fishing practices, as well as health impacts, and cultural impacts in coastal communities should also be better understood.

2.1.2 Key findings and conclusions

- The context of the ORE development is crucial to understanding the expected social and economic impacts of ORE on fisheries. Context elements include the type of ORE, the operational phase (survey, construction, operation or decommissioning), the rules and regulations set on fisheries in the ORE as well as outside the ORE areas, the type of access to fishing (access to specific gears, access to navigate through, or no access) and the historical fishing activities. Also, fisheries are diverse and will thus be impacted differently (i.e. LSF vs. SSF, but also polyvalent vs specialists).
- The ORE context directly affects the fisher's response to ORE development (ranging from continuing fishing as before to having to adapt by displacing their activity or changing their gear, all the way to exiting the fishery) with subsequent economic, social and cultural impacts. A review of existing studies shows that these direct effects are usually negative, regarding income, access to fishing grounds, and catch opportunities, as well as operating costs.

- For a complete understanding of the economic and social impacts, direct and indirect effects must also be included in the assessment. Those include 1) ORE development's impacts on the ecological system that can affect the commercial fish stocks and their availability to fisheries (negatively or positively), 2) further effects on land from the very local to international - ranging from ancillary activities to the value chain and 3) cumulative effects of different ORE development plans adding up to other spatial restrictions, climate change and policy and market changes.
- Building ORE infrastructure at scale introduces a large number of changes to our seas that impact the socio-ecological system at different temporal (short-vs long-term) and spatial (locally or regionalized) scales, implying a need for trade-off analyses to account for such dynamic developments.
- There is a strong need for increased monitoring and research efforts dedicated to measuring the economic and social impacts of ORE on fisheries, linking these to changes in the spatial structure of fisheries and underlying fish resources and to the multiple effects on land (markets and communities). Such monitoring and research is a prerequisite to robust assessments supporting advice in this area.

2.1.3 Data gaps and research needs

Key data gaps and research needs identified can be classified according to the scale of processes considered as key to determining the economic and social impacts of ORE on fisheries. Other data gaps and gaps in knowledge are addressed in section 2.2. and section 2.3.

At the level of fishing operations:

- Fine-scale fisheries operation characterization, including studies on fishing behavioural changes in response to the presence of ORE infrastructure for various project designs;
- Research on gear compatibility and modification studies;
- Risk to safety assessments (collision risks, radar interference, gear/cable interactions, ...).

Intra-annual (short-term):

- Evaluations of the impacts of ORE-related spatial restrictions on fishing on the spatial and temporal patterns of fishing activities, catches and landings
- Evaluation of the short-term indirect effects of ORE developments resulting from these spatio-temporal impacts and from the responses of the social-ecological system (conflicts with other uses, short-term ecosystem responses such as local resource depletion, interactions with other spatial constraints on fishing).

Inter-annual (medium-term):

- Evaluation of the medium-term indirect effects of ORE developments (conflicts with other uses, medium-term ecosystem responses such as changes in the productivity and spatial structure of fish resources, interactions with other spatial constraints on fishing), at both local (single ORE development) and regional (multiple ORE developments) scales;
- Site-choice models to improve siting of ORE and mitigate the consequences of displacing/changing fishing possibilities;
- Port-level analysis of economic impacts (competition for port space, number of and geographic range of processors, ice houses, etc.);
- Evaluations of the medium-term impacts of changed fisheries for the downstream supply chains;

- Analysis of net economic outcomes for coastal communities (i.e., number of ORE jobs created versus jobs lost in other sectors) for the lifetime of an ORE project;
- Evaluations of the impacts on fisher, community and societal wellbeing.

The above data and research needs should be addressed through the implementation of dedicated, standardized and repeated surveys of the fishing sector and other industry and coastal stakeholders. It is important to establish baselines for the current / recent situations of fisheries systems with respect to the areas in which ORE are expected to develop, from an economic, social and cultural perspective. This is particularly important with respect to small-scale fisheries which are likely to be strongly impacted.

2.1.4 Recommendations

The following recommendations were made by WKCOMPORE regarding this section:

- Work collaboratively with the fishing sector to develop and implement data collection systems to improve understanding of changes in fishing behaviour, operations, costs, and overall well-being
- Continue supporting efforts to bridge this information with spatially resolved data on fishing activities (effort, catches and landings), so as to be able to connect observed changes in the economic and social status of fishery systems with changes in the spatial structure of fishing activities. This can be done at the interface of work regarding ORE and other spatial management questions.
- Support the development of tools for integrated scenario analysis to inform decisions regarding the future development of ORE in European seas, allowing for the full consideration of social, economic and cultural consequences for the fishing sector.
- Assess the need for establishing vessel passage corridors in areas where wind farms are installed, as reaching fishing zones often requires navigating large areas, making access distant and costly.

2.1.5 Social and economic impacts of ORE on fisheries are context specific

The context of the ORE development, and how fishers respond is crucial to understanding the expected social and economic impacts of ORE on fisheries. Context elements of ORE include the type of ORE (floating or fixed), the operational phase (survey, construction, operation or decommissioning), the rules and regulations set on fisheries in and outside the ORE areas and the type of access for fishers (access to specific gears, access to navigate through, or no access) (see Figure 2.1). Those elements determine how fishers can respond and from that how they can be impacted directly and indirectly.

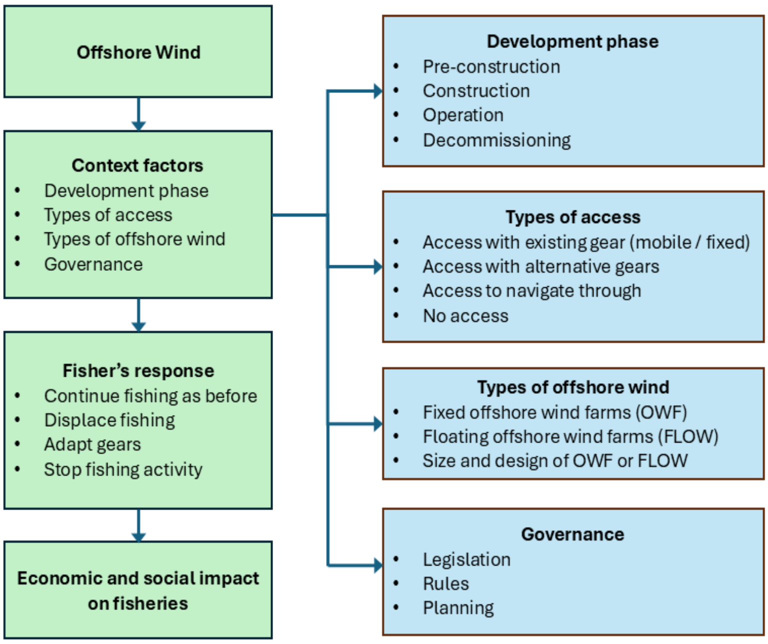

Figure 2.1: Factors determining the social and economic impact of ORE on fisheries

Different contextual factors result in different impact for fishers

First of all, fisheries access can vary with stages of construction. Temporary exclusions may occur during various pre-construction surveys and installation of turbines (e.g., 500m safety buffer).

Secondly, regulatory access to ORE sites during the operational phase varies by country; the UK and the USA allow full access to operate fishing gear within an offshore wind array while the Netherlands, for example, currently only allows experimental fishing commissioned by the government. These rules on access define whether fishers are able to fish within, or navigate through, the site or not. If fishers are still allowed to fish there, there might be no or only very low direct impact of ORE on fisheries. However, there are safety concerns for bottom towed gear even if their use is allowed within an array because of the risk of gear getting caught on a turbine or cable. Fishers may choose not to fish within an array under poor weather conditions or if they have less experienced crew onboard. If they are not allowed to fish in the ORE site, there will be direct economic impacts of reduced catches which typically were caught in that site. In some cases, fishers might still be able to navigate through the ORE site. If this is not allowed or conditions do not allow safe transit, they will also face extra costs to navigate around the ORE site. For fisheries managed using effort controls, this may decrease time spent fishing to compensate for increased transit time back to port.

Thirdly, the types of ORE and project design will matter. Floating or fixed turbines present different challenges to fishing – anchor lines versus scour protection. Distance between turbines and whether cables are buried may determine whether a vessel can tow gear within the array.

Fourthly, the process of designating space for ORE is organized in different ways, affecting the impact on fishers in positive or negative ways. The involvement of fishers in the spatial planning of ORE can vary by country. In the USA, a suitability model was developed to identify areas with minimal conflicts for consideration of offshore wind energy development (NCCOS 2025). However, the fishing industry continues to be concerned over the impacts of offshore wind on their operations and safety.

And lastly, it is important to consider impacts of specific ORE sites to be assessed in a context of other spatial users, management measures and ecological changes. Fishers will continue to face the pressure off ongoing and new spatial constraints from ORE resulting in cumulative social and economic impacts that may strain the industry (ABPmer, 2022).

These complex interlinkages are also reflected in Figure 2.2. As part of an Integrated Ecosystem Assessment, fishing industry members refined a conceptual model based on public comment about offshore wind development in the Gulf of Maine (FishFlOW 2025).

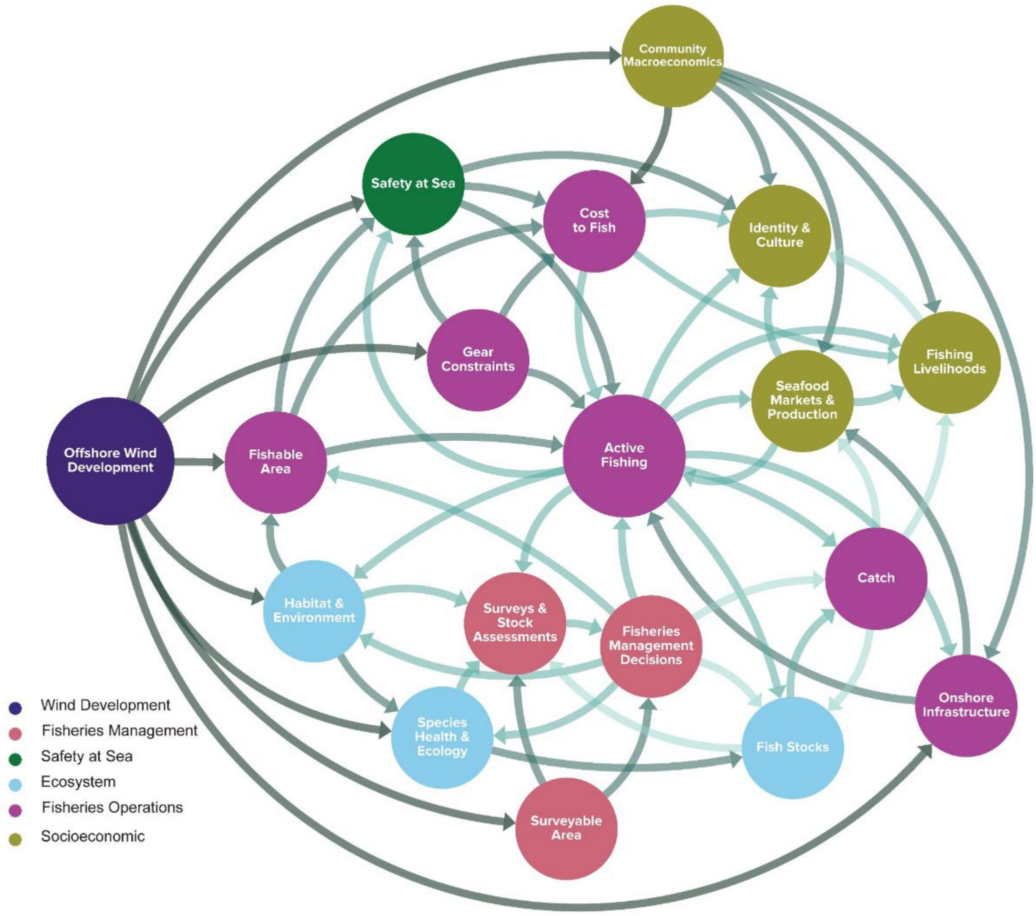

Figure 2.2: Simplified conceptual model of the interactions of offshore wind with fish and fisheries developed based on public comment from the fishing industry as part of an Integrated Ecosystem Assessment (ICES, 2021)

Responses of fishers depend on context and determine impact

Possible responses of fishers are:

- continuing as before (co-existence/co-location),
- continuing fishing, but being displaced (displacement with/without access to navigating through),
- continuing fishing but adapting their gear, (Gear adaptation) or,
- stopping fishing.

The choices fishers make depends on the context of ORE (see Figure 2.1), their own circumstances (licenses, generational renewal, financial resources, type of vessel, vessel size, knowledge) and on other developments (policy changes, market prices, other closures etc.).

Opportunities for co-existence or co-location or multi use as it also is called sometimes are often limited. it is argued by industry as well as in published literature that some fisheries might be more likely to co-locate (e.g. static gear) than others (e.g. mobile gear). Often fishers need to adapt their fishing practice to be able to continue fishing in the area. The cost of adapting to continuously fishing in the ORE area also depends on the layout and orientation of the wind turbines, whether clear corridors are made for fisheries and cables are appropriately mapped and these maps are kept up-to-date, or even appropriate cable protection measures (e.g. mats) used to avoid damages and collisions for both sectors. It thus does not only require adaptation of fishers, but also the ORE sector (ABPmer and MRAG 2023). It was highlighted in previous studies that for continuing fishing in the area, insurance costs and the process to get insurance and permit for the fishing activity can be costly and therefore limit the potential of co-location/co-existence (Marsh et al. 2022).

Thus, the main impact is that most fishers will need to adapt to where or how they fish, which has social and economic consequences.

2.1.6 Research on interactions between ORE and fisheries

A systematic literature review was conducted by the ICES working groups WGECON and WGSOCIAL as intersessional work for part 1, to better understand which direct impacts of ORE on fisheries have been described so far.

Using search terms such as "fisheries", "offshore renewable energy", "economic" and "social impact" (in various forms – see detail in Section 2.3, literature review,), about 1,200 publications were initially identified as potentially relevant. However, after screening the title and abstract, only 139 publications remained which focused on the interaction of commercial fisheries and ORE from a social or economic viewpoint. The full texts of the 139 publications were further analysed and 47 publications were identified which were used for detailed analysis.

The publications reviewed primarily analyse the fishery impacts of ORE in Europe (27 publications) and North America (13 publications), with only few studies representing other continents. With respect to marine ecoregions studied, 20 publications include case studies from the Greater North Sea area, 20 publications describe case studies outside the ICES ecoregions, and 16 publications focus on case studies in the Celtic Seas. Turning to fisheries analysed in the literature, Figure 2.3(a) shows that the most common gear type analysed is static gears followed by bottom towed gears and pelagic towed gears. Thus, the data represents several broad categories of gears. With regards to species groups, Figure 2.3(b) shows the impact of ORE on shellfish fisheries is by far the most analysed species group with about 50% of the ORE analyses. Note that approximately 25% of the publications did not analyse a specific gear type but rather summarized the local fisheries and do not specify further the type of gear or target species.

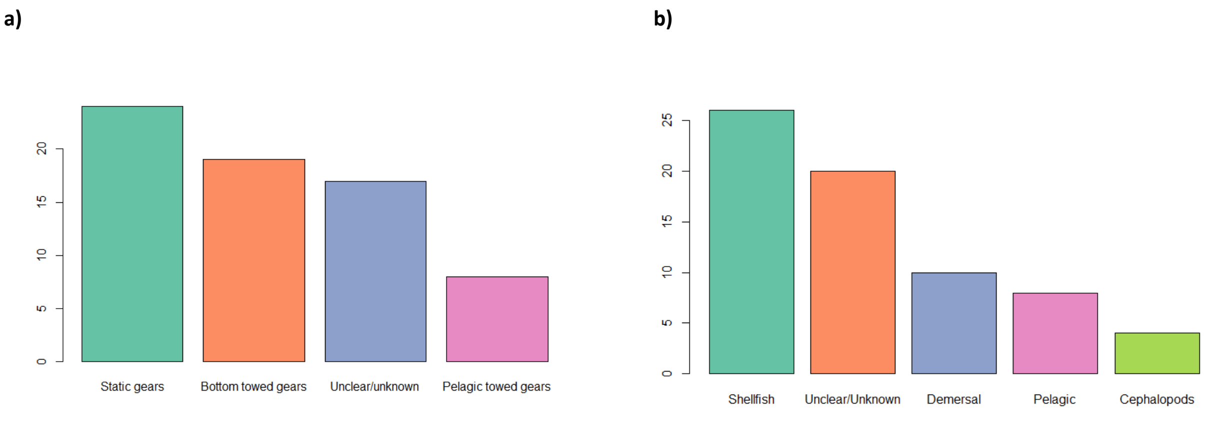

Figure 2.3: a) Fishing gear and b) target species group analyzed empirically in the literature (see section 2.3 for detail)

Most of the papers study fixed offshore windfarms (14) only, while 4 papers study the impact of floating windfarms on fisheries. Most papers (20), however, do not specify further what type of windfarm was considered, while 5 study the impact of fixed and floating offshore wind simultaneously. Moreover, most of the published impacts (21) were described at the planning stage, with 5 papers focusing on the impact of ORE on fisheries in the operating phase of the ORE, and 18 papers describing impacts of ORE on fisheries in multiple phases of the ORE life cycle. Notably, there are no papers with a clear focus on the decommissioning of the constructions.

2.1.7 Evidence of ORE impacts on fisheries

Direct impacts

Direct impacts on fisheries depend on the location (i.e., level of overlap with important fishing grounds) and type of ORE development and regulations dictating fisheries access (see Figure 2.1) and of the subsequent response of fishers.

Evidence from the systematic literature review shows that five direct impacts have been described thus far: impacts on income, changes to fishing grounds, catch opportunities, fishing operation costs and investment into technical gear adaptation measures (Figure 2.4). It was considered whether these were described to have to improved, remained neutral or deteriorated, to understand the direction of the impact of ORE on fisheries.

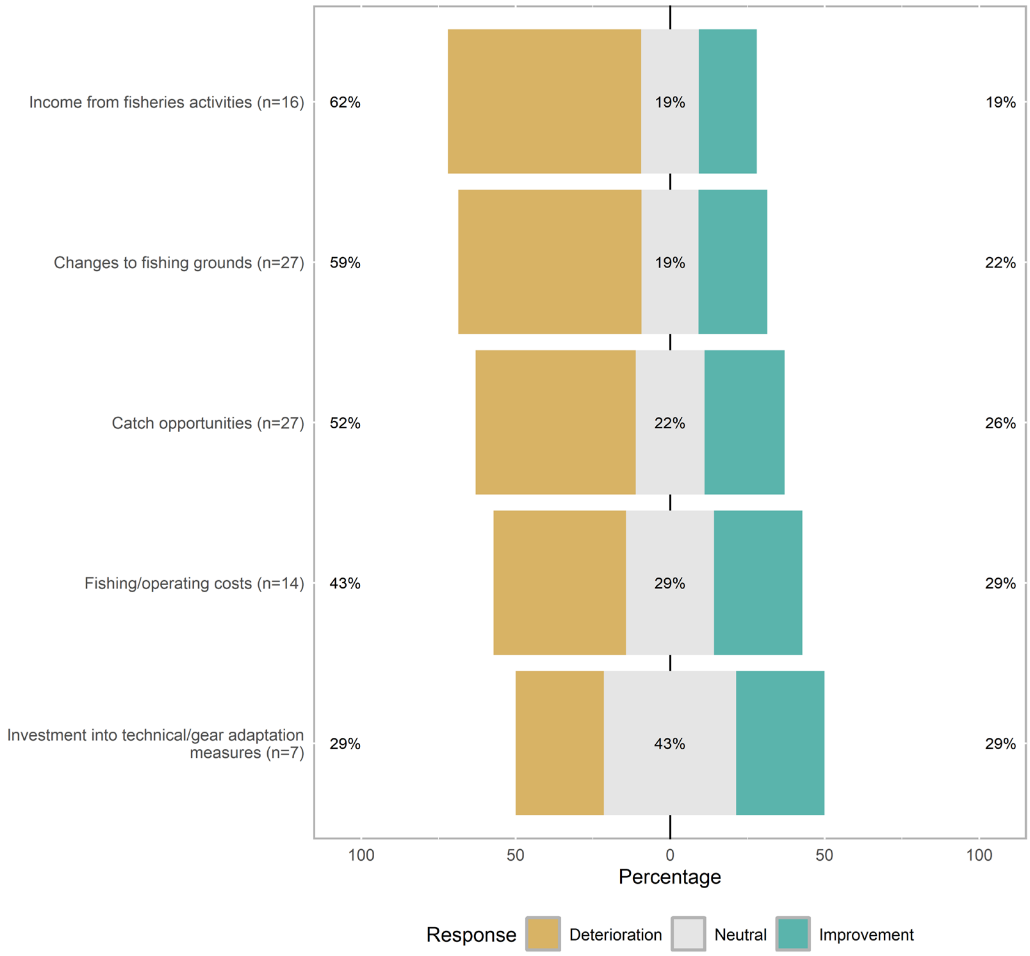

Figure 2.4: Identified direct impacts of ORE on fisheries in the literature. The distribution for each dimension is presented with "n" representing the number of studies analysing each of the dimensions, and whether the reported impact was an improvement, a deterioration or a neutral impact of ORE on fisheries.

As shown in the figure, there is a clear trend that the papers categorize most direct effects as deteriorating for the fishery, with income, access to fishing grounds, and catch opportunities being the dimensions with the highest shares of papers finding deterioration. Notably, these topics are commonly analysed in the literature with e.g. catch opportunities being analysed in 27 of the 47 papers. Since a large share of studies concern static gears, which is the gear type potentially having access to ORE areas, the negative impact found is interesting to highlight.

Indirect impacts

Indirect impacts of ORE on fisheries are not well understood. Changes to target species as a result of an ORE site can occur, for instance if an ORE site is built on nursery grounds stocks can be negatively affected, or ORE sites can function as *de facto* MPA's (if no fishing is allowed) resulting in possible positive effects on some species, potentially resulting in spillover effects (see section 3.2-3.5, ToR a-ii to a-v for the ecological impact of ORE). The ability to detect these changes may be challenging if traditional survey gear can no longer be safely deployed within an array, which can affect stock assessments and fisheries management (Hogan et al. 2023). Changes in fishing effort patterns alter fishery dependent data used in stock assessments, potentially further exacerbating impacts to management. The uncertainty of the long-term effects on fish species can contribute to the degradation of mental health of fishers.

Social and Cultural impacts

As seen above much of the evidenced direct impacts are economical. But it is important to consider that impacts can also be social or cultural. In the ICES workshop WKSEIOWFC (ICES, 2021) participants brainstormed potential cultural impacts of ORE on fisheries by mapping with Mental modeller software showing cause-effect relationships (Figure 2.5). The visual summary demonstrates the multiple factors involved and how many are interdependent. Potential indirect impacts include knock on effects on coastal communities affecting social cohesion, wellbeing and identity, depending on the reliance of communities and wider industries on fisheries. From a social perspective, any social or economic assessment of ORE impacts on the fisheries sector needs to also address the impacts on fishing communities associated with the effected fisheries. As fisheries social scientists would argue that fisheries communities are dependent on and in need of healthy fishing stocks, but vice versa that healthy fishing stocks are contingent upon the presence of healthy fisheries communities (Jentoft 2020).

Resilience and willingness to adapt as well as social capital are all aspects that play a role when assessing cultural impacts of ORE on fisheries (ICES, 2021).

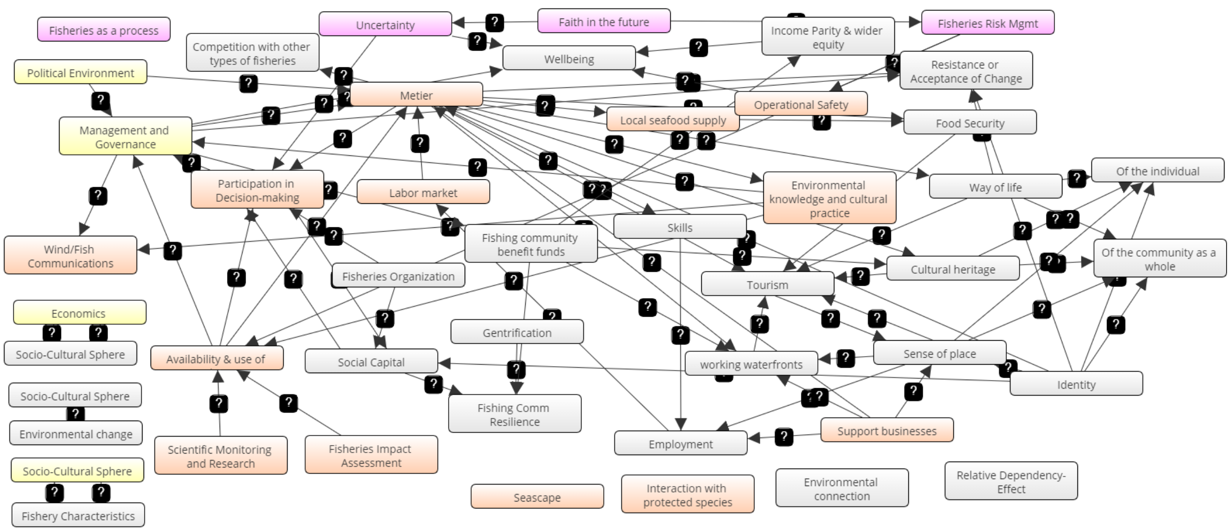

Figure 2.5: Cause effect maps describing interrelationships between changes in fishing behaviour, OWF developments and cultural impacts (Source: ICES 2021)

2.1.8 Trade-offs between negative economic impacts on fisheries and positive economic benefits provided by the ORE sector

To date there have been no studies done to evaluate the trade-offs between the negative economic impacts on fisheries and positive economic benefits generated by the ORE sector. Work has been done on how to perform a trade-off assessment in relation to ORE in the recent ICES workshop WKWIND. The workshop is aligned with ICES' Roadmap for Offshore Renewable Energy, and it focuses on developing guidelines to assess trade-offs between ORE developments and other sectors. For this purpose, a framework was developed, making use of the Social-Ecological Systems (SES) approach (McGinnis & Ostrom, 2014; Ostrom, 2007) to set system boundaries and to identify key elements like governance, stakeholders, and resources, along with their interactions (WKWIND; ICES, 2025).

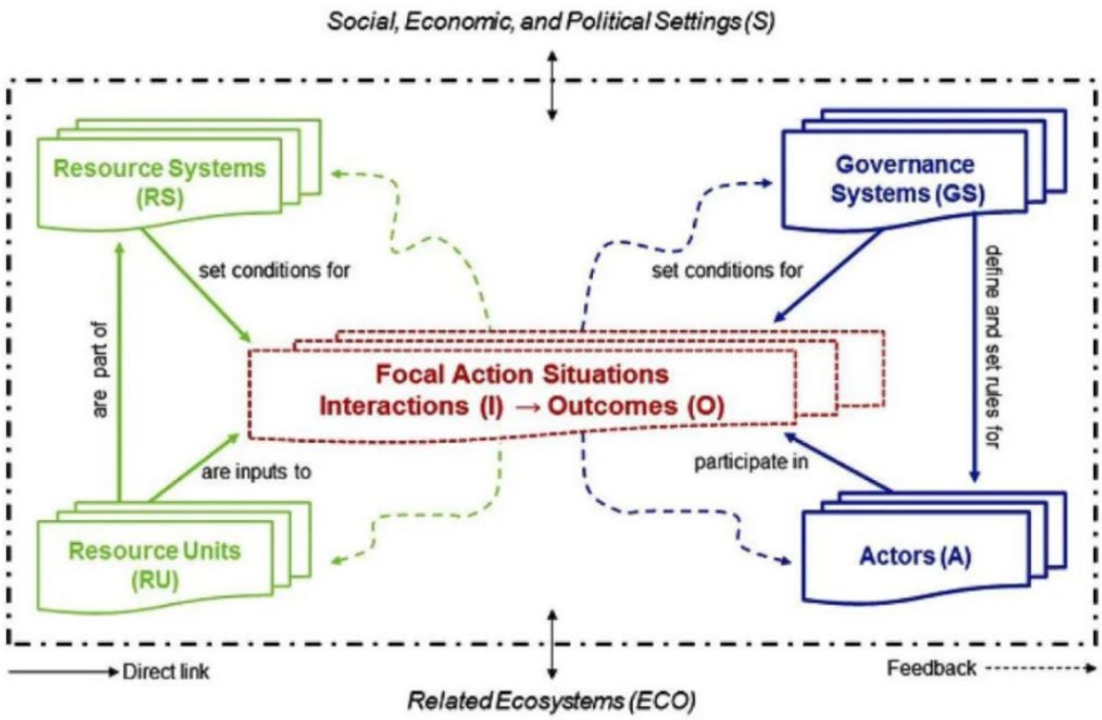

Figure 2.6: Conceptualization of the Social-Ecological Systems Framework (Source: McGinnis & Ostrom, 2014)

The framework identifies the following elements: first- order and higher order effects, cumulative effects, transboundary considerations, life cycle aspects, vulnerability and risk and opportunity (see table 2.1).

Table 2.1 Elements in the framework for trade off assessments (Source: WKWIND; ICES, 2025)

Elements in the framework for trade off assessment	Explanation
First-order and higher-order effects	*First order effects are immediate, short-term effects, easier to assess: i.e. for fisheries: immediate reduction in fishing activity affecting catches in the concerned area. *Higher-order effects are wider changes, medium- long term, operating over ecological time scales and often result from cumulative effects.: i.e. for fisheries: effects of displacement.
Cumulative effects	Cumulative effects stem from the specific restrictions to space in combination with other impacts (other ORE projects, MPAs, etc.) which constrain adaptation.
Transboundary considerations	ORE development but also fisheries and ecosystems function at scales that transcend national and regional boundaries (i.e. global investors in ORE, ecosystems components).
Life cycle aspects	ORE projects should be assessed as a whole, covering the different effects that will occur as the life cycle of the projects develop (from pre/construction via operation to decommissioning). Each phase will have different impacts on the ecosystem and other sectors.
Vulnerability	Certain regions hold critical ecological, economic, and social significance. Constructing offshore renewable energy (ORE) infrastructure in ecologically sensitive zones—such as fish spawning grounds or habitats supporting protected, threatened, or endangered species—could result in severe or irreversible harm to biodiversity. Similarly, limiting access to key fishing zones, especially in areas lacking alternative grounds, may disproportionately impact fisheries-dependent communities. To mitigate these risks, trade-off evaluations must prioritize identifying ecologically, economically, or socially sensitive regions during planning stages. This proactive approach ensures informed decision-making, minimizing the potential for irreversible environmental degradation or socio-economic disruption.
Risk and opportunity	ORE development will induce permanent (or quasi-permanent) changes in marine ecosystems and the associated social and economic systems at different levels. These effects are difficult to predict and assess, because they are related to future conditions which cannot be fully anticipated in the present. Consequently, trade-off assessment should incorporate an uncertainty dimension to account for this component.

2.2 ToR a.i.ii. Summarise the sources of information available, methods that may be applied, and further data and information required, to address the economic and social impacts of ORE on fishers

This section presents a non-exhaustive account of the accessible sources of data (EU DCF, ICES and other datacalls) that could be used for the assessment of the social and economic impacts of ORE on European fisheries. A deeper analysis of these data will be required to determine if aggregation levels will fit the specific purposes of the impacts assessment and required spatial and temporal scales. The data needed will depend on the methods and research design, both of which will determine the information, data needs and availability.

Section 2.2.8 introduces the key research designs, data and methodological approaches that are currently been used in the social science literature. Assessing the social and economic impacts of offshore renewable energy (ORE) on fisheries requires a multifaceted approach that integrates a variety of research designs, data types and sources, and methodological approaches.

We split the data available for analysis of social and economic impact of ORE on fisheries in five broad categories:

i. Fisheries spatial data
ii. Fisheries catch and effort data
iii. Fisheries economic data
iv. Fisheries social data
v. Offshore renewable energy developments data

For each of the categories, we describe the data currently available, and the challenges associated with the current data. Fisheries commercial activity dependent data collection is legally requested and coordinated by European Data Collection Framework or national Data Collection Frameworks (e.g. UK https://www.gov.uk/guidance/data-collection-framework). These Data Collection Frameworks provide legal data provision requirements, coordinate and standardize the data required from industrial fisheries activities (section 2.2.6). In addition to these data sources, there is also ad hoc social data collection (see section 2.2.6.4).

2.2.1 Fishing vessel spatial data

Fishing vessel positional data provides information on fishing vessel position and time. The sources of Vessel Positional data (VPD) are the VMS for Large Scale Fisheries (>12 m loa), iVMS for Small Scale Fisheries and AIS data.

VMS – inshore-VMS (local regulations)

VMS data generally includes information on GPS position, vessel speed and bearing. Limitations of VMS data include the temporal resolution of data (can be 1 -2 hours between pings) VMS data is used for vessel monitoring control and surveillance purposes. All fishing vessels above 12 meters of length (above 15 meters length until 2012) provide geographical position data via satellite to a central receiving station every two hours. The VMS data contain, in addition to the position information (longitude and latitude), the direction and speed of the vessel at the time of data transmission. However, the VMS data do not contain any information about the activity (e.g., fishing or steaming) at the time of the report. (WKSSFGEO2, 2023).

AIS

Automatic Identification System (AIS) contains similar information as VMS but has a higher frequency (1-2 seconds). Its main purpose is to prevent collisions between vessels. Due to the high temporal resolution, it is suitable for analysing fishing operation in detail (e.g. length of gill nets) or areal use in dendritic landscapes like the Wadden Sea. Though AIS is mandatory for vessels above 15 m, not all areas are covered since a terrestrial receiver is needed within range to store AIS data (except for satellite AIS). For more information, see WGSFD report (ICES, 2022).

Use and limitations

To run a spatial analysis of fishing activities, spatial data such as VMS and AIS are necessary. While both VMS and AIS have limitations in the coverage of the fleets (VMS is for vessels >12m, AIS data can be patchy if transmitter is set to low), they usually allow for fine analysis of the fishing activity when available. Due to the frequency of the pings, AIS is deemed more suitable for smaller areas while VMS is sufficient for larger areas (ideally a vessel should not have the time to go from one side of an area to the other between two consecutive pings without a single ping falling in the area).

The main limitation for use of VMS data is that they are held at National levels and that raw data cannot be made publicly available for confidentiality reasons. As a result, analysis done at international level requires a specific datacall, following a standardized script. Examples are shown in section 2.2.7 (ICES VMS and logbook datacall) and section 2.5 (GNSBI). Only aggregated datasets are publicly available.

2.2.2 Fisheries catch and effort data

Fisheries catch and effort data are collected in the form of logbook. In addition to the information collected in the logbook, prices based on sales notes are used to calculate the value of the catch and additional vessel characteristics are added.

Fishing logbooks provide catch data. These only have to be filled in by vessels longer than 10 meters, or longer than 8 meters in most parts of the Baltic Sea. In the logbooks, some gear information is specified, including mesh size and selection devices. The implementation is different among EU MS (and gear types), in some cases the logbook needs to be specified by haul, in others by day and main ICES rectangle.

Logbook data contains some spatial information on fishing activity, such as ICES rectangle and the start/stop position of hauls. Unlike spatial information from VMS and AIS data, the registration of rectangle and start/stop times/positions requires manual input from the fishers and might be gear specific.

Similarly to vessel positional vessels, logbook raw data cannot be made publicly available for confidentiality reasons. Aggregated datasets are available on STECF website (see section 2.2.6), official fisheries dependant data calls), and in ICES RDBES database (see section 2.2.7). However, neither database is fully available for research and access to a full data set is constrained to an approval procedure by the different countries for every single request. This can lead to delays in access to the data and, in the worst cases, denial of access.

2.2.3 Fisheries economic data

Openly available economic data for fisheries is collected annually by EU Member States (MS) and published in the STECF Annual Economic Report (AER; https://stecf.ec.europa.eu/data-dissemination_en) by country, fleet segment, supra region, vessel length and main gear used (see section 2.2.6.4, annual economic reports). While robust at fleet level, this revenue and cost data is difficult to match with spatial data for the placement of ORE. While the exact location of a specific ORE construction is known in detail, fishing revenues and costs for that location are not. To match the resolution of cost and revenue data with ORE locations it is necessary to disaggregate the data.

The WGECON (ICES, 2021) discusses several approaches to disaggregate economic data to lower dimensions or allocate them to specific regions. An example highlighted is the STECF AER approach using effort or value of landings to allocate aggregate costs to different sea regions. While this approach is easy to implement, WGECON points out that "Allocation of costs to fishing regions using effort and revenues (value of landings) from different ICES areas might shift profit towards regions will lower effort and higher value of landings, while in reality the cost structure of fishing fleets in both regions is different." The WKTRADE4 provides details on how the AER data could be combined with fisheries dependent information (FDI) to create economic indicators at a finer geographical scale. The WKTRADE4 report states that following their stepwise data matching "GVA (Gross Value Added) and Gross profit calculated from the AER data could be disaggregated out on finer spatial scale (to the ICES 0.05 degree c-square grid) and fishing effort by métier (EU DCF level 6).". The WKTRADE4 agreed that the most appropriate variables for spatial analyses are GVA and Gross profit. However, these indicators could be complemented in several ways depending on the topic of interest and data availability.

If detailed catch data is available (e.g. at member state level) revenues can be calculated based on available catch data from the ORE area combined with sales notes or average prices per species provided by e.g. the European Market Observatory for fisheries and aquaculture products (EUMOFA; www.eumofa.eu). The capacity to attribute catches at scales at which ORE areas are designated remains a challenge in many cases. Fishing cost items are also difficult to match with actual fishing in a small area since data is usually only available aggregated by fleet segment, and for many cost components, at an annual scale.

Focusing on the broader impacts of ORE on fishing regions or fishing communities, an observation is that the economic data in the AER (as well as landing and effort data) is not reported by port but is aggregated by DCF fleet segment, by species or by FAO area. To allocate economic activities such as landings to ports these must be requested from member states directly or extracted/requested from the Regional Data Bases (RDBs) (WGECON, 2021). The WGECON report points out that "Identification of the ports of landings/first sales markets could also open another way to explore economy of fishing fleet though money flows to specific terrestrial regions within countries." When analyzing the economic importance of local and regional fishing concepts such as multiplier effects are of importance to show how the fishing sector affects other sectors in the economy such as the processing industry. Multipliers for fisheries are generally not available but could be calculated using Input-Output tables.

2.2.4 Fisheries social data: (indicators, profiles and mapping fishing communities)

In accordance with Regulation No 2017/1004, the EU multiannual program for the collection of fisheries and aquaculture data introduced the collection of social variables for the EU fishing fleet under the Data Collection Framework. Since then, 5 variables are collected in all EU member states: nr fishers by fleet, nationality, age, education, and gender. The STECF Expert Working Group on social data have discussed the collection of more social variables for several years. In 2024 it was decided that 12 new social indicators were to be collected.

The new social indicators are:

1. Financial position: compare average net income (self-employed / employee) with national averages
2. Nr of fishers in trade unions per fishing fleet
3. Working conditions: minimum crew required per vessel

4. Working conditions: mandatory safety training
5. Working conditions: time away from home (DAS)
6. Working conditions: time away from home (nr of trips)
7. Working conditions: financial security: average wage in comparison with national minimum wage
8. % of sea allocated to other uses
9. Level of professionalization: nr of years working as fisher
10. Nr of people entering the fishing industry – Nr of people enrolled and graduated in mandatory safety training
11. Nr of people entering the fishing industry – Nr of people enrolled and graduated in fisheries vocational training
12. Nr of people entering the fishing industry – Nr of new entrants in the vessel register

These are expected to be available from 2025 onwards. The STECF EWG will report on these by the end of 2025 in a separate Annual Social Report (comparable to the AER). It will also make use of the recently developed variables.

There are also National Fisheries Profiles (14 currently under review) and the first Community Profiles (approximately 6 developed in France and the Netherlands). The community profiles will be further piloted the next couple of years, thus are not widely available as of yet. The two profiles provide important sources of data that are collected at country (MS) and community levels.

The national fisheries profiles can be a useful tool as they will provide a brief description of some salient social, institutional and legal elements for MS, can help interpret collected social data, allow to compare fisheries sectors among MS, allow for analyses of the respective fisheries for trends as well as for change, and serve as a background document for a Social Impact Analysis (SIA) of fisheries (STECF 2023).

Ports as proxies for fishing communities

In 2019, ICES WGSOCIAL together with WGECON started to map fishing communities by making use of landing ports as proxy. The method developed was first applied in the Celtic Seas and North Sea Ecosystem Overviews. Using fishing ports as proxies, this method links socio-economic indicators (e.g., landings value) to communities, and once identified other social, demographic and economic indicators can be developed that help understand the importance of fishing for society. Identification of the fishing communities helps understand the economic flows to specific coastal regions within countries. In addition, the data could be also used to estimate the dependency on specific commercial stocks and the vulnerability of fishing communities in different regions (e.g. hake in Celeiro or swordfish in A Guarda, both in Galicia, NW Spain). This methodology could be further elaborated and tested by ICES. While landing ports are used as a proxy for fishing communities, they do not capture their full meaning and have a number of limitations. in some fisheries, landing sites are not places where the fleet is registered or is “at home” (e.g. the Swedish pelagic fisheries landing in Skagen port in Denmark). A further limitation of the methodology is that the data used comes from the (RDB(ES)) with Logbook data and VMS, which does not portray the small scale fleets accurately as logbooks are not mandatory for vessels under 10 meters in length, and VMS was not required for vessels under 12 meters in length (CEC, 2009), yet landings by small-scale fisheries, can play a pivotal role in the economic and social pillars of fisheries communities. The interpretation of the data requires understanding that fishing ports with small or sporadic landings volumes may in fact hold substantial contributions to the viability of geographically isolated fishing communities with long-standing traditions and cultural heritage.

2.2.5 Offshore renewable energy developments data

Understanding the extent, nature, precise location and stage (pre-construction, development, operation and decommissioning phases) of offshore renewable energy developments is essential in order to effectively assess the impacts and trade-offs of ORE on other marine resources and users in the marine environment. There are essentially two principal sources of accessible data to the public, beyond detailed information held by national planning authorities. The most up-to-date and accurate information is commercially available from an energy data company called TGS which hosts the 4C offshore database platform (4coffshore.com), which includes data on all stages of windfarm developments including cable and seabed infrastructure types and locations. However, one of the most accessible and freely available sources of information and data on offshore windfarm developments can be obtained from the European Marine Observation and data network (EMODnet), by accessing the European Atlas of the Seas (ec.europa.eu). The EMODnet 'human activities' data layer has polygons depicting windfarm developments at different stage of planning and operations. For example, Figure 2.7 shows polygon data for windfarm locations which are categorised as either; (i) approved sites, (ii) decommissioned, (iii) planned, (iv) operational, (vii) test sites and, (viii) under construction. It can be clearly seen from Figure 2.7 that the greatest number and spatial extent of windfarm sites are at the planning stage (grey polygons), followed by sites that have been approved (blue polygons), sites which are operational (orange polygons) and finally sites which are under construction (red polygons).

Figure 2.7. Map of offshore windfarm developments at different phases of planning and development. Grey polygons are planned sites, blue are approved, orange are operational and red are under construction. Image captured from EMODnet European Atlas of the Seas GIS data viewer (ec.europa.eu).

2.2.6 EU Fisheries data collection

2.2.6.1 EU Data Collection Framework Regulation

The Data Collection Framework Regulation[8] sets out the basic principles and the general rules on the collection, management and use of data, in line with the CFP. It contains provisions on:

- the multiannual European Union programme and its implementation by Member States,
- the communication between the Commission and Member States through the national correspondents,
- the role of regional coordination groups,
- the storage and sharing of data and
- the support of scientific advice.

Fisheries commercial activity dependent data collection is legally requested and coordinated by European Data Collection Framework or national Data Collection Frameworks (e.g. UK https://www.gov.uk/guidance/data-collection-framework). These Data Collection Frameworks provide legal data provision requirements, coordinate and standardize the data required from industrial fisheries activities.

The data required by these Data Collection Frameworks is coordinated by national Fisheries Control Agencies and are available for multiple reporting obligations. The data reporting obligations are established by official organizations that required this information through official international datacalls. The data submitted is used for advice provision, for management based on scientific evidence, or implement management measures in these industrial fishing activities.

The results of these official datacalls are published as authoritative advisory data products (see figure 2.8). All these products follow an exhaustive peer reviewed and quality control process that ensure the best data is available for assessment, evaluations and advisory processes.

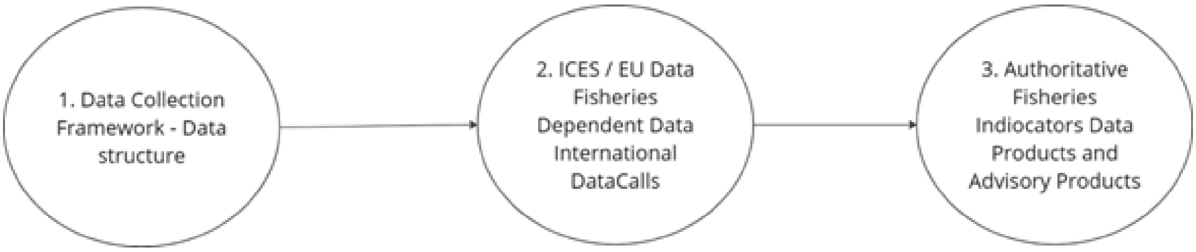

Figure 2.8. Fisheries data collection high level workflow.

2.2.6.2 Fisheries Dependent Information (FDI, STECF)

FDI is an EU data call on Fisheries Dependent Information, issued by DG MARE and processed by JRC. The data call is for landings, discards, effort and fleet capacity, and contains information on vessel length groups and gears. It also includes vessels without logbooks (<10 m) and the sources of the information for those vessels are based on specific declarative forms, logbooks, sales notes or surveys.

The fisheries' dependent data can be obtained from the logbook data and national ports data collection (e.g. landing information, sales notes).

[8] Regulation (EU) 2017/1004; https://dcf.ec.europa.eu/general-information/current-legislation_en

2.2.6.3 Annual Economic Report (AER, STECF)

The collection of fisheries social and economic data in the context of the DCF is conducted by EU Member States through the implementation of annual sampling programs, which are delineated in National Work Plans. This data is furnished in accordance with the provisions stipulated in Regulation 2017/1004, in alignment with Commission Decision (EU) 2016/1251. A comprehensive inventory of data requirements can be accessed on the designated Data Collection website.

Member States provide socio-economic data on an annual basis aggregated by fleet segment according to vessel length and main fishing gear applied as defined in the DCF regulation. The social and economic data is supplemented with landings and fishing effort variables per fishing area and fishing stocks (species). All social and economic data available from EU MS is disseminated through STECF data dissemination tools and economic primary data is available online[9].

The high level of aggregation for the economic and social data means that any analysis at a national administrative level is not possible. The analysis of economic fleet segments by ecoregions is also limited as those are defined at North Atlantic Ocean supra-region level.

The availability of economic data differs between the access individual member states has to national data and open data sources. This is illustrated in figure 2.9 below, from which can be noted that detailed vessel data such as sales notes are at the country level. Although some data in the figure, e.g. logbooks, is not strictly economic, this data is still important for calculating economic indicators.

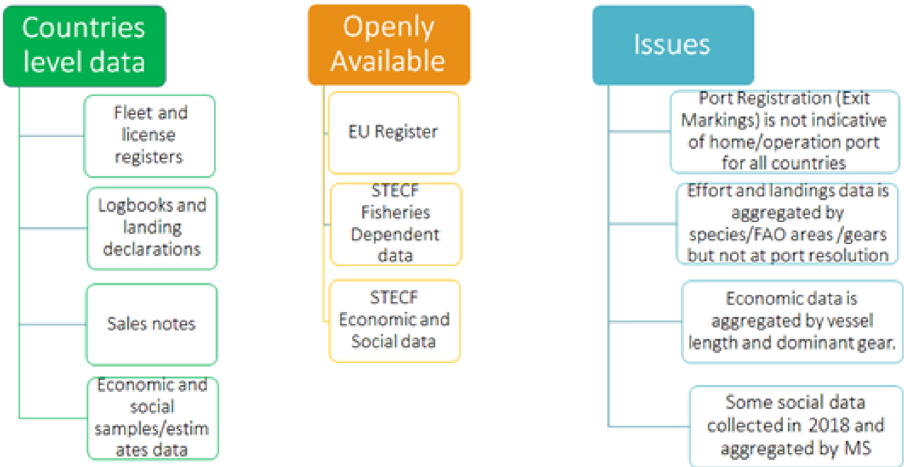

Figure 2.9. Data availability and issues related to open data sources (Source: WGECON: ICES, 2021).

Openly available economic data for fisheries is collected annually by EU Member States (MS) under EU Regulation 2017/1004. This has led to the production of a steady annual flow of data on the costs and earnings of fishing fleets, providing important understanding of the current economic status of the European fishing industry and its evolution in response to changed ecological, economic and regulatory circumstances. The full list of indicators reported by member states is defined in the Commission Delegated Decision (EU) 2021/1167 (Table 7). Items collected for revenues and costs are:

- Revenue
- Gross value of landings
- Other income
- Costs
- Personnel costs

[9] https://stecf.ec.europa.eu/data-dissemination_en

- Value of unpaid labour
- Energy costs
- Repair and maintenance costs
- Other variable costs
- Other non-variable costs

The European Commission Decision of 25 February 2016 set up a Scientific, Technical and Economic Committee for Fisheries, C(2016) to be consulted on any matter relating to marine and fisheries biology, fishing gear technology, fisheries, economics, fisheries governance, ecosystem effects of fisheries, aquaculture or similar disciplines. In accordance with EU Regulation No 2017/1004, the EU multiannual programme for the collection of fisheries and aquaculture data, introduced the collection of social variables for the EU fishing fleet under the Data Collection Framework. Since 2017 the social data collected are merely demographic (number of fishers by fleet, nationality, age, education and gender), In 2024 12 new social indicators were proposed (for summary, see section 2.2.4 fisheries social data).

2.2.6.4 EU funded projects for social data (examples)

PERICLES - Preserving and sustainably governing cultural heritage and landscapes in European coastal and maritime regions.

The project developed an interactive, online cultural heritage mapping portal. It enables data collection and analysis of the distribution of tangible and intangible cultural heritage across eight European case regions (Aegean Sea, Brittany, Denmark, Estonia, Ireland-Scotland, Malta, Portugal and the Wadden Sea) https://www.pericles-heritage.eu/

CABFISHMANN - Conserving Atlantic Biodiversity by Supporting Innovative Small-scale Fisheries Co-management

The project's GeoTool is an accessible portal to map the environmental footprint, fishing activity, economic value, and territorial divisions of small-scale fisheries across the Northeast Atlantic. https://www.cabfishman.net/

SEAWISE

One of the project's aims is to describe and assess the fisheries Social Ecological System, drawing together an understanding of how society, culture, economics, and governance affect fisheries and vice-versa. https://seawiseproject.org/

2.2.7 ICES held data

2.2.7.1 ICES VMS and Logbook Data call

The combination of VMS and Logbook data is currently the most practical and cost-effective way to describe the spatial dynamics of fishing activities and to evaluate the spatial and temporal effects of fishing, for example to describe fisheries activities in, and around, sensitive habitats, wind farms, etc.

For the ICES VMS and logbook data call to national data centres, WGSFD offers a proposed workflow (R code) which combines the VMS data (tacsat format) with a combination of logbook, landings and fleet register data (eflalo format, WGSFD report 2025 in prep.). In this workflow, the tacsat and eflalo data are cleaned and combined to a merged tascsatEflalo data set with all VMS observations being assigned to a fishing trip or logbook even including the information of the ship, catches and revenues per species. In the next step, the activity of a vessel at a VMS position is estimated from the speed observed and the landings and revenues are distributed to the VMS positions identified as fishing activity. In the last step, data on effort (hours, kW-hours), catch (kg) and revenues (euro) are temporally aggregated by month, spatially aggregated per c-square 0.05° and further by metier level 6 (gear class, target species assemblage and gear mesh size), vessel length classes and habitat fished. Further information of average speed per metier is given.

At ICES data center, the national data delivered are further aggregated across nations and, for example, swept area ratio is calculated (see Figure 2.10). This data set feeds in various ICES products (OSPAR- and HELCOM advice), workshops (e.g. WKTRADE), and work groups (e.g. WGCRAN).

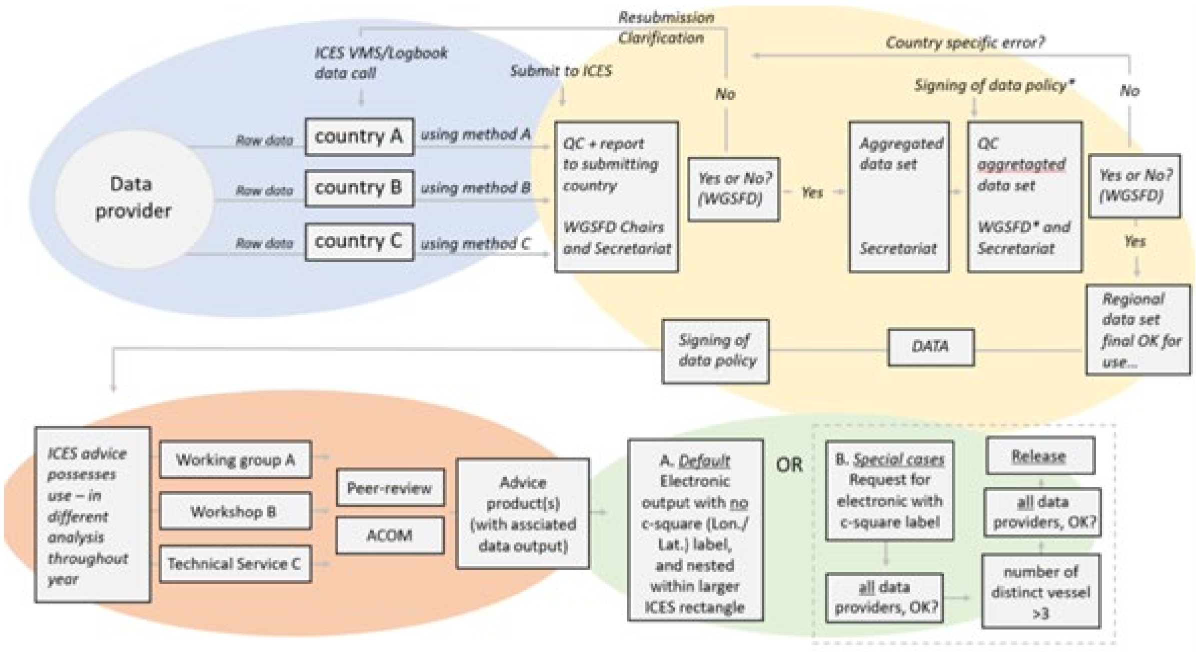

Figure 2.10. Workflow of the ICES VMS & Logbook Datacall. Advice underlying data becomes, in a further anonymised form, publicly available and is further used in multiple research projects and for political advice.

Data Products: List of VMS derived fishing activity data presently at ICES data centre

Variables: Fishing hours, kW-hours, Total weight/value, swept area

Aggregation levels: Year, Month, metier level, length class, habitat (Eunis/MSFD benthic broad habitat) and bathymetry classes (200 m bins), C-square.

Spatial and temporal resolution:

Rationale behind the selection of C-square size 0.05 - closest to encapsulate a 1-hour ping frequency trawl haul in 3 knots. The VMS ping period is one hour in most countries but also two-hour ping period exist in a few countries (e.g. UK and Germany). For mapping purposes gaps between fishing pings is undesirable. Temporal resolution is based on historical needs to describe seasonality but not detailed daily or weekly patterns.

Coverage:

Spatial - ICES areas Northeast Atlantic

Temporal - time period 2009 - 2023

Fleet - Length classes >= 12 m

ICES members states that fulfilled submission to data call are variable throughout years.

Implications of spatial scale

Gridded data makes analysis on spatial scales sub-grid size impossible. A possible workaround would be to make use of raw VMS ping data to do spatial overlays prior to aggregation. An example of this is the WGSFD suggestion of adding habitat information to individual pings to produce better estimates of habitat usage. Also see Greater North Sea Basin Initiative (GNSBI) approach (section 2.5).

2.2.7.2 ICES Regional DataBase and Estimation System (RDBES)

Regional Database and Estimation System (RDBES) is used to support fish stock advice for EU and non-EU countries and to collate and define regional sampling strategies. This database is now replacing the Regional DataBase (RDB), and it includes:

- Data validation, data overview, and data download facilities
- Landing, effort, bycatch, and sampling data
- Flexible sampling schemes upload
- Statistical estimation of biological parameters

Fisheries data comprises Commercial Landings (CL) and Commercial Effort (CE) data. For detailed information please see tables in RDBES documentation.

2.2.7.3 ICES Expert Group ad-hoc data

Non-official data collection is needed to understand small-scale fisheries as it fills in the gaps left by official data sources and provides more information on the fishing activity of this fleet segment. Positional data for small-scale fisheries is scarce due to the legal framework as they are not obliged to use a vessel tracking system. Only vessels with an overall length equal to or greater than 12 meters must be equipped with a Vessel Monitoring System (VMS) (EC No 1224/2009). Member States may exempt vessels with an overall length of less than 15 meters from carrying this equipment if they operate only in territorial waters or spend less than 24 hours at sea. However, the new EU EC 2023/2842 will oblige all vessels to be tracked in the EU during the next five years.

The ICES WKSSFGEO and WKSSFGEO2 workshops have worked on the collection and analysis of spatial data on small-scale fisheries by developing pressure indicators to assess their impact on marine ecosystems, exploring the extent of VMS and logbook data, and producing an anonymized dataset for identifying fishing activities. A database covering 11 case studies in EU and a diversity of métiers (aiming to test methods) has been developed, although data needs to be aggregated to estimate fishing effort (ICES WKSSFGEO2, 2023; Github repository to download data).

2.2.7.4 Data gaps

Data gaps identified above could be resolved with ad-hoc data calls or project-based analysis (e.g. GNSBI). Additionally, changes in the current datacall could be discussed and implemented to increase data usability (e.g. OWF analysis, catch and revenues per species/species classes).

- <u>Company information</u> is not included in the eflalo format where a vessel is typically the lowest unit/level of information. Information on complex ownership (e.g. organisational fleets groups Fisheries Producers Organisations) might be available in national data provider agencies. Landed ports are also available in the source logbook data and could be used to group the fishing activity indicator for regions of interest.
- <u>Small scale fleet</u>: ICES WGSFD Datacall requests data for the fleets that are obliged to use VMS devices. Current legislation requires VMS devices for vessels over 12 meters length. The small scale fleet is not present in the ICES VMS data call and therefore, the fishing grounds with potential interaction between coastal OWF areas and small vessels currently not characterised in VMS based ICES products. (limited existence of SSF data).
- High resolution data products. The recommended resolution to aggregate the average 2 hours VMS pins reported is the 0.05 C-square.

- ICES VMS-Logbook datacall request VMS pins, as well Logbook information, which are used to inform about data gaps (large and small vessels), for Quality Control (QC) and data validation purposes. Currently the non-fishing VMS locations are discarded but could be retained and requested in the data call to be used to report main steam lanes or the estimated total fuel consumption.
- Country-based regulatory frameworks for the operation of OREs, data is needed on whether fishing will be allowed, and under which conditions.

Finally, although social data collection is slowly gaining more attention in the EU, standard availability of social data is a problem for quick social impact analyses.

2.2.8 Methods

This section introduces the key research designs, data and methodological approaches that are currently been used in the social science literature.

2.2.8.1 Research Design

Within the context of social science research, research design can be defined as either exploratory, correlation/association based or cause-and-effect experimental (pre-post, control-treatment). For the most part, social science-based research has focused on cross-sectional, correlation/association based research designs. Such a research design allows researchers to understand the relations between ORE and fisheries. In contrast, cause-and-effect experimental research designs allow researchers to estimate the actual impact of ORE on fisheries. Given data availability limitations and the difficulties of applying experimental methodologies in social research, the majority of research are correlation/association based.

The exception to this is a number of analyses that examine the impact of ORE on fisheries using a pre- and post or control and treatment research design. With regard to a pre-and post-analysis data collected before (ex-ante) and after (ex-post) is required to isolate the impact of ORE development on fisheries, whilst a control and treatment analysis compares data on key parameters such as income in an area that has had ORE development compared to a similar area without such a development. Differences in the parameter of interest are seen as the impact of the ORE development. It is important to note, that as quantitative and simulation capacity develops in the social sciences research community, for example in areas such as Agent Based Modelling (ABM), there is increasing scope for the use of laboratory experiments using computer-based simulations to allow for dynamic simulations of how fishers might respond to ORE developments.

2.2.8.2 Qualitative/Quantitative Data

Regarding methodological approaches much of the research to date has focused on providing quantitative data collected either as primary data by the researchers or collected from pre-existing secondary data to understand the social and economic impacts of offshore wind energy (ORE) on fisheries (Bernard & Gravlee, 2015; Snyder & Kaiser, 2009). Offering researchers the possibility to design specific data collection campaigns, and to use social data via large scale surveys, primary data collection offers a means to collect representative, and broad insight on the topic of interest. Furthermore, as attitudes and perceptions, as well as impacts and outcomes are likely to change over time, it is possible to consistently reproduce this data over time for longitudinal analysis. However, as with all primary data collection, such data is time consuming and costly to collect, and tends to be outside the budget of most research projects.

In contrast, quantitative secondary data consists of pre-existing data often collected by external or national bodies to understand broad trends in a sector. The use of secondary data has both advantages and disadvantages. Using readily available secondary data reduces the cost of carrying out an analysis, and removes the lengthy time requirements involved in collecting primary data. However, the use of pre-existing data may mean that research fails to capture the exact question they seek to address; whilst the researcher does not gain firsthand information, and the ethnographic potential that direct field research offers. Within social science research, secondary data is best suited to give insight on broad trends on attitudes, perceptions and impacts at an aggregate level. For example, secondary spatial data can help identify spatial overlaps between ORE and fishing zones to determine which fleets or regions that may be most affected by ORE development, as well as potential conflicts with other users in the area.

In contrast, if seeking to gain an in-depth understanding of a subject, qualitative data provides a more in-depth understanding of the issue at hand and may be a more appropriate tool (Dwyer & Bidwell, 2019). Qualitative data is data that provides descriptive information and focuses on concepts and characteristics, rather than numbers and statistics. Seeking to approximate and characterize, qualitative data provides more information about an issue than quantitative data. The use of in-depth interviews, focus groups or workshops to collect qualitative data (de Groot et al., 2014) is complementary to the limited information offered by quantitative data (Firestone & Kempton, 2007) or rapid assessments. More time consuming and costly to collect, and only feasible for small samples, primary, qualitative data analyses allow one to dive deeper into a specific question but foregoes the sampling representativity that quantitative measures demands. Quantitative representativity ensures that the proportion of subjects in the study is statistically representative of the larger group, while qualitative research focuses on the depth of information achieved through saturation, meaning that no new insights emerge from additional data collection. Furthermore, longitudinal data collection is possible when data collection consistency can be ensured over time. Finally, participant observation, extended fieldwork, brief-ethnographies etc. offer important data to help ground both secondary and primary data.

2.2.8.3 Analytical methodologies and tools

Different methodologies can be used to assess the (potential) impact of ORE on fisheries. Depending on the stage of ORE development, ex-ante or ex-post analysis can be used (see table 2.2). Those analysis are complementary and should all be used at different stages.

Table 2.2 Summary of the types of analysis for the social and economic impact of ORE on fisheries

Type of analysis			Examples	Stage
Ex-ante	Descriptive	Identification of dependency/importance of fisheries for given fishing grounds	SFD analysis Communities at Sea	Planning
	Modelling	Estimation of social and economic impacts	Bio-economic modelling (see ToR a-vi)	Planning
Ex-post	Descriptive	Identification of impacts of a given measure on the fisheries (and beyond)	Social impact assessment Economic impact assessment Cultural impact assessment Social well-being approach	Post-operation

Ex-ante descriptive analysis

These kinds of analysis are typically looking at zoning and aim at assessing the relative dependency or importance of an area for fisheries. This can be done using spatially explicit fisheries data like VMS data coupled with logbooks. The standard research approach is that heatmaps are made showing the economic value of certain areas. These can then be used by managers in planning for ORE. Looking at some examples in the North Sea (see the GNSBI example in section 2.5 or the current methodology of WGSFD in section 2.2.9), this method expresses the value of areas to an amount of kg and € that fleets can fish in a certain area, based on historical data, often expressed as a percentage of total landings value of the fleet. It can also look at the distribution of the value or effort among the fleets and identify particularly dependent component of the fleet.

What these approaches do not weigh in are other valued aspects of certain area's (i.e. historical fishing grounds, safe fishing grounds), cumulative effects (multiple closures or other limiting policy measures for fleets), relative value, or downstream impacts (on the value chain and or on fishing communities). Decisions on where and how to fish are more than economic as research has demonstrated (Schadeberg et al 2021). A first attempt to mitigate this was used in a recent study where such quantitative assessments were accompanied by qualitative information from active fishers (Deetman et al 2024).

Mapping of communities at sea

St. Martin and Olsen (2017) developed a method to map out areas for fisheries that take different values than economic value of catches per area in consideration. Their 'communities at sea' approach was intended to 'document the presence of community as it relates to fisheries (e.g. shared ecological knowledge, history and culture, common fishing grounds and practices and coproduced adaptations and innovations)' (St. Martin and Olsen 2017). Using vessel logbook data, communities at sea could be mapped clustering fishers working from the same port, using similar gear, sailing on vessels of similar length and design, as they tend to fish for the same species, on the same grounds and at the same time of the year. In addition, they added labour time: nr of days per trip x nr of crew, emphasizing labour input, the size of the community and showing community engagement and dependence upon particular fishing grounds which has been corroborated with ethnographic and community-based fieldwork (St. Martin and Olsen 2017). With their approach, they present an integrated approach, as the qualitative aspects (knowledge, habits) and shared values of fishing grounds (other than only economic) are expressed in a quantitative way, allowing for a direct uptake in policy mapping processes: 'it brings community-level processes and practices into the maps and metrics that inform science and policy' (St. Martin and Olsen 2017). In addition, it allows analysis of change over time (i.e. influence of climate change, introduction of quota – (Olsen 2010, 2011) as well as analyses linked to certain core concepts such as environmental justice.

Ex-ante modelling analysis

Other analysis that can be performed in the planning phase of ORE development are simulation tools, namely, spatially explicit bio-economic models (see Thebaud et al, 2023, summarized in section 2.2.5). Using the descriptive analysis to ensure that the relevant aspects are included in the models, those can subsequently be used as flying simulation tools, with "what-if scenarios". Those models, incorporating a behavioural response of the fishers and feedback loops between the ecological and part of the ecosystem and the fishing fleets are very valuable tools to identify risks and preferred scenarios from a set selected with stakeholders. This kind of modelling approach is discussed in ToR a-vi (see section 4.1).

Ex-post analysis

Once the ORE has been developed and is in operation, it is important to continue to monitor the effect on fisheries. Different methods can be used to this end to assess the impact of ORE on fisheries.

2.2.8.4 Transdisciplinary methods (TD)

Based on the integration of valued and respected stakeholders' knowledge in the assessment of the impacts of ORE. It can be done through stakeholders' participatory workshops. TD methods start with the collaborative identification of the problem issues (what are the impacts of ORE?) all the way to the co-production of potential solutions. TD methods pay particular attention for the inclusion of marginalized stakeholder groups often women, youngsters and elderlies.

Social impact assessments (SIAs)

A social impact assessment, "provides information to agencies and communities about social and cultural factors that need to be considered in any decision" (Clay and Colburn 2020). These factors may include: 1) demographic characteristics, 2) cultural aspects (attitudes, beliefs and values), 3) effects of proposed actions on social support and services, and health and safety issues, 4) impacts on non-consumptive and recreational uses of living marine resources and their habitats like recreational fishing and diving, and 5) historical reliance on fisheries and participation in the industry, particularly within communities where fishing holds significant social and cultural importance, including indigenous and tribal groups (Clay & Colburn, 2020).

SIAs rely on multiple data sources, incorporating both quantitative indicators and qualitative insights, such as interviews that document fishers' experiential knowledge. Unlike economic impact assessments, which focus on market and non-market values, firms, fleets, and industries, SIAs emphasize social and cultural dimensions. However, in some cases, both types of assessments may draw from overlapping data sources.

In fisheries, SIAs follow a straightforward framework: a given measure (e.g., a closed fishing area) can lead to various social impacts (e.g., displacement, reduced catch) for specific groups of fishers (e.g., small-scale gillnet fishers). The outcomes are inherently context-specific, meaning the social effects of management decisions will vary based on the characteristics of the affected communities and fisheries.

Social Wellbeing approach (ex-post)

The Social Wellbeing approach provides a framework for an integrated evaluation of the social and economic benefits that communities receive from commercial fish harvesting. It is based on interviews and literature reviews to identify the contributions of the fishing sector to coastal communities in seven domains: 1) a resilient local economy, 2) community health and safety, 3) education and knowledge generation, 4) a healthy environment, 5) integrated, culturally diverse, & vibrant communities, 6) cultural heritage and community identity, and 7) leisure and recreation (Voyer et al. 2017). The analysis of the contributions before (baseline data) and after the establishment of the ORE platforms will measure their impact on fishing communities.

Community Capital Framework (ex-post)

The Community Capital Framework (CCF) was originally deployed to facilitate the monitoring of rural communities' progress towards sustainable development. CCF us a straightforward tool that can be used to assess the social and economic impacts of any intervention – in this case ORE projects – in the community wellbeing and development. The framework identifies seven types of capitals that contribute to a community's resilience and development (Flora et al. 2024). The seven capitals are:

- Natural Capital – Environmental resources like land, water, air, and biodiversity.
- Cultural Capital – Traditions, values, heritage, and shared identity.
- Human Capital – Skills, education, health, and knowledge of individuals.
- Social Capital – Relationships, networks, and trust within the community.
- Political Capital – Influence, power, and access to decision-making.
- Financial Capital – Monetary resources, investments, and wealth
- Built Capital – Infrastructure, buildings, roads, and technology.

Cultural impact assessment (CIA)

Any effect on a people's way of life as passed down through the generations is a cultural impact. This impact is therefore particular important for fishers that engage in fishing activities as a way of life often associated with small-scale fisheries and their communities. In the case of ORE, a CIA should be performed if the following criteria are relevant:

- The ORE is placed adjacent to an area with a century (or more) old coastal community, Aboriginal community or to ocean spaces were traditional fishing techniques and customary rules to manage the fisheries are still in place,
- The ORE is placed in an area that is a proposed or in place cultural protected area or to a spiritual site,
- The ORE is placed in a fishing ground with a prevalence of culturally relevant marine species and harvesting techniques are present,
- The ORE is placed in a place or space mentioned in important traditional oral histories, and
- The ORE is placed in an area with presence of unique or otherwise valued seascape formations

A CIA should guarantee that the presence of offshore windfarms will risk the preservation of local languages (including local names), customary rules and laws, traditional knowledge, pass on of values and worldviews and cultural heritage. Ex-post CIAs need Baseline Data collection through qualitative and quantitative means (see section 2.4, project review).

2.2.9 Current methodologies applied by WGSFD to produce fishing advisory products (e.g. ICES ecosystems and fisheries overviews)

1. Method to derive fishing activity indicators from ICES VMS&Logbook Annual data call:

- Source data is obtained from Logbook and VMS data sources
- Classification methods to separate fishing activity from steaming
- Fishing VMS locations & Logbook are combined to obtain high resolution fishing activity indicators
- Aggregate the activity indicators by square 0.05 and reported units required in the data call (e.g. month/year, vessel length category, metiers level X).
- The activity indicators available are:
- Effort in fishing hours, Effort kW* fishing hours, total landings weight, total landings value, trawl swept area (see WGSFD, ICES, 2022)
- Additional indicators can be derived such: CPUE and LPUE

2. Methods to identify important/core fishing grounds:

- Cumulative effort within a c-square, remove the lower tail of the effort (e.g. 10% of the lower cumulative effort) .
- Identify the c-square cells that are consecutively important fishing areas over the time period selected (e.g. years, months, etc)
- Exploratory method used by WGSFD members to evaluate the variability of fishing activity inside management regions and OWF license areas (ICES, 2022).

3. Identify the fishing activity in and out of offshore wind licenses areas (SFD report 2020):

- Spatial intersection between fishing activity Csquare and the boundaries of the OWF license area
- Calculate the proportion of the square cell that is overlapped by the OWF license area.

4. Calculate the proportion of fishing effort in and out of the offshore wind based previously calculated proportional overlapping, considering the even distribution of fishing effort within a csquare.

- Enhanced methodologies discussed in SFD:
- Analysis of the intersection between fishing activity data collected at local scale resolutions required for the OWF license area scale assessments.

Currently the ICES VMS & Logbook datacall request the data reported at 0.05 degrees csquares. (approx. 5 x 3 Km cells). These csquares could cover part or entire OWF licenses areas. There is a current data gap between the scale of the OWF areas and the regularly collected fishing activity data (see section 2.2.2.4, data gaps).

There has been discussion about the changes on the data call reporting resolution, such as increasing data requested aggregated to csquare size of 0.01. This resolution would permit to do a spatial analysis to identify if activity occurs within the boundaries of an OWF. Afterward the data have to be aggregated again to the coarser 0.05 resolution recommended to be used.

2.2.10 Spatially explicit bio-economic modelling (from Thebaud et al 2023)

Internationally, there has been a growing need for fisheries management to address the spatial dimensions of fishing and its interactions with ecosystems and other activities, raising the question of how economic research can contribute. Specific marine areas and habitats warrant special management due to their importance in terms of marine ecosystem biodiversity, functioning and services (see also topic XII). Additionally, interactions of fisheries with other marine sectors occupying marine areas and spatial allocations for other industries (e.g. aquaculture, energy, and transport) are increasingly being considered[10]. Infrastructure protection and safety reasons lead to more or less permanent fishing restrictions in the areas used for those alternative sectors, possibly changing biological production, biodiversity, and ultimately, fishing opportunities (Causon and Gill, 2018).

Spatial economic modelling approaches to fisheries management exist. The original economic literature on this topic applied econometric techniques to investigate spatial decisions of fishers (Wilen et al., 2002; van Putten et al., 2012; Girardin et al., 2017; Andrews et al., 2020; Dépalle et al., 2021). These models are particularly used in the context of evaluating the impacts of marine reserves, but the approach enables studying spatial management policies in general, namely the impacts on fishing costs and effort displacement resulting from alternative policies (e.g. Bastardie et al., 2014). This includes for example consideration of changing travel distances from port because of developments in travel pathways, or of changes in fishing location choices following changes in in fish population distributions (e.g. due to climate change).

There are several barriers to developing such integrated spatial management advice. Integrating the spatial dimension requires dealing with two types of dynamics: the spatial behaviour of fishers and spatially explicit fish population models. The applied literature, however, does not account for fish stock spatial dynamics and typically considers one target species only. Nielsen et al. (2018a) found that only 12 out of the 35 integrated models they included in their study had a spatial resolution sufficient to investigate sub-stock dynamics. Another barrier relates to the data needed as input for the models. To reach the adequate spatial scale to investigate area closures, individual and fine-scale spatial data are required, raising confidentiality issues.

Within ICES, several working groups touch on the evaluation of area-based management and spatial fisheries management options and performance. Among them, the Working Group on Fisheries Benthic Impact and Trade-offs (ICES, 2021b) focuses on fishing impacts on seafloor integrity from a spatial perspective, with support from the ICES Working Group on Spatial Fisheries Data[11], which collects and analyzes spatial fisheries data. Such working groups help document the best places and timing for fishing gear restrictions as spatial management mitigation tools. Despite this, it appears that very few initiatives in ICES have sought to evaluate the performance of spatial management measures. This is true of biological studies (because applying the Before-After-Control-Impact design is a challenge in lack of true temporal baseline and counterfactuals, see Underwood, 1992). But evaluations of the economic

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10 https://www.ices.dk/community/groups/Pages/WKBEDPRES2.aspx

11 https://www.ices.dk/community/groups/Pages/WGSFD.aspx

impacts of spatial management options are even sparser, given the relatively recent focus in ICES on collecting and using economic and social data. This contrasts with other regions, where studies of the economic consequences of spatial management have been conducted and are being considered by advisory bodies (e.g. Abbott and Haynie, 2012; Bisack and Sutinen, 2006). In the context of ICES, recent ad hoc initiatives have considered the question of balancing spatially resolved environmental and fisheries economics considerations, for example in relation to the risks of habitat degradation[12] (see e.g. Bastardie et al., 2020) and protective measures adopted as part of deep-sea access regulations[13]. However, to date, ICES has not implemented any advice that incorporates economic or social considerations on spatial fisheries management.

Spatially resolved economic analysis

As the importance of spatial structure in the distribution of fish populations, and the need to account for this in designing spatially explicit management measures, has become increasingly acknowledged, so has research focused on describing, explaining and predicting the spatial allocation of fishing activities and their interactions with the spatial dynamics of fish resources (Eales and Wilen, 1986; Sanchirico and Wilen, 1999; Holland and Sutinen, 2000; Smith, 2000; Smith et al., 2009; Dépalle et al., 2021). The analyses have particularly been used to examine the potential bio-economic consequences of spatial management measures such as closed areas and marine protected areas (Hannesson, 1998), with more recent work highlighting the importance of considering economic behaviour in examining the potential benefits of such measures (Smith and Wilen, 2003; Haynie and Layton, 2010; Albers et al., 2020).

In the context of ICES, recent ad hoc initiatives have examined balancing spatially resolved environmental and fisheries economics considerations; an example being the risks of habitat degradation and protective measures adopted as part of deep-sea access regulations. However, to date, ICES has not implemented any advice that incorporates economic or social considerations to spatial fisheries management. This contrasts with other regions where studies of the economic consequences of spatial management have been conducted and are being considered by advisory bodies (Bisack and Sutinen, 2006; Abbott and Haynie, 2012).

2.2.11 Analysing trade-offs associated with area-based and spatial management

Spatially resolved economic analysis of fisheries focuses on associating fishing stakeholders at the vessel, fleet, and community levels to chosen fishing areas and quantifying the importance of these areas in terms of catch rates and profitability. Based on behavioural change scenarios, the economic consequences of spatial restrictions to fishing on re-allocation of effort in space and time and to métiers can be estimated (Blau and Green, 2015). Such preliminary analyses provide economic information needed for trade-off analyses, as well as reducing the potential for surprises in the outcomes (Wilen et al., 2002). Research in ICES could incorporate existing models to assess the past performance of spatial management to project possible paths of alternative futures, as well as the fleets likely to be impacted by a proposal. This would enable impact assessment of changes in fishing pressure on the biological and ecosystem components with effects propagating to the economics of the fishery. While ICES hosts many data sets that could help condition such impact assessment models a major obstacle would still be the limited data collection or resolution of data collected on certain variables (e.g. catch), that currently does not fit spatial and time resolutions that matter to stakeholders and policymakers.

Increasingly, the above spatial fisheries management considerations need to be cast in the context of the broader marine spatial planning aimed at allocating ocean space in an ecosystem-based management perspective (Katsanevakis et al., 2011). This includes both conflicts between fisheries and other maritime

12 https://www.ices.dk/community/groups/Pages/WKTRADE3.aspx

13 https://www.ices.dk/community/groups/Pages/WKEUVME.aspx

activities, and the potential for co-locating activities. The benefits from co-locating uses such as windfarms with fisheries has begun to be investigated (Stelzenmüller et al., 2021) but very few practical examples exist. More scientific effort should be put into elucidating the possible ecological-economic effects of reserving space to windfarms, from local to overall effects on marine biodiversity and fishing opportunities (e.g., (Bastardie et al., 2014)). While relative economic returns have only rarely been considered before introducing spatial management measures, integrating measures of economic benefits into existing ecological models would allow assessment of how these benefits may be distributed across ICES regions and among beneficiaries such as local communities, the tourism sector or different fishing vessels. Such assessments should consider whether compensation should be considered in the course of implementing the measures as well as the timespan over which the benefits accrue, and uncertainty regarding outcomes of the spatial measures (e.g. including climate change effects). Such integrated understanding could provide new knowledge on hotly debated topics to inform policymakers' decisions. Examples of this could include case studies documenting the possible fishing effort displacement in response to implementation of conservation areas (e.g. in the EU, Natura 2000 designated areas) that might require costly short-run adaptation of fishing strategies balanced with possible long-term benefits from improved productivity of the exploited ecosystem (e.g., (Bastardie et al., 2020)). Another example would be evaluation of large-scale exclusion scenarios such as those associated with "Brexit" that would lead to excluding the EU fleet from the UK Economic Exclusive Zone (Dépalle et al., 2020).

2.3 Literature review on the social and economic impact of ORE on fisheries

Method for conducting systematic literature review

This review was conducted according to the PSALSAR Framework for systematic literature reviews, a systematic review process designed for the environmental sciences (Mengist, Soromessa and Legese, 2020). Systematic reviews typically follow four basic steps (SALSA): search (S), appraisal (AL), synthesis (S) and analysis (A). The PSALSAR Framework however includes two further steps; a protocol step that defines the research protocol (and reporting results step, at the initial and last step, respectively.

Step 1 – Protocol – Defining the study scope

Using the PSALSAR framework, a Protocol was designed and set out the study scope. Based on the ICES request, 'what are the economic and social impacts of ORE development on commercial fisheries?' papers were limited to studies investigating the social and economic impacts of ORE development on fisheries were included in the review.

Step 2 – Search – Fixing the research terms and researching studies

To gather all the literature as comprehensive as possible to cover the economic and social impact of ORE, the search strategy was developed and piloted among authors of the review in July 2024. As part of the pilot, two research databases Scopus and Web of Science were searched. Research terms were divided into three categories:

Fisheries related: (fish* OR seafood)

AND

ORE related: ("OWF*" OR "wind farm*" OR "offshore wind" OR " offshore renewable energy" OR "offshore energy")

AND

Socio-economic related: (econ* OR socio-econ* OR socioecon* OR social*)

As part of the pilot, 233 papers from Scopus and 325 papers from Web of Science. Excluding duplicates (n = 143), 415 papers were identified in total. Based on title and abstract screening, a further 119 papers were removed, leaving 296 papers for further analysis.

Further analysis of these papers by the research term found that the 3 initial research terms were too limited, and further refinement was required to address the scope of the special request.

Based on the pilot, the terms were updated to:

(fisher* OR “fishing”)

AND

ORE related: ("OWF*" OR "ORE" OR "MRE" OR "wind farm*" OR "offshore wind" OR "offshore renewable energy" OR "offshore energy" OR "marine renewable energy")

AND

Socio-economic related terms: (econ* OR socio-econ* OR socioecon* OR social* OR impact OR displace* OR distribut* OR compet* OR complian* OR tactic* OR strategic* OR invest* OR disinvest* OR exit OR entry OR discard* OR diversif* OR gear OR efficien* OR behaviour* OR behavior* OR trade-off* OR tradeoff* OR conflict* OR insur* OR "benefit*" OR "cost*" OR "willingness to pay" OR "income" OR "compensat*" OR "subsid*" OR "job*" OR employ* OR "valu*" OR "welfare" OR "monetary" OR revenue OR profit* OR “GDP” OR “GVA” OR heritage* OR communit* OR seascape OR “health*” OR “just*” OR “transition*” OR equity OR rural OR coastal OR peripheral OR vulnerab*)

A further 893 papers from Scopus and 550 papers from Web of Science were identified in October 2024. Combining the papers from the pilot search with the newly identified papers and removing duplicates, 1,178 papers were identified for title and abstract screening.

Step 3 – Appraisal – Selecting studies

The 1189 papers with full citation information were exported into excel for title and abstract screening. Exclusion criteria for the tile and abstract screening included:

- Papers that were not in English
- Papers that did not include the impacts of ORE development on commercial fisheries
- Papers that did not focus on offshore renewable
- Papers that did not focus on either the social or economic impact/consequences of ORE development on commercial fisheries
- Screening was undertaken by 4 partners and 141 papers were included into the final list of studies for data extraction.

Step 4 – Synthesis – Data extraction and categorise the data

The 139 eligible full texts were assigned based on the predefined exclusion criteria were identified for data extraction. An online data extraction form was developed, tested, and modified via Microsoft Form. This was made available to all reviewers who volunteered from the two ICES working groups WGECON and WGSOCIAL. The data extraction form included two sections: publication details and study details. Initial publication details included the source, type, and title of record along with author and journal details. The initial information was filled in for each of the 139 publications, however, if the publication was identified as empirical study, the reviewer was asked to extract a second set of information from the publication. The second set of information included data on the study location (country and marine area), year of the data collection. Study details were further broken down into 4 distinct sections; including study design, methods and data, details of the fisheries (gears, vessels, species), details of the ORE (type of ORE considered, site and the geographical extent of the ORE), governance issues (proposed access rights for fisheries, conflicts identified, fisheries response to the ORE and the social and economic impact of the ORE on fisheries. The extracted study details were downloaded to Microsoft Excel and there double-checked that all 139 studies when available data was extracted.

Step 5 – Analysis – Data analysis, result and discussion

The analysis of the data was conducted in R. Only papers which described empirical findings (47) were further considered to inform this report. From these, 12 impacts were identified, 5 direct and 7 indirect, most of them resulting in a deterioration of the situation for fisheries.

Step 6 – Report – Conclusion, advice report writing and production

The results were summarised in section 2.1.1.

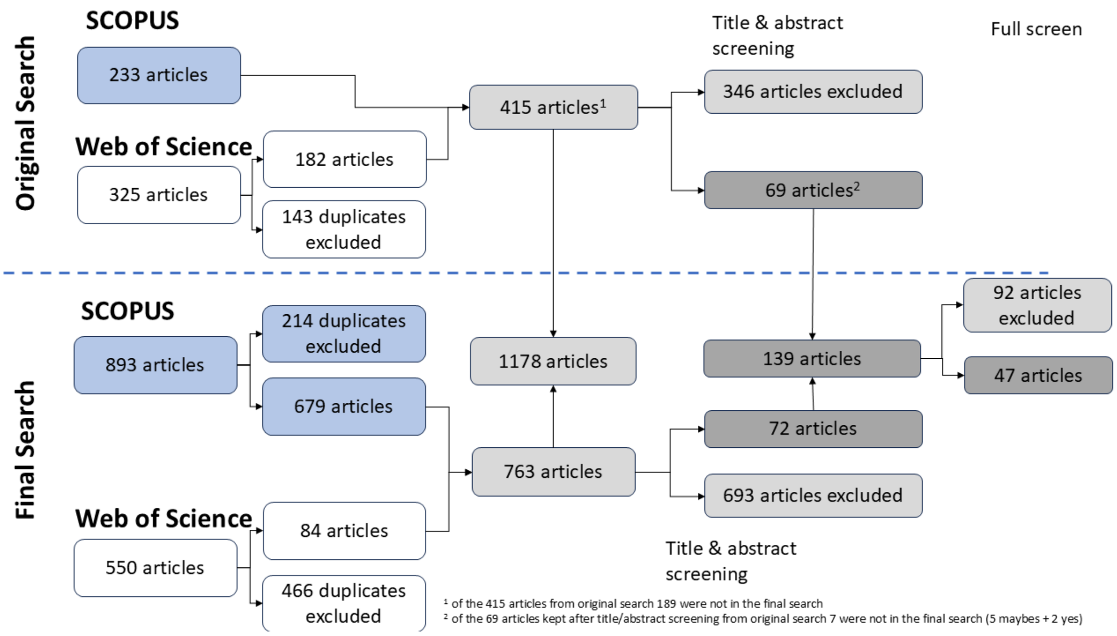

Figure 2.11. Article screening and selection for the literature review

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2.4 Project review

Given the dynamic nature of the research field, the ICES working groups WGECON and WGSOCIAL initiated a review of evaluation projects known by their members, asking the latter to provide their expert knowledge. In total, 16 project reviews were undertaken, comprising seven different countries (France, Ireland, Netherlands, Spain, Portugal, Sweden and USA). This project review mainly focused on methods which are used to investigate the interactions between commercial fishing and offshore wind farms from an economic and social perspective. The survey aims to provide examples of what has been done and show which criteria have been prioritised in existing studies. By understanding what has been done, the study will highlight what research needs to take place and what metrics might best work in order to provide the economic and social evaluations required for fisheries-windfarm interactions.

The survey of the working group members was organized using a matrix asking respondents to summarise current or recent projects, by addressing the following points: (1) the case study, (2) study objectives, (3) governance, (4) stakeholders involved, (5) approach and methodology, (6) study structure, (7) limitations, (8) data collection, (9) application of results, and (10) dissemination. The matrix was sent with explanatory notes for each of these 10 criteria. The information from individual case studies and approaches was then collated. Information from these studies provides insights on the metrics that are most often used for economic and social evaluations and the research that still needs to take place. While this is not an exhaustive list of approaches used, it gives an insight into the latest developments in the ICES area on how the economic and social impacts of ORE on fisheries are being assessed.

The dissemination of project results has been shown to take place not only in the shape of scientific papers (such as F1, F3, SE2) but also using reports (ES1, US3, IR1) (more report than scientific article), presentations at conferences, websites, and often in natural languages (not only in English) to make the work more accessible. Some of the work done had been transformed into regulations, such as the work done in project US-2.

One illustrative example of this implication can be seen with the case studies ES1 where the objective was to quantify, analyse and visualize in socioeconomic terms the fisheries and aquaculture activities in Galicia (NW Spain) to support the Regional Government on MSP. This project was led by CETMAR, Univ. Las Palmas de Gran Canarias (ES), HELCOM (FI), SHOM (FR), CNR (IT), CEREMA (ES). The results were shared in the shape of a report in Spanish and QGIS maps.

Table 2.3. List of Projects reviewed by WGECON and WGSOCIAL

Study	Country	Reference(s)/Links
ES-CETMAR	Spain	Project ongoing, access is confidential
F-1	France	Buchholzer H., Le Grand C. Frésard M., Le Floc'h P. (2021). La vulnérabilité socio-économique des pêcheurs professionnels face au projet d'un parc éolien flottant entre Groix et Belle-Ile, Livrable 42, Projet ANR Appeal, 59p. Buchholzer, H., Frésard, M., Le Grand, C., & Le Floc'h, P. (2022). Vulnerability and spatial competition: The case of fisheries and offshore wind projects, Ecological Economics, 197, 107454. Le Grand, C., Buchholzer, H., Frésard, M., & Le Floc'h, P. (2023) Vulnérabilité et concurrence spatiale : le

Study	Country	Reference(s)/Links
		cas des pêcheries et des projets d’éoliennes en mer. Ouvrage “Vulnérabilité (s) environnementale (s), perspectives pluridisciplinaires
F-2	France	Confidential report and free, public report (RESCORE platform): Julie Furiga, Anatole Danto. Adaptations des pêcheurs artisans aux changements : Zone de Groix-Belle-Île, 2020. [Rapport de recherche] France Energies Marines; Université de Caen; JéOcéan; European Sustainability Center. 2022. ⟨hal-03563560⟩
F-3	France	Scientific papers; conference extended abstracts; Ecopath model;
US-1	USA	The reporting tool along with a data access portal has been fully implemented and available to the Public at the URL shown under the project collaborators (https://www.fisheries.noaa.gov/resource/data/socio-economic-impacts-atlantic-offshore-wind-development?utm_medium=email&utm_source=govdelivery).
US-2	USA	Project website (https://sites.rutgers.edu/smdsf/) and multiple scientific publications.
US-3	USA	Scientific report by BOEM in FY 2024.
US-4	USA	The database will contain confidential data and so will only be available to researchers with the appropriate permissions. The visualization tool will be publicly available, although we are not sure if data-download will be supported yet. The visualization tool will contain aggregated data so as to protect confidential data.
IRE-1	Ireland	Report: "Participatory mapping of small fishing vessel activities for marine spatial planning." Published by BIM in January 2025. https://bim.ie/wp-content/uploads/2025/01/Final-participatory-mapping-report-1.pdf
FR 4	France	Publication in process, but some maps have been published online during the national public debate in France (2023-2024). See the "cahiers d'acteur" with links gathered hereafter: https://valpena.univ-nantes.fr/accueil/zone-dimportance-pour-la-peche
NL 3	Netherlands	https://edepot.wur.nl/660870
NL 1	Netherlands	Stand van zaken passieve visserij windparken op zee - WUR; the results are published and free accessible; mostly in Dutch but the summary is also available in English
NL 2	Netherlands	https://www.wur.nl/nl/project/Win-Wind.htm; the results are published and free accessible; partly in Dutch and partly in English
SE 2	Sweden	Waldo, S., & Blomquist, J. (2024). Hur påverkas svenskt yrkesfiske av havsbaserad vindkraft? (Rapport 2024:2). Agrifood Economics Centre. (In Swedish). https://www.agrifood.se/Files/AgriFood_Rapport20242.pdf
SE 3	Sweden	Can offshore wind farms offer regenerative solutions for depleted fish stocks? https://gupea.ub.gu.se/handle/2077/82602
P1	Portugal	chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.ipma.pt/export/sites/ipma/bin/docs/organizacionais/prr-c21-i07.01-20240708_Apresentacao_Eolicas_rv_f.pdf

2.4.1 Types of Data in Project review

In the 16 projects reviewed for this report, the type of data used were not always described. Where specific metrics were described, these exclusively related to economic aspects. Two studies relating to social and socio-ecological aspects (F-2, F-3) did not mention any specific metrics used. Three studies (ES-CETMAR, F1, FR4) used quantitative indicators to quantify economic impacts, but did not specify which indicators were being used. One study (FR-4) noted the difficulty of the choice of metrics available. Where described, economic metrics usually referred to landing values, either as an explicit number (NL3, SE2, SE3, P1), as a percentage change in expected revenues (US-2), or as the share of landing value by fishery/vessel/port impacted (SE2). Only two studies (IRE-1 and P1) explicitly stated looking at effort metrics (number of days, number of vessels). None of the projects mentioned specific reference levels being used to quantify what level of economic disruption might be acceptable/not acceptable.

One study (US-1) described using a standardised set of economic metrics as part of its socio-economic reporting tool. Potential impacts on landings and revenues by top species can be calculated alongside insights into the most impacted gears/ports. Other insights are included such as share of revenue by affected vessels, number of trips/vessels and dependence by species on the wind area as a proportion of the regional values. This range of metrics gives a broad overview of the impact that a future wind development might have and illustrates the possibilities of what metrics can be calculated, but this requires a large volume of fishery and socio-economic data which may not be available for many projects. It further highlights that most of these case studies assess primarily only the direct impacts of ORE on fisheries.

The type of data used in fisheries research varies depending on the objectives of each study. In order to understand potential impact of ORE on fisheries, it is important to understand the specificity of fisheries in certain areas, yet fisheries are complex and diverse. Data can either be extracted from existing databases or collected specifically for analysis. Our review shows that most studies rely on pre-existing datasets (including spatial data).

One illustrative case study (SE2) aimed to contribute to marine spatial planning (MSP) of Sweden by assessing the expected economic impacts of offshore wind power on commercial fisheries and the municipalities where landings occur. This study required one of the most extensive datasets to feed into its model (RUM). Implementing the model required detailed information on the expected profitability and availability of fishing areas for each vessel, including data on fishing activity within designated energy zones and overall fishing activity. To obtain this data—sourced from logbooks, VMS records, and price statistics—the researchers submitted a request to the EU Scientific, Technical and Economic Committee for Fisheries (STECF). These data were partial and they had missing data in particular for passive gears.

The complexity of fisheries data is mentioned in many of the different projects, and using such data comes with several limitations. One major challenge is access, as illustrated by FR1, which relies on data from the French Fisheries Information System, or US4, which uses PacFIN data. These routine datasets can only be accessed through formal data request procedures, usually requiring government authorization. Furthermore, they may be incomplete, lack sufficient resolution (as noted in SE-3), or fail to account for vessels without electronic tracking systems, such as plotters (as highlighted in IRE-1). This can lead to gaps in understanding, particularly for small-scale fisheries where fine-scale data is crucial for accurately assessing spatial and socio-economic dynamics - particularly since OWF parks or their cables are often overlapping with these types of fisheries.

In contrast, some studies collect primary data directly, mainly through interviews. These interviews can serve different purposes, such as informing modelling efforts (SE-3) or analysing fishers' perceptions (FR2). While direct data collection allows for a more tailored approach, it also has limitations. Accessibility remains a challenge, as researchers may face difficulties in establishing contact with key stakeholders, which can hinder the progress of the study. Also, the time constraints of the research studies can shorten the field work.

Some projects explicitly mentioned how they overcame such limitations. In Ireland, for instance, they used participatory mapping and involved extensive engagement with stakeholders by developing an extensive network including the Southeast Regional Inshore Fisheries Forum (SERIFF), BIM regional officers, Lune Geographic, and local fishers to address spatial data gaps for vessels under 12metre (IRE

1). The direct engagement with fishers enhanced trust and the accuracy of the spatial fisheries information, but this was a labour-intensive process. Afterwards, however, participants still expressed that they fell that the participation rate of 73% was limited. The commercial sensitivity of such data restricts the sharing of this approach with the public and therefore constrains its broader application.

The case studies showed that researchers tend to produce very applied research, engaging with stakeholders (even working with them) during the process and aiming to disseminate the work in some cases in non-traditional ways.

Table 2.3. Summary of data used in the different projects reviewed. In white quantitative data, in light blue qualitative data.

	ES-1	F-1	F-2	F-3	F-4	IRE-1	NL-1	NL-2	NL-3	SE-1	SE-2	US-1	US-2	US-3	US-4	P1
Activities data	X	X		X	X	X	X	X		X	X	X	X		X	X
VMS data	X				X	X			X	X		X	X		X	X
stock distribution data													X		X	X
observer's data															X	
safety guidelines data								X								
price data				X				X	X	X			X		X	
Interviews		X	X	X	X		X	X			X			X		
Group meeting			X						X							

2.5 Case Study: Greater North Sea Basin Initiative

To manage the cumulative impacts of the expanding anthropogenic uses of the Greater North Sea basin the ministries of North Sea neighbouring countries started the Greater North Sea Basin Initiative (GNSBI). Within this initiative six work tracks aim to elucidate the different aspects of impact:

1. Governance: Explores current and needed arrangements for the GNSBI to function properly
2. Nature restoration and conservation: Setting up a program for cooperation regarding conservation, enhancement and restoration of nature
3. Multiple use of space: Setting up criteria and sharing best practices on co-use and decommissioning/circularity of offshore wind energy
4. Cumulative impacts: find a common approach on cumulative impact assessments based on existing work to identify and observe ecological boundaries and options for enhancement and protection of the marine environment.
5. Long-term perspective of fisheries: Creating insight in key fisheries areas and socioeconomic/food impacts of spatial developments at North Sea Basin scale
6. Knowledge sharing: Coordinating the exchange of best practices, (scientific) information, data, plans and assessments. The result of this work could be incorporated into the already established compendium

The aim of the work track Long-term perspective of fisheries (chaired by France and Germany) is

1. Describing the spatial pressure through new and/or expanded anthropogenic activities on fisheries, e.g. by assessing their overlap with current fishing areas and to create a common evidence base:
   a. The 1st step is to achieve a common North Sea wide mapping of important fisheries areas linked to other indicators of importance e. g. Volumes, value, [jobs offshore and onshore,] ports
   b. The 2nd step is to forecast the roll-out of other anthropogenic activities by 2030 and overlay those with the mapped fishing areas to establish areas of conflict potential between fisheries and other anthropogenic uses.
2. From this evidence base,
   a. develop recommendations how to better incorporate fisheries into the MSP process, and secure a long term perspective for North sea fisheries
   b. (re)position fisheries in the wider range of human activities and environmental issues in the MSP process and/or develop other support/remedial measures, including by looking at possible opportunities/synergies arising from these new developments.

Work Track Long-term perspective of fisheries – mapping and overlap

The work track "Long-term perspective of fisheries" (WT-Fi) is about to produce a North Sea wide mapping of important fisheries areas linked to indicators of importance e. g. volumes, value and harbours and uses Individual Stress Level Analyses (ISLA) concept the evaluate cross sector/cross border impact from ORE and nature protection areas on the fisheries.

What is new: In difference to e.g. ICES work groups GNSBI uses national laboratories' data including single VMS positions, single vessel information and species caught, and exact spatial and specific fisheries management information on nature protection sites and in offshore wind power areas.

Challenges. The compilation of specific management data took about 12 months. These was not available neither at EU bodies, nor at ICES. About 850 shape files were collated from WT-Fi partners and publicly available source. A further challenge for some of the national labs was to provide the requested input data comprising information on species caught per logbook event (merged tacsatEflalo).

The work is ongoing (February 2025) and the aim is to produce the report by summer 2025.

2.5.1 Work Track Background

From three offered approaches:

a. use public available ICES-OSPAR advice underlying data
b. use ICES available data (vms data call)
c. use national laboratories’ data including single vessel information and species caught

Option c) was chosen by GNSBI-work track partners (Ireland, France, Belgium, Netherlands, Germany, Denmark, Sweden, Norway).

Thünen Sea Fisheries developed a workflow to map effort, catch of species/species groups, and revenues. Further, the approach estimates the economic relevance of (wind farm) areas and the Stress Level (SL, “indication of challenge”, “conflict potential”) of specific fisheries and individual vessels (Schulze et al. 2012). The individual stress levels are used to compile Individual Stress Level (ISL) profiles of national fleets, coastal regions and harbor communities.

The workflow of points 1.1 and 1.2 (North Sea wide mapping and overlap) is organized in 5 steps (Figure 2.12).

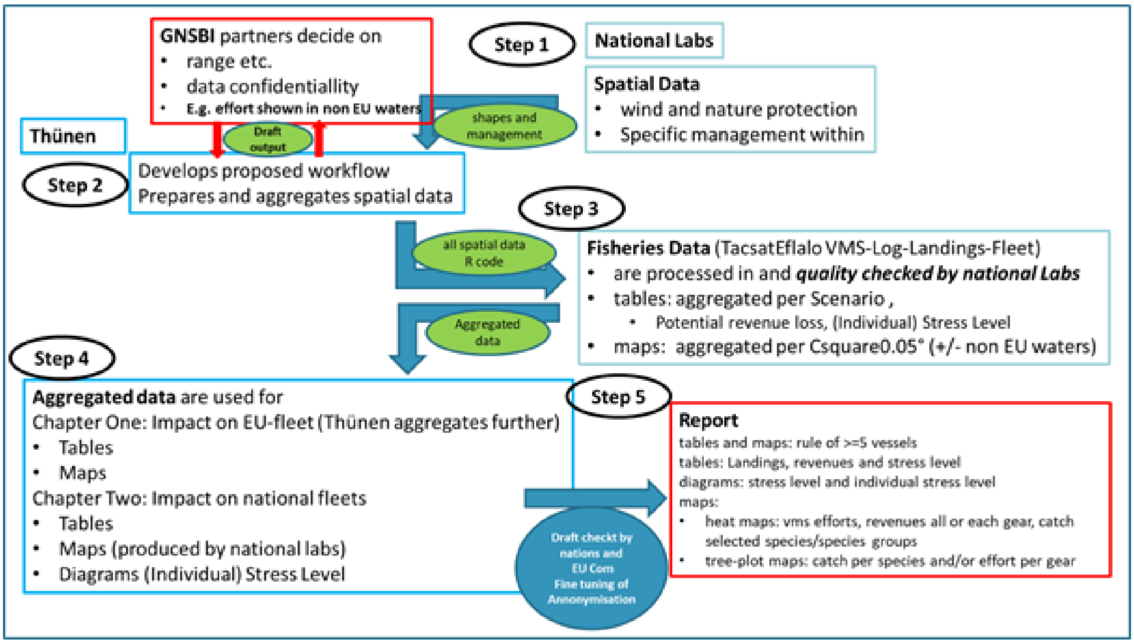

Figure. 2.12: GNSBI work track “Long-term perspective of fisheries” workflow.

The GNSBI area comprises northern waters from Ireland over Channel, Southern North Sea, German Bight up to Norwegian waters (Figure 2.13)

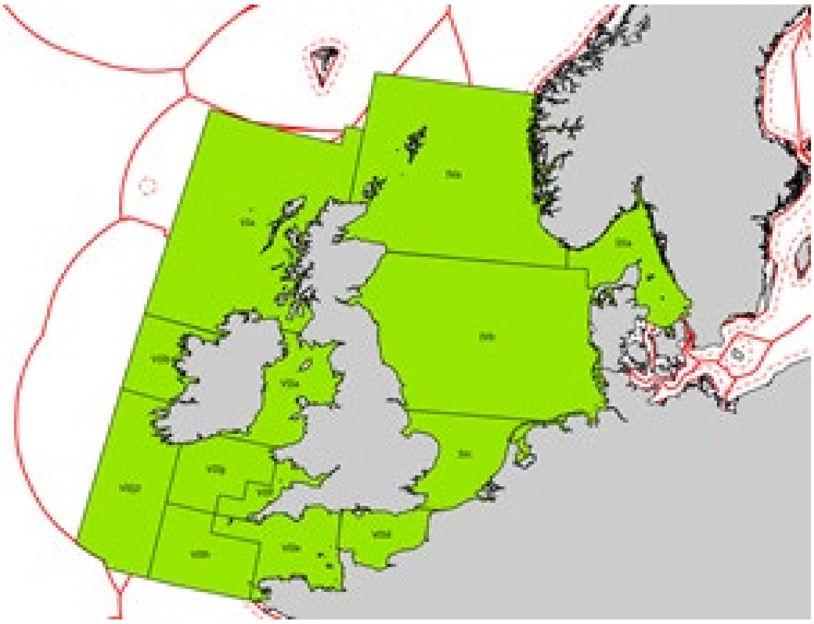

Figure 2.13: GSNBI area in green.

2.5.2 Stressors, Scenarios and Periods

The decided stressors to be included in this WT were:

a. Offshore Renewables (mostly Wind farms). To be built until latest 2030 and nationally decided to be built until end 2023 (cut-off date)
b. Nature protection. Specific Natura 2000 fisheries management decided until end of 2023 (not the designated areas in total)

From these two stressors, three scenarios were agreed on to be analyses

Nature Protection	NatPrt	Specific management in e.g. Natura 2000 areas
Offshore Renewables Wind	Wind	Specific management wind farms
Cumulative	NatPrWnd	Cumulative scenario Nature Protection and Wind

2.5.3 Confidentiality issues

Masking of effort and revenue values and cells in maps with data entities of <= 5 vessels.

2.5.4 Data pre-processing according to ICES standards

National labs have tacsat (VMS data) and eflalo (logbook, landings, vessels and trips data) formats available and tacsat and eflalo are cleaned, merged to tacsatEflalo, active pings are identified and catch and revenues are distributed to pings (see ICES VMS data call proposed workflow, ICES WGSFD report 2022). Overlay with competing areas was performed on vms positions (no aggregation to rectangles) and anonymised and aggregated data will be delivered by the WT partners.

2.5.5 Spatial data

An unforeseen challenge was the compilation of specific management data (fine scale shapes and management within) which took about 12 months. About 850 shape files were collated from WT partners (IE, BE, NL, DE, DK, SE, NO) and publicly available sources (https://kingfisherrestrictions.org, https://emodnet.ec.europa.eu/en, UK). For all shapes the (proposed) specific management was documented: exclusion of gears, time of year/season the management is in place.

2.5.6 Gears and gear classes

Ten gear/gear classes were selected by WT partners to be analysed.

pelagic trawls & seines, passive gears not entangling birds & mammals, passive gears entangling birds & mammals, demersal seines, sand eel fisheries, pandalus fisheries, demersal trawls & dredges, beam trawls targeting demersal fish, TBB targeting C. crangon, all other gears

2.5.7 Species and species classes

16 species/species classes were selected by WT partners to be analysed.

brown shrimp, flatfish of interest, flatfish others, cod, saith, gadoids others, anglerfishes, sandeels, crabs (Lobster, Rock crab) , norwgian lobster, clupeids (herring, sprat) , mullets, cephalopods, mackerels, molluscs of interest, all other species

2.5.8 Output

2.5.8.1 Mapping

Two types of maps were produced and presented to WT partners (Figure 2.14).

- Heat maps of effort, revenues and catch per species/species classes
- Tree plot maps, unscaled and scaled

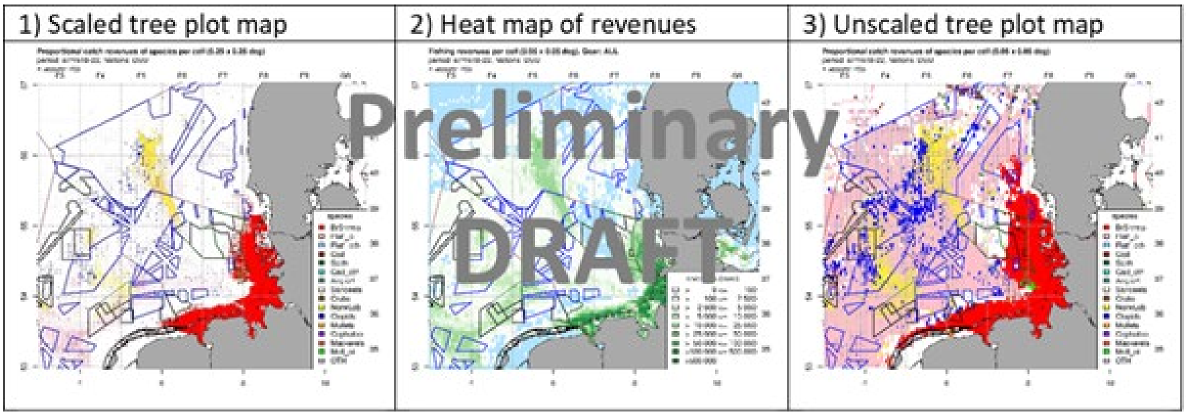

Figure 2.14: Example of scaled tree plot maps (Gerritsen and Lordan, 2014) in which the filling of cells reflects the total value in a cell in relation to the cell with the highest total value (e.g. catch weight, revenues). Scaled tree plot maps therefore combine e.g. the information of total revenue per cell like a heat map (2) and the information on catch composition by revenue e.g. per species in a cell (3).

2.5.8.2 Catch of species and revenues in future areas

Revenues per fisheries and catch per species/species classes are reported in regard to the agreed confidentiality regime (Figure 2.15).

unit	Scenario Name	Brown Shrimp	Flatfish of interest	Flatfish others	Cod	Gadoid others	Saith	Anglerfish	Sandeels	Crabs	Norway Lobster	Clupids	Mullets	Cephalopods	Mackerels	Molluscs of intrest	Others
Catch, mean yr-1 (kg)	NatPrt	441 231	931 995	161 286	44 341	134 570	19 524	19 999	1 940 793	30 247	125 096	3 610 232	59 230	26 938	199 515	149 821	1 330 421
	Wind	47 309	2 595 549	349 59[illegible]	[illegible]14	338 712	[illegible]	9 022	8 53[illegible]191	42 800	123 876	13 822 253	29 966	17 983	2 078 703	39 946	4 597 098
	NatWnd	488 540	3 485 645	498 99[illegible]	71 73[illegible]	471 [illegible]	24 [illegible]	[illegible]	[illegible]	72 [illegible]	[illegible]	17 4[illegible]485	88 496	43 842	2 278 136	188 146	5 861 048
SL_catch (%)	NatPrt	1.52	2.29	1.05	0.24	0.07	0.17	0.54	1.62	3.61	1.87	0.88	4.2	1.9	0.18	0.87	1.03
	Wind	0.16	6.37	2.27	0.15	0.1[illegible]	[illegible]04	[illegible]	[illegible]	5.[illegible]	1.85	3.38	2.13	1.27	1.83	0.23	3.56
	NatWnd	1.69	**8.56**	3.24	0.39	0.25	0.21	0.78	**8.75**	8.65	3.72	4.27	6.28	3.09	2.01	1.1	4.54

Figure 2.15: Example output of catch in future management areas and potential proportional loss (SL_catch) per species/species classes.

2.5.8.3 Stress Level profiles – Indicator of Challenge

Stress Level of specific fisheries and Individual Stress Level (ISL) profiles are produced to inform about the potential outcome of management options (Figure 2.16). ISL profiles can be produced e.g. for national fleets, harbors and coastal regions.

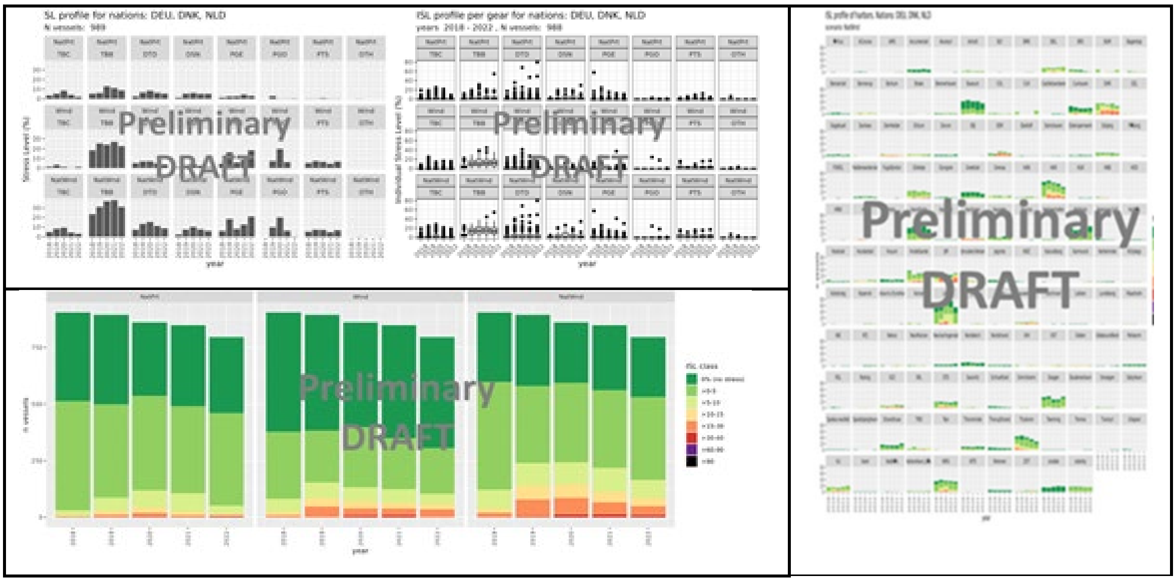

Figure. 2.16: Example output of SL (upper left) and ISL(upper middle) per gear/gear class, ISL profile of GNSBI fleet (lower left) and ISL profiles of harbour communities (right)

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3 PART 3

Review of the ecological, hydrographic, fisheries and select species impacts of ORE developments

This section addresses WKCOMPORE ToRs a.ii., iii., iv. and v. (see section 1.3) that provide the scientific basis to answer request questions d), f), g) and h) (see section 1.1):

d) Summarize the known ecological impacts of ORE developments and their intensity (severe, medium, limited, unknown) on main commercial fish species[14] for the areas listed above and at population levels (positive and negative impacts) looking at the different phases of ORE development (survey, construction, operation, decommissioning). A specific case study on the effects on recruitment of western Baltic herring and of the effects on harbour porpoises should be developed.

f) Provide a review, based on the most recent literature, to describe how changes on hydrodynamic conditions produced by ORE may change the food availability to filter-feeders and influence phytoplankton primary production;

g) Provide a review, based on the most recent literature, of the ways artificial structures could influence the colonization of new areas by species, both indigenous and non-indigenous species. Based on data available for other structures (e.g. oil & gas), also from other locations (e.g. US), extrapolate how this colonization will affect ORE developments.

h) Provide a review, based on the most recent literature, of the ways in which pelagic species (especially commercial fish species) may react to dynamic cables suspended in the water column (floating wind);

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14 species included in the ICES advice on list of Descriptor 3 species to support reporting by EU Member States under MSFD Article 17 (https://doi.org/10.17895/ices.advice.21332967)

3.1 General introduction

ToR a.ii to a.v are related to the effects of the different phases of the life cycle of fixed and/or floating offshore wind farms on marine ecosystem components:

ToR a.

ii. The known ecological impacts of ORE developments and their intensity (severe, medium, limited, unknown) on main commercial fish species for the areas listed above and at population levels (positive and negative impacts) looking at the different phases of ORE development (survey, construction, operation, decommissioning). A specific case study on the effects on recruitment of western Baltic herring and of the effects on harbour porpoises should be developed;

iii. How changes on hydrodynamic conditions produced by ORE may change the food availability to filter-feeders and influence phytoplankton primary production;

iv. The ways artificial structures could influence the colonization of new areas by species, both indigenous and non-indigenous species. Based on data available for other structures (e.g. oil & gas), and from other locations (e.g. US);

v. The ways in which pelagic species (especially commercial fish species) may react to dynamic cables suspended in the water column (floating wind);

To maximise consistency between these ToRs, experts agreed on common understanding of different life stages of (floating or fixed) offshore wind farms and pressures associated with them. In addition, we agreed on a confidence scoring strategy applied for these ToRs.

3.1.1 Fixed and Floating offshore wind farms

Due to the increasing demand for renewable energy, a growing number of offshore wind farms (OWF) are already operational and more offshore wind farms are planned. The overwhelming majority of offshore wind farms to date have been constructed as ‘fixed’ structures (Figure 3.1), often surrounded by a ‘scour protection layer’ (SPL), which is a layer of coarse stones around a foundation to prevent sediment scouring. Such SPL is needed around gravity-based and monopile foundations, which together account for almost 90% of the in installed fixed turbines (Negro *et al.*, 2017).

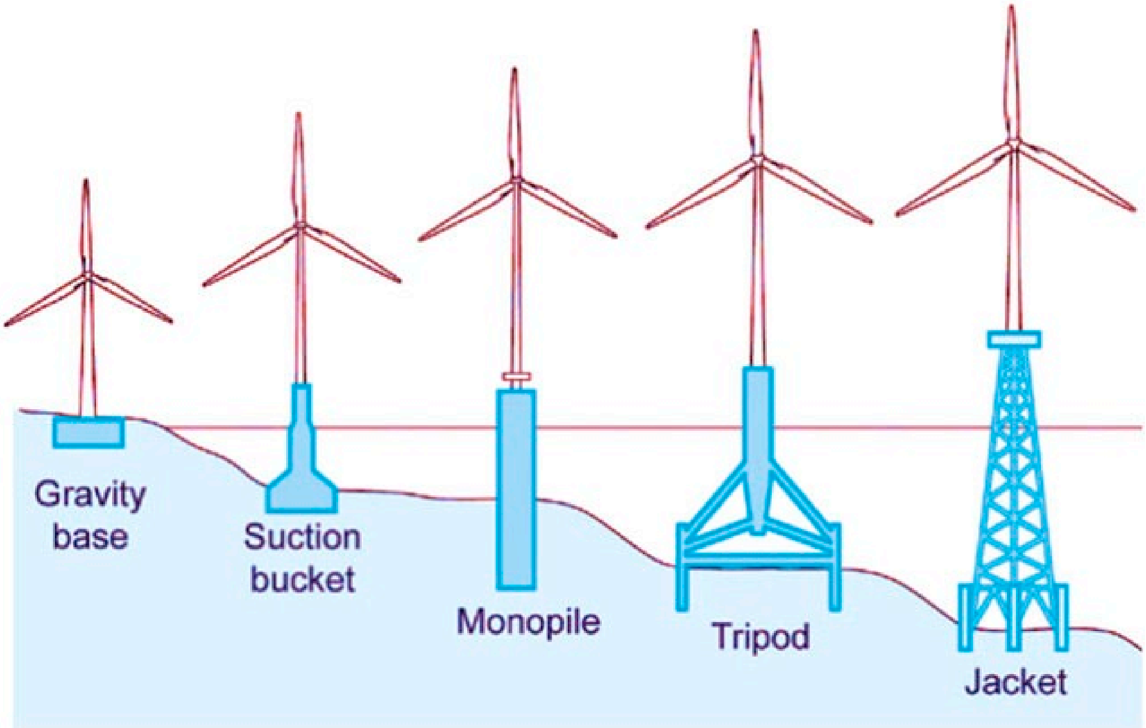

Figure 3.1 Fixed wind turbine foundations (Puruncajas et al., 2020)

'Fixed' offshore wind farms are generally constructed in shallow waters (< 70m) at a relatively short distance to shore (Díaz and Guedes Soares, 2020). However, this is not always possible in areas with narrow continental shelves and/or steep bathymetry. Accordingly, there is a relatively recent trend to test the deployment of floating offshore wind (FLOW) turbines (Figure 3.2.) in these areas, which can be installed to a depth up to 900 m (Sclavounos *et al.*, 2009). The deployment of FLOW is in its early stage, with few deployments (mostly experimental/pilot projects) in Portugal, Spain, France, UK and Norway and China (IRENA, 2024).

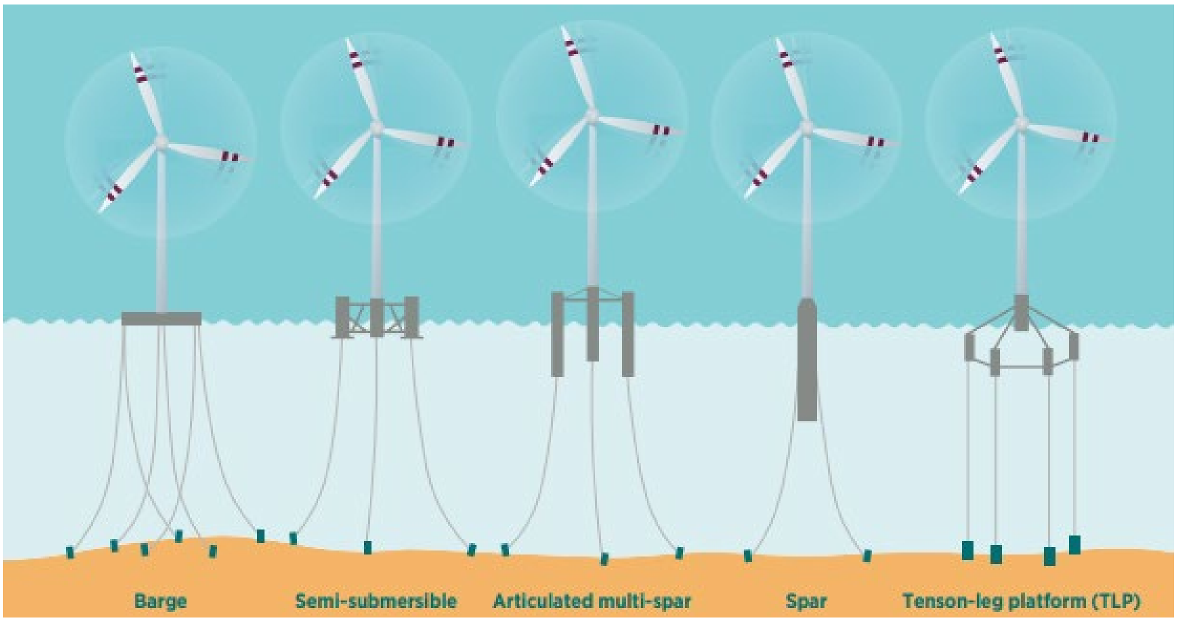

Figure 3.2 Different types of FLOW turbines foundations (IRENA 2021)

The following sections mainly report effects of fixed OWF with the exception of the report for ToR a.v) that specifically tackles potential effects of dynamic cables of FLOW on commercial fish species and ToR a. iv) in which potential effects of heating of the cables on biofouling are described.

3.1.2 OWF phases

For the sake of this report, four different phases in the lifetime of an OWF were defined. Each of them imposes specific pressures on marine ecosystems (see below). These phases are recognised both for fixed and floating offshore wind farms:

- *Pre-construction survey*: period during which the physical environment (bathymetry, sea floor, underwater heritage, obstructions, hydrodynamic conditions, etc) of a future (floating) OWF is investigated. This period ends when the survey is completed. Pre-construction pressures are only related to survey ACTIVITIES.
- *Construction phase*: period during which the OWF is built. This period starts with the first construction activity and ends when the OWF is fully constructed. Construction period pressures are related to construction ACTIVITIES (sea floor levelling, cable burial, turbine piling, SPL installation...) only and do not reflect the effects of the presence of turbines.
- *Operational phase*: starts with the end of the construction phase and ends with the start of the decommissioning activities. Pressures are related to PRESENCE of operational turbines, and maintenance ACTIVITIES.
- *Decommissioning phase*: starts with the first activities leading to removal of the OWF and ends when the OWF is fully removed. Pressures are related to decommissioning ACTIVITIES only.

3.1.3 Pressures

While the marine environment is affected during all phases of the OWF life cycle, there are differences in the nature of the underlying mechanisms, and their spatial and temporal extent. An assessment of these effects requires an understanding of the cause-effect relationships (Dannheim *et al.*, 2020) linking human activities and/or the presence of the structure with their potential effects. To assess OWF impacts in a standardised way, it is important to clearly define the pressures that cause the changes to the environment. In the context of OWF related pressures, literature (Bergström *et al.*, 2014; Wawrynskowski *et al.*2025, Galparsoro *et al.*, 2022), earlier (ICES 2011, 2019) and ongoing (WGMBRED 2025) ICES work as well as web-based tools (ORIES https://pml.ac.uk/science/offshore-renewable-impacts-on-ecosystem-services/) provide pressure lists. These lists were reviewed, harmonised and related to the OWF life phases for further use (Table 3.1).

Table 3.1 List of pressures associated with different stages of offshore wind development

PRESSURE	Pre-construction	Construction	Operation	Decommissioning
Loss of soft sediment, covered by scour protection			presence of scour protection, cable mattresses, foundation footprint	
Introduction of artificial hard substrate			presence of scour protection, cable mattresses, foundation footprint	
Change in sediment composition			fining and organic enrichment of sediment due to presence of fouling fauna on turbines	cable & SPL removal activities

PRESSURE	Pre-con-struction	Construction	Operation	Decommissioning
Sediment resuspension, transport and smothering		Piles (fixed OWF) or anchoring (FLOW) installation, cable trenching activity	Yes, scouring after installation of turbines and SPL (presence)	cable & SPL removal activities
Abrasion of sediment by seabed disturbance		cable trenching, seabed levelling activities; floating cables & moorings presence	FLOATING OWF: presence of dynamic cables and mooring installations	
Change in water current			presence of installations	
Change in stratification			presence of installations	
Introduction of Underwater noise: impulsive	seismic survey activity	UXO clearing and piling activities		possible drilling, explosions, seismic surveys
Introduction of underwater noise: continuous		noise generated by DP vessel activity	presence of devices, maintenance vessel activity	vessel traffic DP vessel activity
Electromagnetic fields	EMF survey activity		EMF from presence of cables	
Introduction of synthetic and non-synthetic contaminants			presence of corrosion protection systems, anti-fouling paints, leaking of lubricants and hydraulic fluids, particles released during abrasion of turbine bladed	
Introduction of litter			breaking of turbine blades, fires in turbines	
Collision risk		maintenance vessel activity	maintenance vessel activity	
Entanglement risk in cables	seismic survey equipment		FLOATING OWF: presence of dynamic cables	
Visual disturbance		maintenance vessel activity (and moving ORE parts)	maintenance vessel activity: moving ORE parts	presence of vessels
Introduction non-indigenous species via relocation of floating turbines		presence of floating ORE relocated from other locations to farm site	relocation activity of floating ORE between farm and ports for repairs	Relocation of floating ORE from farms to decommissioning yard

None of the pressures are present throughout the entire OWF life cycle, and the operational phase is associated with the largest variety of pressures. It is clear that some ecosystem components will be subjected to multiple pressures. The methodology to investigate multiple pressure on fisheries activities is done according to the DPSIR approach (OECD 1993) as explained in the report in ToR a vi. Pressures were therefore related to expected state changes by WKCOMPORE experts. It should be not noted that not all ecosystem components are importantly affected by all pressures and associated state changes. Pressures are considered of meaningful importance if it can be expected that they add significantly to already existing pressures (i.e. introduction of noise by vessels for maintenance is not considered as a relevant addition to noise in an area with heavy vessel traffic).

Some of these pressures are specific to the presence of (floating) OWF and formulated in such way that they can be linked to the receptors defined in the WKCOMPORE Terms of Reference. To facilitate comparison with other frameworks, the identified pressures and corresponding state changes were mapped to the pressure defined by the Marine Strategy Framework Directive (MSFD; Table 3.2).

Table 3.2. Pressure/Impacts defined by WKCOMPORE experts (left column) and their relationship to MSDF themes and pressures (right column).

Impact COMPORE	Corresponding MSFD– pressures (consolidated version June 2017 Table 2 - https://eur-lex.europa.eu/eli/dir/2017/845/oj/eng)	State change
Loss of soft sediment, covered by scour protection	Physical - Physical disturbance to seabed (temporary or reversible)	Sediment/ nutrient/ contaminant fluxes
Introduction of artificial hard substrate	*Not covered by MSFD*	Colonization of hard substrate
Change in sediment composition	Physical - Physical disturbance to seabed (temporary or reversible)	Sediment/ nutrient/ contaminant fluxes
Sediment resuspension, transport and smothering	Physical - Physical disturbance to seabed (temporary or reversible)	Sediment/ nutrient/ contaminant fluxes
Abrasion of sediment by seabed disturbance	Physical - Physical disturbance to seabed (temporary or reversible)	Sediment/ nutrient/ contaminant fluxes
Change in water current	Physical – Change to hydrological conditions	Turbulent wakes, wind wakes
Change in stratification	Physical – Change to hydrological conditions	Changed thermal stratification
Underwater noise: impulsive	Substances, litter and energy - Input of anthropogenic sound (impulsive, continuous)	noise
Underwater noise: continuous	Substances, litter and energy - Input of anthropogenic sound (impulsive, continuous)	noise
Electromagnetic fields	Substances, litter and energy - Input of other forms of energy (including electromagnetic fields, light and heat)	noise
Introduction of synthetic and non-synthetic contaminants	Substances, litter and energy - synthetic substances, nonsynthetic substances, radionuclides) — diffuse sources, point sources, atmospheric deposition, acute events,	Sediment/ nutrient/ contaminant fluxes
Introduction of litter	Substances, litter and energy - Input of litter (solid waste matter, including micro-sized litter)	Sediment/ nutrient/ contaminant fluxes
Collision risk	Biological - Disturbance of species (e.g. where they breed, rest and feed) due to human presence	collision
Entanglement risk in cables	Biological - Disturbance of species (e.g. where they breed, rest and feed) due to human presence	entanglement
Visual disturbance	Biological - Disturbance of species (e.g. where they breed, rest and feed) due to human presence	Changed light clues
Introduction of non-indigenous species via relocation of floating ORE	Biological - Input or spread of nonindigenous species	Colonization of hard substrate

It is clear that the MSFD pressure list is at a higher level when compared to the list identified by WKCOMPORE experts (e.g. the MSFD pressures). Physical disturbance to seabed (temporary or reversible) is reflected by four different pressures recognised for documenting pressure-receptor links. It must be noted that the offshore wind pressure 'introduction of artificial hard substrate,' resulting in alteration of hydrodynamical conditions (ToR a iii), and colonisation by indigenous and non-indigenous species (ToR a iv) is not recognised by the MSFD pressures.

3.1.4 Confidence

While many bottom fixed OWF are currently present in the marine environment, there is still a scarcity in sound scientific knowledge on the effect of these structures at different spatial (local to regional) and temporal (days to decades) scales. The current knowledge is often derived from relatively short-term monitoring efforts, that are rather targeted towards documenting changes at the wind farm scale while a sound understanding of cause-effect relationship and underlying mechanisms is needed to provide the knowledge supporting energy policy developments, planning decisions and potential mitigation actions (Hooper et al., 2017; Dannheim et al., 2020). Furthermore, access to offshore wind farms for scientific research is often limited due to security reasons or hampered by the presence of turbines (Coolen *et al*., 2022; Lipsky et al., 2024). As such, the information provided here is often based on indirect knowledge (e.g. on knowledge of similar species, or similar pressure-receptor links in other environments, or at other types of structures) and/or expert knowledge. To take into account these shortcomings in the scientific knowledge base supporting the different parts of this report, we used a confidence scoring scheme (adopted from Dannheim et al., 2020) to reflect our confidence in the reported findings and recommendations. Confidence was classified as 'low' when information has been derived from sources that only cover general understanding of the cause-effect relationship, or by "informed judgement" where very little or no information is present at all on the cause-effect relationship. 'Moderate' confidence reflects a situation where information has been derived from sources that consider comparable effects of a particular cause-effect relationship or outside the area of interest. Confidence was scored as 'high' when information has been derived from sources that specifically deal with the cause-effect relationship of ORE in the area of interest and experimental, modelling or field work has been done to investigate the specific cause-effect relationship.

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3.2 ToR a.ii. The known ecological impacts of ORE developments and their intensity (severe, medium, limited, unknown) on main commercial fish species for the areas listed above and at population levels (positive and negative impacts) looking at the different phases of ORE development (survey, construction, operation, decommissioning). A specific case study on the effects on recruitment of western Baltic herring and of the effects on harbour porpoises should be developed;

CASE STUDY: Potential Impact of Offshore Wind Farms (OWF) on commercial fish species for the North Sea, Celtic Sea and Baltic Sea

3.2.1 Confidence statement

The application of the trait-based assessment framework is composed out of multiple steps where different types of information is gathered and combined to be used in a next step. Linking the OWF-induced state changes to fish population characteristics has been done by expert judgement and the published current knowledge base of cause-effect relationships. This step is ranked with a moderate confidence.

Identifying response traits and their modalities and linking them to the population characteristics was done largely based on expert judgement and is ranked with low confidence. The information on the degree of trait modality association was largely based on primary literature. However, the information is not tailored to a specific region. This step is ranked with a high confidence. Final vulnerability scores are based on a sum of the impact scores. There is, however, uncertainty about the degree of impacts from different state changes on the different traits and therefore this step receives a low confidence. Therefore, we rate the overall certainty of the chapter's content as moderate.

3.2.2 Key findings

- Assessing the potential impact of offshore wind farms (OWF) (fixed and floating) on commercial species requires a detailed understanding on how related human operations and the pressures they exert cause environmental effects leading to population-level impacts across spatial and temporal scales.
- Combined pressures caused by OWFs and broader influences like climate change create and other human pressures cause cumulative risks, demanding integrated environmental assessments such as cumulative effects assessments (CEA) and multi-scale management strategies.
- Our trait-based framework (TAFOW) links OWF-induced state changes to population characteristics and response traits, allowing to assess species vulnerabilities to all phases of OWF life cycle.
- Applied to 34 commercial species in the North Sea, Celtic Sea, and Baltic Sea, TAFOW identified sediment resuspension as the most impactful state change, with highest vulnerabilities in the Celtic Sea driven by larval dispersal and predator-prey interactions.
- Our assessment revealed that from the 34 commercially most important fisheries resources, herring, great scallop, and monkfish are the most vulnerable species across the three regions.
- Trophic interactions and recruitment survival of fisheries resources are particularly vulnerable population characteristics to pressures that are exerted by operational OWF.

3.2.3 Data gaps and research needs

Research on OWF effects emphasizes physical and hydrodynamic habitat changes, such as hard substrate colonization and turbulence, and sensory disruptions from energy emissions (e.g., underwater noise, electromagnetic fields). Anthropogenic pollution and impacts on vulnerable early life stages like eggs and larvae are underexplored. Indirect effects, such as prey availability and water circulation changes, are difficult to scale to population impacts. Observed effects vary by species, with some benefiting from increased abundance near OWFs, while others face stress from sediment resuspension.

Current research is based on localised effects of OWFs on commercial and non-commercial fish. There is a need for upscaling of OWF effects to the population level to identify potential large-scale effects. Further research on the effects of OWFs on species traits could help us to understand mechanistic relationships and quantify potential impacts at population and fish community level, rather than focusing solely on individual species.

3.2.4 Recommendations

- While this study provides initial insights, comprehensive risk analyses require resilience estimates, spatial-temporal overlap assessments, and harmonized monitoring strategies. Integration with ICES working groups is essential to refine population-level impact assessments of OWFs.
- This assessment is using an approach that can relatively easily be repeated with updated knowledge.

3.2.5 Summary

The relationship between OWF activities and their pressures on ecosystems that commercial species inhabit, involves understanding causal pathways linking human operations to environmental effects that can lead to population-level impacts across spatial and temporal scales. Combined pressures from local OWF activities and broader influences like climate change create cumulative risks to ecosystems, necessitating integrated assessment of environmental impacts and multi-scale management strategies.

Current research on OWF effects on commercial species focuses on physical and hydrodynamic habitat changes, such as hard substrate colonisation and turbulence respectively, and sensory environment changes relating to energy emissions (e.g., underwater noise and electromagnetic fields). Furthermore, anthropogenic pollution is a further cause of potential effects on these species. The knowledge base tends to focus on the adult life stage with limited knowledge of impacts on vulnerable early life stages of fisheries resource species, like eggs and larvae. Indirect effects, such as altered prey availability and water circulation, are challenging to up-scale to population-level impacts. Observed impacts vary by species and context, with some species showing increased abundance near OWFs and others being detrimentally affected through the stress of sediment resuspension.

To address such knowledge gaps, a trait-based framework (TAFOW) is introduced that links OWF-induced state changes to fish population characteristics and species response traits, using traits like behavioural plasticity or salinity tolerance to assess vulnerabilities. TAFOW allows to assess the vulnerabilities of fish and some invertebrates to state changes caused by the pressures related to the construction, operation and decommissioning of OWF. The framework is exemplified for 34 commercially relevant fisheries species in the North Sea, Celtic Sea, and Baltic Sea considering only the state changes and pressures related to operational fixed bottom installed OWF.

In general, results revealed that the population characteristics recruitment survival and trophic interactions are highly vulnerable to the state changes caused by operational OWF. Applying the trait-based framework showed that sediment resuspension emerged as the most negatively impactful state change for the here considered response traits and species. Hence almost 50% of the commercial species in each region had highest vulnerabilities in relation to sediment resuspension.

The total sum of vulnerability scores identified herring, great scallop, and common monkfish as the most vulnerable species. Flatfish like sole, plaice, and turbot, along with crustaceans such as brown crab and European lobster, also showed high vulnerability scores. Other commercial species, including squid, sandeel, and Norway lobster, demonstrated elevated vulnerability levels. However, because the relation between response traits and the population characteristics was drawn with rather low confidence, more or different species could be classified as highly vulnerable with increasing knowledge.

While this study offers initial insights by quantifying potential impact of the state changes caused by operational installed OWF on commercially important fisheries resources, a comprehensive risk analysis should also entail estimates for population resilience, for example, through life history traits, and spatial and temporal overlap analysis with OWFs. The actual spatial and temporal overlap of respective population characteristics with the spatial footprints and frequencies of the pressures will ultimately determine the degree of impact. In the future, harmonized monitoring strategies that cover a range of habitats and integration with ICES working groups are essential to advance population-level impact assessments of OWF.

3.2.6 Current knowledge base on the effects of OWF on fish populations

3.2.6.1 Identifying causal pathways for the effects of OWF and management responses

In section 3.7 of this request, the relationship between the activities related to the life cycle of OWF installations and the related environmental changes and pressures they exert are described in detail. The identification of causal pathways entails a profound understanding of human activities or operations and the related mechanisms (state change and pressures) that can result in adverse effects on respective ecosystem components (Stelzenmüller et al., 2018). As described in detail in (Elliott et al., 2020), human activities have a spatial and temporal component, an intensity, duration and frequency component. The resulting pressures will also have these components and will therefore affect the environment at different spatial and temporal scales and with different intensities. Disentangling cause-effect pathways is supported by a number of conceptual frameworks (e.g. DPSIR) which provide guidance on how to link activities to generic pressures and to physical, chemical and biological attributes, and then translate the impacts into policy responses (Elliott and O'Higgins, 2020).

In this context, the total man-made pressure load in and around OWF licence areas depends on the respective development stage and specific local context, such as proximity to other human activities exerting similar types of pressures. For example, other human activities, such as sand and gravel extraction or fishing, exert similar pressures as those from OWF. In addition, other pressures originating from outside the area of interest entailing climate change, effects of ocean acidification and sea-level rise or contaminants, increase the complexity and overall pressures load within a seascape. In particular, the effects of climate change on commercially exploited fish species may lead not only to changes in spatial species distribution but also to recruitment failures due to mismatches in food variability during critical life stages and subsequent regime shifts in ecoregions (Sguotti et al., 2022). Taken together, combined local pressures and large-scale natural disturbance increase the risk of adverse cumulative impacts on fish populations also at regional levels (Cormier et al., 2022).

Mitigating unwanted effects particularly across various spatial scales requires management responses implemented through a programme of measures. In turn, this requires knowledge of the area in which the human activities take place, the area covered by the pressures generated by the activities on the prevailing habitats and species in which pressures are defined as the mechanisms of change, and the area over which any effects (whether adverse or beneficial) occur on both the natural and human systems (Cormier et al., 2022). In practice, this means that environmental impact assessments for offshore renewable energy (ORE) licensing sites need to be integrated with regional environmental assessments for maritime spatial plans (Stelzenmüller et al., 2021). This needs to be further aligned to regional sea assessments that determine good environmental status (GES), as required by the Marine Strategy Framework Directive (MSFD; (EC, 2008)).

The need for multi-scale assessment of environmental impacts and the need for equally multi-scaled management responses leads to the question of fit-for-purpose benchmarks or thresholds for evaluating the level of impact or risk. The co-occurrence of many species allows the defining of community tipping points, which reflect compositional community changes along gradients of multiple human induced pressures (Kraan et al., 2024). The authors applied machine learning clustering algorithms to group species into defined categories according to their responses. This approach allowed to address multiple human activities at various scales. However, their results showed that man-made structures, such as submarine power cables and offshore wind farms, had only a marginal effect on structuring fish and benthic communities. This illustrates that at a North Sea wide assessment scale, the rather local effect of OWF on epibenthos and demersal fish communities was not detected, since samples and available data were not at the appropriate spatial scale (Kraan et al., 2024). Thus, the mismatch of assessment scales and the lack of monitoring data from OWF areas and their proximity often hampers the evaluation of the effect sizes of ORE on fish and fisheries (Gill et al., 2020; Stelzenmüller et al., 2022).

3.2.6.2 Effects of ORE on fish populations

The general effects of human activities and operations related to OWF on fish populations have been increasingly studied and reviewed over the past ten years (Gill et al., 2024). Current research focuses on the impacts caused by the installation, presence of devices and infrastructure and decommissioning causing local state changes with respect to the level of pollution, noise and electromagnetic effects or the type of habitat or habitat quality (Kulkarni and Edwards, 2022).

As outlined in (Gill et al., 2024) the current knowledge base is largely limited to adult fish life stages, with clear knowledge gaps regarding particularly essential fish habitats, such as spawning or nursery areas. Effects from disturbance of these habitats could propagate through the fish life cycle and have subsequent impacts at the population level. Hence, OWF influence the fish early-life, including egg, larval and juvenile stages through various direct mechanisms, such as electromagnetic emissions, underwater noise, and chemical pollution (Öhman et al., 2007; Svendsen et al., 2022) The effect of changes in the hydrodynamic regime is detailed in section 3.3 of this report and the effects of noise and electromagnetic fields are explained under section 3.5.

In contrast, indirect effects on early life stages includes alterations in water circulation, prey availability, and predation. Fish early-life stages, particularly eggs and larvae, have a limited capacity to actively escape harmful stressors or affected areas. One of the key knowledge gaps is how to quantify the local-scale impacts of OWFs on the early-life stages of fish and scale them up to the population level relevant for management (Gill et al., 2024). The ICES Working Group of Offshore Wind Development and Fisheries (WGOWDF) is currently developing a comprehensive database that links potential cause effect pathways to existing evidence and observed direct and indirect effects.

Therefore, assessing OWF effects at population levels requires a detailed understanding of the above-described causal pathways between the pressures exerted by the human activities and operations associated with the different life cycle stages of OWF to response traits of fish. In Table 3.3, we briefly summarise the current knowledge on observed direct effects of OWF life cycle stages on the adult and juvenile fish, as well as larvae. Here, we neglect the effects of surveys within OWF licence areas, as they are very punctual and can be neglected in the light of larger scale fish monitoring and surveys conducted at larger scales.

Table 3.3: Brief overview of observed direct effects of OWF on adult fish, juveniles, and fish larvae. Note this is not deemed to be a comprehensive review but reflects a common understanding.

Life stage	Effect Type	Life cycle OWF	Observed direct effects of OWF	References
Adult	Habitat change	Operation	Delays in migration and reaching their destinations can negatively affect their spawning activities.	(Hawkins, 2020); (Westerberg and Lagenfelt, 2008)
	Habitat change	Operation	Increased abundance and (temporary and seasonal) aggregation of soft-bottom and complex-bottom species near OWFs; such as cod, plaice, dab, haddock or pouting; increased species diversity and changes in community composition. Several observational studies indicate that complex-bottom oriented species are attracted by the turbines and scour protection of offshore wind farms. The effects of OWFs on soft-bottom associated species remain conflicting. Some studies show no effects from OWFs on soft-bottom species, while other studies indicate negative effects	(Bergström et al., 2013; Gimpel et al., 2023; Methratta and Dardick, 2019; Stenberg et al., 2015; Bicknell et al., 2025) (Andersson and Öhman, 2010; Krone et al., 2013; Reubens et al., 2014; Reubens et al., 2013; Stenberg et al., 2015; van Hal et al., 2017; Wilber et al., 2022) (Krone et al., 2013; Lindeboom et al., 2011; van Deurs et al., 2012) (Buyse et al., 2022)
	Habitat change	Operation	Changes in diet and feeding behaviour, such as e.g. increased consumption of mussels and associated epifauna colonizing the turbines. However, substantial changes in overall dietary habits are not consistent. Some observational studies particularly indicate a strong aggregation of piscivore fish around OWF structures.	(Gimpel et al., 2023; Mavraki et al., 2021; Wilber et al., 2022; Buyse et al., 2023) (Methratta and Dardick, 2019)
	Noise	Operation and construction	Noise can adversely affect fish that rely on sound for spawning behaviours such as Atlantic cod.	(van Hoeck et al., 2023; Gimpel et al., 2023)
	Noise and EMF	Operation and construction	Noise and electromagnetic fields can influence fish behaviour, development and physiology, including species such as salmon, sea trout, cod, haddock, crabs and lobsters. Some studies suggest minor effects on fish orientation and movement, but evidence is limited and not conclusive. Limited in situ data are available to make any clear predictions on how electromagnetic changes affect sensitive species such as rays and sharks. Fish rely on sound for communication, prey detection, predator avoidance and orientation. Noise from OWFs, particularly during pile driving, can mask critical biological sounds, alter behavior, and potentially cause injury or death.	(Annebelle et al., 2021; Hawkins, 2020; Duarte et al., 2021; Hutchison et al., 2018; Popper and Hawkins, 2019) (Hermans et al., 2023; de Jong et al., 2020; McQueen et al., 2024; Simpson et al., 2016)

Life stage	Effect Type	Life cycle OWF	Observed direct effects of OWF	References
Juvenile	Noise	Construction	In situ pile driving experiments showed no immediate or delayed mortality of juvenile sea bass (*Dicentrarchus labrax*), but led to stress responses such as reductions in oxygen consumption rate and low whole-body lactate concentrations.	(Debusschere et al., 2014; Debusschere et al., 2016)
	Noise	Operation	Juvenile black rockfish (*Sebastes schlegelii*) exposed to wind farm noise showed temporary hearing threshold shifts	(Yining et al., 2023)
	Noise	Operation	Juvenile black rockfish (*Sebastes schlegelii*) exposed to wind farm noise showed altered swimming and feeding behaviors, indicating potential fitness consequence.	(Yining et al., 2023)
	EMF	Operation	Swimming speed of juvenile Atlantic Lumpfish (*Cyclopterus lumpus*) was reduced by 16% due to EMF exposure	(Durif et al., 2023)
Eggs and larvae	Turbidity	Operation and construction	Turbulences and mixing can influence survival rates and availability of patches of larvae food	(Schilling, 2020)
	Noise	Operation and construction	Noise can affect sea bass larvae which can influence their survival and development. Continuous noise can affect cod larval development	(Debusschere et al., 2016)
	Noise	Operation	Low-frequency noise affects swimming orientation of Atlantic cod (*Gadus morhua*) larvae	(Cresci et al., 2023)
	EMF	Operation	Larval swimming speed was reduced by 60% due to EMF exposure (lab experiments) haddock larvae (*Melanogrammus aeglefinus*)	(Cresci et al., 2022)
	EMF	Operation	Accelerated rate of embryogenesis of northern Pike (*Esox lucius*) due to EMF	(Fey et al., 2019)

Overall, there are three main pathways causing direct and indirect effects on fish: i) changes of habitats and associated colonising fauna through the OWF infrastructure (Degraer et al., 2020; Glarou et al., 2020), ii) changes of local and regional hydrodynamic regimes, and iii) noise and electromagnetic fields (van Berkel et al., 2020). In summary, the effects in relation to introduced hard substrates comprise increases in some fish abundance and diversity (Gill et al., 2024), causing also changes in dietary habits and potential effects from noise and electromagnetic fields.

Changes of local and regional hydrodynamics, including turbulence, mixing, and vertical stratification lead to temporary changes in fish behaviour and movement. The effects of noise and electromagnetic fields on fish behaviour and physiology are complex and seem to be specific to species- and their life-stages. Here, we work on the basis that the magnitudes of the observed effects (Table 3.3) vary regionally and are context-dependent. Thus, the prevailing overall pressure load (see section 3.1) within a seascape determines the vulnerability of fisheries resources to state changes generated by the pressures related to OWF life cycles.

3.2.7 A trait-based assessment of the vulnerability of fish populations to the life cycle of OWF

3.2.7.1 Linking OWF pressures, state changes and response traits

The limited knowledge and lack of empirical evidence highlights the barrier to quantifying impacts on fish populations in a way that is meaningful for management responses. Therefore, we introduce an assessment framework that addresses the ecosystem state changes (see section 3.2.7) in relation to the life cycle of OWF as well as all life stages of fisheries resources. Building on the work of the ICES Working Group WGOWDF, we defined the state changes caused by pressures related to the OWF life cycle (Table 3.4), as well as nine population characteristics that reflect the different life stages of fisheries resources (Table 3.5).

Table 3.4: List of general state changes that are related to the pressures exerted by the different activities and operations throughout the life cycle of OWF (construction, operation, decommissioning).

State change	Abbreviation	Explanation
Sediment resuspension	Sed_res	Process of particles being resuspended into the water column and inter alia causing turbidity.
Sediment deposition	Sed_depo	Deposition of sediment from the water column on the floor
Colonization of hard substrate (at monopiles and scour protection)	Col_hard_sub	The colonization of monopiles by fouling communities, which in turn attract other species.
Sediment/nutrient/contaminant fluxes	Sed_Nut_Con_flux	Fluxes and transport of sediment, nutrients, and contaminants across OWF boundaries
Changed seabed-water column (stratification, mixing)	Strat_mix	Variations in water mass stratification and mixing that modify the exchange of fluxes between the seabed and the water column
Turbulent wakes	Turb_wakes	Chaotic flow pattern behind monopiles.
Changed thermal stratification	Thermal_strat	Changes in thermal stratification of the water column.
Changed energy emissions/ environment (noise)	Noise	Changes in electromagnetic and noise emissions.
Changed light cues	Changed_light	Changes in light pattern affecting the light sources that are used for migration, feeding, etc.
Wind wakes	Wind_wakes	Disturbed air flow behind the wind farms

Table 3.5: List of nine population characteristics that address adult, juveniles and larvae of fish used for this report.

Population characteristics	Abbreviation	Life stage
Altered aggregation	Altered_agg	Adult
Altered distribution	Altered_dist	Adult
Altered migration	Altered_mig	Adult
Changed colonisation	Changed_col	Adult
Changed feeding patterns	Changed_fee	Adult
Larval dispersal (passive or active)	Larval_disp	Eggs and larvae
Predator-prey interactions	Pred_pray_in	Adult
Recruitment (survival of the juveniles)	Rec_survival	Juveniles
Reproduction	Reproduction	Adult

The third pillar of our assessment framework (hereafter referred to as trait-based assessment framework for assessing the vulnerability of fish populations to OWF; TAFOW) is a set of response traits that allow us to quantify the potential effects of those state changes on the defined population characteristics. Hence, species' traits reflect their vulnerability to a given pressure and allow for a mechanistic insight into how species interact with, react to, and shape their habitats. Thus, in a trait-based "response-and-effect framework", traits that respond to environmental gradients ("response traits") are distinguished from traits that affect ecosystem processes ("effect traits") (Beukhof et al., 2019; Hadj-Hammou et al., 2021). An example is the disproportionate effect of trawling on large fish measured by the large fish indicator (Greenstreet et al., 2012).

Drawing also on the expertise across the ICES Working Groups related to offshore renewables (WGMBRED, WGORE, WGOWDF), we identified a set of response traits (reflecting all life-stages of fish) and their modes that allow for the assessment of responses to the defined state changes (Table 3.6).

Table 3.6: List of 14 response traits and trait modes that reflect the response to state changes induced by the activities and operations associated to the life-cycle of OWF.

Response traits	Trait modes
Behavioural plasticity (i.e., migration shifts and habitat switching)	High Low
Diet specialization	Generalists Specialists
Fecundity	High Moderate Low
Feeding behaviour	Group feeders Solitary

Response traits	Trait modes
Feeding mode	Benthivores
	Detritivores
	Herbivores
	Piscivores
	Planktivores
Feeding time	Diurnal
	Nocturnal
Habitat dependence /resilience to habitat alteration	Generalists
	Specialists
Habitat selection/spawning location	Demersal spawners
	Egg guarders
	Egg hider
	Pelagic spawners
	Viviparous
Migration behaviour (or migrating pattern)	Life-stage migration
	No migration
	Seasonal migration
Oxygen tolerance	Hypoxia-sensitive
	Hypoxia-tolerant
Salinity tolerance	Large tolerance
	Small tolerance
Sensory adaptations	Electrosense and magnetosense *
	Mechanosense (Lateral line)
	Smell and taste
	Hearing
	Vision
Thermal tolerance (Biogeographic affinities)	Arctic
	Atlantic
	Boreal
	Lusitanian

Response traits	Trait modes
Trophic level	Apex predator
	Primary consumer
	Secondary consumer

*** note electric relates to feeding and magnetic relates to migration and orientation.**

TAFOW combines those three tables in one "look up" table which reflects the linkages for each combination of state change, population characteristics, and response traits (Annex 3). From this "lookup table" any causal pathway can be selected by choosing the relevant state changes, population characteristics and traits. In Figure 3.3, the defined linkages between state changes and population characteristics are illustrated as a network. Following the definition of direct and indirect effects provided in (Tulloch et al., 2022), the linkages (hereafter referred to as edges) represent direct effects on the population characteristics caused by the state changes. Two types of information can be extracted from the network of state changes and population characteristics (Figure 3.1), first the number of edges connecting population characteristics and state changes. Second, the representation of an edge by the total number of traits (indicated by the relative edge width) that express how well this can be measured. For instance, the population characteristics of predator-prey interactions and changed feeding behaviours are affected by many different state changes, as opposed to altered migration which is caused by the colonisation of hard substrate, noise, EMF and/or sediment resuspension. This suggests that trophic relationships are more vulnerable to the OWF related pressures as the other population characteristics such as altered migration. Further the new hard substate triggers change across many population characteristics, while thermal stratifications cause changes in feeding behaviour, larvae dispersal, prey-predator interactions, and recruitment survival. The latter suggests that this state change can have adverse effects, in particular on early life stages of fisheries resources.

TAFOW is applicable for all causal pathways linked to the pre/construction, operation and decommissioning of OWF. We do acknowledge the rising discussions regarding the best solutions for decommissioning of OWF with the aim to enhance environmental targets (Knights et al., 2024). However, causal pathways considered here do not further differentiate various decommissioning scenarios which would result in different activities and types of operations.

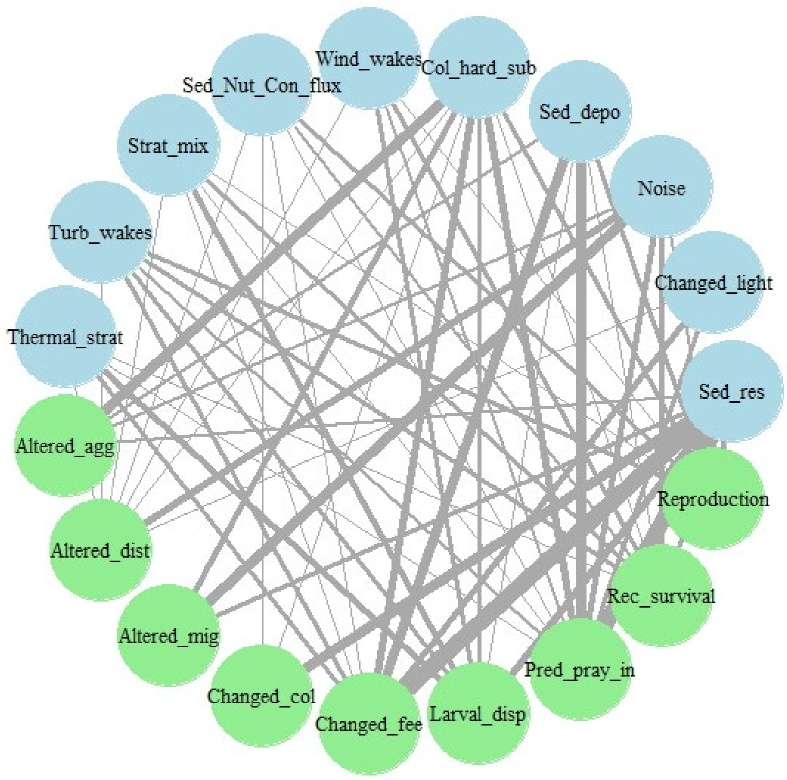

Figure 3.3: Network representation of the risk pathways for the population characteristics considered here (green nodes; see Table 3.5 for abbreviations) and the state changes caused by all human activities or operations and their pressures related to the life cycle of OWF (blue nodes; see Table 3.4 for abbreviations). Connections (called edges) represent pathways, and the width of the edge is proportional to the number of response traits reflecting that effect.

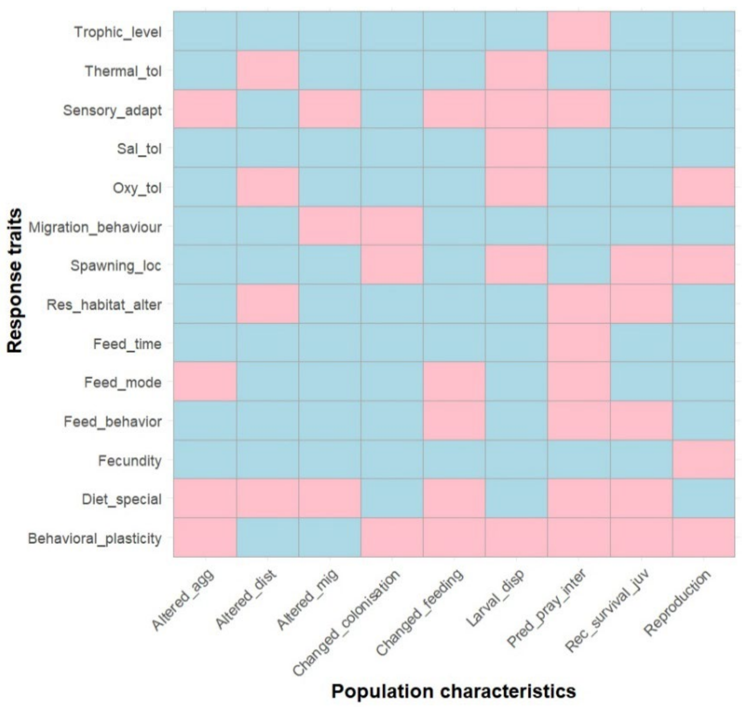

Figure 3.4: Matrix representing the links (pink) between the defined nine population characteristics and the respective response traits that reflect the OWF related effects; blue cells indicate the absence of a link.

The representation of traits across the population characteristics is shown in Figure 3.2. Hence, the matrix indicates the relationship between a response trait and the defined population characteristics (pink cell). We defined as a rule of thumb that TAFOW should address each population characteristic by at least three response traits. However, larvae dispersal and the recruitment survival of juvenile are reflected by six and five traits, respectively. The next step of our framework is key and entails defining a narrative for an impact for each response trait mode caused by the state changes that are expected from OWF construction, operation, or decommissioning (Table 3.4). For each causal pathway, it is determined whether the response of a trait to a state change is positive (+1), neutral (0), or negative (-1), providing the means to quantify the direction of impact (Annex 4 contains an example narrative table). Positive effects are regarded as general benefits; hence no further benchmarks are defined. In a next step, the species of interest need to be classified into the different modes of the 14 response traits using a 'fuzzy coding' approach, where species are assigned affinity values from 0 (none) to 4 (complete) expressing their affinity to each modality (Chevene et al., 1994). The final step of the framework requires the connection of the narrative of expected impact with the values of the trait modes. In the subsequent section, we describe in detail the application of TAFOW to fisheries resources in the North Sea, Baltic Sea, and Celtic Sea.

3.2.7.2 Potential OWF impacts on species populations in regional seas

Selection of fisheries resources

We used the regional lists of commercially relevant taxa provided by ICES for each MSFD (sub)region covering also the Greater North Sea, Celtic Sea and Baltic Sea (ICES, 2022) to select the fisheries resources. The regional species lists are based on landing weights and landing values (€) aggregated by EU Member States from FDI landings data covering the period 2015–2020 and include UK landing statistics (ICES, 2022). Since this request is related to fisheries species, we used landing values to select a subset of species for each region and set a threshold value of 90% for the cumulative contribution to the total landing value. For the three regions, the fisheries' target species comprise fin fish, molluscs, and crustaceans which contribute 90 % of the total landing value (Annex 5). In Figure 3.5 the value of landings is presented by species and region, indicating the relative contribution of the 34 fisheries species to the total value of landings across the three regions. The two pelagic species mackerel (*Scomber scombrus*) and herring (*Clupea harengus*) are the most valuable resources in the North Sea, Celtic Sea (mackerel), and Baltic Sea (herring).

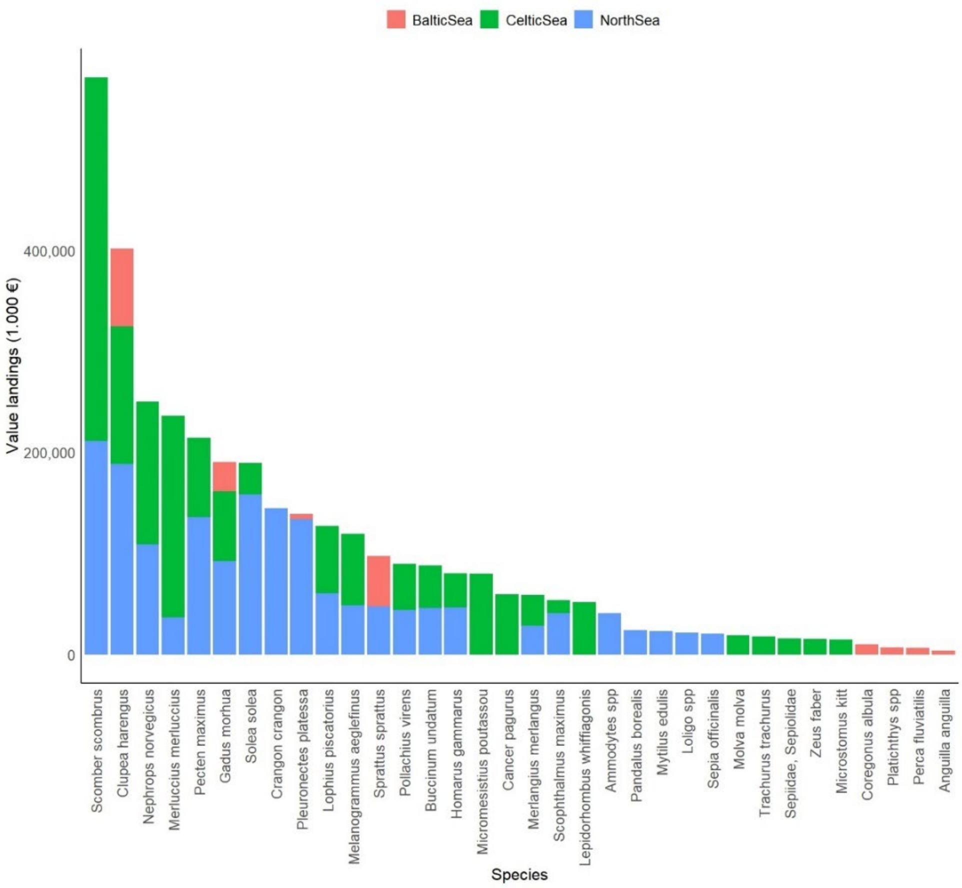

Figure 3.5: Total landings (1000 €) by species in the Greater North Sea, Celtic Sea, and Baltic Sea. The figure includes all species contributing to 90% of the total landings in each region.

Quantifying vulnerabilities of fisheries resources to OWF induced state changes and pressures

Here, we assess the impacts of operating OWFs on the above selected 34 fisheries resources in the Greater North Sea, Celtic Sea and Baltic Sea. For this we identified from the lookup table the causal pathways between the related state changes, key population characteristics and response traits. These characteristics were chosen to encompass essential aspects of the adult, juvenile, and larval phases of fish populations, specifically addressing recruitment (juvenile survival), predator-prey interactions, altered distribution, larval dispersal (both passive and active), and reproduction (see Table 3.3).

As described in section 3.1 we identified response traits that show a responsiveness to state changes only associated with the operational phase of OWFs, resulting in 17 causal pathways. These pathways encompassed traits such as feeding behaviour, sensory adaptations, behavioural plasticity (e.g., migration shifts and habitat switching), and habitat use. According to the description above we described the narrative and indicated if a response of a trait to a state change would be positive (+1), neutral (0), or negative (-1) (Annex 4).

The modes of the four traits were fuzzy-coded for the 34 species (Annex 6). While each species was listed by its respective region, the actual trait coding for a species remains largely consistent across all three regions, given the difficulty in finding region-specific information. An exception was for instance herring (*Clupea harengus*) which was coded differently for the North Sea and Baltic Sea (see description in Section 3.2.11). Although significant intraspecific trait variation is observed with increasing latitude (Myers et al., 2021), the three regions considered in this study span comparable latitudes. Consequently, intraspecific trait variations were not accounted for in our analysis.

To calculate the overall vulnerability for species populations we transformed the fuzzy-coded traits (scale of 0 to 4) into binary values (0 or 1). Hence, a species was assumed to exhibit a given trait modality (1) if its fuzzy-coded value was above 2, while values of 0 or 1 were assigned a 0, indicating the species did not exhibit the modality. For traits with a fuzzy coded value of 2, binary coding was context-dependent, for instance for the response trait behavioural plasticity, we adopted a rather precautionary approach. Hence, for species with low plasticity and an assigned value of 2, the trait mode value was transformed to 1, since lower behavioural plasticity increases vulnerability. Similarly, for sensory adaptations, species with a value of 2 for vulnerable modalities such as relying on vision were assigned a transformed value of 1.

The now binary-coded trait modalities were then multiplied by the respective impact values for each of the causal pathways (-1, 0, +1, see Annex 4) which resulted in a vulnerability score for each species. These species vulnerability scores were then summarised by state change and population characteristics (Figure 3.6 and 3.7).

Based on the selected response traits, the state change sediment resuspension caused by the pressures associated to operational OWF has the potential to cause the most negative responses (Figure 3.6). For example, for the state change sediment resuspension nine out of 22 species (41 %) in the Celtic Sea had vulnerability scores of -6 or -7. In the North Sea, ten out of 21 species (48 %) had vulnerability scores of -6 or -7 and in the Baltic Sea five out of 10 species (50%) had highest vulnerabilities scores. This indicates that across all regions roughly half of the commercial species are negatively affected by sediment resuspension.

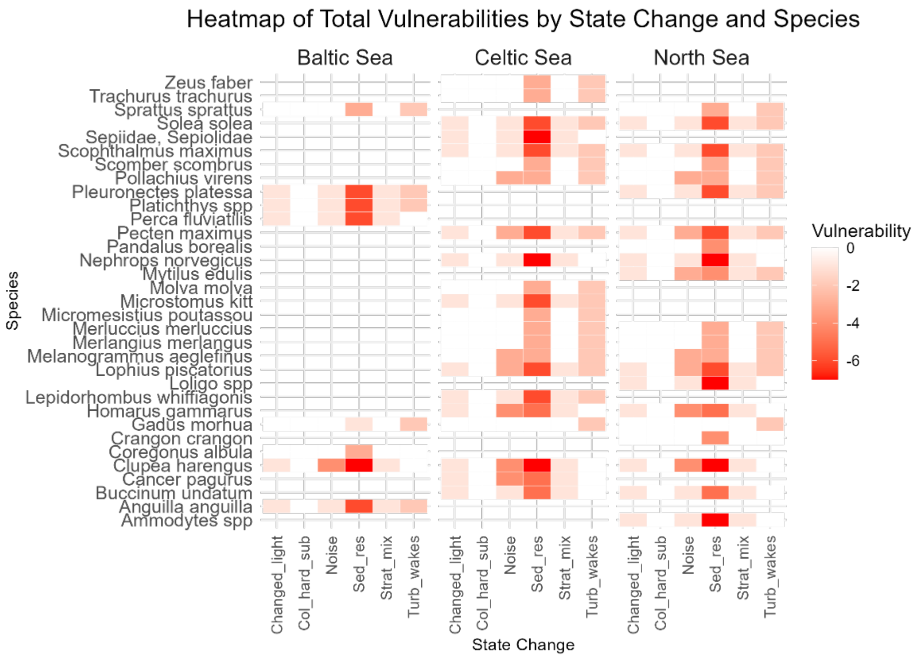

Figure 3.6: Heatmap depicting the overall vulnerability across all state changes associated with the operational phase of an OWF for each species and region. The values, ranging from 0 to -7, are derived by summing all impact scores, where more negative values indicate a higher vulnerability.

For all three regions, larval dispersal and predator-prey interaction showed highest vulnerabilities of fisheries resources with respect to operational OWFs (Figure 3.7). To identify the most vulnerable species for the here selected cause-effect pathways and response traits the total sum of vulnerability scores was calculated for each species (Figure 3.8). Overall herring (*Clupea harengus*), great scallop (*Pecten maximus*) and common monk fish (*Lophius piscatorius)* showed the highest vulnerabilities scores. Flat fish such as sole (*Solea solea*), plaice (*Pleuronectes platessa*), and turbot (*Scophthalmus maximus*) have comparably high vulnerabilities (-11). Similar high scores were reached by the crustacean species brown crab (*Cancer pagurus*) and European lobster (*Homarus gammarus*). The relative comparison across the commercial species shows that squid (*Loligo spp*), sandeel (*Ammodytes spp*) or Norway lobster (*Nephrops norvegicus*) have also increased vulnerability scores (-10).

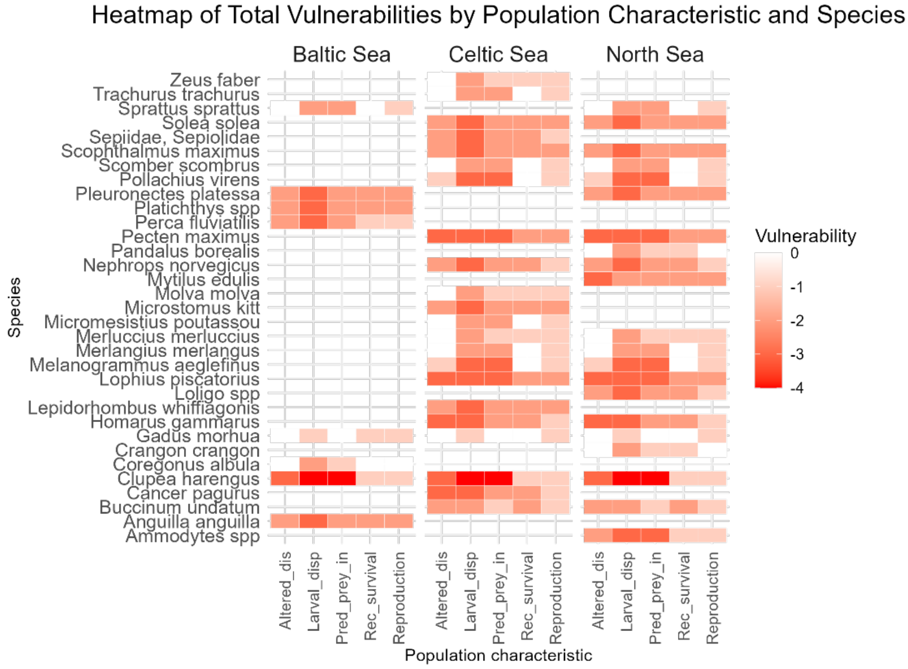

Figure 3.7: Heatmap depicting the overall vulnerability across selected population characteristics for each species and region. The values, ranging from 0 to -4, are derived by summing all impact scores, where more negative values indicate a higher vulnerability.

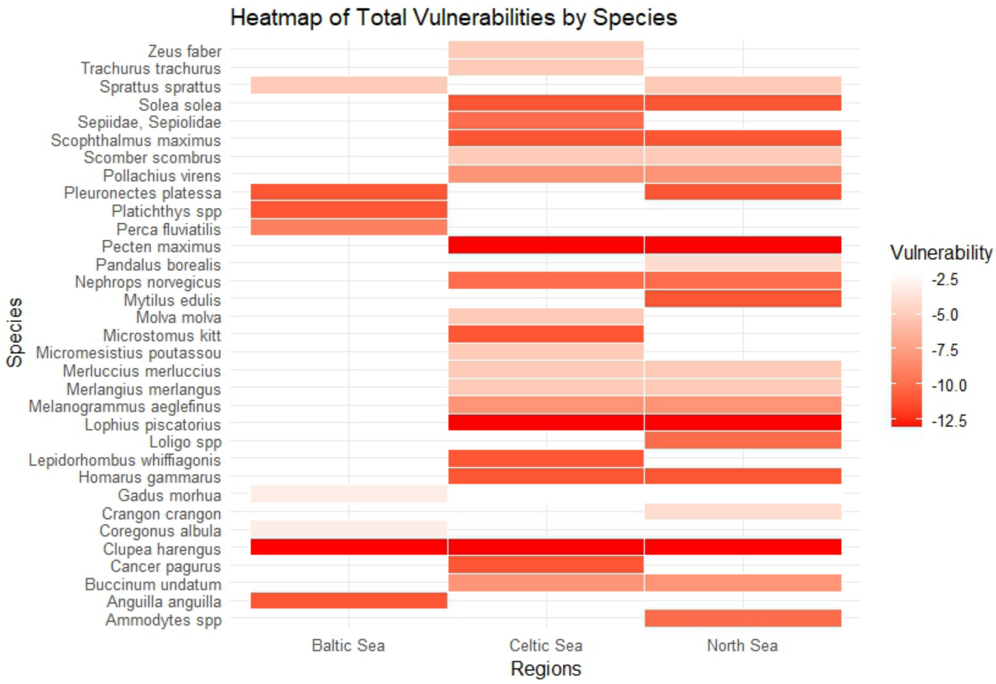

Figure 3.8: Heatmap depicting the overall vulnerability by species and region. The values, ranging from -2 to -13, with more negative values indicate a higher vulnerability in relation to the here selected cause-effect pathways and response traits.

Hence, it is important to note that the selected response traits reflect the responsiveness of population characteristics towards the state changes listed in Table 3.4. A comprehensive risk analysis would need to entail an assessment of population resilience, such as the consideration of life history traits in the narrative of impact. However, here we summed the impact scores thereby combining positive and negative effects for the respective causal pathways. As shown in Annex 2 for the here presented assessment of key fisheries resources, only a few positive or beneficial pathways were identified. The summation of scores means that the positive effects lowered the overall vulnerability score for a respective species. Thus, no additional weighing was applied for positive effects.

In the future, the TAFOW framework should be combined with a spatial overlap analysis between species (adults, juveniles, larvae) occurrence and OWF areas (Stelzenmüller et al., 2015). Such a contextualisation of the analysis allows for conclusions on the expected degree and range of impact.

3.2.8 Conclusions and recommendations

The relationship between OWF related human activities and their pressures on ecosystems requires a detailed understanding of causal pathways linking human operations to environmental impacts across spatial and temporal scales. Combined pressures from local OWF activities and broader influences like climate change create cumulative risks to ecosystems, necessitating integrated assessment of environmental impacts and multi-scale management strategies. However, mismatches in assessment scales and inadequate monitoring data often hinder accurate evaluations of OWF impacts on marine fish communities and also on fisheries resources, highlighting the need for fit-for-purpose benchmarks and comprehensive spatial analyses.

The effects of OWFs on fisheries resource species have been increasingly studied, focusing on impacts from installation, operation, and decommissioning, including habitat changes, noise, pollution, and electromagnetic fields. While much research emphasises adult fish, there are significant knowledge gaps regarding early life stages, such as eggs, larvae, and juveniles, which are particularly vulnerable to stressors like noise, altered hydrodynamics, and chemical pollution. Indirect effects on fish include changes in prey availability, water circulation, and predation dynamics, but scaling these local impacts to population-level effects remains challenging. Observed impacts include increased fish abundance near OWFs, changes in dietary habits, and varied responses to noise and electromagnetic fields, which depend on species, life stages, and regional contexts. Overall, the magnitude of OWF-related effects is shaped by the cumulative pressure load within a given seascape, imposing further research and context-specific management strategies.

Given the current limitation of empirical evidence of the impact of OWF on fish populations we introduced a trait-based framework (TAFOW) which allowed an assessment of relative vulnerabilities of species to the ecosystem state changes caused by the life cycle of OWF with fixed installations. Hence, TAFOW links ecosystem state changes across the OWF life cycle to fish population characteristics, building on work by ICES and identifying key pressures and response traits. Response traits reflecting species' vulnerability, such as behavioural plasticity and salinity tolerance, therefore provide insights into responses to environmental changes. TAFOW entails a lookup, narrative and species trait table to establish causal pathways between the expected state changes, population characteristics, and response traits and their modes, with impacts measured as positive, neutral, or negative.

Here we assessed the impacts of operational OWFs on 34 fisheries species in the North Sea, Celtic Sea, and Baltic Sea by linking OWF-induced state changes to population characteristics and response traits. Response traits, such as feeding behaviour, sensory adaptations, and behavioural plasticity, were evaluated to determine species vulnerabilities through 17 causal pathways. Our results reveal that trophic interactions and recruitment survival are particularly vulnerable to OWF pressures. Further sediment resuspension is the state change that caused the most negative responses for the here selected species.

Vulnerable species included herring, great scallop, and monkfish across the three regions. Followed by flat fish such as sole, plaice and turbot as well as brown crab and European lobster. These results give a first indication which fisheries species could be most vulnerable to operational OWF at population level. However, as indicated in Table 3.3 plaice and brown crab for instance show increased abundances around monopiles with a scour protection layer. This underlines the limited understanding between local observations and potential negative impacts at population levels. Further it has to be noted that the calculation of vulnerabilities is based on the allocated trait modes (Annex 4), narrative of impacts (Annex 3) and the way how this information was used in our analysis. The fuzzy coded traits were converted to binary trades and positive effects (benefits) were accounted for but not treated differently through an extra weighting scheme.

The response traits in this study reflect how population characteristics respond to OWF-induced state changes, but a comprehensive risk analysis should also consider population resilience and life history traits. In addition, integrating the TAFOW framework with spatial overlap analyses of species distributions and OWF areas is essential to fully assess the degree and range of impacts. The wide range of ICES working groups allow to operationalise such an integration. Nevertheless, harmonised impact monitoring strategies are needed to address species responses to OWF induced pressures at population levels.

3.2.9 References for potential impact of Offshore Wind Farms (OWF) on commercial fish species case study

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3.2.10 Case Study: Baltic proper harbour porpoise

CASE STUDY: Summary of the known ecological impacts of offshore renewable energy developments on Baltic proper harbour porpoise population

Confidence

The low population density of Baltic Proper harbour porpoise poses significant challenges in monitoring impacts of changes in anthropogenic pressures on the population. In addition, ORE development in the core distribution area is at an early stage. Hence, most information was derived from studies outside of the area of interest and confidence levels can only be considered moderate to low. Several potential cause-effect relationships have yet to be investigated and their inclusion is only based on expert judgement, resulting in low confidence levels.

Key Findings

- Even without additional pressure from offshore renewable energy development, the Baltic Proper harbour porpoise population is Critically Endangered and declining (Carlström et al., 2023; Koschinski et al., 2024). Consequently, a threshold of zero is set for anthropogenic mortality (Helcom, 2023)
- Baltic Proper harbour porpoise will likely be directly affected during all stages of offshore renewable energy development, and especially by the introduction of underwater noise. Given the aforementioned critically low population size, even moderate impacts are to be avoided.
- It will be critical to minimize the introduction of impulsive underwater noise (especially during pre-, construction and decommissioning phases) as this has the potential not only to displace individuals in a wide area, but also to cause irreversible hearing damage and missed foraging events.
- Only direct impacts of ORE development were considered in this assessment, meaning indirect impacts will need to be the subject of later studies. These include potentially critical aspects such as changes to bycatch risk following displacement of fisheries activities and ecosystem changes altering prey-species availability.

Data gaps and research needs

- Given the low population density most information will continue to be derived from studies outside of the area of interest.
- There is a need for underwater noise measurements in the area. Existing pile driving sound propagation models were not developed for the central region of the Baltic Sea which is influenced by stratification and desalination.
- Knowledge is scarce on the population-level impact of various human activities in the area and a cumulative impact assessment of multiple pressures on the population is a prerequisite to coordinate conservation actions across all anthropogenic activities.
- Knowledge of potential far field effects of wind energy extraction e.g. impact on stratification and ecosystem functioning as these could affect Baltic Proper harbour porpoise at wider spatial scales.

Recommendations

- Avoid offshore wind farm development in the core distribution area for Baltic Proper harbour porpoise
- Avoid construction activities during the reproductive period as well as when porpoise densities are the highest
- The highest standard of mitigation should be used to minimize the introduction of impulsive underwater noise (especially during construction and decommissioning phases) as this has the potential not only to displace individuals in a wide area, but also to cause irreversible hearing damage. This includes making noise abatement compulsory during UXO removal.
- Apply appropriate measures to reduce additional vessel noise e.g. by reducing vessel speed, optimizing routes and use of vessels with a silent class notation.
- To understand and predict population-level impacts of various human activities in the area (including OWFs) gather data to parameterize process-based simulation models for the Baltic Sea porpoise population(s), such as DEPONS (Home | DEPONS)
- Environmental monitoring data should be made publicly available to parameterise relevant models on pressure propagation and porpoise response

3.2.10.1 Introduction

The Baltic Sea has an estimated development of 93.5 GW of offshore wind capacity by 2050 (EC, 2019). This anticipated roll-out of offshore renewable energy (ORE) in the Baltic Sea is expected to impact local populations of harbour porpoise (*Phocoena phocoena* (Linnaeus, 1758)). Of the three recognized populations (Figure 3.10.1, from Koschinski et al., 2024), there is particular concern about the already Critically Endangered and declining Baltic Proper harbour porpoise population (Carlström et al., 2023; Koschinski et al., 2024). Based on acoustic data collected during the SAMBAH project, Amundin et al. (2022) estimated an abundance of 71–1105 individuals (95% CI, point estimate 491). ORE deployment in the Baltic region could contribute to the extinction of this genetically and biologically distinct marine mammal population. As part of the advice request to ICES to compile evidence on the impacts of offshore renewable energy on fisheries and marine ecosystems, we review existing literature to determine ecological impacts of ORE developments on Baltic Proper harbour porpoise at the different phases of ORE development. We focus on offshore wind as this represents > 99% of installed capacity in the next five years.

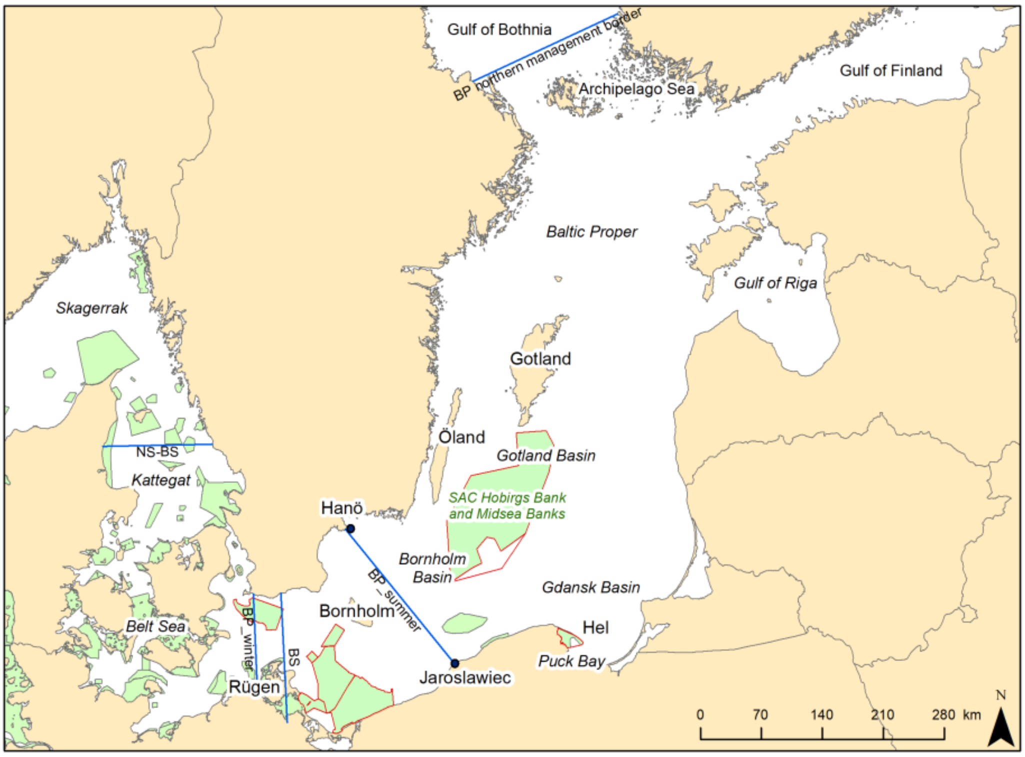

Figure 3.10.1. Map of the management borders for all three harbour porpoise (*Phocoena phocoena*) populations in the Baltic region (North Sea population (NS), Belt Sea population (BS) and the Baltic Proper population (BP)) are shown. The Natura 2000 sites where harbour porpoises are listed are shown in green. Sites outlined in red are those to which seasonal or year-round closures for fisheries apply (Koschinski et al., 2024).

3.2.10.2 Methods

Per the advice request, ecological impacts of ORE developments were assessed looking at the different phases of development of an offshore wind farm (OWF), which were defined as follows:

- Pre-construction survey: the period during which the physical environment (bathymetry, sea floor…) of a future OWF is investigated. This period ends when the survey is completed. Pre-construction pressures are only related to survey activities.
- Construction: This period starts with the first construction related activity and ends when the OWF is fully constructed. Construction period pressures are related to construction activities (including UXO removal, sea floor leveling, cable ploughing, turbine piling, SPL installation...) but do not include pressures related to the presence of installed structures as these are discussed under operation.
- Operation: These comprise the pressures related to the presence of operational ORE devices, and maintenance activities.
- Decommissioning: starts with the first activities leading to removal of the ORE, and ends when the ORE is fully removed. The pressures discussed here are related to decommissioning activities only.

At the preparatory workshop for defining the scientific strategy for this report (ICES HQ, 8-10 October 2024), an expert group developed a table identifying pressure-ORE development phase combinations (See Intro to ToR a ii to v, Table 1) Pressures were only associated with activities when there is an ecologically meaningful change in pressure intensity against the existing baseline. As an example: vessel noise, generated by a surveying vessel in a busy environment during pre-construction does not clearly alter the existing level of vessel generated baseline noise in the area.

In line with ICES, WGMME (2015, 2019), ecological impacts on Baltic Proper harbour porpoise were classified as high, medium, low or unknown, adopting a traffic light system for each pressure-ORE development phase combination, using the following criteria:

- High (red) = evidence or strong likelihood of negative population effects, mediated through effects on individual mortality, health and/or reproduction;
- Medium (yellow) = evidence or strong likelihood of impact at individual level on survival, health or reproduction but effect at population level is not clear;
- Low (green) = possible negative impact on individuals but evidence is weak and/or occurrences are infrequent.
- None (black) = no direct negative impact on individuals
- The category "unknown" (grey) is defined for cases where there was little or no information on the impact of these pressures on harbour porpoise.

In addition, confidence levels are assigned based on the criteria developed in Dannheim et al. (2020) (Table 3.10.1).

Table 3.10.1. Confidence levels for assessing the probability of impact on marine life from pressures associated with offshore renewable energy devices.

Based on Dannheim et al. (2020)			
	low	moderate	**high**
Confidence	information has been derived from sources that only cover general understanding of the cause-effect relationship, or by "informed judgement" where very little or no information is present at all on the cause-effect relationship	information has been derived from sources that consider comparable effects of a particular cause-effect relationship or outside the area of interest	information has been derived from sources that specifically deal with the cause-effect relationship of ORE in the area of interest. Experimental, modelling or field work has been done to investigate the specific cause-effect relationship

Please note, only direct impacts of ORE development were considered in this assessment, meaning indirect impacts will need to be the subject of later studies. These include potentially critical aspects such as changes to bycatch risk following displacement of fisheries activities and ecosystem changes altering prey-species availability.

3.2.10.3 Results

A summary overview of pressure-ORE development phase combinations with indication of their potential impact on Baltic Proper harbour porpoise population is given in Table 3.10.2. Where potential impacts were identified, individual change-effect relationships are discussed below.

Table 3.10.2. Pressure-ORE development phase combinations with indication of their potential impact on Baltic Proper harbour porpoise population. Impacts are classified as high (red), medium (yellow), low (green), none (black) or unknown (grey) and confidence levels are indicated as either low (*italics*), moderate (regular font), or high (bold).

(PRESSURE)/CHANGE	**Pre construction survey**	**Construction**	**Operation**	**Decommissioning**
Loss of soft sediment, covered by scour protection			Yes, presence of scour protection, cable mattresses, foundation footprint	
Introduction of artificial hard substrate			Yes, presence of scour protection, cable mattresses, foundation	
Change in sediment composition			Yes, fining and organic enrichment of sediment due to presence of fouling fauna on turbines	
Sediment resuspension, transport and smothering		Yes, cable trenching	Yes, scouring after installation of turbines and SPL (presence)	Yes, cable & scour removal
Abrasion of sediment by seabed disturbance		Yes, e.g. cable trenching, seabed levelling	Yes, FLOATING ORE: presence of dynamic cables and mooring installations in floating ORE	Yes, cable & SPL removal activities
Change in water current			Yes, presence of installations	
Change in stratification			Yes, presence of installations	
Underwater noise: impulsive	Yes, seismic survey activity	Yes, UXO clearing and piling activities	Yes, sonar	Yes, possible drilling, explosions, seismic surveys
Underwater noise: continuous	Yes, noise generated by vessel activity	Yes, noise generated by vessel activity	Yes, noise generated by presence of ORE device as well as vessel activity	Yes, noise generated by vessel activity
Electromagnetic fields	*Yes, survey activity*		*Yes, EMF from presence of cables*	
Introduction of synthetic and non-synthetic contaminants			*Yes, presence of corrosion protection systems, anti-fouling paints, leaking of lubricants and hydraulic fluids (presence)*	
Introduction of litter			*Yes, breaking of turbine blades, fires in turbines (turbine presence)*	

(PRESSURE)/CHANGE	Pre construction survey	Construction	Operation	Decommissioning
Collision risk	Yes, survey vessel activity	Yes, maintenance vessel activity	Yes, maintenance vessel activity (moving parts of sub-merged ORE)	
Entanglement risk in cables	*Yes, seismic survey equipment*		*Yes, presence of dynamic cables in floating ORE*	
Visual disturbance		Yes, maintenance vessel activity (and moving ORE parts)	Yes, maintenance vessel activity (and moving ORE parts)	Yes, presence of vessels
Introduction non-indigenous species via relocation of floating ORE		Yes, from other loca-tions to farm site	Yes, relocation activity between farm and ports for repairs	Yes, relocation from farms to decommissioning yard

Analysis per cause/effect relationship phase

Impulsive underwater noise

Preconstruction survey

Prior to construction, geotechnical surveys are needed to determine subsoil conditions and inform design choices. These include seismic surveys potentially generating high levels of impulsive sound. A study on the impacts of such seismic survey on harbor porpoise in the North Sea showed reduced echolocation behaviour at distances of up to 12 km from the active airguns (Sarnocińska et al., 2020). Such disturbance events are likely insignificant to the energetic status of an individual porpoise, but frequently repeated disturbances may have fitness consequences (Wisniewska et al., 2018).

Construction

Pile driving remains the most common method used to install foundations for offshore wind turbines, particularly for monopile and jacket foundations. The process involves using a large hammer to drive steel piles 10s of meters into the seabed and generates high levels of underwater sound during several hours per foundation. Each pile driving event results in displacement of porpoises out to approximately 20 km (Tougaard et al., 2009; Brandt et al., 2011). Noise mitigation has been shown to reduce both the spatial (to approximately 14 km) and temporal extent of displacement (Brandt et al., 2016; Rumes & Zupan, 2021). Construction of a single wind farm requires repeated pile driving events typically occurring over a period of two to four months resulting in temporary habitat loss (Brandt et al., 2016; Rumes & Degraer, 2020). The occurrence of temporary threshold shift (TTS) can be caused by single events with very high sound levels (Lucke et al., 2009; Schaffeld et al., 2019) or by the repeated reception of sound events with lower sound levels (Kastelein et al., 2016; Kastelein et al., 2017). Based on Lucke et al. (2009), it is assumed that impulsive sound leads to TTS from a threshold value of 164 dB re 1 $\mu Pa^2 s$.To avoid physically injuring porpoises, pile driving activities are often preceded by the use of acoustic deterrent devices (ADDs) which intentionally generate evasive responses over multiple kms and themselves contribute to the overall habitat degradation (Elmegaard et al., 2023, Voß et al., 2023). However, the deterrence distances achieved by ADDs may not be sufficient to prevent TTS from multiple exposures (Schaffeld et al., 2020). Other construction activities such as foundation and turbine installation also change acoustic habitats through increased vessel activity and have been shown to result in porpoise displacement (Benhemma-Le Gall et al., 2021). Optimising mitigation measures will need to take into account and distinguishbetween disturbance from multiple sources (e.g. pile driving, UXO removal, ADDs, vessels).

OperationVessels operating in the wind farm that are equipped with sonar systems generating sonar pulses below 200 kHz will potentially have adverse effects on harbour porpoise. However, given the high frequency and directed nature of the pulses generated, these will have a much smaller range than the continuous underwater noise produced.

Decommissioning

There are multiple options for decommissioning offshore wind farms, both in techniques used as in degree of removal. Foundations can be fully or partially removed or left in place. Erosion protection layers and cables can either be removed or left intact. Although strongly dependent on these options, the process will be accompanied by a temporary increase in underwater noise resulting in the displacement of porpoise. This was found during decommissioning of an oil and gas platform in Scotland when higher sound levels caused small-scale and short-term displacement of porpoises, but immediately after the work was complete there was increased occurrence (Fernandez-Betelu et al. 2024)

Continuous underwater noise

Vessel noise has been shown to induce a range of behavioural responses in porpoises ranging from vigorous fluking, bottom diving, interrupted foraging to cessation of echolocation (Dyndo et al., 2015, Wisniewska et al., 2018). As part of studies on the effects of ship activities during the construction of OWFs, extensive behavioural reactions of harbour porpoises and a displacement was observed at up to four kilometres from construction vessels (Benhemma-Le Gall et al. 2021). The ship-based preparatory work immediately prior to pile driving already had a significant negative impact and led to a decrease in acoustic detections of harbour porpoises of up to 33 % in the 48 hours prior to pile driving (Benhemma-Le Gall et al. 2023).

A fair amount of vessel traffic takes place inside operational wind farms consisting of e.g. crew transfer vessels (CTV), maintenance vessels, and hotel ships. When docking to a wind turbine, the CTV slowly moves towards the foundation and on first contact between the bow and pile quickly turns up the engine speed to hold the position and enable the crew to enter the turbine. The dynamic positioning systems of these vessels introduces additional noise. Operational fixed offshore turbines will themself generate underwater noise which can exceed background levels by 20 dB re 1 μPa (Norro et al., 2016) and will add significant noise levels to the region even though intense shipping activities occur (Anderson et al., 2011). Initial measurements from floating offshore wind turbines in Scotland show noise fields to be above median ambient noise levels in the North Sea for maximum distances up to 4.0 km from the turbine array (Risch et al., 2023). In addition, floating turbines generate impulsive 'snaps' or transients either occurring individually or in rapid repetitions, creating a 'rattling' or 'creaking' noise (Burns et al., 2022). At the floating offshore wind farms, recorded harbour porpoise detections were reduced at the recording site closest to the turbine compared to the site further away, which could indicate longer term displacement and/or reduced vocalisation behaviour (Risch et al., 2023). A recent study using digital aerial surveys found that the probability of observing a harbour porpoise significantly decreases closer to wind turbines (Leemans & Fijn, 2023). This would suggest that harbour porpoises avoid close distances to operational wind turbines because of underwater noise.

Collision risk

The area is not suited for tidal stream turbines. Hence, vessels are the only potential collision risk, with the main risk coming from high speed vessels. Although ship-strikes are typically associated with large whale species, various smaller cetaceans are known to be at risk (Schoeman et al., 2020). In the United Kingdom, approximately 4-6% of stranded small cetaceans (harbour porpoise, common dolphin, white-beaked dolphin and Risso's dolphin) show evidence of physical trauma which could be attributed to ship strike (Evans et al., 2011). High speed crew transfer vessels could elevate collision risk in previously low risk areas. Service operating vessels aka hotel ships, which host technicians overnight, can travel at slower speeds, reduce the number of transfers and thereby reduce the risk and severity of vessel strikes.

Electromagnetic fields

Electromagnetic field (EMF) intensities decay as a function of distance from the source and can be modelled using cable properties (core/ shielding materials, configuration, amperage, voltage) and the local geomagnetic field. The total zone affected by cable induced magnetic fields (DC and AC) in Hutchison et al. (2020), was 5–10 m on either side of the cable, inferring the potential area of influence to be 10–20 m wide. The effects of EMFs on cetaceans can include a temporary change in swim direction, detours in migration routes or alterations to hunting behaviour, depending on the persistence and magnitude of the EMF (Torres, 2017). It has been shown that bottlenose dolphins have electromagnetic receptors and can perceive electric fields (Hüttner et al., 2022; Hüttner et al., 2023). Fairly little is known on the detectability of EMF emissions from subsea cables by porpoises. Gill & Desender (2020) argue that, since harbour porpoises do not spend significant time in close proximity to the seafloor, changes in electromagnetic field emissions from subsea cables are less likely to influence their behaviour. This statement can be contested, as they spend significant time foraging for benthic fish prey (e.g. Linnenschmidt et al., 2013).

Introduction of litter

The contribution of offshore wind to the introduction of litter at sea can be considered negligible compared to other anthropogenic sources such as land-based sources and fisheries. Proper waste disposal procedures will prevent all but accidental introduction of litter due to offshore wind developments.

Introduction of synthetic and non-synthetic contaminants

Offshore wind farms contribute to the introduction of contaminants e.g. through the presence of corrosion protection systems, anti-fouling paints, or accidental discharge of lubricants and hydraulic fluids. Locally elevated concentrations for the elements aluminium, zinc, indium, gallium and lead have been observed near existing wind farms (BSH & Hereon, 2022). Potential impacts on the marine environment are the subject of ongoing studies.

Entanglement

Injury and mortality from ORE related entanglement can occur if marine mammals become directly entangled in inter-array cables or moorings (primary entanglement), become entangled in derelict fishing gear or other marine debris caught on cables or moorings (secondary entanglement), or when an organism is already entangled in an item that then becomes entangled on the structures (tertiary entanglement).Concern for entanglement of marine mammals caused by ORE devices is primarily focused on floating devices, in function of their mooring types (Benjamins et al., 2014), and whales (Farr et al., 2021). While the risk to porpoise theoretically exists, we found no documented cases of entanglement of porpoise with ORE infrastructure. This is in stark contrast to the widely reported entanglement in fishing gear which remains the greatest threat to the Baltic Proper porpoise (ICES, 2020a).

Visual disturbance

To our knowledge there is no research directly related to visual disturbance of harbour porpoises. However, given the harbour porpoise's place as a prey animal in the ecosystem, as well as its behaviour in response to, for example shipping and underwater noise, it can be expected that the visual moving shadows from wind mills may cause stress reactions in harbour porpoises.

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3.2.11 Case Study: Western Baltic Herring

CASE STUDY: Summary on potential effect of Offshore Wind Farms on Western Baltic Herring

Confidence

Confidence: **Low.**

The potential consequences of offshore renewable energy on the Western Baltic herring migration are highly speculative due to the lack of any sound scientific baseline for assessing these potential consequences and impacts. Research on migration routes and population dynamics is currently underdeveloped, and the forms of fundamental ecosystem research required to develop these types of understanding are not promoted by recent project calls. Accordingly, answering the questions related to dynamic ecosystem components and their management becomes increasingly speculative. A dedicated "case study" on OWF effects particularly on the Western Baltic herring stock therefore lacks a solid data foundation and, at best, can only be presented as "expert judgement" with low confidence. Informed judgement based on OWF effects on herring stocks elsewhere (as far as applicable) has a limited applicability due to the specific offshore/inshore migration patterns of the Western Baltic Herring stock.

Key Findings

- Effects on Western Baltic herring (WBH) due to OWF construction and operation are not yet apparent related to OWF sites already existing.
- Impulsive noise (survey, construction, decommissioning phase) might potentially affect migration and habitat connectivity (pathways from feeding-/overwintering grounds to inshore spawning grounds).
- Alteration of spawning habitat by OWF is unlikely for the spring spawning population of WBH (estuary/lagoon spawners), but might potentially occur for autumn spawning herring (shelf spawners).
- Alteration of electromagnetic fields might potentially affect larval herring orientation and migration.

Data Gaps and Research Needs

- Most recent data on migration routes date back to the 1980s.
- Data on autumn herring spawning grounds date back to the 1970s
- Urgent research needs to update spatial & seasonal migration patterns
- Field studies should address effects of underwater noise on herring behavior at various life-stages
- Studies on how local effects of OWF presence affects feeding conditions for adult and larval WBH

Recommendations

- Update the information on the current spawning grounds of WBH in different seasons, and assess their overlap with planned OWFS
- Update the spatial and temporal information on WBH migration routes and assess possible overlap with planned OWF
- Update the knowledge on important cause-effect relationships with respect to all life stages of OWF and WBH behaviour (including attraction to OWF)

- Establish knowledge on the relative importance of local OWFs effects compared to regional scale trends (e.g. climate-related processes)
- Investigate possible positive effects of OWF (feeding, nursery, shelter) on WBH
- Increase the understanding of how local food-web changes in the OWF can affect the autumn spawning WBH
- Increase the understanding of how local changes at the basis of the food web (phyto- and zooplankton) affect early life stages of autumn spawning WBH

3.2.11.1 Potential consequences of offshore wind farms (OWF) on Western Baltic Herring

The growing development of offshore renewable energy, particularly wind farms, in the Baltic Sea holds significant promise for clean energy generation. However, alongside its potential environmental benefits, this expansion may have unintended consequences for the marine life in the region, particularly for migratory species such as the Western Baltic herring (*Clupea harengus*). However, those consequences should be understood in addition to other disturbances by e.g. recent constructions related to gas pipelines or LNG terminals which are situated in the immediate vicinity of major spawning grounds. What we do know from countless studies are the devastating effects of oil pollution on global herring stocks and other marine life. Compared to the risks already taken by establishing oil platforms and respective transport of fossil fuels, the risks introduced by OWF are most probably negligible. All the potential OWF- impacts (Gill et al. 2024) are largely unstudied for this stock. Therefore, any assessment of the isolated effects of OWF construction and operation can only be speculative, relying on ecological principles and the known behavior of marine species in relation to anthropogenic changes. A trait-based evaluation of potential consequences has also been compiled in ToR a ii (see section 3.2.7).

In addition, any potential effect of OWF development also needs to be seen within the context of ongoing climate change for which the Baltic Sea is highly sensitive due to its physical settings (Meier et al. 2022). The consequences of global warming in the Baltic Sea includes warming winters which in turn results in decreased reproductive success for WBH (Polte et al 2021).

A risk assessment of OWF effects on herring has been conducted in the North Sea by researchers of IMARES, Wageningen (NL). They concluded that the building and presence of windmills would probably not affect North Sea herring in the specific area (ter Hofstede et al. 2008).

A comprehensive review of potential consequences of OWF on small pelagic fishes in U.S. waters (including Atlantic herring) can be found in Hogan et al. (2023). The authors compiled all potential impacts to a set of speculative consequences particularly related to increased noise emissions. A repetition of this approach would not gain any new insights, and we here point out that the thorough review by Hogan et al. (2023) did not result in the identification of definite effects on herring distribution and abundance.

3.2.11.2 Assessment of effects concerning WBSS herring migration routes

Herring are known for their seasonal migration patterns, which are closely linked to spawning cycles, feeding areas, and environmental cues such as water temperature, salinity, and food availability (e.g. Moyano et al. 2023). OWF installations could potentially have direct impacts on these migration routes. "The observations on herring distribution around subsea cable at a Danish windpark suggest that the migration of herring migration across the cable route may be impaired although not completely blocked (DONG 2006). The physical presence of large structures on the seafloor and in the water column as well as increased noise level associated with construction and operation of the facilities, may force herring to alter their migration patterns. However, already existing wind farms along the spawning migration routes of WBH from overwintering areas (Øresound) to the south-western Baltic Sea did not cause any documented change of migration patterns. However, the knowledge on these migration patterns is quite outdated as it stems from tagging experiments conducted in the 1980s (Nielsen et al. 2001) and it is not clear how valid they still are today. For the same reason, it is difficult to provide informed consultancy on marine spatial planning or conduct any science-based risk assessment of potential OWF effects on this stock.

In general, the visual, auditory, and electromagnetic disturbances caused by construction activities and the ongoing operation of these renewable energy sites has the potential to affect herring migration as they produce noise and electromagnetic fields, both of which are known to affect marine organisms. The cumulative effects of noise pollution and electromagnetic disturbances could alter their orientation or disrupt their sensitive migration cues (Laurien et al. 2024), leading to delays or detours from established routes. Consequently, if OWF facilities become installed within the immediate migration routes of the stock (which are currently unknown), the above effects might be encountered.

3.2.11.3 Potential impacts on feeding grounds and spawning areas

Offshore renewable energy sites may also overlap with critical feeding and spawning grounds for herring. The presence of sub-surface turbine structures might increase abundance of hard substrate benthos and therefore increase the density of meroplankton as those echinoderms, bivalves and barnacles produce planktonic larvae (Floeter et al. 2017). This meroplankton could potentially increase the prey field for small pelagic fishes, such as herring and pose a benefit for feeding conditions. In fact, one of the rare field studies in the vicinity of a wind farm in the German Bight found a slightly increased (but not significant) number of small pelagic fish schools (potentially clupeids) on the wind farm site (Floeter et al. 2017). Field studies from China suggest that due locally increased primary production caused increased zooplankton density in OWF sites overall promoting the abundance of small pelagics (i.e. anchovies) in the area (Wang et al. 2019). “Wilber et al, 2022 used 7 years of observations and did not detect any effects of the first US wind farm on herring abundance that differed from the regional trend”

In addition to altering feeding grounds, the construction and operation of these renewable energy facilities may inadvertently influence herring spawning areas. Spawning herring requires specific conditions for successful reproduction, and disturbances to these areas, whether through noise, sediment disruption, or changes in water quality or food availability, could lead to reduced reproductive success. The vicinity of OWF facilities to spawning areas is discussed as a reason why juvenile herring declined in the area of the “Scroby Sands” windfarm in UK waters (Perrow et al. 2011).

However, as the major spawning areas for WBH are located inshore, within the bays, lagoons and estuaries of the Southwestern Baltic Sea (Figure. 3.11.1, Polte et al. 2021), it is rather unlikely that OWF installations would affect reproductive success directly (but see above for potential effects on spawning migration).

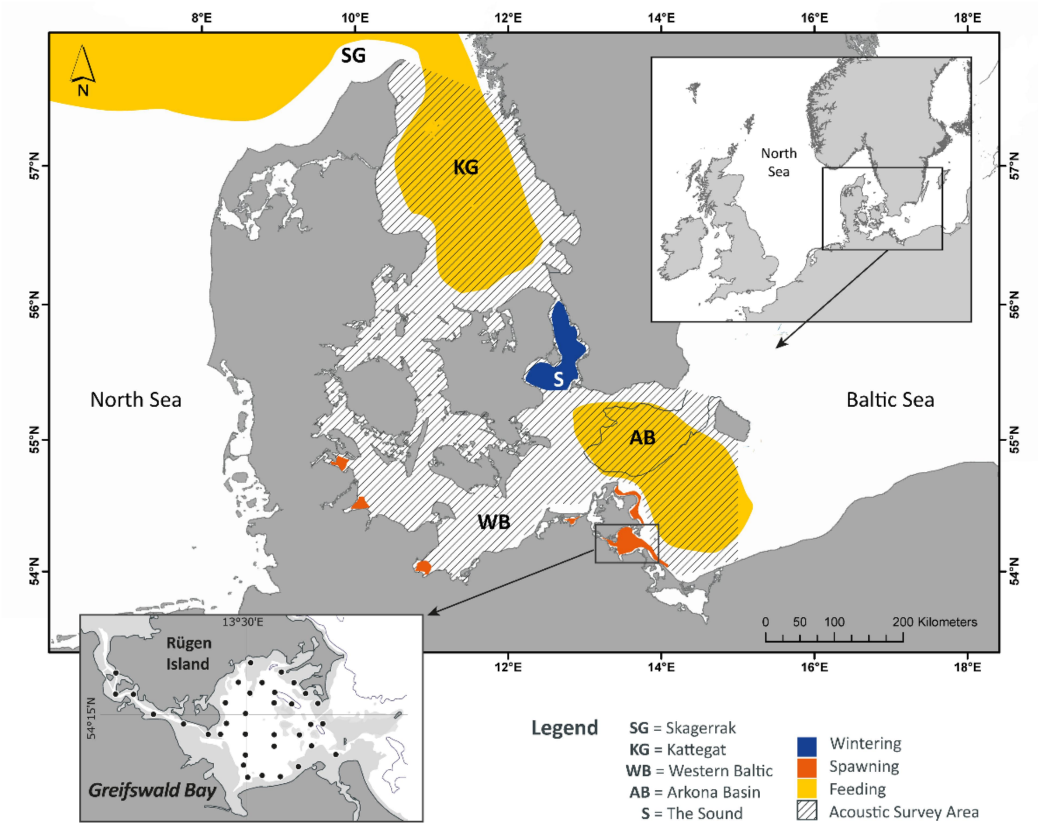

Figure 3.11.1. Spawning areas of WBH in the Western Baltic Sea (from Polte et al. 2021)

3.2.11.4 Potential behavioral changes and stress

Increased human activities and environmental changes in the Baltic Sea resulting from offshore renewable energy could induce behavioral stress in herring populations. Fish are highly sensitive to environmental changes, and their response to new structures or disturbances in their environment could be varied. Behavioral stressors particularly during the construction phase, could manifest as increased energetic costs in navigating around or avoiding turbines, which might deplete the resources available for other vital functions such as feeding and reproduction. On the other hand, an increase of meroplankton by larvae of hard substrate settlers, such as barnacles, could potentially increase food availability for plankton-feeding herring, this way attracting herring schools to the OWF sites. However, this is again highly speculative.

3.2.11.5 Speculation on long-term ecological effects

While herring may initially adapt to the presence of offshore wind farms, the long-term consequences could involve shifts in population dynamics. Migration patterns that have evolved over millennia might be disrupted in ways that cannot be immediately predicted, leading to cascading effects throughout the entire ecosystem. For example, herring are a key species in the Baltic Sea food web, serving as prey for larger predators such as cod and seals. Any disruption to herring migration or population density could ripple through the entire ecosystem, affecting predator-prey relationships and potentially leading to shifts in species composition and foodweb structure in the region.

Additionally, the establishment of offshore wind farms could promote new species to the area, attracted by the artificial reefs formed by the turbines (see ToR a iv) or provide additional food and habitat for already established non-invasive fish species. At the moment, it is unclear if this has an effect on native species in the Baltic Sea. In addition, there is evidence that seals, which are important predators on herring (Scharff-Olsen et al. 2019) can be attracted to offshore wind farms (Russel et al. 2014)

3.2.11.6 Conclusion

There is high uncertainty in the assessment of potential impacts of offshore renewable energy on the Western Baltic herring migration due to the lack of a sound scientific baseline as e.g. research on migration routes and population dynamics is permanently underfunded. Accordingly, answering the questions related to highly mobile and dynamic ecosystem components and their management becomes increasingly speculative. While it is difficult to quantify the effects OWF facilities might have on Western Baltic herring stocks without detailed studies, it is clear that herring, like many marine species, are highly susceptible to changes in their environment. It is to this point unclear if the disturbance by the construction noise etc. will be outweighed by a beneficial reef effect (e.g. by increased shelter & food) during operation of the OWF (e.g. Wang et al. 2024). The introduction of large-scale renewable energy infrastructure into the Baltic Sea must consider these potential impacts and prioritize research to understand and mitigate the consequences for fish populations, particularly migratory species like the Western Baltic herring.

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3.3 ToR a.iii. How changes on hydrodynamic conditions produced by ORE may change the food availability to filter-feeders and influence phytoplankton primary production

3.3.1 Confidence

Confidence: Celtic Sea/Baltic Sea: **low-moderate** ; North Sea: **moderate-high**

While impacts from OWF on ocean hydrography are relatively well understood and agreed upon, the ecosystem response to these physical changes remains poorly understood. Few studies have modeled these effects, laboratory studies and observational data are scarce. Available studies are exclusively done for the North Sea. There is general agreement that OWFs will have ecological impacts, but identifying clear cause-effect chains is difficult due to the complex, nonlinear interactions of processes like primary production, remineralization, grazing, and advection/diffusion at various temporal and spatial scales. Furthermore, ecosystem responses can be site-specific, depending on the background hydrographic conditions. This results in inconsistent conclusions.

3.3.2 Key Findings

- Offshore wind farms impact ocean conditions through a combination of altered atmospheric conditions, the influence of underwater structures on currents and stratification acting mainly during operation phase in the presence of installations.
- Strong tidal velocities can mitigate the effects of atmospheric wakes but also increase mixing by underwater structures.
- **Impacts on Marine Ecosystems:** The effects of OWFs on marine ecosystems are complex and vary by location and study conditions. They can be positive or negative, significant or negligible. Current knowledge is fragmented, making precise regional-scale assessments difficult.
- **Direct Effects on primary production:** Underwater structures directly affect ocean dynamics by causing friction and flow obstruction. This increases turbulence, reduces current speed, and weakens water stratification up to 400 meters behind the structures. Enhanced mixing induced by OWFs may increase nutrient availability in the euphotic zone, promoting local phytoplankton production in the near-field of the structures. This effect applies primarily to fixed-bottom foundations.
- **Indirect Effects on primary production:** Reduced wind speeds within atmospheric wakes decrease wind-driven currents and ocean mixing, strengthening water stratification on scales up to 100 km away from the OWFs. Large wind farms create vertical circulation patterns (upwelling and downwelling). This can increase primary production around and decrease it inside wind farm areas.
- **Regional upscaling:** The currently planned OWF installation in the North Sea can induce changes in hydrographic conditions that might alter spatial and temporal dynamics in the marine ecosystems. In a published model scenario considering the installation of 120GW in the North Sea, local ecosystem changes could reach up to 10% not only at the OWF side but on a regional scale.

3.3.3 Data gaps and research needs

- Data gaps: quantitative estimates/in-situ observations of changes in ecosystem productivity through hydrographical changes
- Lack of knowledge on cause-effect-chains related to direct and indirect effects
- Lack of knowledge on the relative contribution of direct- vs indirect effects on regional scale, cumulative impacts on primary production
- Lack of knowledge on how the effects on primary production impact food resources for filter feeders in the OWFs and propagate through the foodweb
- Generally, more process-oriented observations and modelling studies are needed to systematically quantify the effects in different regions.

3.3.4 Recommendations

- Establish a systematic observation network in and around the OWFs to separate OWF induced effects from natural variability
- Monitor ecosystem changes on larger regional scale during construction and operation to provide a data basis for an applied precautionary principle
- Follow suggestions from recent studies on windfarm design to minimise impacts on hydrodynamics and related ecoystem changes by installing larger turbines (Akhtar *et al.*, 2024) and large spacing between the turbines. Physical influences and combined effects of the ORE installations

The influences of offshore wind installations on the physics of the sea can essentially be attributed to two main types of disturbances:

- **Direct Effects:** The underwater installation acts as an obstacle, directly disrupting the surrounding environment.
- **Indirect Effects:** Changes in atmospheric conditions alter currents, the structure of the water column (stratification), turbulence, temperature, and salinity.

Direct effects of underwater structures on ocean hydrography occur through friction and blocking by the pile structures (Sumer and Fredsoe, 2006; Lekkala *et al.*, 2022)), as shown through observations and numerical models. The turbulent wakes behind (in relation to the flow) the structures influence the mixing and the flow field (Lass *et al.*, 2008; Carpenter *et al.*, 2016a). When water flows around a blunt object, a turbulent vortex street forms, with its extent determined by the object's size, shape, flow speed, and water stratification and density (Lekkala *et al.*, 2022). This process increases turbulence and reduces flow velocity in the downstream area.

Research, especially on monopile structures commonly used in offshore wind farms (OWFs) in the North and Baltic Seas, shows that these effects are localized. Mixing increases by about 10% up to 400 m behind a structure (Lass *et al.*, 2008; Cazenave *et al.*, 2016; Schultze *et al.*, 2020), but strong tidal currents can extend the impact beyond 1 km (Cazenave *et al.*, 2016). The increased turbulence reduces water stratification, particularly thermal layering in summer.

Especially in coastal regions where constructive scour protection is not used, such as in the British EEZ, the turbulent wakes are often characterised by an increased concentration of suspended particulate matter (SPM) (Forster, 2018). This makes them visually distinct from their surroundings and easy to identify on satellite images (Vanhellemont and Ruddick, 2014). A detailed study by Forster, (2018) shows that the changes are accompanied by an increased concentration of re-suspended sediment in the surface water and a lower concentration of re-suspended sediment in the near-bottom water layer. The increased turbulence therefore leads to a vertical redistribution of the sediment concentration.

Regional upscaling of direct effects – While the effect of direct mixing is initially rather localised, it can be assumed that the effect is potentiated with a large number of fixed structures over a relatively large area. Dorrell et al. (2022) hypothesized considerable local effects of additional mixing on the same scale as topographically induced mixing, e.g. in flows over sandbanks. This would result in a broader, more permeable thermocline with possible consequences for e.g. vertical transport, surface water heat storage capacity and CO_2 exchange with the atmosphere. Dorrell's hypothesis is based on a review of the processes and a scale estimate. As described above, the relevant spatial scale for mixing at a pile is in the order of $O(10^2\text{-}10^3\text{m})$. From a pile to a wind farm, we are talking about spatial scales in the order of $O(10^1\text{-}10^4\text{m})$. For very large wind farms and densely built turbines, this can influence the local stratification. The magnitude of this effect, however, is the subject of current research and still uncertain. Initial modelling studies (Cazenave *et al.*, 2016; Christiansen *et al.*, 2023) as well as observations in existing wind farms (Floeter *et al.*, 2017), indicate more local effects that are largely limited to mixing within the wind farms. However, the associated decrease in flow velocity is effective on a regional scale because the mixed water masses are transported further (Christiansen *et al.*, 2023). Carpenter et al. (2016b) attempted to quantify the potential for structure-induced mixing using a theoretical modelling approach. Despite relatively large uncertainties in the estimates, they concluded that the additional mixing is not as relevant for smaller wind farms (at length scales of L~8km). For larger wind farms (L~100km), the effect can be up to 10 times stronger. For a significant effect on the stratification strength of the North Sea, considerable parts of the North Sea would have to be covered with wind farms (Carpenter *et al.*, 2016b).

Indirect effects of atmospheric wake vortices on the ocean are mainly caused by energy extraction from the atmosphere. Compared to the direct effects, these indirect effects impact currents on larger scale, as the wake vortices in the lee of wind farms can extend up to 65 km and even further under stable atmospheric conditions. Within these wake vortices, the wind speed is reduced by up to 43 % (Platis *et al.*, 2020). These changes in the wind field have a significant impact on the ocean below: The reduced wind stress reduces current velocity and mixing in the affected areas. This in turn increases the stratification of the water. **While the direct effect of offshore structures increases mixing, the indirect effect of reduced wind speeds counteracts mixing. However, both processes lead to a reduction in flow velocity.**

The combination of individual wake vortices from all wind turbines within a wind farm creates a large-scale wind deficit behind the OWF. Modeling studies show that this effect grows with increasing OWF size (Akhtar *et al.*, 2022). These local modifications in water transport result in convergences and divergences in the current field. When the wind farm size approaches the internal Rossby radius (around 10 km in the North Sea), vertical upwelling and downwelling circulations form, creating a dipole structure. Earlier studies (Broström, 2008; Ludewig, 2014) (Floeter *et al.*, 2022a) indicate that these circulations cause vertical velocities of several meters per day and affect mixing, stratification, temperature, and salinity. Although some basic processes have been understood using observations and idealised modelling approaches, the reality is much more complicated and the response of the oceans to the artificial perturbations depends not only on the wind field and its variability, but also on the regional hydrodynamic structure (van Berkel *et al.*, 2020) including in terms of depths, tides, residual currents, stratification and fluxes.

Christiansen et al. (2022) show the interactions between the effects of atmospheric wake vortices and tidal currents. On average, tides have a mitigating effect on the wind effects of offshore wind farms. It should be noted here that the tides cause significant mixing in the North Sea system and ensure that no summer temperature stratification forms in the shallow coastal regions of the North Sea. While the tidal currents determine how the hydrodynamics react to the reduction in wind speed, the stratification conditions determine the effects on vertical transport and mixing. The study shows that the periodic tidal currents mitigate the effects of wind speed reduction on current velocities, resulting in hydrodynamic changes that are only half as strong as in a system without tides. It also shows that changes in stratification strength are only relevant in stratified regions, while the relevance for situations with very low

PEA is hardly significant, as the water column is already strongly mixed. **This has clear implications for the effects of wind farms in the North Sea compared to the Baltic Sea.**

Regional upscaling of indirect effects – Christiansen et al. (2022b) used regional ocean modeling to demonstrate that the high density of wind farms in the German Bight is already altering its hydrodynamic structure. Simulations focused on the summer months (June-August), when stable atmospheric conditions favor wake vortex formation. Results show that closely spaced wind farms create cumulative effects, including a large-scale dipole-shaped anomaly in surface deflection and changes in stratification thickness and altered temperature and salinity distributions. Reduced mixing at wind farms further increases stratification, particularly as summer stratification declines.

For specified wake intensity (8% deficit, 30 km length), surface current velocity deficits range from -0.0025 m/s to peaks beyond -0.005 m/s, consistent with earlier studies (Ludewig, 2014). These deficits represent up to 5% of mean residual surface current velocity in May (~0.1 m/s), which accounts for 10–25% of interannual and decadal variability (Daewel and Schrum, 2017). These hydrodynamic changes extend beyond the German Bight, affecting regions along the Danish coast.

Simulations by Daewel et al. (2022), using a hypothetical 120 GW wind farm scenario confirm that closely spaced wind farms amplify cumulative effects. These include regional reductions in current velocity, stratification depth and strength changes, and dipole structures in vertical circulation. Reduced current velocities also decrease bottom shear stress, particularly in less tidally influenced parts of the southern North Sea, potentially redistributing sedimented biogenic materialt. However, the extent of sediment mobilization and redistribution remains uncertain and requires further research.

Cumulative effects – While the direct and indirect effects are of about the same order of magnitude in relation to the change in mixing, they act on different spatial scales. Both processes overlap and are also dependent on the design of the wind farms. Both the size of the turbines (Akhtar *et al.*, 2024) and the installation density of the turbines play a role here. There are no published studies on this yet. However, it can be assumed that the effects on mixing in the near-field of the wind farms are rather dominated by the direct effects, while in the far-field the indirect effects play a greater role. In addition, less dense development of wind farms leads to a reduction in direct mixing.

3.3.5 Impacts on the marine ecosystem

The impact of OWFs on the marine ecosystem can be both positive and negative, ranging from negligible to significant. The current state of knowledge is still relatively fragmented. The assessment of these ecosystem impacts through BACI (before-after-control-impact) surveys is challenging due to the substantial natural variability of the coastal regions, regional and global trends and the focus of studies on selected fish species and/or specific faunal communities (van Berkel *et al.*, 2020). Even if individual studies attempt to quantify the changes in the food web with the help of observations (Wang *et al.*, 2019) it remains uncertain to what extent the measured changes are actually attributable to the OWF and are not determined by the variability in the system. The literature to date contains a number of studies relating to the direct effects of OWF on marine fauna (Bergström *et al.*, 2013), such as artificial reefs effect (Degraer *et al.*, 2021) or the effects of acoustic disturbance on fish and marine mammals (Madsen *et al.*, 2006; Mooney *et al.*, 2020). The effects of changes in ocean physics on marine ecosystems are correspondingly more complex, since, as described above, various processes interact with each other, some of which are counteracting each other. Compared to observations, numerical models enable more accurate BACI studies, as scenarios with and without disturbance can be simulated (van der Molen *et al.*, 2014). Based on the processes described above, one would expect the following process chains on primary production:

Direct effects - As described in (Dorrell *et al.*, 2022), the additional mixing would weaken the stratification and, in the case of an otherwise stratified water column, introduce additional nutrients into the mostly (during summer stratification) nutrient-limited intermediate and surface water. This would lead to an increase in phytoplankton production (Fig. 1). Floeter et al. (2017) assessed the effects of non-operational OWFs on the pelagic ecosystem under stratified conditions based on observations at and around two OWFs in the German Bight and found a clear indication of increased mixing within the OWF. It is likely that this also affects nutrient availability in the euphotic zone, but the measurements do not show a clear response of nutrients and chlorophyll-a within the OWFs. However, this is neither an indication in favour nor against the process described for the following reasons: i) The changes in nutrient concentration would initiate a cause-effect chain that stimulates primary production that effectively enters the food web. The effects would not be visible immediately, but only with a time lag and mixing and transport processes need to be considered in addition. ii) In a dynamic system such as the southern North Sea, which is characterised by strong tidal and residual currents, changes in the biotic and abiotic environment are subject to advective processes. iii) The changes to be expected depend strongly on the hydrodynamic conditions (e.g. fronts), which makes it difficult to distinguish natural from induced changes.

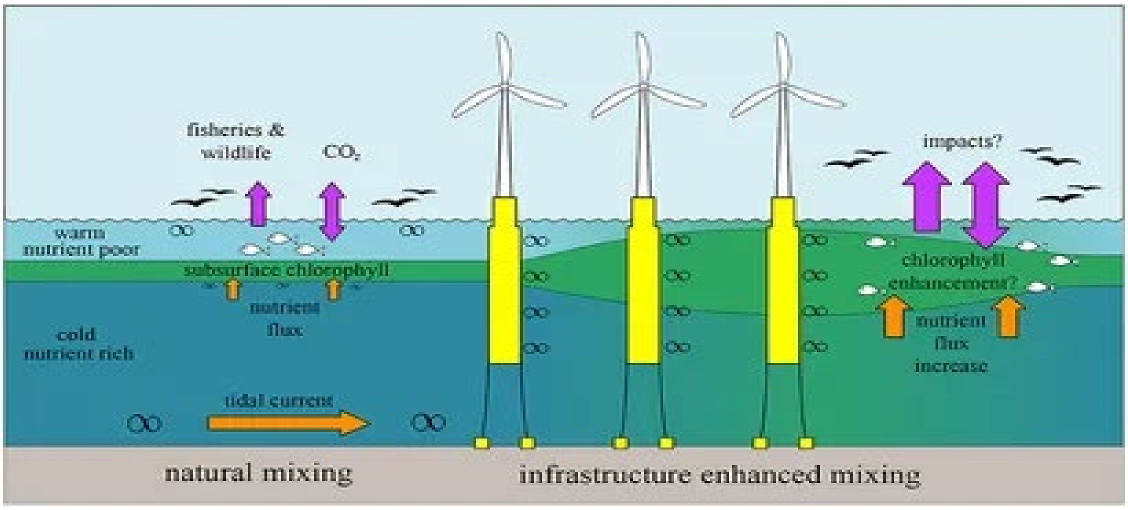
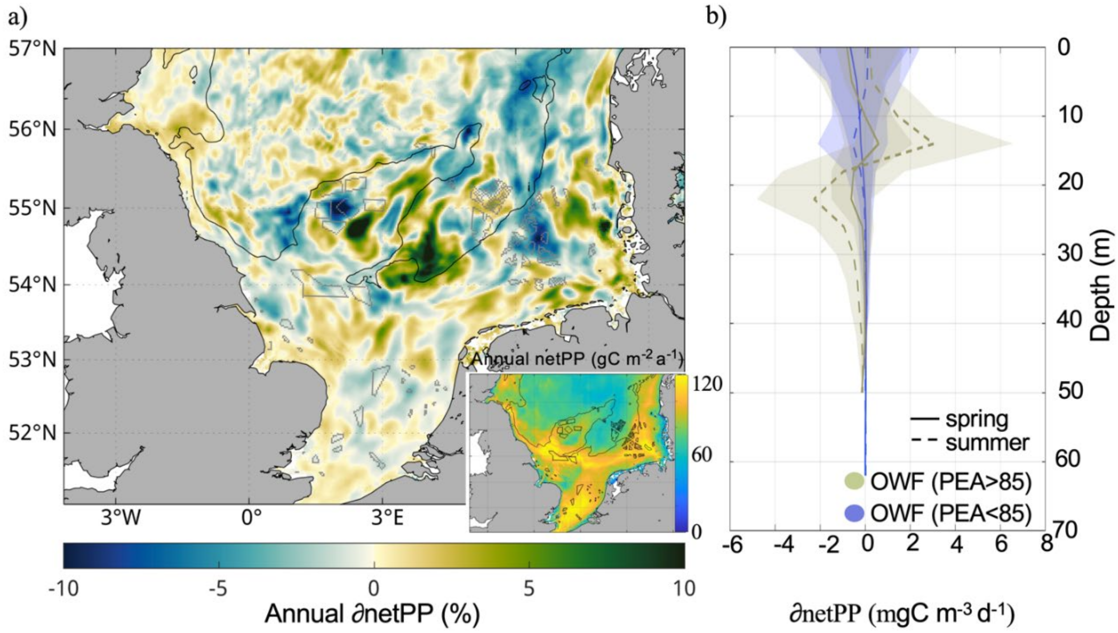


Fig. 3.12: Simplified illustration of possible ecological effects of additional mixing. Mixing causes cold, nutrient-rich bottom water to be mixed with warm, nutrient-poor surface water, which reduces the strength of the stratification and possibly promotes plankton growth in the intermediate water of the thermocline. (Source: (Dorrell *et al.*, 2022) Fig. 14)

Indirect effects - i) Reduced wind-driven mixing and increased stratification: In contrast to direct additional mixing, a shallower surface layer and greater stratification strength can be expected to reduce annual primary production, as the summer surface layer is more separated from the nutrient-rich deep water and contains fewer nutrients. Zhao et al. (2019) used a modelling study to describe the influence of tides on the distribution of primary production in the North Sean and take the effect of additional mixing and stratification into account. Their study confirms the idea that is stronger stratification leads to reduced primary production. Comparing the maps of annual primary production (e.g. from simulations as in Zhao et al. (2019)) with the planned OWF locations we find spatial overlaps between planned OWF areas and certain hotspot of primary production in the southern North Sea. With regard to the shallow summer stratification, Floeter et al (2022b) hypothesized that this process would also bring more nutrients into the euphotic zone and promote primary production there. Although model results (Daewel *et al.*, 2022) support this hypothesis, they do not necessarily show an increase in productivity. Instead, there is a vertical shift in the so-called 'subsurface' (intermediate water) chlorophyll maximum (Figure 12). Below the – often nutrient limited - summer surface layer, a chlorophyll maximum usually forms at the thermocline, where the phytoplankton still has access to light from above and nutrients from the deep water below. If the thermocline shifts further towards the surface, the chlorophyl maximum also shifts but leads to a shading effect on the layers below.

ii) Formation of up-/downwelling dipoles with persistent wind direction. Theoretically, the formation of upwelling regions leads to the transport of additional nutrients into the euphotic zone. While the physical effect is not necessarily visible due to the constantly changing wind directions on a monthly or annual average (Floeter et al., 2022), the effect on primary production would be visible accordingly. The results from model simulations (Fig 13a) (Daewel *et al.*, 2022) do indeed show an increase in primary production in the immediate vicinity of the wind farms, while in the wind farm clusters themselves the reduced stratification leads to a reduction in production.



%.

Fig. 3.13: Relative change in the annual averaged net primary production for 2010 (OWF-REF). The black contour line shows the potential energy anomaly (PEA) - i.e. a change in stratification of 85 J m-3 that roughly separates the seasonally stratified areas from the mixed areas. b Vertical profiles of the change (mean and standard deviation) in net primary production within the off-shore wind farm areas; blue: less stratified and mixed areas (PEA < 85 J m-3); green: stratified areas (PEA ≥ 85 J m-3) (solid lines: spring; dashed lines: summer). (OWP: simulation experiment taking offshore wind farms into account; REF: reference simulation). (Daewel et al., 2022)

Cumulative effects - As with the physical effects, an estimate of the cumulative ecosystem effects is initially purely hypothetical, as there are no corresponding modelling studies, and the observations do not provide any clear indications. However, if we follow the same logic, we can assume that on a larger spatial scale the indirect effects generated by the wind reduction downwind of the turbine dominate the system, but locally the direct mixing effects within the wind farms can provide additional nutrients.

Lower trophic Level Foodwebs and prey for filter feeders

In offshore wind farms (OWFs), the artificial reef effect represents an intervention in the ecosystem that initially affects the local environment around OWF structures. According to (Degraer *et al.*, 2020), these new structures are rapidly colonized by biofouling communities, which mainly consist of mussels, macroalgae, barnacles, suspension feeding arthropods, and anemones (see Tor a - iv). Studies conducted in Belgian wind farms show that benthic biomass around the foundation structures can be up to 4,000 times higher than before construction, with 89% of the biomass concentrated on the scour protection (Rumes *et al.*, 2013). At the scale of an entire wind farm, biomass can increase up to 14-fold.

More than 95% of the biomass on artificial reefs consists of suspension feeding organisms that extract particles, including phytoplankton, from the water. Voet *et al.* (2022) estimated the amount of water cleared in the process to be in the order of 7.5 olympic swimming pools per day. This reduces particle density, decreases water turbidity, and likely leads to a reduction in the standing stock of primary producers. A modeling study suggests that large-scale expansion of OWFs could reduce local primary production by up to 10% (Slavik *et al.*, 2019).

The previously explained processes describe how modifications in the physical environment might alter food resources for sessile suspension feeders on the OWF constructions. However, no conclusive studies on the interactions and cumulative impacts are currently available. The impact of the suspension feeders on NPP is in the same order of magnitude as the proposed effects from the physical disturbances. The available modelling study on the **indirect effects** suggests a slight reduction of phyto- and zooplankton inside the OWF in predominantly mixed areas and a slight reduction in phyto- but an increase on zooplankton biomass in OWFs located in seasonally stratified areas of the German Bight (Daewel *et al.*, 2022). The changes, however, are relatively small and can hardly be generalized. Both models (Daewel *et al.*, 2022) and observations (Floeter *et al.*, 2022a) indicate that the development of up-/down-welling dipoles would lead to increased primary production in the immediate vicinity of Offshore wind farms. This could increase the food availability for suspension feeders when advected into the OWFs.

On the other hand, the **direct effect** of structure induced mixing might mix up nutrients into the euphotic zone and increased primary production and phytoplankton biomass as a consequence. This would directly enhance prey availability for filters feeders on the structures. However, as of now, there is no conclusive evidence of this process, neither from observations nor from models. As detailed above, in situ observations by Floeter *et al.* (2017) did not show a significant increase in primary production. Regarding zooplankton the most distinct features observed were the high meroplankton densities in water bodies that previously drifted through the wind farm area. This, however, indicates the relevance for OWF for benthic macrofauna but not necessarily a change in secondary production. Further, there is no clear indication form the observations for a change copepod distribution related to the OWF (Floeter *et al.* 2017).

3.3.6 Specific conditions in North Sea, Baltic Sea and Celtic Sea

North Sea

The studies discussed so far have been carried out almost exclusively in the North Sea. There the physical environmental impacts of the large-scale expansion of offshore wind energy production are mainly determined by the changes in the wind field and would lead to a reduction in vertical mixing and residual currents in the southern North Sea. Locally, within the wind farms, however, there is stronger mixing depending on the density of structures. The hydrography in the North Sea is particularly characterised by the shallow bathymetry and the strong tidal currents. As described in Christiansen et al. (2022), the indirect effects are mitigated by the tidal currents. Large regions of the southern North Sea (up to a depth of approx. 30 m) are strongly mixed by the tides all year round. The model results show that the hydrodynamics in these regions are only slightly influenced.

On average, model results do not show a general increase or decrease in total production in the entire North Sea on a regional scale (southern North Sea) (Daewel et al., 2022). The simulated scenario shows a spatial restructuring of primary production with reduced production within the wind farm clusters and an increased production in the shallow coastal regions and in the Oyster Ground area. This also has consequences for other ecosystem variables. Increased production at Oyster Ground leads to an increase in the local, seasonal oxygen minimum in the bottom layer of the region (Greenwood *et al.*, 2010), which was confirmed by model simulations (Daewel et al., 2022). In other regions, however, we see an increase in bottom water oxygenation. The model also shows a redistribution of biogenic material in the sediment from shallower to somewhat deeper regions. In general, the changes in the local ecosystem components can amount to up to 10% of their original values without OWF disturbance.

In addition, van der Molen et al.,(2014) showed that the presence of OWF in relatively shallow-well mixed areas of the North Sea (i.c. Dogger Bank), leads to changes in water mixing, cascading into increased resuspension of sediment material that then affects both the benthic ecosystem and the light climate in the water column.

Baltic Sea

The Baltic Sea is an almost closed system that is only connected to the North Sea and the North Atlantic by a narrow and shallow entrance. A key feature of the Baltic Sea is the imbalance between freshwater input and evaporation, which leads to constant salt stratification and generally low salinity levels and can contribute partially or completely to ice formation in winter. Due to the limited exchange capacity and the strong stratification, significant inflows of saline and oxygen-rich water from the North Sea, so-called Major Baltic Inflows, occur only rarely (Schinke and Matthäus, 1998; Omstedt and Nohr, 2004). As the time interval between the inflows can be several years to decades, the water in the deep basins can stagnate and become anoxic over long periods of time and can also enter the surface through circulation processes, putting pressure on the ecosystem. The long-term dynamics of the biogeochemical cycles in the Baltic Sea are also influenced by the inflows and interim periods of stagnation as well as by the exchange between sediment and water (Rodhe *et al.*, 2004). Long periods of stagnation and high natural and anthropogenic nutrient loads thus lead to additional eutrophication of the Baltic Sea. The characteristic time scale (water residence time) of the Baltic Sea is approx. 30 years (Rodhe *et al.*, 2004); if the delay in turnover processes due to the storage capacity of the sediment is considered, it is even closer to 50 years for biogeochemical processes.

In the Baltic Sea, there are currently almost no studies on large-scale effects on ocean circulation. However, based on the information available to date (Arneborg *et al.*, 2024), it can be assumed that the indirect effects from the wind vortices dominate on larger spatial scales. Unlike in the North Sea, there are no significant tides in the Baltic Sea, which means that they are not expected to have a moderating effect. On the other hand, the mixing at the structure tends to be smaller than in the North Sea, as the inflowing water has lower velocities. In contrast to the North Sea, the Baltic Sea is characterized by a permanent halocline. This is caused by a strong inflow of fresh water from the continent and Scandinavia and the limited access to the North Sea. Here we can initially only speculate that the expected reduction in mixing influences the depth of the summer surface layer and possibly also the depth of the halocline. Since a large part of the expansion will take place along the Swedish coast, the reduction in the wind field may also reduce the upwelling of deep water along the Swedish coast.

Celtic Seas

The Celtic Seas ecoregion includes the northwestern continental shelf and Seas and is largely influenced by the oceanographic conditions of the North Atlantic. It is a typical temperate shelf sea system, where seasonal and spatial variations in hydrography and primary production are, just as in the North Sea, determined by the interplay between bathymetry, seasonal changes in solar radiation, prevailing winds from west and south, and strong tides (Simpson, 1981; Ruiz-Castillo *et al.*, 2019). Shallow and coastal regions, like the Irish Sea, are mixed throughout the year and are separated by fronts from deeper, seasonally stratified regions. At the shelf edge and slope region observations and models indicate strong internal mixing over the 200m isobath caused by a breaking internal tide during the stratified season (New and Pingree, 1990; Kossack *et al.*, 2023).

Similar to the North Sea, primary productivity in these regions is highly structured by the hydrographical conditions. With high productivity in the shallow and coastal regions stimulated by tidal mixing and particularly at the tidal mixing front, while lower annual primary production is found in the seasonally stratified, deeper regions (Holt *et al.*, 2009; Kossack *et al.*, 2023). A recent modelling study by (Kossack *et al.*, 2023) showed that tidal impact on primary production is generally low in deep central and outer shelf areas with the exception of the southwestern Celtic Sea. Their study showed that here tidal forcing substantially increases annual mean primary production by 25%. They suggest that, beside tide-generated vertical mixing of nutrients across the pycnocline, largely attributed to the internal tide field, also tide-induced lateral on-shelf transport of nutrients might contribute to this increase.

To our knowledge, there is no published study which explores the impact of OWF on the hydrography and consecutive impacts on primary production for the areas of the Celtic Sea ecoregion. Therefore, we can only speculate on the potential impacts based on the knowledge described above. Currently plans for OWF installations in the Celtic Seas are in near coastal and shallow areas like e.g. in the Irish Sea. Those areas feature high tidal currents and are typically mixed throughout the year with high primary production. As described in (Christiansen *et al.*, 2022) the tidal currents could mitigate the indirect impacts from the wind wakes while, at the same time, increase the impacts and radius of the direct effects from structure induced mixing. This might increase resuspension of material and influence the light climate of the system. The residual current system in these areas is rather complex (Pingree and Le Cann, 1989) why it is not possible to comment on the potential impacts of OWF on the currents without dedicated modelling studies. In general, we can assume that the hydrodynamics modification by OWF also lead to changes in ecosystem productivity in the Celtic Seas. However, due to the complexity of the interactions further, dedicated studies are necessary.

3.3.7 Discussion

In general research in this field remains limited. There is broad agreement on the individual effects and processes influencing hydrography and ecosystem dynamics. However, studies vary in their assessment of the overall impact and the effects on marine ecosystems (Floeter et al., 2022), which is further complicated by limited data and uncertainties in in-situ observations.

A key unresolved debate concerns the relative influence of direct and indirect factors on currents and stratification. Some studies suggest large-scale mixing effects from OWPs (Carpenter et al., 2016; Dorrell et al., 2022), while others argue that changes in wind patterns play a more dominant role (Daewel et al., 2022). These opposing effects on stratification are critical for evaluating ecosystem impacts.

The ecosystem impacts of these physical changes remain poorly understood. Few studies (van der Molen et al., 2014; Daewel et al., 2022) have modeled these effects, and observational data is scarce (Floeter et al., 2017, 2022). There is general agreement that OWFs will have ecological impacts, but identifying clear cause-effect chains is difficult due to the complex, nonlinear interactions of processes like primary production, remineralization, grazing, and advection/diffusion. This results in inconsistent conclusions. For instance, van der Molen et al. (2014) found increased primary production due to reduced sediment resuspension, while Daewel et al. (2022) observed reduced primary production in the same region. These discrepancies may stem from differences in wind farm configurations, highlighting the need for further research.

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3.4 ToR a.iv. The ways artificial structures could influence the colonization of new areas by species, both indigenous and non-indigenous species. Based on data available for other structures (e.g. oil & gas), and from other locations (e.g. US)

CASE STUDY: Colonization of offshore renewable energy structures by biofouling communities: the effects of associated pressures

3.4.1 Confidence

Confidence in the effects on colonisation varies across pressures. Confidence in the effect of structures on habitat availability is very high: multiple studies show OWFs provide habitats for biofouling species. Confidence in the stepping-stone effect is moderate to high, with evidence mainly from outside OWFs and mostly species-specific. Confidence in the effect of transport of floating structures is moderate, based on evidence from other industries. For impressed current cathodic protection (ICCP) and Galvanic Anode Cathodic Protection (GACP), confidence is low, relying on personal observations, limited experimental studies and coral experiments in tropical waters. Confidence in temperature effects caused by cooling water outlets and cables is moderate, as increased growth rates are known but unstudied in OWFs. Confidence in sound pollution effects is low to moderate, with limited studies on only a few biofouling species.

3.4.2 Key findings

- Offshore wind farms (OWFs) provide stepping stones for species dispersal across unsuitable environments, benefiting both indigenous and non-indigenous species (NIS), especially benthic species with long larval pelagic phases. However, the relative influence of OWFs compared to other artificial substrates remains unclear. All NIS observations in OWFs had previously been reported from the region.
- Floating OWFs likely harbour non-indigenous species (NIS) and facilitate their spread through turbine transport between ports and wind farms. Evidence from similar structures supports this, but direct studies on floating OWFs are lacking.
- ICCP systems may enhance calcifying organism growth in biofouling communities, with potential regional variations due to environmental factors. Confidence in this effect is low, as it lacks robust empirical support.
- GACP may impact biofouling communities through metal toxicity effects, but confidence is low due to limited studies.
- Elevated temperatures on cooling water pipes and dynamic cables in OWFs might influence biofouling community composition and growth rates. However, evidence remains inconclusive, necessitating further study.
- OWF sound pollution may impact biofouling organism behaviour, with variability across species. The relationship between sound and invertebrate behaviour in OWFs is poorly understood, and its ecological significance remains uncertain.

Overall, OWFs contribute to ecological changes in marine environments by providing habitats and altering species distribution pathways. However, many potential effects, especially regarding non-indigenous species, environmental interactions, and biofouling community dynamics, are underexplored, emphasising the need for targeted research.

3.4.3 Data gaps

- Insufficient data exist to compare the relative effects of OWFs and other artificial hard substrates on the distribution and colonisation by species, including those of conservation importance.
- Information on the abundance and distribution of non-indigenous species within biofouling communities of OWFs is scarce.
- Direct studies on the presence and impact of non-indigenous species on floating OWF turbines during transportation between ecoregions are lacking.
- The role of ICCP systems and GACP in influencing biofouling growth and the variation of these effects across environmental conditions remains unexplored.
- Research into how elevated surface temperatures and electromagnetic fields from dynamic cables influence biofouling community dynamics is minimal.
- The behavioural effects of sound pollution from OWFs on biofouling organisms are poorly understood, with no direct studies available for most species.

3.4.4 Recommendations

Most effects described here are poorly understood. Therefore, the recommendations focus on the need for studies to fill in the data gaps. We recommend the following studies:

- To collect data fundamental for ecosystem models and general understanding of wind farm effects on ecosystems, conduct long-term studies of biofouling communities at OWFs, focusing on sampling, taxonomic identification, biomass measurements and functional traits.
- Investigate the role of floating OWFs in transporting non-indigenous species, with targeted studies on turbines before and after transportation between ports and wind farms. Preventative measures such as biofouling removal before transport are recommended.
- Explore the ecological impact of ICCP systems and GACP on biofouling growth at OWF foundations, with attention to regional variations in salinity and temperature.
- Perform experimental studies on the effects of elevated surface temperatures and electromagnetic fields from dynamic cables and cooling systems on biofouling communities.
- Initiate research on the impact of sound pollution from OWFs on settlement and behaviour of biofouling organisms, emphasising interspecies differences and long-term ecological effects.
- Promote international collaboration to address these gaps using standardised methodology, ensuring a comprehensive understanding of OWF impacts in diverse marine environments.

3.4.5 Case Study Introduction

This section considers the ways artificial structures in offshore wind farms (OWFs) could influence the colonisation of new areas by epibenthic species. Species in this regard are considered to be the biofouling community which we define as the community settling on the submerged parts of the turbine foundations and surrounding scour protection rocks, including directly associated species living on and between the attached biofouling organisms.

Although many variations of offshore renewable energy structures exist (ICES, 2019), biofouling studies have been mostly performed on offshore wind turbine foundations. Therefore, the primary focus of this review chapter is on OWF effects.

The construction of OWFs and, consequently, the turbine foundations which are often surrounded by a rocky erosion protection layer (synonyms: scour protection layer, rock dump), introduces artificial hard substrate in the marine environment. Bottom-fixed OWFs are often constructed in sandy and gravelly bottom dominated areas, using foundations that penetrate the water column from water surface to seabed (Coolen *et al.*, 2020a), creating a habitat suitable for settlement of indigenous as well as non-indigenous species (De Mesel *et al.*, 2015; Coolen *et al.*, 2020b; Boutin *et al.*, 2023). Many of the biofouling species found on these installations are rare on soft sediment bottoms (Coolen *et al.*, 2020d), thus the introduction of this hard substrate leads to a local increase in benthic biofouling species diversity and abundance (Degraer *et al.*, 2020; Coolen *et al.*, 2022). However, compared to natural hard substrata, biodiversity and functional diversity of artificial structures can also be reduced (Brzana *et al.*, 2024).

These community-alterations result in a change in the trophic food web of the ecosystem (Raoux *et al.*, 2017; Pezy *et al.*, 2020) via shifts from deposit to suspension feeders (Coolen *et al.*, 2020d) with increased consumption of planktonic species from the water column (Mavraki *et al.*, 2022), increased fluxes of nutrients (Coolen *et al.*, 2024), and increased organic material deposition (particles, *biofouling drop-off*; Degraer et al., 2020). Furthermore, the colonising species serve as a local source of larvae and food source for higher trophic levels (Reubens *et al.*, 2011). Biofouling communities may compete with pelagic grazers such as juvenile fish and copepods for similar trophic resources. However, empirical data on this resource overlap and potential interspecific competition remain limited and evidence is indirect (Bruschetti *et al.*, 2016, Nunn *et al.*, 2012, Mavraki *et al.*, 2022). Existing OWF-specific studies have primarily focused on filter feeding by dominant biofouling species (Voet *et al.*, 2021, Mavraki *et al.*, 2022), whereas the dynamics within mixed fouling communities—where intraspecific competition for food resources may also occur—have received less attention (Mavraki et al., 2020a).

Generally, our understanding of the impact of OWFs on the spread of biofouling organisms and their impact on the environment is low, as only a small number of monitoring studies have presently been conducted, which in most cases were short term or restricted to single observation studies (Zupan et al., 2023; Dauvin, 2024). Furthermore, since most OWFs to date are located in the North Sea, and most biofouling studies carried out provide data on the southern North Sea (Degraer *et al.*, 2020; Coolen *et al.*, 2022), our understanding of the effects on the spread of species outside this region remains highly limited.

However, multiple pressures influencing the spread of colonising biofouling species via OWF have been suggested (Wilding *et al.*, 2017; Dannheim *et al.*, 2020) and the current state of knowledge on the cause-effect relations that have been identified, will be reviewed here.

Pressures

Multiple pressures were identified as potential causes of changes in the colonisation of new areas by biofouling species:

a) The introduction of artificial hard substrates increases habitat availability from the intertidal zone to the deep circalittoral zone, which facilitates the colonisation of the area of wind farm construction by both indigenous as well as non-indigenous species. The establishment of the biofouling community may further be affected by the following (sub)pressures:

  I. The use of impressed current cathodic protection on turbine foundations likely increases growth rates of calcifying organisms in the biofouling community.

  II. Chemicals leaching from Galvanic Anode Cathodic Protection may influence the biofouling community in diverse ways.

  III. Increased temperatures on cables and cooling water outlets may change survival and growth rates of species in the biofouling community.

b) The transport of floating wind turbines between ports and wind farms facilitates the exchange of non-indigenous biofouling species between regions.

c) Continuous underwater noise from turbines may affect settlement rates and behaviour of biofouling species.

These pressures are reviewed in the following sub-sections.

Although of influence on the introduction and distribution of biofouling species in general (GESAMP, 2024), vessel traffic during pre-construction surveys, construction, maintenance, and repair during operational life, and decommissioning of OWF was not considered in full detail here.

Non-indigenous species (NIS) are known to be found on all types of offshore artificial structures (GESAMP, 2024). Here we define NIS (synonyms: alien, exotic, non-native, allochthonous) as: '*Species, introduced outside of their natural range (past or present) and outside of their natural dispersal potential. Their presence in the given region is due to intentional or unintentional introduction resulting from human activities.*'

3.4.6 Introduction of hard substrates facilitates species colonisation

The placement of artificial hard substrates such as steel, concrete and other materials in the marine environment increases habitat availability for biofouling species (Dannheim *et al.*, 2020). In particular when introduced in a sandy seabed dominated environment, this artificial hard substrate increases local habitat complexity, biodiversity and functioning (Coolen *et al.*, 2020d; Dannheim *et al.*, 2020; Degraer *et al.*, 2020, Boutin *et al.*, 2023). As such, the placement during construction and presence of turbine foundations during the operational life of an OWF increases biofouling habitats, an effect that is then reduced following the decommissioning and removal of an OWF. The magnitude of this reduction depends on the extent of decommissioning: when more of the hard substrate (foundations, erosion protection layer) is removed, the magnitude of change likely increases (Knights et al., 2023; Spielmann et al., 2023), although no direct impact studies have been conducted on the effect of removal of the artificial hard substrates during OWF decommissioning.

The availability of artificial hard substrates in OWFs should be considered against a background of many other forms of 'fixed-location' artificial hard substrates present in marine waters. For example, oil and gas platforms (Picken, 1985; Guerin, 2009), shipwrecks (Leewis and Waardenburg, 1991; Zintzen *et al.*, 2006; Hickman *et al.*, 2023), navigational buoys (Macleod *et al.*, 2016; Coolen *et al.*, 2020a), artificial reefs (Vivier *et al.*, 2021; Taormina *et al.*, 2022), coastal artificial hard substrates including jetties, pontoons, dikes, bridges (Fletcher, 1981; Ashton *et al.*, 2006) all add to the large pool of artificial structures present in the marine environment (GESAMP, 2024). Furthermore, mobile artificial hard substrates form a network of pathways through which biofouling species can be introduced and facilitated to colonise the fixed-location hard substrates. These mobile hard substrates include jack-up rigs (Reichart *et al.*, 2017), semi-submersible offshore installations (Wanless *et al.*, 2010), large and small ships recreational vessels, and ocean-observing infrastructure such as buoys and gliders (GESAMP, 2024).

Colonisation of species to an area is determined by the suitability of the area for successful recruitment of the organisms (Tempesti *et al.*, 2022). Pathways of introduction include the natural ability of species to distribute themselves, e.g. via active migration or water currents as eggs or pelagic larvae, which may be facilitated by OWFs in areas that would be otherwise unsuitable for survival due to a lack of hard substrates (Adams *et al.*, 2014). OWFs in this example would not be the vector of introduction but would act as a stepping-stone from which the next generation of the organism would be able to further distribute itself (Coolen *et al.*, 2020a). This effect likely facilitates species with a long pelagic larval stage, as distances between OWFs across ecological barriers may still be large (Coolen *et al.*, 2020a), but with increasing numbers of OWFs installed, distance between them will reduce, likely facilitating shorter pelagic larval stages as well. OWFs also modify the currents and turbulence near the foundations which can play an important role in the settlement process of biofouling species (Ajmi *et al.*, 2022). Further natural introduction vectors are floating natural materials such as woods and algae (Thiel and Gutow, 2005; Want *et al.*, 2023a). Well-known anthropogenic vectors of introduction include hull fouling on vessels and organisms in ballast water (GESAMP, 2024) which can introduce reproducing adults (Wanless *et al.*, 2010) to an OWF area, allowing their offspring to colonise the artificial hard substrates. Again, the presence of the OWF in this example would not cause but only support the introduction by offering habitat after introduction.

The presence of OWFs may support the colonisation of areas by biofouling species. Since the biofouling community may include NIS, the OWFs also facilitate the colonisation of NIS to areas (De Mesel *et al.*, 2015; Coolen *et al.*, 2020b). In studies comparing natural vs. artificial substrate, most NIS were more abundant on artificial substrate, especially on the parts closer to the water surface (Brzana and Janas, 2024). However, to date, reports on fixed OWF foundations in the North Sea mostly show low percentages of NIS among the biofouling communities, with no first observations of NIS in the OWFs reported to date: Less than 3% of the NIS reported in European waters have been observed in OWFs and no NIS exclusive to OWFs in Europe are known (Dauvin, 2024). OWFs may also facilitate pelagic species with a sedentary life stage such as jellyfish species, which may include NIS. It has been suggested that artificial structures in the marine environment play a role in the increase of jellyfish blooms (Duarte et al., 2013). Generally, there is a lack of published quantitative data on NIS on OWF structures. This should be addressed in future research by an increase in data collection through sampling to quantify the densities and biomass of NIS per unit of area (Dauvin, 2024).

Like NIS, species of conservation value such as the European oyster *Ostrea edulis,* the Ross worm *Sabellaria spinulosa*, the white stony coral *Desmophyllum pertusum*, and others might use OWF habitats to colonise areas from which they are currently absent. To date, only a single observation of *O. edulis* on OWF structures has been reported, although the identification of the species was challenged later (Lengkeek *et al.*, 2013; Kerckhof *et al.*, 2018). Anecdotal observations have also been reported from other artificial structures in offshore waters (Kerckhof *et al.*, 2018; Coolen *et al.*, 2020c), but evidence for any meaningful influence of OWF hard substrates on the colonisation of *O. edulis* of the area is lacking. Multiple initiatives are working towards methods for large scale reintroduction of *O. edulis* in the southern North Sea (Kamermans *et al.*, 2018; Ter Hofstede *et al.*, 2023; ter Hofstede *et al.*, 2024), making use of unfished areas in OWF to conduct introduction experiments. Unlike *O. edulis*, *S. spinulosa* has repeatedly been reported as present on the foundations or rocks present in OWFs (Leonhard and Christensen, 2006; Coolen *et al.*, 2020b; Zupan *et al.*, 2023, Kingma *et al.*, 2024), at offshore gas platforms and pipelines (Braithwaite *et al.*, 2006; Coolen *et al.*, 2020d, 2020b) as well as on the seabed within OWFs, possibly caused by reduced fishing efforts in the OWF (Pearce *et al.*, 2014). No reports of the significance of OWFs for the distribution of *S. spinulosa* are available, but since clear overlap between existing and future offshore wind areas and the species' distribution are present (Pearce *et al.*, 2014; Bos *et al.*, 2019), it is likely that the species is facilitated by the presence of OWF in the region. *D. pertusum* has been reported in a single study on a deeper water floating turbine foundation (Karlsson *et al.*, 2022), but since the species is commonly reported on deep water offshore platforms (Gass and Roberts, 2006) it is likely that the species will colonise most deep-water wind structures within its distribution range. Similar influence on other species of cold-water corals or gorgonians can be expected in regions such as the Mediterranean Sea where OWFs are emerging, as gorgonians and cold water corals have been observed on offshore platforms the Mediterranean and other regions (Love et al., 2019, Relini *et al.*, 1998). Monitoring of the influence of OWF on all these species of conservation value should be included in current and future OWF monitoring programmes.

To date, biofouling monitoring programmes have been designed on different organisational levels, without any international standardisation (Coolen, Vanaverbeke *et al.*, 2021, Coolen *et al.*, 2022). Some countries have taken a national approach (e.g. Belgium, Germany), resulting in standard data formats on a national level (e.g. BSH, 2013), while in other countries study methods vary between OWFs. However, with national approaches, differences in monitoring programmes between countries remain (Dannheim et al., submitted). There is a clear need for standard monitoring protocols, in particular to facilitate new programmes in emerging OWF regions. This will also facilitate international data exchange (Murray *et al.*, 2018).

There is no literature that specifically quantifies the effect of OWF against the background of multiple effects on introduction and colonisation by biofouling species. It is, however, likely that the size of impact of the installation, presence, and subsequent removal of OWF foundations, is largest in areas with the following characteristics:

- Seabeds dominated by sandy sediments, since the addition of artificial hard substrates will strongly increase the habitat available to biofouling organisms.
- Large distances from natural hard substrates such as rocky coasts and rocky seabeds, since these also host epibenthic communities which may already host the species that would colonise OWFs.
- Low numbers of other artificial hard substrates, which would likely already host the biofouling community that would colonise the OWFs.
- Close to shipping lanes and other routes of vessels since these may introduce biofouling species to the area via their hull fouling.

Regional differences

Regional differences can be expected between the Baltic, North Sea including the English Channel, and Celtic Sea. Introduction of species via natural pathways such as water currents is likely lower in the Baltic, in particular in eastern parts where water current speeds are lower than in the North Sea, the English Channel and Celtic Sea. Shipping and natural spread of NIS previously introduced to the North Sea are very important introduction pathways in the Baltic Sea. With low salinities in the Baltic and low temperatures in winter, other species can be expected to colonise than will be found in the other seas.

Conclusion, gaps, and recommendations

Conclusion: Artificial hard substrates provided by OWFs are likely to facilitate distribution pathways of species by providing stepping stones across distribution barriers, allowing species to survive and further distribute in otherwise unsuitable environments. Furthermore, the hard substrates facilitate the colonisation of areas by benthic species with a long duration of the larval pelagic phase, by providing suitable habitat for hard substrate coloniser. This effect is present for indigenous as well as non-indigenous species. It is unclear what the relative size of the effect of OWF is against the large number of other artificial hard substrates present in the marine environment.

Knowledge gaps: Evidence of OWF effects against the background of other artificial (fixed as well as mobile) and natural hard substrates is highly limited. Data on abundance of non-indigenous species in biofouling communities in OWF is very limited and future observations should be encouraged.

Recommendation: Continued data collection, from the pre-construction phase, throughout the whole OWF life-cycle, including post-decommissioning and comparisons to reference sites, in long time-series, using international standard methods, is recommended. This should include information on biofouling communities through sampling and taxonomic identification, counts, biomass and functional trait measurements. Specific studies into the relative size of the impact of wind farms in relation to the effect of many other artificial structures should be conducted in an international context.

3.4.7 Impressed current cathodic protection may increase growth rates of calcifying organisms

Impressed current cathodic protection (ICCP) is a technique to prevent corrosion of exposed parts of turbine foundations by applying an impressed current on the steel, inducing a negative polarisation, which makes the steel immune to corrosion (Christodoulou *et al.*, 2010). Although this technique was not reported as being regularly applied on offshore wind foundations (Price and Figueira, 2017), it is used in several OWFs in the North Sea (personal observations, Joop Coolen). One of the known effects of electrification of steel structures is mineral accretion as the flow of electrons from the impressed current facilitates calcium carbonate and magnesium hydroxide adherence to the steel (Hilbertz, 1979). The principle of electrification is also applied in coral restoration in tropical waters, where it has been suggested to increase growth of corals attached to the steel surfaces (Zamani *et al.*, 2010), but it has also been reported to have negative impacts on coral survival under (Knoester et al., 2024). This technique has been tested on oysters in temperate waters, where increased growth rates were observed (On Shorr *et al.*, 2013). Currently, no literature on the impact of ICCP on biofouling organisms on OWF foundations is available. If there are any impacts associated with ICCP, it is likely that the calcifying organisms among the biofouling communities will be predominantly affected. However, since the voltage and amperage both influence the mineral accretion effect and growth of the organisms (Goreau, 2014), it is unclear whether an increased growth effect can be expected on OWF foundations with active ICCP systems.

Regional differences

Conductivity increases with salinity, therefore changes in salinity would likely influence the mineral accretion process of ICCP, which would then influence the effect on biofouling growth rates. However, no studies describing these relations have been found. It can be expected that the effect of ICCP on biofouling growth rates is smaller in the lower saline Baltic waters compared to the North Sea and Celtic Sea. Water temperatures are of influence on the accretion process (Margheritini *et al.*, 2020) and therefore, regional differences in temperature may influence the biofouling growth effect of ICCP as well.

Conclusion, gaps, and recommendations

Conclusion: ICCP may increase the growth rate of (some of) the calcifying organisms in the biofouling community, with regional differences, but confidence in the presence and size of the effect on OWF turbine foundations is low.

Knowledge gaps: No specific studies have been found on the impact of ICCP on biofouling growth on OWF turbine foundations. No information on regional differences in the effect is available.

Recommendation: Specific studies into the general impact of ICCP systems at OWF foundations on the development of the biofouling communities should be conducted, with attention to effects of differences in salinity and temperature.

3.4.8 Galvanic Anode Cathodic Protection may impact biofouling communities

In addition to ICCP, Galvanic Anode Cathodic Protection (GACP) is the a common way to protect steel structures in OWFs (Watson *et al.,* 2024). Aluminium-based and to a lesser extent zinc-based galvanic anodes are routinely used resulting in substantial amounts of material dissolving over the structure's 25-year life (Kirchgeorg *et al.,* 2018; Watson *et al.,* 2024). These metals (and others such as indium, but in much lower quantities) are known to be toxic to marine life, but the evidence for direct effects is limited to specific species e.g. Pacific oysters (*Magallana* [*Crassostrea*] *gigas*; Levallois *et al.,* 2022, Ebeling et al., 2023) and species that are not likely to be part of the biofouling community (Levallois *et al.,* 2023). Currently, no literature on the impact of GACP on biofouling on OWFs is available. It is, therefore, unclear what the effects on the whole biofouling community could be.

Regional differences

Salinity and temperature are likely to affect the dissolution rate and bioavailability of the metals, which would influence the potential effects on the biofouling community. However, no studies describing these interactions have been found and so regional differences are as yet unknown.

Conclusion, gaps, and recommendations

Conclusion: GACP may impact the biofouling community, although the effects are likely to be species-specific with confounding regional differences. Confidence in the effects on OWF turbine foundations is low.

Knowledge gaps: No specific studies have been found on the impact of GACP on biofouling on OWF turbine foundations. No information on regional differences for the potential effects is available.

Recommendation: Monitoring of the release of metals from GACP protection systems and specific studies (*in situ* and experimental simulations) investigating the impact of GACP systems on biofouling at OWF foundations should be conducted.

3.4.9 Increased temperatures on cables and cooling water outlets may change survival and growth rates

Water temperature influences growth and survival rates and then ecological successions of marine organisms (Hiscock *et al.*, 2004). The disposal of cooling water and increased surface temperature of power cables in OWFs likely increases temperatures of the habitat available to biofouling communities or to small infauna living near the cables. This may influence growth and survival rates of specific species.

Power generated in OFWs is converted to high voltage direct current (HVDC) before transport across the large distances to shore. This conversion is executed in HVDC converter stations, a procedure that generates heat as a by-product. This heat can be removed from the system via the use of cooling water, which is pumped from the surrounding sea, then re-circulated into the surrounding waters (Middleton and Barnhart, 2022). The use of cooling water is known to influence local water temperatures and increase growth in fouling organisms (Jenner *et al.*, 1998). If the cooling water is discharged via submerged pipelines, this might result in locally increased substrate temperatures which may influence survival of organisms during low winter temperatures or high summer temperatures. However, limited information on the use of cooling water in converter stations in existing wind farms is available. Many current wind farms stations are air-cooled (personal communication Annemiek Hermans, TenneT), and no direct evidence for the effect in offshore wind farms is available.

Dynamic power cables present in floating offshore wind (FLOW) farms are exposed to the surrounding water. During the transport of electric energy through the cables, some of the energy is lost as heat which increases their external surface temperature (OSPAR Commission, 2012). This heat is conducted to the outer surface of the cable where it will dissipate into the surrounding water. Biofouling communities on the cable may be exposed to these increased temperatures which may be up to 10°C above surrounding water temperatures (Maksassi *et al.*, 2022). This increase in temperature may change biofouling colonisation success by favouring species with a tolerance to higher water temperatures (Taormina *et al.*, 2018). However, results available from the studies conducted to date suggest limited effects via this mechanism. In California, no difference was found between exposed power cables on the seabed and nearby pipelines, but surface temperatures of the cable and pipeline were not considered in the study (Love *et al.*, 2017). The in-situ data acquired at the Jersey-Cotentin electric connection (30 MW), at the Ushant (Brittany; 500 KW) test site and at the SEM-REV (NE Atlantic; 8 MW) test site showed no significant heating of the surface of the cables - and therefore of their immediate environment (Taormina *et al.*, 2020). Considering that the temperature deviations measured on these three cables were always lower than the probes' sensitivity (0.06°C) it is likely that the ecological impact related to the temperature of the cables laid on the seabed and in the water column during operation was negligible, but this hypothesis has not been tested. Moreover, the electrical power of the cables used in these studies was low compared with those of industrial-scale OWF export cables. A study around an exposed cable in Australia, which was encased in an iron shell, showed no differences in colonisation with the surrounding reef, but surface temperature was not considered (Sherwood *et al.*, 2016). Anecdotally, in the Hollandse Kust Zuid offshore wind farm, during ROV inspections on the scour protection and power cables leading into the turbine foundations, high densities of the non-indigenous slipper limpet *Crepidula fornicata* were observed on the cables, but not on the scour protection (personal observations Oscar Bos, Wageningen Marine Research). This indicates the biofouling community on the cables can differ from the other hard substrates, although no observations were made that explained the difference. No direct further evidence for an effect of increased temperature on biofouling on dynamic cables in FLOW farms is available.

Regional differences

Regional differences can mainly be expected due to a difference in water temperature regime between regions.

Conclusion, gaps, and recommendations

Conclusion: Temperatures of the artificial hard substrate surfaces on cooling water pipes (if present) and dynamic cables in OWFs may be higher than other hard substrates in the wind farm but evidence is inconclusive. Whether this causes a difference in biofouling community composition and growth rates is unknown.

Knowledge gaps: No specific studies have been found on the impact of increased surface temperatures on cooling water outlets or dynamic power cables in offshore wind farms.

Recommendation: Specific studies into the impact of increased surface temperatures in offshore wind farms should be conducted. Experimental studies are needed to specifically address the potential effect of temperature of dynamic power cables, while considering the possible confounding effect of electromagnetic fields of the cables on biofouling.

3.4.10 Introduction of non-indigenous species via relocation of floating wind turbines

Currently, three FLOW farms, which have a reduced scale compared to fixed OWFs, are operational in the North Sea. In each case, these operational wind turbines were assembled at coastal locations and towed to the offshore location (principlepower.com, 2022; Equinor, 2023, 2024), often over large distances such as from the southeastern to the northwestern part of the North Sea (principlepower.com, 2022). During their operational life, FLOW turbines may be transported to coastal locations for maintenance and repairs and then redeployed (Equinor, 2024) or relocated to a new site. No direct evidence from FLOW exists, but the transport of other types of large floating structures, such as drilling platforms, between locations is a well-described vector for the dispersal and introduction of non-indigenous species (Foster and Willan, 1979; Mienis, 2004; Ferreira *et al.*, 2006; Gard AS, 2008; Wanless *et al.*, 2010; Yeo *et al.*, 2010). When transported across hydrographic barriers to natural migration such as currents, different temperature regimes and salinity or an absence of suitable habitats, this offers a significant risk for NIS introduction (Lewis *et al.*, 2005; GESAMP, 2024). In addition to introduction to a region, traffic from supply and surveillance vessels and secondary transport within regions may promote the colonisation of NIS throughout the area. This has been shown for the transport of NIS between marinas, where small vessels travel relatively short distances but still provide pathways for further spread of NIS after initial introduction (Ashton *et al.*, 2006; Marchini *et al.*, 2015; Foster *et al.*, 2016). Thus, even when not transported between ecoregions, transport of floating offshore structures may facilitate the distribution of NIS within regions.

To date, only one survey of biofouling on FLOW turbines has been published. In this study of the Hywind FLOW farm (east coast of Scotland), no NIS were observed, although the authors noted the ROV video survey method had limited ability to detect small species (Karlsson *et al.*, 2022). Studies of ROV footage obtained around oil and gas platforms have also suggested low detectability of small species or species covered by others (van der Stap *et al.*, 2016; Schutter *et al.*, 2019; ter Hofstede *et al.*, 2022). Therefore, the lack of observations of NIS should not be taken as proof that NIS are absent on floating turbine foundations and associated cables. An observation of NIS on a FLOW was made in the WindFloat 1 location in Portugal, where the NIS *Schizoporella errata* (Bryozoa) was found. This was the first evidence of this species in Portuguese mainland waters (unpublished data WavEC). Furthermore, since NIS have been described as present in several bottom-fixed OWFs (De Mesel *et al.*, 2015; Coolen *et al.*, 2020b; Dauvin, 2024) as well as on many other types of floating structures (Thiel and Gutow, 2005; Macleod, 2013; Ros *et al.*, 2013; references in GESAMP, 2024) it is likely that NIS are present on FLOW turbine foundations. Studies conducted at tidal and wave energy development sites in Scotland found no NIS at full scale test sites (Want *et al.*, 2021, 2023b), although the non-indigenous sea squirt *Styela clava* and the Japanese skeleton shrimp *Caprella mutica* have been recorded in sheltered waters used by support vessels and where devices may be received before deployment (Want *et al.*, 2017; Want and Kakkonen, 2021). No direct knowledge is available on NIS on floating turbines before and after transport, or on the success of NIS colonisation at their destination. The risk of colonisation of the transport destination by NIS is higher when floating turbines are transported between similar environments across species' natural distribution barriers. Especially when transporting between ecoregions (for example: from a future wind farm in the Celtic Sea to a maintenance port in the North Sea, and vice versa, NIS might be introduced to the ecoregion. Transport within the ecoregion then could facilitate the further distribution of the NIS inside the region. Following recommendations from the GESAMP expert group on NIS in biofouling (GESAMP, 2024), when transporting floating turbines between ecoregions, biofouling should be removed and disposed of in a safe manner before entering destination ports. Transport within ecoregions should be minimised to reduce further spread of NIS after introduction.

Regional differences

Regional differences such as salinity and temperature are likely to be of influence on the survival of NIS when introduced via floating turbine foundations.

Conclusion, gaps, and recommendations

Conclusion: FLOW farms are likely inhabited by non-indigenous species. Evidence from other floating offshore structures suggests that transport of floating turbines between ports and wind farms can transport and introduce non-indigenous species between ecoregions.

Knowledge gaps: Little evidence of NIS on FLOW turbine foundations exists. Data on the presence of NIS on the foundations, before and after transport between ports and wind farms and vice versa, is lacking.

Recommendation: Targeted studies on the presence of NIS on the different parts of floating wind turbines before and after transport from ports to wind farms and *vice versa,* through sampling and taxonomic and functional traits identification, counts and biomass measurement are recommended.

When transporting floating turbines between ecoregions, biofouling should be removed and disposed of in a safe manner before entering destination ports or installation in the wind farm. Transport within ecoregions should be minimised to reduce further spread of NIS after introduction.

3.4.11 Continuous operational turbine noise may influence settlement of invertebrates

The continuous movement of turbine components causes sound to be transferred via the turbine foundation to the water column (Pangerc *et al.*, 2016). The increase of anthropogenic noise is recognised as a rising pollutant in marine waters (Wang *et al.*, 2024). Noise has been shown to influence settlement of invertebrate larvae of multiple species (Anderson *et al.*, 2021; Schmidlin *et al.*, 2024). Furthermore, noise may influence behaviour of adult invertebrate species (Wang *et al.*, 2022; Ledoux *et al.*, 2023), although there is high variation in the size of the effect of noise on different species (Solan *et al.*, 2016). Indifference to anthropogenic low-frequency noise and substrate-borne vibration has been suggested to facilitate the success of dominant fouling species on offshore wind turbine foundations (Burgess *et al.*, 2023; Wang *et al.*, 2024). These species may have a competitive advantage over other potential colonisers which consequently may lead to the observed putative prevalence of species that seem to be indifferent to anthropogenic noise and vibration on operational turbines. However, potential effects are complex and, for example, can be expressed as physiological stress (Wale *et al.*, 2019; Cheng *et al.*, 2024) reducing the fitness of species. Although understanding of some of the interactions between anthropogenic noise and marine invertebrate behaviours and life cycles is increasing, the available knowledge on the impact of anthropogenic noise on invertebrates is still limited (Solé *et al.*, 2023). Specific studies on how noise of offshore wind turbines changes colonisation of species have not been found.

Regional differences

Regional differences can mainly be expected due to a difference in background noise regimes between regions. It is likely that in regions with low ship traffic or construction sounds the influence of OWF noise on colonisation is highest.

Conclusion, gaps, and recommendations

Conclusion: An effect of noise on a selection of biofouling organisms' behaviour is likely, but confidence in this cause-effect relation is low to moderate, depending on species.

Knowledge gaps: The understanding of the interaction between sound and invertebrate behaviour in general is poorly understood and for most species, data is lacking. There is no direct knowledge on the interaction between OWF noise and invertebrate.

Recommendation: Specific studies into the impact of increased noise pollution from offshore wind farms on colonisation of biofouling should be conducted.

3.4.12 References

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3.5 ToR a.v. The ways in which pelagic species (especially commercial fish species) may react to dynamic cables suspended in the water column (floating wind)

CASE STUDY: An expert review, supported by the most recent literature, of the ways in which pelagic species (especially commercial fish species) may react to dynamic power cables suspended in the water column (floating wind) for Celtic Sea, Greater North Sea and Baltic Sea (ICES ecoregions).

3.5.1 Confidence

Overall confidence in the topic of the impacts of dynamic power cables on commercial pelagic fisheries species is low. There are only a small number of commercial scale floating offshore wind (FLOW) developments anywhere worldwide and these are small installations with no known studies on species interaction with the few dynamic power cables present. Therefore, most of this review is based on expert judgement, with that judgement using, where available, evidence from fixed offshore wind and subsea power cable studies. Such evidence is field and/or laboratory-based cause and effect studies and opinions within reviews. Most of the evidence focuses on non-commercial, adult life stages of species.

3.5.2 Key findings

- Most commercial species with a pelagic life stage within an ecoregion will overlap in spatial distribution with dynamic cables throughout the time that the cables are in the water column (construction, operation and decommissioning).
- Interactions between species and cables leading to responses will relate to either direct energy emissions, physical effects and/or indirect ecological effects.
- Only during the operation of dynamic power cables will energy emissions represent potential stressors to commercial pelagic fisheries species.
- The timing of exposure to energy emissions will be determined by the operational characteristics of the cables and the length of time that species use the pelagic environment around dynamic power cables.
- Owing to an almost complete lack of evidence, an approach to assess whether commercial species will interact and react to dynamic power cables is proposed.

3.5.3 Data gaps and research needs

- Freely available and easily accessible location and spatial extent of FLOW and the associated dynamic power cabling within an ecoregion
- The range of depths and areas of occurrence of dynamic power cables.
- Identification of targeted species occurrence and distribution in relation to the location and extent of dynamic power cables (for assessing spatial and temporal overlap).
- 3-Dimensional data of targeted species use of the water column to inform the likelihood of encounter with dynamic power cables.
- Responses of species to dynamic power cables interactions.

3.5.4 Recommendations

- As the knowledge base is extremely limited at present, evidence from proxies, such as buried cables from fixed offshore wind or mooring systems for other marine structures are referred to where appropriate. These proxies are, in their own right, limited but more importantly their comparability with dynamic power cables needs to be assessed. It is therefore recommended that an assessment from the cable perspective (requiring engineering expertise) and a consideration of the interactions with marine species is undertaken for both fixed and dynamic cables. In terms of commercial species, the life-history characteristics and spatial and temporal occurrence are required to be considered.
- The likelihood of encounter (including the duration) and responses by commercial pelagic species to dynamic power cables should be the focus of specific studies, most likely achievable for prioritised species. The criteria for prioritisation should be set out and could be based on levels of interaction with dynamic cables (i.e. high number of interactions and/or long duration of interaction).
- A risk assessment for targeted species within an ecoregion should be undertaken. This could build on the stepwise approach presented here.

3.5.5 Dynamic cables and floating offshore wind

Dynamic power cables are used to transmit the power generated by floating offshore renewable energy technology from the sea surface, through the water column, between the array of turbines and on to either offshore substations or fixed export cables in/on the seabed. In terms of floating offshore wind (FLOW) developments, the cables will be categorised into turbine array cables and export cables. These cables can be generally regarded as similar in terms of their potential interactions with pelagic commercial fisheries species. The key knowledge required is the cable characteristics, the marine areas where fFLOW is expected to occur and the commercial fisheries species distribution and the species-specific attributes that could result in a reaction by the species. Here, a review of each of these knowledge requirements is presented with specific consideration of species and proposed FLOW development areas in the Celtic Sea, Greater North Sea and Baltic Sea (ICES ecoregions).

Subsea power cables are an essential feature of offshore wind developments (and all types of renewable energy technology) as they transmit the electrical power generated by the devices (e.g. turbines) to shore and into the electricity grid network for domestic and industrial use. Knowledge regarding FLOW and environmental interactions in general is limited, however, some environmental changes that are associated with FLOW have been identified (Farr et al 2021; IRENA 2024) and a subset of these are relevant to the consideration of dynamic cables (Table 3.7).

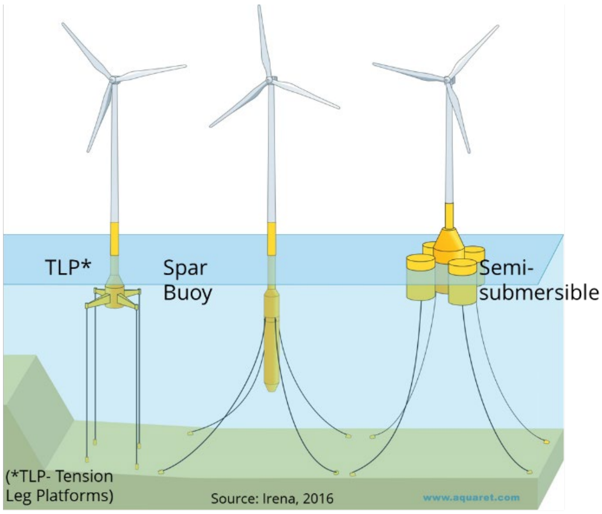
There are several potential direct or indirect interactions between subsea cables and commercial fisheries species. It is important to note that some of the attributes are common to any subsea power cable, including those used for fixed offshore wind and power interconnectors, and therefore this review includes relevant evidence from these related technologies (as summarised in Table 3.7). However, the placement and motion of dynamic cables in the water column provides some aspects unique to this technology.

Table 3.7. Summary of key attributes of dynamic subsea cables and their potential direct and indirect interactions with commercial pelagic fisheries species. P indicates shared attributes; O indicates no shared attributes.

Cable interactions	Key attributes	Dynamic cables – floating technologies	Seabed/buried cables – fixed technologies	Interconnectors
		Attributes that are shared (P/O)		
Direct				
Energy emissions				
Electromagnetic fields (EMFs)	Electric and magnetic fields are emitted by power transmission	P	P	P
Sound/Noise	Cables can electrically resonate and create sound (e.g. hum) during operation	P	P	P
Vibration	Cables can mechanically resonate (i.e. vibrate)	P	O	O
Temperature	Power transmission creates heat within the cable and at the cable surface	P	P	P
Physical				
Collision	Species may physically collide with the cable structure in the water column	P	O	O
Entanglement	Following collision, some species may become entangled in the cable(s)	P	O	O
Habitat association	Commercial species (one or more life stages) associate with the cable (e.g. refuge for early life stages)	P	P	P
Indirect				
Colonisation by prey species	Species that colonise/associate with, the cable physical structure attract predators that are commercial species	P	P	P
Hydrodynamic effects	Water movement affecting thermal, saline or physical properties (e.g. turbidity) within the column that species rely on	P	O	O
Seabed sweep	Potential for physical abrasion of seabed introducing sediment into water column	P	O (buried) P (laid on seabed)	O (buried) P (laid on seabed)

The depth of water and the design of the FLOW structure and moorings will determine the extent of the changes that can occur to the marine environment (see Table 3.7). For example, the mooring system can be tensioned or non-tensioned (e.g. catenary; Figure 3.13a), which means the dynamic power cables effects may be unique or add to potential interactions, such as entanglement with catenary moorings. The catenary moorings can also be adjusted in terms of their movement (Figure3.13b).

(a)



(b)

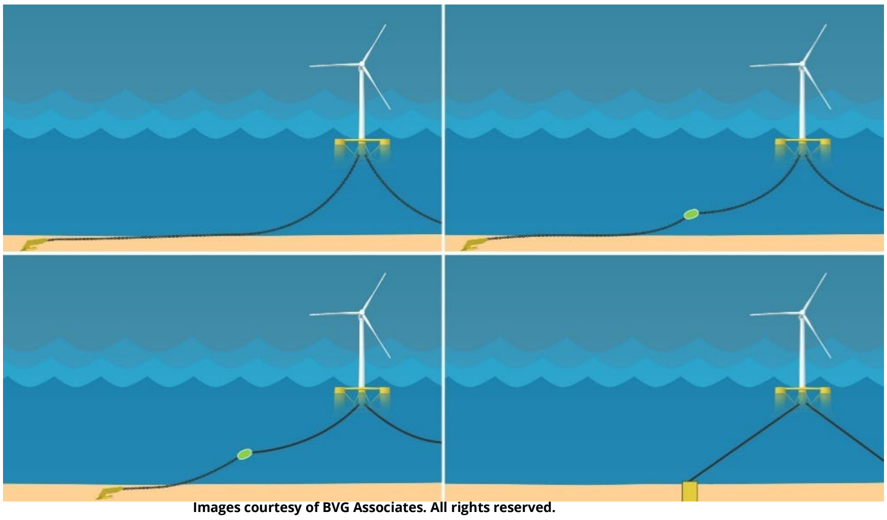


Figure 3.13. Floating offshore wind turbine mooring options. (a) Tension leg platform moorings restrict the movement of the turbine, whereas catenary moorings allow the turbine structure greater potential to move within the water column. (b) Catenary moorings can also be adjusted for movement (i.e. more or less taut).

Floating devices have individual mooring systems, and a dynamic power cable. These cables will likely hang freely in the water column between devices within an array and will be subject to movement and potential encounter by commercial pelagic species. Transmission to shore of the power generated will be through one or more export cables and may be route via an offshore substation. Each export cable will have a dynamic section and a fixed section if the cable is on the seabed or buried. There are several components that will reduce the physical movement of the export cable compared to the freely hanging interarray cables (Figure 3.14).

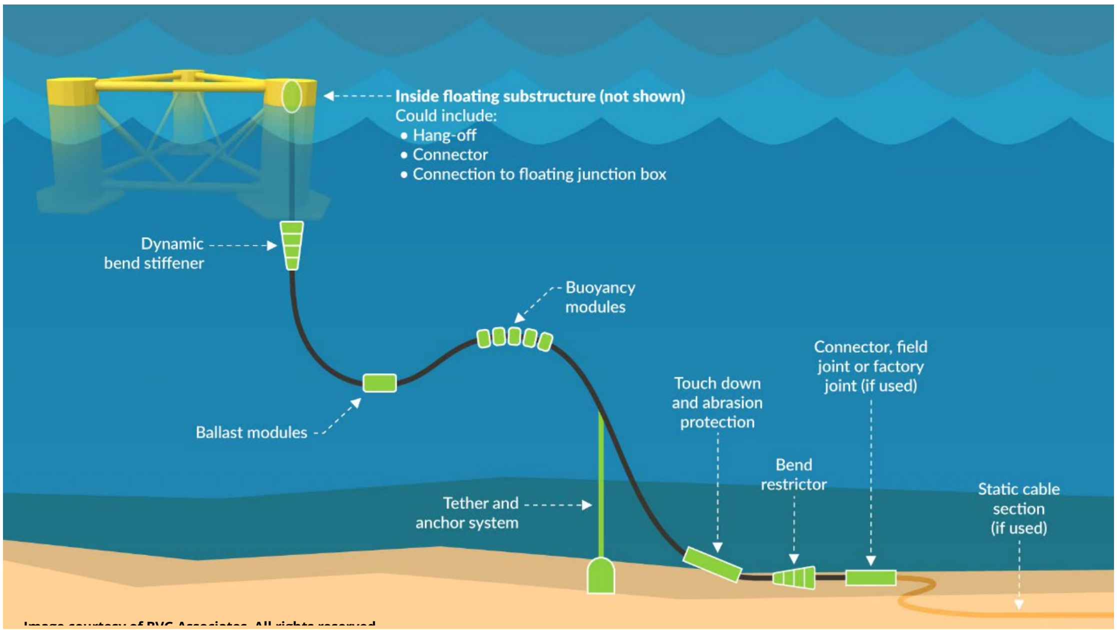


Figure 3.14. Typical dynamic cable system components for floating offshore wind turbines. An actual system may not use all of these components at the same time.

Whilst the physical movement of a dynamic cable can be restricted (in the case of the export cable), both the interarray and the export cable(s) share other properties less dependent on the physical dynamics. Namely, energy emissions, in the form of electromagnetic fields (EMF), noise and vibrations, and temperature (Table 3.7). The noise and vibration properties of intensity and frequency will likely change with the level of tension and to some degree physical movement. Hence, these properties may make them less or more likely to be detected by species. External temperature changes are expected to be restricted to the surface of the cable and dissipated quickly by the surrounding water, based on knowledge from seabed associated cables (Taormina et al. 2018). The magnetic component of the EMFs, however, is not expected to be altered by the physical movement differences, however induced electric fields from the movement are possible. The propagation of the magnetic field will be similar within the water column in a to magnetic fields emitted into the seabed if buried, or the adjacent water column for seabed surface-laid cables (Figure 3.15; Hutchison et al. 2020). The induced electric fields will propagate further in the open water than those associated with buried cables, where the seabed properties will dampen the propagation distance.

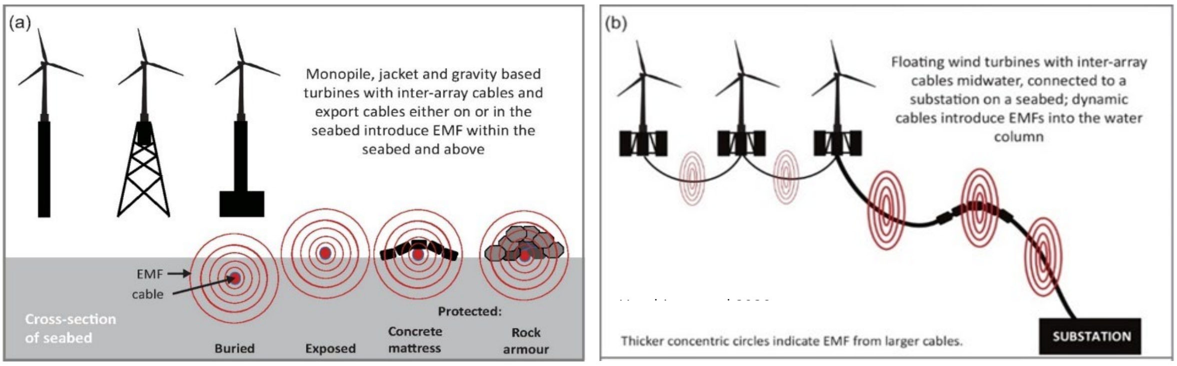


Figure 3.15. Introduction of EMFs into the marine environment by offshore wind devices regardless of cable type and location (a) Fixed offshore wind turbines (monopile, jacket and gravity-base) emit EMFs into the seabed and water column, with the EMF intensity and frequency the whether passing through the seabed or cable protection (as these do not have magnetic properties). (b) Floating wind turbines with interrray cables hanging in the water column between turbines and export cable with water column sections and seabed/fixed sections (either directly to shore or to an offshore substation). From Hutchison et al (2020).

Dynamic power cables will be either High Voltage Alternating Current (HVAC) or Direct Current (HVDC). Engineering and economic consideration will determine which type of cable will be used. Current expectations are that HVAC will be used for the turbine interarray cables and the cable to the substation if the distance is relatively short. Turbine cables are attached to each turbine tower, and they are smaller, both physically (diameter) and in the power they transmit from each turbine, compared to export cables. If, however, the floating offshore development is located at some distance from shore, it is predicted that HVDC export cables are more likely to be used because of better power transmission efficiencies and relative costs (van Eeckhout et al. 2010). Regardless of the type of cable, the physical characteristics and properties of the cable materials and the power levels transmitted will determine the intensity and frequency of EMFs emitted into the surrounding environment. Also, HVDC cables will directly emit magnetic fields but contain direct electric fields, whereas HVAC cables will directly emit magnetic fields and induced electric fields (Gill and Desender 2020), which should be considered when assessing potential reactions by commercial pelagic species.

3.5.6 Potential for reactions of commercial pelagic fisheries species to dynamic cables

In terms of the potential reactions to dynamic cables there is an extremely limited evidence base (Hutchison et al 2020; Gill et al. 2020; Farr et al. 2021). Therefore, the narrative set out in this section reflects expert judgement on the topic supported by knowledge within the reference section below. The sub-sections following are based on Table 3.8 cable interactions.

Table 3.8 Summary of expert judgement on the potential reactions of commercial fisheries species to subsea cables associated with floating renewable energy devices and their potential direct and indirect interactions with commercial pelagic fisheries species. Supporting evidence is provided by published references most from studies or reviews of subsea power cables of fixed renewable energy devices and interconnectors.

Cable interactions	Potential reactions to dynamic cables	Reference
Direct		
Energy emissions		
Electromagnetic fields (EMFs)	Commercial species may react to either electric or magnetic fields or both (see Figure 3.16). The reactions, which can occur at one or more life stages are behavioural, developmental or biochemical.	Gill and Desender 2020
Sound/Noise	Cables can electrically resonate and create sound (e.g. hum) during operation	Taormina et al. 2018
Vibration	Cables can mechanically resonate (i.e. vibrate)	Taormina et al. 2018
Temperature	Power transmission creates heat within the cable and at the cable surface	Taormina et al. 2018
Physical		
Collision	Species may physically collide with the cable structure in the water column	Copping et al. 2021
Entanglement	Following collision, some species may become entangled in the cable(s)	Copping et al. 2021
Habitat association	Commercial species (one or more life stages) associate with the cable (e.g. refuge for early life stages)	Copping et al. 2021

Cable interactions	Potential reactions to dynamic cables	Reference
Indirect		
Colonisation by prey species	Species that colonise/associate with, the cable physical structure attract predators that are commercial species	Farr et al 2021
Hydrodynamic effects	Water movement affecting thermal, saline or physical properties (e.g. turbidity and wake changes) within the column that affects species occurrence and/or abundance	Farr et al 2021
Seabed abrasion	Potential for physical abrasion of seabed introducing sediment into water column, which increases turbidity and the potential for seabed spawners and eggs to be disturbed.	Farr et al 2021

Energy Emissions

Energy emissions, as defined in the Marine Strategy Framework Directive (MSFD; EU) 2017/848, are considered under the Descriptor 11. Electromagnetic fields, noise and vibrations, and temperature change are expected to be the energy emissions most relevant to dynamic power cables. Each of these emissions have properties that come from the operation of the power cable. Therefore, to understand the range of intensities, frequencies, and duration that species may experience requires knowledge on the cable characteristics and materials that relate to each of the energy emissions. Furthermore, species will either respond actively or passively to the energy emissions (Figure 3. example for EMFs). Species that have the sensory apparatus and ability to sense and therefore detect and respond to the energy emissions are regarded as active responders, which will typically occur through behavioural and movement-type responses. All other species are regarded as passive in terms of exposure to energy emissions that may affect their physiological, biochemical or developmental/genetic processes. A crucial factor to consider is whether the species will encounter dynamic power cable energy emissions.

Electromagnetic fields (EMFs)

The transmission of electricity in any power cable will emit EMFs, in the form of both electric and magnetic fields. In terms of dynamic cables, the properties and materials of the cable and the cable transmission type (HVAC or HVDC) will determine the intensity, frequency and duration of the EMFs emitted (Taormina et al., 2018). EMFs will be present along the length of the cable and propagate into the surrounding water column with an expected propagation distance of metres to 10s of metres, which will be determined by the EMFs intensity and frequency (Taormina et al., 2018).

Some commercial fisheries species are known to have specific electro- and/or magneto-sensory apparatus (e.g. elasmobranchs or migratory species; Gill et al. 2020; Gill and Desender 2020) and can respond actively when encountering EMFs. Direct active responses could be attraction or avoidance of the cable or diversion from a migratory path or local orientation (Figure 3.12). Indirect effects could be predation on prey species that associate with the cable because of EMFs. Any commercial species can encounter EMFs passively if their life history leads them to be associated with areas where dynamic cables are installed. Such passive encounter is currently expected to be most important for sedentary life stages (such as embryos within eggs; Figure 3.16) or low mobility because of association with the cables, perhaps as refuge or for feeding on colonising prey (Table 3.8).

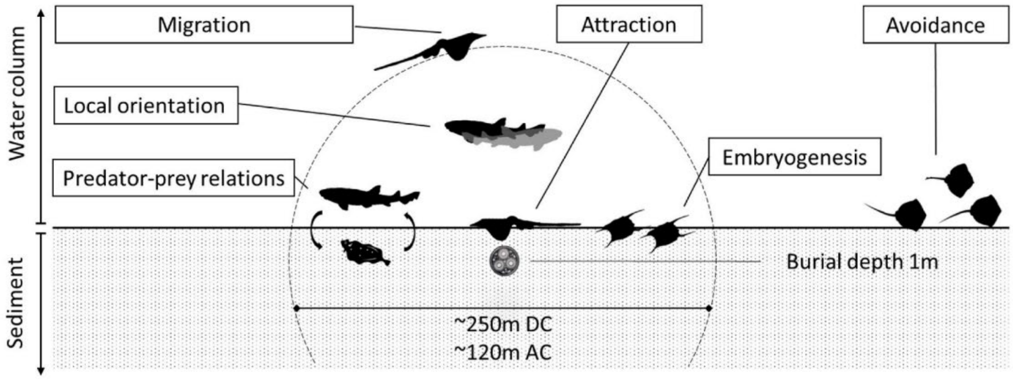


Figure 3.16 Schematic overview of possible elasmobranch active and passive responses exposed to modelled magnetic fields (Figure inspired by Albert et al., 2020). Potential impact range based on a perception level of 0.005 µT, modelled levels for the OWF export cable IJmuidenVer (2 GW direct current subsea power cable) and Borssele (700 MW alternating current subsea power cable) transporting maximum amount of power is indicated by dotted line. Note: animals are not to scale. (Adapted from Hermans et al. 2024).

Sound/Noise

The primary source of sound that can be regarded as a noise (i.e. artificial sound adding to the ambient sound) comes from the cables electrically resonating during power transmission. This sound appears as a hum that may cause either an attraction or avoidance response by pelagic species during operation of the wind turbines. The propagation distance of the sound is determined by the intensity and frequency, with low frequencies propagating furthest. Whether there is an attraction or avoidance reaction, or no response will be determined by the sensory sensitivity of a species, and the particular life stage, which will determine the length of time exposed to the noise (see Popper and Hawkins 2019, for review of fish species response to changes in the acoustic environment).

Vibration

Similar to sound/noise, the source of vibration is mechanical resonance of the cable within the water column (Ringsberg et al. 2025). This resonance can be transmitted from turbine tower vibrations, that the cable is connected to, or from the cable itself vibrating within the water column. In terms of propagation distance of the vibration, it is determined by the intensity and frequency, with low frequencies propagating furthest. Whether there is an attraction or avoidance, or no detectable response of a species will be determined by the sensory sensitivity of the species, and the life stage, which will determine the length of time exposed if the noise is encountered.

Temperature

During electrical transmission the cable components heat up. This is a well know aspect of electricity transmission and engineers design the cable operating temperature be lower than 90 °C to reduce the energy transfer losses (Gulski et al. 2021). The heat at the surface of a dynamic cable has not been measured (to date), however, with water moving past the cable surface the propagation of the heat into the surrounding environment is expected to be only a few cms at the most. Therefore, the likelihood of commercial species actively encountering higher temperatures is expected to be negligible, however for species that have more sedentary of passive traits there may be some interaction.

Physical interactions

Collision

The potential for fisheries species to collide with dynamic power cables is speculative. Collision will only occur if species encounter the physical cable, do not detect it and therefore do not avoid it. As fisheries species all have sensory abilities allowing them to detect physical objects, it is expected that collision will be highly unlikely to occur. However, there is no existing evidence of pelagic species movement response to dynamic power cables. It is known from reviews of interactions between species and other marine energy devices (e.g. tidal turbines; Copping et al. 2021) that collision will only occur if the structure moves faster than the species can respond. Dynamic power cables will move to some degree; however, this movement is expected to be relatively slow. With more cables in the water column the potential for collision will increase but by how much is also speculative.

Entanglement

Similar to collision risk, the potential for entanglement is predicted to be low. However, it will depend on how mobile the cables are and in the context of FLOW with catenary moorings then the potential for entanglement in both mooring lines and dynamic cables increases; but the level of risk is speculative.

Habitat association

The direct association of commercial species with the dynamic cable as habitat is possible in the context of the fish aggregation effect or a life history stage that requires structures to attach eggs onto or to seek refuge early in life. The whole FLOW development (turbines, floating foundations, mooring systems and dynamic cables will represent large structures in the water column which will attract fisheries species. The habitat association/attraction could be for several reasons and could occur for one or more life stages. Importantly, direct habitat association could increase the risk of fisheries species interacting with other dynamic cable attributes, such as energy emissions. There may also be some species that have longer-term association that may lead to reef effects (as seen for less mobile and non-commercial species).

Indirect effects

Colonisation by prey species

Any structure in the water will be colonised by epibenthic species, particularly those with planktonic phases of life that settle out of the water column onto hard structures. Such colonisation may provide food for fisheries species at different life stages. Therefore, this indirect attraction to prey to the cable could increase the likelihood of species encountering the dynamic cable.

Hydrodynamic effects

Both the main turbine structures, the mooring system and the array of dynamic power cables will affect local hydrodynamics. There are several potential consequences, ranging from increase mixing of water, changes to water velocity, to increased turbidity in the surrounding water column. The hydrodynamic environment is particularly important for pelagic species and any changes may affect water clarity, water temperature or salinity may have consequences to occurrence and/or abundance of fisheries species. Furthermore, early life stages within the water column may be affected in terms of dispersal or position with the water column by downstream effects associated with hydrodynamic changes.

Seabed abrasion

If dynamic cables come into contact with the seabed, then seabed sweep and potentially abrasion will occur. This is most likely in areas where FLOW is deployed in shallower waters and also waters with high tidal range which may bring the cable nearer to the seabed. If catenary moorings are used it is expected that dynamic cables will add to the sweep and abrasion of the mooring lines. The main considerations for pelagic fisheries species are increase in suspended sediment in the water affecting visual predation. For species that have benthic spawning then these areas could be physically disturbed by the sweep and abrading action of the dynamic cable and/or the settling out of suspended sediment, which could smother the developing eggs.

3.5.7 Areas identified for floating wind

At the time of reviewing the evidence and writing this report, there were no publicly available information on the locations identified as suitable for floating wind development at the spatial scale of the three ICES Ecoregions. It is important to have these data when looking to assessing the potential interaction between commercial pelagic fisheries species and dynamic cables. Only very general information is available from Ørsted to indicate areas globally that have floating offshore wind potential (Figure 3.17). Figure 3.17 indicates that within all three ICES Ecoregions there is some potential for floating offshore wind and if these areas are developed then they will have dynamic cables.

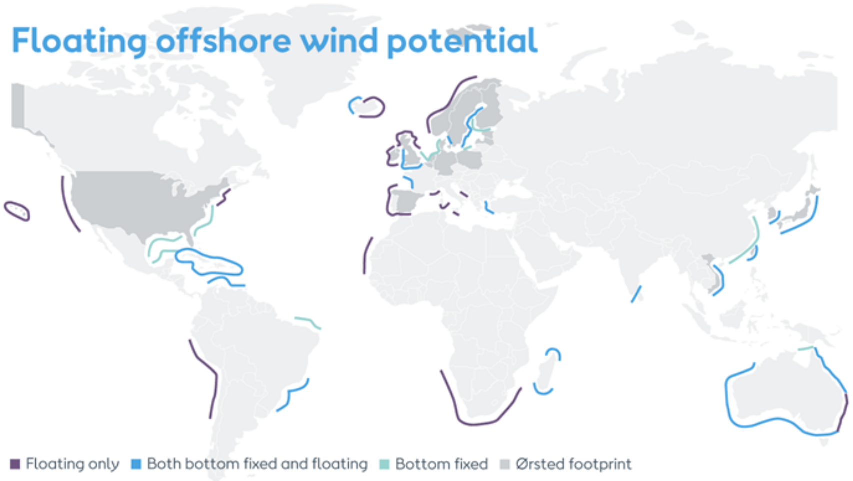


Figure 3.17 Depiction of potential areas for floating offshore wind adjacent to the coasts of countries worldwide. Darker lines highlight areas where floating wind (and therefore dynamic cables) could be deployed. Darker blue areas show areas suitable for both floating and fixed wind energy developments. Source Orsted.

There are specific data on the planned/consented areas for FLOW publicly available from specific countries (e.g. U.K. Round 5 planning areas for floating wind in the Celtic Sea; Figure 3.18). In the context of the overlap with species distribution and fishing areas, the marine spatial plans for FLOW within the jurisdiction of each country would have to be consulted and data obtained at the same spatial scale as the data on commercial fisheries species and fishing, when considering the potential for interactions with dynamic cables.

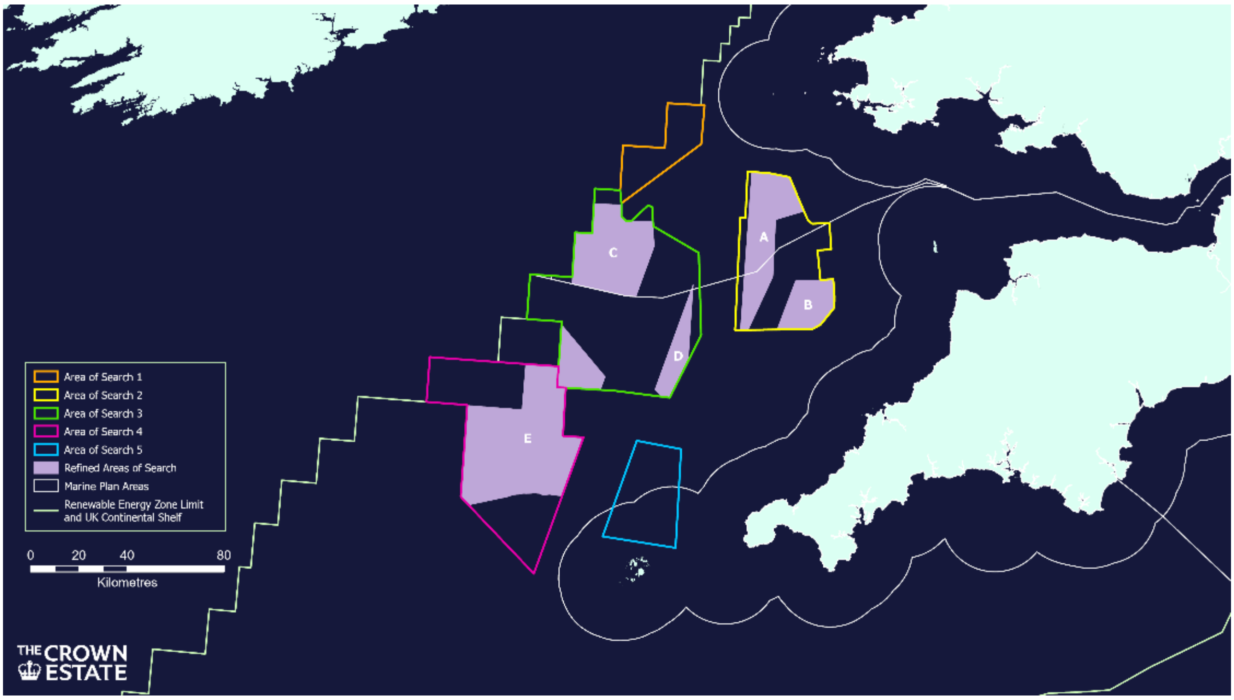


Figure 3.18. Areas for planned floating offshore wind in the Celtic Sea. Initial areas deemed suitable for floating technology are shown as coloured polygons. Lilac coloured areas A – E are the refined areas identified as planning areas available after taking into account other uses of the areas. Source: The Crown Estate.

3.5.8 Review of pelagic species distribution in ecoregions

The potential for commercial species to encounter dynamic cables relates to any traits that bring them into the pelagic habitat. Such traits could be associated with one or more life history stages. For example, migrating adult fish moving through the water column or planktonic larval stages of some crustaceans. Table 3.9 shows the commercial species that have been identified through this review that occur in the three ICES Ecoregions of interest to the advice request. Almost all species regardless of the Ecoregion could encounter dynamic cables as they have a pelagic stage within their life history (Table 3.9). It is the pre-adult stages that are most associated with the pelagic zone. However, for many of these species their time spent in the pelagic phase of life may be short (i.e. a matter of days or weeks) for early life stages. Whereas, for some of the species that are likely to encounter dynamic cables it is the adult stage of life when the likelihood is high because they inhabit the pelagic zone for longer periods of time (i.e. months or years).

It is important, therefore, to assess the life history stage or stages that a species may be in the pelagic zone and also the length of time that each life stage is pelagic. With a longer period of time in the pelagic zone then the likelihood of encountering dynamic cables increases and therefore the potential for reaction will increase too.

Table 1.9 Commercial species (or families) and their taxon group regarded as having a life history stage with pelagic association within the three ICES Ecoregions. The list of species and their pelagic-related traits within the three ecoregions, were determined from Annex 4 traits and reference to Fishbase.

Species	Common name	Taxonomic Grouping	Life stage pelagic association	
			Pre-adult	adult
ICES Ecoregion: North Sea				
Ammodytes spp.	Sandeels (=Sandlances)	Fish	P	P
Clupea harengus	Atlantic herring	Fish	P	P
Gadus morhua	Atlantic cod	Fish	P	P
Crangon crangon	Common shrimp	Invertebrate	P	
Pecten maximus	Great Atlantic scallop	Invertebrate	P	
Lophius piscatorius	Angler (=Monk)	Fish	P	
Nephrops norvegicus	Norway lobster	Invertebrate	P	
Melanogrammus aeglefinus	Haddock	Fish	P	P
Merlangius merlangus	Whiting	Fish	P	P
Merluccius merluccius	European hake	Fish	P	P
Pleuronectes platessa	European plaice	Fish	P	
Homarus gammarus	European lobster	Invertebrate	P	
Buccinum undatum	Whelk	Invertebrate		
Pollachius virens	Saithe (=Pollock)	Fish	P	
Scomber scombrus	Atlantic mackerel	Fish	P	P
Scophthalmus maximus	Turbot	Fish	P	
Solea solea	Common sole	Fish	P	
Sprattus sprattus	European sprat	Fish	P	P
Pandalus borealis	Northern prawn	Invertebrate	P	
Mytilus edulis	Blue mussel	Invertebrate	P	
Loligo spp	Common squids nei	Invertebrate	P	P
ICES Ecoregion: Celtic Sea				
Clupea harengus	Atlantic herring	Fish	P	P
Gadus morhua	Atlantic cod	Fish	P	P
Nephrops norvegicus	Norway lobster	Invertebrate	P	
Lepidorhombus whiffiagonis	Megrim	Fish	P	

Species	Common name	Taxonomic Grouping	Life stage pelagic association	
			Pre-adult	adult
Lophius piscatorius	Angler (=Monk)	Fish	P	
Pecten maximus	Great Atlantic scallop	Invertebrate	P	
Melanogrammus aeglefinus	Haddock	Fish	P	P
Merlangius merlangus	Whiting	Fish	P	P
Merluccius merluccius	European hake	Fish	P	P
Cancer pagurus	Edible crab	Invertebrate	P	
Micromesistius poutassou	Blue whiting (=Poutassou)	Fish	P	P
Microstomus kitt	Lemon sole	Fish	P	
Buccinum undatum	Whelk	Invertebrate		
Homarus gammarus	European lobster	Invertebrate	P	
Molva molva	Ling	Fish	P	
Pollachius virens	Saithe (=Pollock)	Fish	P	P
Scomber scombrus	Atlantic mackerel	Fish	P	P
Scophthalmus maximus	Turbot	Fish	P	
Sepiidae, Sepiolidae	Cuttlefish, bobtail squids nei	Invertebrate	P	
Solea solea	Common sole	Fish	P	
Trachurus trachurus	Atlantic horse mackerel	Fish	P	P
Zeus faber	John dory	Fish	P	
ICES Ecoregion Baltic Sea				
Anguilla anguilla	European eel	Fish	P	P
Clupea harengus	Atlantic herring	Fish	P	P
Coregonus albula	Vendace	Fish	P	P
Gadus morhua	Atlantic cod	Fish	P	P
Perca fluviatilis	European perch	Fish	P	
Platichthys spp	European flounder	Fish	P	
Pleuronectes platessa	European plaice	Fish	P	
Sprattus sprattus	European sprat	Fish	P	P

3.5.9 Potential for interaction between commercial pelagic species and dynamic cables

There is currently no direct evidence on which to determine the potential for interaction between commercial pelagic species and dynamic power cables. However, it is clear that there needs to be an agreed approach to the assessment of the potential interactions, which will require knowledge on the areas where floating devices are planned, the scale of the development as well as spatial and temporal knowledge of the commercial pelagic fisheries species.

With this context in mind, it is advised that the following stepwise approach is taken towards determining the likelihood of interaction for any species of interest. Each step addresses a key question (in **Bold**):

Step 1. **Where are the FLOWs?** - Identify the geographic location of FLOW planned or consented areas within the ecoregion.

Step 2. **Where are the dynamic cables?** - Determine the number and extent of the dynamic cables in those locations through the number of turbines and the associated cable array. In addition, the export cable(s) routes, whether to an offshore substation or directly to shore, noting that the length of the cable in the water column (and therefore dynamic) should be estimated.

Step 3. **Where are the species of interest?** - Obtain best available data on species spatial occurrence and, where possible, abundance for species within an ecoregion (or other spatially defined area such as, ICES rectangles or c-squares which provides better spatial resolution) that have a pelagic stage within their life history (i.e. including adult and pre-adult life stages; Table 3).

Step 4. **What is the overlap between species and cables?** - The spatial data on the dynamic cables (Steps 1 and 2) and the fisheries species (Step 3) need to be overlaid in a suitable spatial data platform to determine if there is any spatial overlap between species of interest and dynamic cable locations.

Step 5. **Check point in process**

- If there is spatial overlap (from Step 4) then there is a likelihood of encounter between the species and the dynamic cable, **move onto Step 6**.

- If there is no overlap then **stop** the process as there is no need to proceed any further.

Step 6. **What are the spatial and temporal attributes of species of interest for each interaction?** - For each species of interest, each interaction, whether direct or indirect (Table 3.) should be considered in turn. This will require specific knowledge of the species in relation to the length of time that they will be interacting with the dynamic cable(s). The key determinants of the timing will be length of time in the pelagic environment, the depth range over which the species normally is found during this time, and its sensory abilities for the energy emission interactions. For example, larval life stages may be pelagic for a matter of days or weeks or adults may be months or years if they have site attachment traits. Once each interaction is assessed then a statement on how likely the interaction is should be assigned. This could take the form of simple qualitative categorisation of high, medium or low. More sophisticated categorisation can be developed as the knowledge base increases in the future.

Step 7. **What is the likelihood of interaction for selected species?** - Step 6 will provide indications of species with different levels of interaction with dynamic cables. This provides potential criteria on which to select particular species of interest (i.e. high number of interactions and/or long duration of interaction). To determine the likelihood of interaction resulting in reaction then more specific data are required. It is crucial to have data on the range of depths that the dynamic cables will occur in (taking into account knowledge on expected device movement and tidal ranges within an ecoregion) and data on the duration, intensities and frequencies of cable operation (for energy emissions). These data should then be assessed with regards to the outputs from Step 6 – to give a likelihood of interaction, therefore encounter and potential reaction.

Step 8. **How confident is each step?** - Apply a standard rating to each step to provide an overall confidence judgement in the assessment of species response to dynamic cables.

Step 9. **What are the knowledge gaps to address?** - Identify where the key knowledge gaps are for each step and recommend resolution of these knowledge gaps, acknowledging that there may need to be some agree prioritisation criteria applied to enable key knowledge gaps to be addressed.

3.5.10 Key Recommendations and Evidence gaps

Based on expert judgement, however this is with low confidence, it is expected that commercial pelagic species that have either multiple life stages or long periods of pelagic habit such as xxx, yyy will be most likely to encounter dynamic cables. These species must occur within the areas planned for FLOW regardless of ecoregion. Furthermore, following encounter the reactions of the species will depend on their species-specific attributes, such as their sensitivity to the identified stressors associated with dynamic cables; therefore, a species-centric approach should be applied (see Hutchison et al 2020). If a species has a long period of life or a critical stage in life that is affected by one or more stressors then appropriate management responses should be developed. At this stage it is premature to identify these without studies on specific species. However, the stepwise approach set out here provides the opportunity to target efforts to determine those species that should be investigated further in the context of dynamic cables. Furthermore, following these steps will allow risk assessment to be undertaken (such as detailed in Hermans et al. 2024). Since most commercial pelagic species depend on primary production at some stage of their life, changes in primary production expected from hydrodynamic impacts may either counterbalance or aggravate the effects of cables.

In terms of evidence gaps, it is important to improve knowledge on:

1. Location and spatial extent of FLOW deployments and the associated dynamic cables within an ecoregion (or other spatially defined area such as, ICES rectangles).
    a. The range of depths and areas of occurrence of dynamic cables are required.
2. Species occurrence and distribution in relation to the likelihood of encountering dynamic cables.
    a. Spatial and temporal data for areas of overlap are needed.
    b. 3-Dimensional data in terms of species use of the water column is needed to inform the likelihood of encounter with dynamic cables.
3. Knowledge on interactions between species and dynamic cables is very limited, and evidence on the reactions of species to dynamic cables is absent. At the moment knowledge from proxies, such as buried cables from fixed offshore wind or mooring systems for ships or other marine structures are used. However, the comparability between these and dynamic cables requires
    a. An assessment from the cable perspective (which will need engineering expertise).
    b. Consideration of interactions with marine species and how transferable this knowledge is.
4. The likelihood of encounter and reaction by commercial pelagic species to dynamic cables leading to a risk assessment for species within an ecoregion. This could build on the stepwise approach outlined above.

3.5.11 References

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4 PART 2

Cumulative impacts assessment methods of ORE and mitigation measures

This section addresses WKCOMPORE ToRs a.vi, and a.vii (see section 1.3) that provide the scientific basis to answer the request questions (see section 1.1):

e) Provide recommendations for next steps to define methodologies to model cumulative impacts of offshore wind on commercial fisheries (temporary, permanent) and the possibility to adopt mitigation measures.

i) List options for mitigation measures, good practices, and spatial planning for ORE developments and assess their strengths, weaknesses, implications and uncertainties. List priorities for research and monitoring related to these options.

4.1 ToR a.vi. Recommendations for next steps to define methodologies to model cumulative impacts of offshore wind on commercial fisheries (temporary, permanent) and the possibility to adopt mitigation measures.

4.1.1 Key messages and recommendations

- An important distinction is made between CEA/ecosystem models which are based on risk assessment framework approaches used strategically to identify ecosystem components in areas at highest risk, from CEA/ecosystem models which can quantitatively assess the interactions between windfarm developments and fisheries in support of operational management advice.
- For the ecosystem models and tools evaluated in this study (in terms of their operational utility) we recommend the top-ranked (Category 1 and 2) models (e.g. VMStools, FishSET, DISPLACE, OSMOSE, Community Profiling Tools and EwE/ Ecospace), be more widely applied and validated for operational management purposes.
- We recommend further international collaboration to better integrate national fisheries and environmental data sets and data flows to improve CEA/ecosystem model applications at a range of spatial/ temporal scales.
- We recommend the development of case studies to demonstrate the practical application of available strategic risk-based assessment frameworks (such as BowTie, FEISA, ODEMM and SCAIRM) and to link them explicitly with the outputs of quantitative (mechanistic) CEA models (described here as category 1 and 2 models) to better support operational management advice.
- We recommend the improvement of model inter-operability for CEA, especially between ecological, economic and social models/ tools.
- We recognize there is no single CEA/ecosystem model or assessment tool that can provide a comprehensive assessment of all component interactions at a social, economic and ecological level, between windfarm developments and fisheries. We therefore recommend using a combination of CEA/ecosystem models operationally.
- We recommend an increased focus on the use models and spatial analysis tools to explore long time-series fisheries and environmental data (>10 years) to better describe and understand the spatial/temporal dynamics of core fishing areas and climate effects in response to offshore windfarms.
- We recommend an evaluation of selected Category 1 and 2 model outputs with respect to better informing potential mitigation options, that is to evaluate if the models lead to an evidence base that will allow specific measures to be effectively identified and taken.

4.1.2 Introduction

The origins of Cumulative Effect Assessment (CEA) are linked to the formation and rise of environmental impact assessments (EIA). EIA was first formalized following the enactment of the National Environmental Policy Act of 1969 (NEPA) in the USA (Willsteed *et al*., 2017). Nowadays, the need for CEA has increased due to the growing prevalence of marine activity and pressure footprints such as those created by offshore windfarm developments (Willsteed *et al*., 2017, 2018 a-b), and the challenges imposed by climate change effects (Simeoni *et al*., 2023).

The recent adoption of Cumulative Effects/Impacts Assessment methods (CEA/CIA) can support marine planning by providing a realistic view of the anticipated uses and impacts from multi-sectoral activities (e.g. industry, recreational activities), helping to balance economic growth and environmental targets.

For marine activities, there is an increasing need to consider the effects and pressures alongside the impacts of other activities. In addition, there is a need to consider the cumulative effects of all activities in a management area and to determine whether there are synergistic or antagonistic interactions (Stelzenmüller *et al*., 2018; Simeoni, *et al*., 2023). This assumes that an area has a limited capacity to integrate and sustain projects and developments before encountering significant and potentially irreversible adverse effects. These impacts can compromise ecosystem functionality and adversely affect the provision of various ecosystem services.

It is noted that cumulative effects and cumulative impacts assessments, as terms (CEA/CIA), are often used interchangeably (see Blakley and Franks, 2021). However, Piet *et al*. (2021) argued *effect* is the immediate consequence of the pressure on some attribute (e.g. mortality, reproduction) of an ecosystem component (acting at the level of the individual organism or population), according to a defined pressure-effect relationship or impact pathway. In contrast, *impact* should be expressed as an assessment endpoint and so the distinction between a CEA and CIA corresponds to the difference between a midpoint and endpoint in the impact pathway.

Several pathways can be distinguished through which offshore wind may have an impact on commercial fisheries:

1) Direct effect on fisheries through spatial footprint. This applies specifically for those fisheries not allowed to fish in OWF areas, e.g. large bottom trawlers
2) Through the resource, i.e. target (shell)fish species, which may be impacted by OWF. Note, however, this may be negative but could also be positive. OWF may also cause changes in the spatial distribution of (shell)fish e.g. through changes in the hydrodynamics.
3) Through the cumulative impacts on the wider ecosystem where the limited ecological carrying capacity and the fact that both OWF and fisheries contribute to those cumulative impacts require that an increase of one activity (i.e. OWF) necessitates the decrease of another (i.e. fisheries)

In order to define the next steps required to develop CEA/ ecosystem methods and tools to address the interactions between ORE developments and fisheries it is first necessary to evaluate the currently available CEA/ ecosystem models and tools, especially those which have the greatest utility and potential to support quantitative operational management advice in the short to medium term. The ecosystem models selected contrast with conceptual models (Olsen et al., 2023) and ecosystem risk-based assessment frameworks (Bow-Tie, ODEMM, SCAIRM and FEISA) which are typically employed to conduct an initial 'high-level' or strategic assessment of ecosystem component interactions and associated impact risks (including human activities and pressures) operating at a range of spatial/ temporal scales of interest. Examples of products based on such risk assessments are the ICES ecosystem overviews. However, their utility to support operational management advice, in less well tested. The following review of CEA/ ecosystem models and tools is therefore focussed on those models/ tools which can (or have the potential to) quantitatively assess the interactions between ORE and fisheries and which can effectively support CEA risk-based assessment frameworks.

4.1.3 Overview of selected CEA modelling tools considered

This part of the request evaluates selected CEA/ ecosystem models to assess the cumulative impacts of offshore wind developments on commercial fisheries (both temporary and permanent). They were selected on the basis they are capable, or have the potential through further development, to quantify cumulative impacts and trade-offs associated with the ecological, social and economic components of the ecosystem. A selection of the ecosystem models and assessment tools which have been evaluated in Table 4.1 are further described below:

Ecopath with Ecosism (EwE) and Ecospace is an ecological/ecosystem modelling software framework that has three main modules: *Ecopath* – provides a mass-balanced ecosystem overview based on a diet composition matrix, including different functional groups/ecosystem components across different trophic levels; *Ecosim* – provides a time dynamic simulation component that can be used for exploring for example, policy related scenarios; *Ecospace* – provides an explicit spatial and temporal dynamic simulation component that can be used, for example, to explore the trade-offs between fisheries and offshore wind farms (OWFs). The EwE modelling framework has been recently applied for exploring the trade-offs between fisheries and OWFs in the southern North Sea (Püts et al. 2023); for exploring the impacts and cumulative effects on the ecosystem in relation to aquaculture and Marine Renewable Energy (MRE) in the ICES VIa area on the West Coast of Scotland (Serpetti et al., 2012). The main advantage of the EwE and Ecospace modelling framework is the capacity to adapt and modify the model for exploring for example, different policy scenarios; one of the main limitation, in some cases, may be that in order to run specific policy oriented scenarios, the availability of validation data is required, in relation to the assumptions and uncertainties underlying the model parametrisation.

DISPLACE is an agent-based bioeconomic modelling platform for advisory purposes (Bastardie et al., 2014). It integrates fisher's decision-making processes to simultaneously evaluate economic and ecological sustainability of a fishery. It combines a spatial explicit agent-based model for fishing vessels that covers allocation of fishing effort and includes vessel movements with spatially explicit and size-structured models for several marine living resources (fish and benthos) and species. The model analyses revenues, operating costs and fuel use for fishing operations, including possible changes with scenario-based testing. It simulates short- and medium-term impacts detailing the spatial and temporal dimensions for particular fisheries activities, local communities or national fleets. DISPLACE has been previously applied to several European fisheries and fisheries management regimes under changing ocean productivity. DISPLACE is an open-source project and the details of all calculations and other technicalities can be found online in the code as well as the documentation that comes with it. DISPLACE can be used jointly with spatial management designation tools. Hence, spatial plans may come from fish stock distribution persistence analysis identifying relevant areas (e.g. spawning or juvenile fish aggregations) or from pre-existing spatial plans (biodiversity conservation areas, offshore windmill farms, etc.).

ATLANTIS (Fulton et al. 2011) is a deterministic ecosystem model with a flexible, modular framework which integrates physical, chemical, ecological, and fisheries dynamics in a spatially explicit, three-dimensional domain. Over the past two decades, Atlantis has served as a strategic management tool for exploring ecological hypotheses, simulating climate scenarios, and testing human impacts on the environment, including fisheries, changes in land use, pollution, and energy development (Audziionyte et al 2019). Worldwide, there are more than 45 Atlantis models exploring a wide range of marine systems, including the Baltic (Bossier et al 2018), but to our knowledge not the North Sea and the Celtic Sea. Sensitivity analysis methods for increased confidence of Atlantis has been published by f.ex. Bracis et al (2020). Atlantis is suitable for evaluating the effects of offshore wind energy development on fisheries directly by implementing no-take areas, but also indirectly to changes in the marine ecosystems, f.ex. by changing the mortality of species affected by the wind farm (f.ex. seabirds), and/or by adding abiotic habitats which corresponds to man-made structures such as wind-mill parks, pipelines etc. as a fraction of each polygon. In an abiotic fraction of a polygon, OWF induced changes in current, temperature, salinity and nutrients availability can be modelled by a high-resolution oceanographic model and then used as a forcing field for Atlantis. Setting up Atlantis for a new region is a complex task that requires expertise in marine ecology, oceanography, fisheries science, and numerical modelling. While Atlantis is highly flexible and powerful, the setup process is data-intensive and requires careful calibration.

Spatial analysis tools, the analysis of high-resolution fisheries data (including VMS, AIS and log-book catch-data) obtained either directly from national governments or via international data center's (such as those managed ICES, and the EC) can be assessed using a range of bespoke and widely available spatial analysis tools, such as VMStools which is an open-source software package built in R specifically developed to process, analyze and visualize logbook and VMS data (VMStools). In addition, FishSET is a spatial economics toolbox developed as an R package for assessing societal preferences on the sites and allowable uses for marine managed areas and conducting integrated and predictive modeling of fishermen's choice of fishing grounds. Since the 1980s, fisheries economists have employed spatial models to better understand and explain the factors that influence the spatial behavior and fishery participation choices that fishers make when fishing. This is important for predicting how fishers may respond to, for example, marine protected areas (MPAs), climate-related species range shifts, changes in fishing costs or fish prices, fish size differences, or the implementation of various management actions such as catch share policies. FishSET was developed to standardize data management and organization, provide easily accessible tools to enable location choice models to provide input to the management of key fisheries; organize statistical code so that predictions of fisher behavior developed can be incorporated and transparent to all users. FishSET enables organizing and visualizing data; developing, improving and disseminating modeling best practices; and simulating policy scenarios to explore the welfare consequences of management decisions. At the time of drafting this report, there were no examples of using FishSET to investigate the effects of windfarms on fisheries.

OSMOSE (Object-oriented Simulator of Marine ecOSsytEMS) is an individual-based ecosystem model, that provides an end-to-end modelling framework that can be used to explore and evaluate the interactions across scales, between for example, fisheries impacts on food webs, and provide guidance for the implementation of Marine Protected Areas (MPAs), and to support fishery management in relation to the effects of fishing and climate change (Moullec et al. 2019; Morell et al. 2023). The OSMOSE framework has the capability to represent ecosystem dynamics and spatial lifecycle dynamics at a basin-scale in relation to climate and anthropogenic impacts, however it requires extensive data information, for example, on species' life histories for the parametrization of the model. Limitation of the model may be related to the availability of data for the parametrization on specific model compartments, and model calibration.

GADGET is the Globally applicable Area Disaggregated General Ecosystem Toolbox. Gadget is a flexible and powerful software tool that has been developed to model marine ecosystems, including both the impact of the interactions between species and the impact of fisheries harvesting the species. Gadget simulates these processes in a biologically realistic manner and uses a framework to test the development of the modelled ecosystem in a statistically rigorous manner. Gadget has successfully been used to investigate the population dynamics of stock complexes in Icelandic waters, the Barents Sea, the North Sea and the Irish and Celtic Seas. Gadget may aid strategic planning by highlighting the expected long- or medium- term consequences of alternative management strategies on a large number of ecosystems features that may go beyond the traditional fishery management metrics such as fishing mortality and biomass of target fish stocks. There are currently no examples of using Gadget to investigate the cumulative effects of windfarms on fisheries.

FishRent/SIMFISH are bio-economic models, which help to simulate and understand how fisher folks could respond to management options and natural variations (e.g. climate change). Originally, the FishRent model was a joint effort developed by several institutes during the EU project entitled "Study on the renumeration of spawning stock biomass" (Salz et al 2011). The new versions of the FishRent model or SIMFISH include the economics of multiple fleet segments, the impact of fishing on stock development and the spatio-temporal interplay of fleet segments and fish stocks (Bartelings et al, 2015, Simons et al. 2014). Those models are dynamic feedback models with several submodules, considering a possible effort redistribution, but also accounting for the economic conditions (e.g. revenues and fishing costs), helping to determine fishing effort and that management regulation itself and how these changes will alter profitability and effort decisions by fleet segments will affect the commercial fish stocks. The FishRent/SIMFISH model was used to investigate the effects of closures due to windfarms and nature on fisheries in the North Sea (see Bartelings et al. 2015 and Hamon et al. 2021) . It also contributed toa publication integrating fisheries with marine spatial planning (see Janßen *et al*., 2016). Further details are captured in this website: FishRent.

Community profiling tools aim to describe and characterise the interactions of actors within a community and their relation to particular resources from a social science perspective. Up to now such methods have not been much used in advice for fisheries. Although it has taken initial efforts in 2019 to launch a fisheries community profile system, the EU is lagging behind in developing tools to understand the social impact at the level of fisheries communities compared to frontrunner countries such as the US or Australia (European Commission, Joint Research Centre, Scientific Technical and Economic Committee for Fisheries 2024). In their EWG 24-05 the STECF developed a definition of fisheries community for the purpose of developing fisheries community profiles (FCP) intended to support the potential of assessment of positive and negative impacts of policy decisions, management measures or of shocks and crises and act as one tool to improve the understanding of the social dimension of the CFP. However, application is still in the early stage and first cases are currently under review. According to the definition in EWG 24-05 fisheries communities are place-based but can pertain to wider geographical areas which gravitate towards (fishing) harbours, and are likely to include fisheries-based organisations and ancillary industries in the seafood value chain. As a tool fisheries community profiles support cumulative risk assessments by providing the social and economic relation between fishing as an activity and the associated places and local communities.

ISIS-Fish is a seasonal, spatial simulation model describing the dynamics of fishery resources, exploitation and management. It was developed to investigate the effects of combinations of fishery management measures on fishery dynamics. It can be used to compare the effects of conventional management measures such as total allowable catch (TAC), fishing effort management, fishing gear restrictions and spatial management measures such as marine protected areas (MPA). It has also been used to address functional zones restoration issue (https://doi.org/10.1016/j.marenvres.2025.106983). The spatial resolution of the model is flexible and adjusted to the questions addressed by the model and the available data to set the model. ISIS-Fish has been designed to be as generic as possible so that it can be applied to different types of fisheries. It includes a database that holds a knowledge base for each fishery that can be easily updated. This knowledge base includes the parameters describing each population and each fishing activity (fleet and métiers scale). ISIS-Fish is very flexible to allow several hypotheses to be tested, in particular the relationships between the stock of reproductives and reproduction, selectivity functions for fishing gear, etc., making it suitable for modeling a wide range of pelagic, benthic and demersal fisheries. Functions describing fishery management measures and the response of fishermen to these measures and to environmental and economic conditions can be coded using an interactive script editor. ISIS-Fish simulates Abundance, Biomass, Catch and Revenue time series (with a month time step) at several scales (population, spatial zone, age/length group, fishing metier, fleets, gear). At the time of drafting this report, there were no examples of using ISIS-Fish to investigate the effects of windfarms on fisheries.

Impact Assessment bio-economic Model (IAM) for fisheries management is a discrete time (annual), multi-fleet or multi-vessel, multi-métier, multi-species bio-economic model with "age" components for the biological part, and "commercial category" components for the economic part. It is a tool for academic and non-academic knowledge integration which models dynamics and interactions between fish stocks, vessels or fleets, fisheries governance and fish markets. IAM enables scenario simulation, optimization and impact assessment of management strategies, including transition to MSY, input and output controls, and other measures such as changes in selectivity. For instance, it can be used to evaluate the socio-economic consequences of alternative TAC and quotas allocation options, a well as exploring the conditions for fisheries viability and sustainability. The modelling platform enables stochastic simulations to assess the biological and socio-economic impacts of alternative scenarios and management strategies, facilitating the comparison of trade-offs from a multi-criteria perspective. Currently non-spatially explicit, the model could be adapted to the OWF-Fisheries interaction question via the definition of spatially resolved fishing métiers, where data available enables such definition. Individual vessel parameterization could also be useful for a spatially implicit implementation, relevant for studying the economic impacts of OWF-fisheries interactions. At the time of drafting this report, there were no examples of using IAM to investigate the effects of windfarms on fisheries.

Table 4.1 highlights differences in model specifications with respect to their utility for application to support operational management advice. The models have been ranked according to their assessed operational readiness, e.g.; Category 1 models and tools are assessed to be operationally 'fully' ready and have wide application in assessing various aspects of OWF and fisheries interactions, although they may benefit from having more comprehensive access to national fisheries and environmental data streams to be fully effective in all regions and at all spatial/ temporal scales; Category 2 models and tools are only partially operationally ready, they may require the inclusion of additional parameters which can quantitatively evaluate the interactions between windfarm developments and fisheries. Some of the required sources of information, data and knowledge required to further parametrise these models is presented in Part 3 of the present report (see section 3). However, their model structure and spatial domains have the flexibility to allow such parametrization to be implemented with relatively little effort subject to the availability of relevant data sets. In some instances, models have been developed and applied in different regions, but they have the utility to be adapted and applied to the North Sea, Celtic Sea and Baltic Sea given the known availability of relevant data sets in these regions; by contrast, Category 3 models require considerable further development and modification to achieve operational readiness for management advice. We recognise that there is a lack of necessary detail presented in Table 4.1, describing the specific parameters included in each of the models, and what other parameters would be required with supporting data, to effectively assess the interactions between OWF developments and fisheries. An evaluation of an additional level of detail (including parameters assessed) would be required to supplement Table 4.1 to ensure the operational categorisation as indicated in Table 4.1 is appropriate.

Table 4.1. Selected models and tools either used, or have the potential to be used, to assess different aspects of cumulative effects between offshore wind developments and fisheries. The models have been evaluated against criteria relevant for the assessment of their operational readiness to support management advice.]

Models/ Tools	Evaluated Model Attributes/ Critera															Operational readiness to support management advice (1 fully ready , 2 partially ready, 3 needs further development)
	Type	Description	Spatial extent	Availability/ developed	Impacts on fisheries/ relevance	Input data requirements/ availability			Routinely used in management advice	Resources to develop/apply	User Skills	End user type	Support marine spatial planning	Credibility/ widely accepted	selected sources/ references	
						Quantitative	quantitative	Qualitative								
Spatial overlap analysis (VMS/ AIS tools)	Spatial MSP	Spatial overlap analysis of fishing activities	Global/ Regional/ Local	North Sea, Celtic Sea, Baltic Sea	Directly related to estimates of stock status (CPUE) through integration with logbook data.	Inputs and parameters are quantitative, biomass, economic, vessel position, readily available.			Yes - seabed impacts, economic impacts, trade-off with windfarms and MPAs	Minimal	High level of proficiency required, knowledge of the data	Managers, Industry, Scientists, Policy Makers	Yes	Yes	WGSFD reports (ICES)/ GNSBI project	1
EwE/ Ecospace	Ecological/ Ecosystem	Ecosystem mass balance model	Regional/ ecoregional	North Sea, Celtic Sea, Baltic Sea	Quantification of changes in stock biomass and distribution, and loss of fishing opportunities at fleet and species level in response to different management and MSP scenarios such as lost access to fishing grounds	Inputs and parameters required are quantitative using a preditor/ prey matrix and biomass estimates for each trophic level.	For some pressures in Ecosim parameters are can be semi-quantitative, data on mortality, recuritment	-	Not yet	Regional sea models are avaiable, additional parameters are required to assess the effects of wind farm developments on fisheries using existing data and knowledge, minimal effort to develop.	High level of proficiency required to run different management scenarios	Managers, Industry, Scientists, Policy Makers	Yes - Ecospace and analysis of trade-offs	Growing acceptance and application in research, but somewhat limited in terms of their wider stakeholder credibility application	https://www.sciencedirect.com/science/article/pii/S030438001500575X	2
DISPLACE	Bio-economic	Dynamic spatial multi-agent bio-economic model taking into account spatial population dynamics as well as fishing effort displacement.	Regional / ecoregional / local	Baltic Sea, North Sea, Celtic Sea, Ionian Sea, Adriatic Sea, mesopelagic Danish vessels, and Californian current applications (see References)	Integrate knowledge of fishing behaviour in modelling fishing dynamics; model the spatial structure of fish populations; quantify the dynamic ecological footprint of individual fleets/fisheries; explore the ecological, production and economic effects of smaller and larger marine area closure scenarios, and associated tradeoffs and co-benefits.	Inputs and parameters are quantitative	fisher knowledge encoded via decision trees		Yes, has been used to inform ICES work on benthic impacts of fishing, as well as STECF work on the socioeconomics impact of VMEs designation, in particular	Effort required to develop applications in areas where has not yet been applied (~2 months), need for understanding and collecting data at the resolution required (ICES data and biological traits per species/stock, "vessel- to fleet-based economic information, and spatial data) to assess interactions between OWF and fisheries, regarding ecological responses, as well as fishing dynamics and economic and social dimensions	High level of proficiency required in R and collecting fisheries related data, knowledge of the fleet dynamics	For model use: Researchers; Experts For model outputs: Managers, Policy Makers, Researchers, Spatial Planners, Industry and Civil Society Stakeholders	Yes (test platform of area closure scenarios including permanent or seasonal closures per type of activity)	Well established as a research tool and advisory support tool. Open-source software (Graphical User Interface + Simulator). Core model coded in C++	https://maritime-spatial-planning.ec.europa.eu/practices/model-spatial-fishery-planning-and-effort-displacement	2
OSMOSE	Spatial MSP	Multi-species IBM	Regional/ ecoregional	North Sea,	Under development through the SEAwise project.	Inputs and parameters are quantitative			Not yet	Developed under SEAwise project for the North Sea.	High level of proficiency required	Managers, Policy Makers	Yes, can support MSP, but not so easily	Widely accepted as a research tool, but limited applicability to assess effects of windfarms on fisheries.	SeaWise project https://seawiseproject.org/	2
Community profiling	Social	Describes the wider importance of fisheries for a local community	Localised around place-based communities	German North Sea coast	Direct relevance at social/ community level		Interviews and questionnaires are the main sources of data sources. Focus groups.	-	Not routinely used in management advice	Requires time and effort to ensure effective (extensive) stakeholder engagement/ dialogue.	High levels of proficiency in applying social methods/ questionnaires.	Fisheries Managers, Policy Makers, Spatial Planners	Yes - at a local level, evaluating trade-offs	Commonly used in planning, impact assessments and licensing.	https://www.climatexchange.org.uk/wp-content/uploads/2023/09/wind_farms_-_review_of_good_practice_on_community_engagement_-_final_report_14_06_16.pdfDetails pending (Andreas)	2
FishSET	Ecological/ Ecosystem	The Spatial Economics Toolbox for Fisheries (FishSET) is a set of tools developed as an R package for assessing societal preferences on the sites and allowable uses for marine managed areas, and conducting integrated and predictive modeling of fishermen's choice of fishing grounds.	Regional / ecoregional / local	Alaska - Bering Sea, Gulf of Mexico	Organizing and visualizing data; developing, improving and disseminating modeling best practices; and simulating policy scenarios to explore the welfare consequences of management decisions.	Inputs and parameters are quantitative			Yes - NOAA informs the management of Marine Protected Areas in U.S. waters by using FishSET	Effort required to implement applications to European regions, using available data on fisheries and OWF interactions of a similar nature as used in the US; need for understanding and collecting data at the resolution required to assess interactions between OWF and fisheries, regarding fishing dynamics and economic and social dimensions	R language, high level of proficiency required in econometric models of spatial fishing behaviour, knowledge of the data	For model use: Researchers; Experts For model outputs: Managers, Policy Makers, Researchers, Spatial Planners, Industry and Civil Society Stakeholders	Yes	Growing acceptance from regional (US) to global (European sea area)	https://noaa-nwfsc.github.io/FishSET/index https://www.fisheries.noaa.gov/national/socioeconomics/marine-protected-area-economics-research	2
FISHRENT	Bio-Economic	Bio-economic model	Regional/ ecoregional	North Sea	Spatial/ temporal assessments of fleets and fish stocks dynamics, including economic parameters.	Inputs and parameters for biotic components are quantitative.	Social and economic data tends to be semi-quantitative		Not yet - mainly research driven	North Sea model is available, but would require additional parameters to assess wind farm effects on fisheries. Moderate effort to develop.	High level of proficiency required to interpret model outputs, multi-disciplenary team required	Fisheries managers, Policy Makers, Economists, Spatial Planners	Yes	Not widely used or applied.	VECTORS (FP7) anßen H, Bastardie F, Eero M, Hamon KG, Hinrichsen HH, Marchal P, Nielsen JR, Le Pape O, Schulze T, Simons SL, Teal LR, Tidd A (2016) Integration of fisheries into marine spatial planning: Quo vadis? Estuar Coast Shelf Sci in press, DOI:10.1016/j.ecss.2017.01.003PDF Dokument	3

		Evaluated Model Attributes/ Critera														
Models/ Tools	Type	Description	Spatial extent	Availability/ developed	Impacts on fisheries/ relevance	Input data requirements/ availability			Routinely used in management advice	Resources to develop/apply	User Skills	End user type	Support marine spatial planning	Credibility/ widely accepted	selected sources/ references	Operational readiness to support management advice (1 fully ready , 2 partially ready, 3 needs further development)
						Quantitative	quantitative	Qualitative								
ISIS-FISH	Bio-Economic	ISIS-Fish is a seasonal, spatial simulation model describing the dynamics of fishery resources, exploitation and management. It was developed to investigate the effects of combinations of fishery management measures on fishery dynamics. It can be used to compare the effects of conventional management measures such as total allowable catch (TAC), fishing effort management, fishing gear restrictions and spatial management measures such as marine protected areas (MPA). It has also been used to address functional zones restoration issue (https://doi.org/10.1016/j.marenvres.2025.106983). The spatial resolution of the model is flexible and adjusted to the questions addressed by the model and the avaliable data to set the model.	Regional / ecoregional / local	Bay of Biscay, West-Mediterranean Sea (EMU1) - Gulf of Lion, English Channel	ISIS-Fish has been designed to be as generic as possible so that it can be applied to different types of fishery. It includes a database that holds a knowledge base for each fishery that can be easily updated. This knowledge base includes the parameters describing each population and each fishing activity. ISIS-Fish is very flexible to allow several hypotheses to be tested, in particular the relationships between the stock of reproductives and reproduction, selectivity functions for fishing gear, etc., making it suitable for modeling a wide range of pelagic, benthic and demersal fisheries. Functions describing fishery management measures and the response of fishermen to these measures and to environmental and economic conditions can be coded using an interactive script editor. ISIS-Fish simulates Abundance, Biomass, Catch and Revenu time series (with a month time step) at several scales (population, spatial zone, age/length group, fishing metier, fleets, gear).	Inputs and parameters are quantitative		Stakeholder knowledge can be used to define the structure of the system modelled, as well as behavioral rules	Used to support STECF work on Western Mediterranean fisheries management	Effort required to develop applications at the spatial resolution relevant to address OWF - Fisheries interactions; need for understanding and data at the resolution required to assess interactions between OWF and fisheries, regarding ecological responses, as well as fishing dynamics and economic and social dimensions	High level of proficiency required, knowledge of the data	For model use: Researchers; Experts For model outputs: Managers, Policy Makers, Researchers, Spatial Planners, Industry and Civil Society Stakeholders	Yes	Well established as a research tool, and now accepted as a decision support tool in STECF for Western Mediterranean	https://isis-fish.org/v4/user/usermanual/introduction.html ; https://doi.org/10.1016/j.ecolmodel.2009.01.007 ; https://doi.org/10.1016/j.ecolmodel.2003.04.001 ; https://doi.org/10.1016/j.fishres.2024.106998; https://doi.org/10.1093/icesjms/fsac148	3
GADGET	Multi-species stock assessment	Multi-species model for fish stock assessments	Regional/ ecoregional	Baltic Sea, North Sea, Celtic Sea	Quantifies changes in multispecies biomass for different fishing scenarios and climate conditions.	Inputs and population parameters required are quantitative.			Yes - in some instances	Regional sea models are avaiable, additional parameters are required to assess the effects of wind farm developments on fisheries using existing data and knowledge, moderate effort to develop.	High level of proficiency required to run different management scenarios	Fisheries managers	No - only through spatial domain but this is linked to stock units	Many applications and case studies in support of fisheries management	https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0211320 https://gadget-framework.github.io/gadget2/userguide/	3
IAM	Bio-Economic	IAM : Impact Assessment bio-economic Model for fisheries management is a discrete time (annual), multi-fleet or multi-vessel, multi-métier, multi-species bio-economic model with "age" components for the biological part, and "commercial category" components for the economic part. It is a tool for academic and non academic knowledge integration which models dynamics and interactions between fish stocks, vessels or fleets, fisheries governance and fish markets.	Regional, ecoregional	Bay of Biscay mixed fisheries, Western Mediterranean sea demersal fisheries, Australian South-East Fishery	Modelling platform for scenario simulation, optimization, and impact assessment of management strategies, including transition to MSY, input and output controls, and other measures such as changes in selectivity. For instance, it can be used to evaluate the socio-economic consequences of alternative TAC and quotas allocation options and exploration of conditions for fisheries viability and sustainability. The modelling platform enables stochastic simulations to assess the biological and socio-economic impacts of alternative scenarios and management strategies, facilitating the comparison of trade-offs from a multi-criteria perspective.	Inputs and parameters are quantitative		Stakeholder knowledge can be used to define the structure of the system modelled, as well as behavioral rules	Yes, used to support STECF work on Western Mediterranean Sea Multi-Annual management Plan, as well as multi-annual plan in Bay of Biscay	Currently non-spatially explicit; could be adapted to the OWF-Fisheries interaction question via the definition of spatially resolved fishing métiers; need for understanding and data at the resolution required to assess interactions between OWF and fisheries. Individual vessel parameterization could also be useful for a spatially implicit implementation and relevant for studying the economic impacts of OWF-fisheries interactions.	High level of proficiency required, knowledge of the data	For model use: Researchers; Experts For model outputs: Managers, Policy Makers, Researchers, Spatial Planners, Industry and Civil Society Stakeholders	Not currently	Well established as a research tool, and well accepted as a decision support tool in STECF	https://ifremer-iam.github.io/IAM/	3
ATLANTIS	Ecologocal/ Ecosystem	End to end deterministic ecosystem model	Regional/ ecoregional	Baltic Sea	Not yet developed or parameterised for wind farms and fisheries interactions	Inputs and parameters are extensive and quantitative			Not yet??	Extensive effort required to up-date for wind farm and fisheries interactions	High level of proficiency required to interpret model outputs, multi-disciplenary team required	Scientists	Yes, can support MSP, but not so easily	Widely accepted as a research tool, but limited applicability to assess effects of windfarms on fisheries.	https://research.csiro.au/atlantis/home/about-atlantis/ https://www.sciencedirect.com/science/article/pii/S0304380023001734?via%3Dihub	3

4.1.4 Next steps (recommendations) to develop and apply models and tools to assess the cumulative effects of windfarms on fisheries.

- We recommend the top-ranked (Category 1 and 2) models evaluated against their operational readiness in Table 4.1 (e.g. VMStools, FishSET, DISPLACE, OSMOSE, Community Profiling Tools and EwE/ Ecospace), be more widely applied and validated for operational management purposes to assess ORE interactions and fisheries.
- Encourage further international collaboration to better integrate national fisheries and environmental data sets and data flows to improve CEA and ecosystem model application at a range of spatial/ temporal scales.
- We recommend the development of case studies to demonstrate the practical application of available strategic risk-based assessment frameworks (such as BowTie, FEISA, ODEMM and SCAIRM) and to link them explicitly with the outputs of quantitative (mechanistic) CEA/ecosystem models (described here as category 1 and 2 models) to better support operational management advice.
- Improve model inter-operability for CEA, especially between ecological, economic and social CEA ecosystem models/ tools.
- We recognize there is no single CEA/ecosystem model or assessment tool that can provide a comprehensive assessment of all component interactions at a social, economic and ecological level, between windfarm developments and fisheries. We therefore recommend using a combination of CEA/ecosystem models operationally, eventually linking outputs of different models through risk assessment frameworks.
- We recommend some increased focus on the use models and spatial analysis tools to explore long time-series fisheries and environmental data (>10 years) to better describe and understand the spatial/temporal dynamics of core fishing areas and climate effects in response to offshore windfarms.
- We recommend an evaluation of selected Category 1 and 2 model outputs with respect to better informing potential mitigation options, that is to evaluate if the models lead to an evidence base that will allow specific measures to be effectively identified and taken.

It is clear that, while there are a wide range of ecosystem models available to support CEA, the models in all cases have been developed to address specific questions and meet specific needs. Therefore, the parameterization, data and case studies to support the assessment of cumulative effects of offshore wind farms on fisheries will have in most cases to be further developed with additional parameters, data and validation to support planning and management decisions at a policy level. However, the sub-group agreed that the selected CEA/ ecosystem models, especially when in combination, have the potential to effectively support operational management of the impacts and trade-offs between ORE and fisheries in the eco-regions in question. Furthermore, the wider application of these models will require additional end-user familiarization to make them fully operational in the context of planning and management. In addition, once these models are applied, these outcomes will also require translation, helping to ensure that the information generated for different management scenarios can be effectively used in management advice and Strategic Environmental Assessments (SEA). Supporting the selection and design of mitigation and management measures.

As demonstrated, several cumulative impact modelling tools, currently available (in particular VMStools, FishSET, DISPLACE, OSMOSE and EwE/Ecospace), can be widely applied and in some cases further developed to assess the impacts of offshore wind farms on fisheries. These tools enable the holistic analysis required to address the complexity of the objectives (e.g. in spatial planning and in defining mitigation measures), integrating both ecological and socio-economic components. Widely used in various contexts, they offer the ability to evaluate different scenarios and management options, maximizing the trade-offs among different activities, being therefore potentially powerful tools to support decision-making and MSP development. Their relevance is further enhanced when incorporating insights from co-design and co-use processes, developed in collaboration with key stakeholders (see ToR vii, section 4.2.5.2) on Conflict Mitigation and Fisheries Sector Engagement). By employing iterative feedback approaches, these tools may help to shape cost-effective, transparently discussed mitigation and management plans, eventually improving the balance between offshore wind energy development and fisheries sustainability.

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4.2 ToR a.vii. Options for mitigation measures, good practices, and spatial planning for ORE developments and their strengths, weaknesses, implications and uncertainties. Priorities for research and monitoring related to these options.

4.2.1 Key Messages

In this advice we look at Maritime Spatial Planning (MSP) as the key strategic tool for marine area development based on political objectives set out in political strategies and legislation. Implementation of guidance and provisions in spatial plans is based on subordinate and mostly sectoral administrative processes such as licensing and approval procedures for specific projects. While fishing activities are not managed through the MSP process, MSP provides a framework for managing the interactions between offshore wind and fishing activity. MSP implementation facilitates stakeholder engagement, evidence led decision making, and conflict resolution. However, for effectively managing impacts from OWFs on fisheries and resolving conflicts between these two maritime sectors within marine planning, the following factors need to be considered:

- **Spatial Competition and Pressures:** Marine Spatial Planning (MSP) addresses spatial competition between offshore wind and fishing activities, considering also cumulative pressures from other sectors like protected areas and underwater cables.
- **Political Priorities and Trade-offs:** Analyzing political priorities in policies and laws is essential for spatial planning. Current priorities at European and national levels indicate that large-scale offshore wind development will significantly impact fisheries.
- **Planning Instruments and Legal Frameworks:** Recognizing the specific planning instruments, their hierarchy, and legal status is crucial for implementing appropriate measures at the correct administrative levels.
- **Tailored Scientific Advice and Risk Assessment:** Scientific advice must be specific to the planning level and instruments. Operational measures should be checked with affected stakeholders, requiring science-based risk assessments and trustful communication.
- **Mitigation Measures and Stakeholder Engagement:** Mitigation measures, including zoning and co-use of areas, are vital to reduce impacts on fisheries. This requires proper provisions, regulations, and incentives, along with regular communication between policymakers, wind farm operators, fisheries, and local communities.
- **Need for political and financial support:** Given already existing economic pressure on many fisheries and cumulative spatial pressure on the sector, necessary adaptation of the sector requires political and financial support specifically to small-scale fishers and family businesses to allow successful transformation to new forms of fishing.

4.2.2 Approach, uncertainty and data gaps

Looking at mitigation options was dedicated by ICES to WGMPCZM, which is actively looking at developments in Maritime spatial planning and the use of marine areas since 2010 (and before that acted as WGICZM). The advice is therefore based on expert discussions within WGMPCZM concerning the development of MSP over many years and accompanied by a non-comprehensive analysis of scientific and grey literature referring to interactions between offshore wind farms and Maritime Spatial Planning (MSP) and the role of fisheries in MSP. This section also draws on material from a currently disclosed report of the Helmholtz-Zentrum Hereon for the German parliament in which two members of WGMPCZM have been involved. Publication of this report, providing an extensive overview of impacts from offshore wind farms on marine ecosystems including an analysis of political and legal objectives at EU level as well as the legal base for the German marine planning system is only possible after final approval by the parliament. However, the authors of that report are allowed to use material from it.

Members of WGMPCZM include scientists of various disciplines as well as policy makers and representatives of government authorities. However, as engagement in ICES WGs is voluntary, not all ICES Member States have (regular) representatives within the WG, discussions may be biased along the perspectives of active members and countries in the group. In addition, a full comparative analysis of the legal context and the regulatory setting for all ICES Member States covering all regulations and their legal base in the wind farm planning process, during operation and for decommissioning phases is not available.

4.2.3 Context: Understanding MSP and its role in planning for marine use

Since the beginning of this century, marine/maritime spatial planning (MSP) has become an established planning process for dealing with the increasing use of marine space and the need to protect and conserve marine biodiversity. MSP activities have been initiated in North America as well as most other parts of the world (Ehler 2021), and, in particular, in European regional seas (Cormier et al., 2015). As outlined in the Marine Spatial Planning Quality Management System (ICES CRR 327, Cormier et al. 2015) maritime spatial planning is an exercise that brings together complex sector and environmental policy frameworks with future development objectives. In addition to engagement activities with stakeholders, MSP also requires substantial policy analysis in collaboration with other competent authorities, working within an MSP governance structure and underpinned by scientific advisory processes (Cormier et al. 2015).

Definitions of MSP vary in the literature and in policy documents of countries and organizations. Despite the use of similar terms, there are subtle differences in interpretation regarding principles, priorities, ecological targets and time horizons (Mayer et al. 2013). UNESCO-IOC has defined MSP as "a public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic and social objectives that have been specified through a political process"(Ehler & Douvere 2009). Looking at the prevailing differences in perceptions, attitudes and values as well as different policy goals and interests from a variety of marine actors, it becomes obvious that MSP (and other types of integrated planning) are not simple data-based decision-making processes, but social processes and actions which rely on different forms of communication and social interaction (Kannen et al. 2013). Importantly, MSP is a spatial planning tool, which, in contrast to sectoral planning and management, is concerned with the spatial distribution of activities and not the management of activities themselves. For example, MSP can coordinate the spatial distribution of offshore wind farming but not whether offshore wind farming actually then takes place. Similarly, depending on the planning context, MSP can help to encourage or restrict the spatial and/or temporal distribution of fishing activity, but not the fishing sector per se. The same applies to nature conservation, where MSP is an important supporting tool in terms of planning provisions for maritime sectors, but is not directly tasked with e.g. MPA design or managing biodiversity or fish stocks.

Within the EU, MSP is guided by the EU MSPD (Directive 2014/89/EU) from 2014, which obliges all EU Member States (with a coast) to develop maritime spatial plans, aimed at promoting;

- the sustainable growth of maritime economies,
- the sustainable development of marine areas and
- the sustainable use of marine resources

while taking into account land-sea interactions and enhanced cross-border cooperation, in accordance with relevant UNCLOS provisions (Article 1, Directive 2014/89/EU).

This Directive on MSP was originally expected to support the European Blue Growth Strategy (COM(2012) 494 final), now referred to as the Sustainable Blue Economy (COM/2021/240 final , see also Zaucha et al. 2024). The umbrella for all these strategies is formed by the Integrated Maritime Policy for the European Union ('IMP', COM(2007) 575 final) with the objective to support the sustainable development of seas and oceans and to develop coordinated, coherent, and transparent decision-making in relation to the Union's sectoral (marine) policies, whilst achieving good environmental status as set out in the Marine Strategy Framework Directive (Directive 2008/56/EC).

In these policy contexts, the objectives of MSP in the EU are to:

- reduce conflicts and create synergies between different activities;
- encourage investment through predictability, transparency and legal certainty;
- increase cross-border cooperation between EU countries to develop renewable energy, allocate shipping lanes, lay pipelines and submarine cables, among others;
- protect the environment by assigning protected areas, calculating impacts on ecosystems and identifying opportunities for multiple uses of space.

Although the Directive on MSP sets out a general framework, Member States remain responsible and competent for designing and determining the format and content of such plans. Member States are responsible for any necessary legal and institutional arrangements and the allocation of maritime space to different activities and uses (Cormier et al. 2015). As a strategic and overarching planning tool, MSP has to refer to a wide range of agreements, policies and legislation both at the national (and sub-national) as well as international level. National and European laws and Acts for the various marine sectors thus define the specific policy objectives and targets for marine uses that guide an MSP plan, such as marine renewable energy targets and EU fisheries policy.

Furthermore, MSP can take different forms and use a more regulatory or more strategic approach (Ehler et al. 2019). While regulatory plans are binding plans that define spatial priorities (e.g. zoning maps) and associated rules and regulations, strategic plans are usually less spatially explicit and sometimes merely provide policy directions, e.g. on the nature of marine activities preferred in a planning area (Zaucha et al. 2024). The legal effect of plans also varies, as plans can be:

- legally binding, so that other authorities (e.g. for licensing) must adhere to the provisions of the plan, e.g. the National Marine Planning Framework (NMPF), Ireland's Marine Spatial Plan, or
- binding in a way that they guide subordinate plans that may be prepared at a different scale, or
- non-binding, thereby having no direct legal effect, like for example in Sweden or Norway (Zaucha et al., 2024).

Depending on the nature of the plan, different tools are employed to guide spatial use. One of the most common spatial designations are priority areas for specific uses or sectors, which restrict other activities in the same space (Zaucha et al., 2024). Given that maritime uses are changing rapidly, and given the added impacts of climate change, adaptability is an increasing focus in MSP. This includes requirements to anticipate future developments, such as species shifts in response to climate change and the impacts this may have on sectors such as fisheries, as well as MPA design and management (e.g. Maxwell et al., 2015; Queiros et al., 2021).

While MSP plans are important decision-making platforms and frameworks for the governance of marine space, they often rely on other tools to implement their provisions. While MSP plans may designate priority areas for offshore wind, how offshore wind farms are then constructed within the priority areas and what operating conditions may be required is generally specified in more technical licensing or permit conditions (e.g. technical specifications for wind farm construction). Some countries, e.g. Germany also have a dedicated sector plan for offshore wind farm development which sets out which areas are to be developed for offshore wind in what year including also the required grid connections. MSP, and its ability to regulate sectoral activity and/or co-use, therefore needs to be seen in conjunction with these additional sector-specific tools and provisions. In contrast, in Ireland the National Marine Planning Framework (NMPF) is the overarching plan for offshore wind farm development; a sectoral plan does not have a legal framework. The NMPF is Ireland's MSP, a Designated Maritime Area Plan (DMAP) is the zoning or area identified for auction, a Maritime Area Consent (MAC) is issued from the licensing authority (MARA) and gives a developer a route into the planning system.

This structure of hierarchical planning is illustrated by the planning models for offshore wind farms in Germany and Ireland, each consisting of a structured hierarchy of connected procedures (Figure 4.1 and 4.2). However, key components of the process are similar in other countries and for most other human activities (except fisheries in most countries), specifically the requirement of a site-specific approval or licensing procedure for any specific (sectoral) project while guided by a large-scale area-based (cross-sectoral integrative) maritime (spatial) plan and associated sectoral policy objectives.

Figure 4.1: System of planning instruments across spatial scales for offshore wind farms in the German EEZ (Nolte 2024)

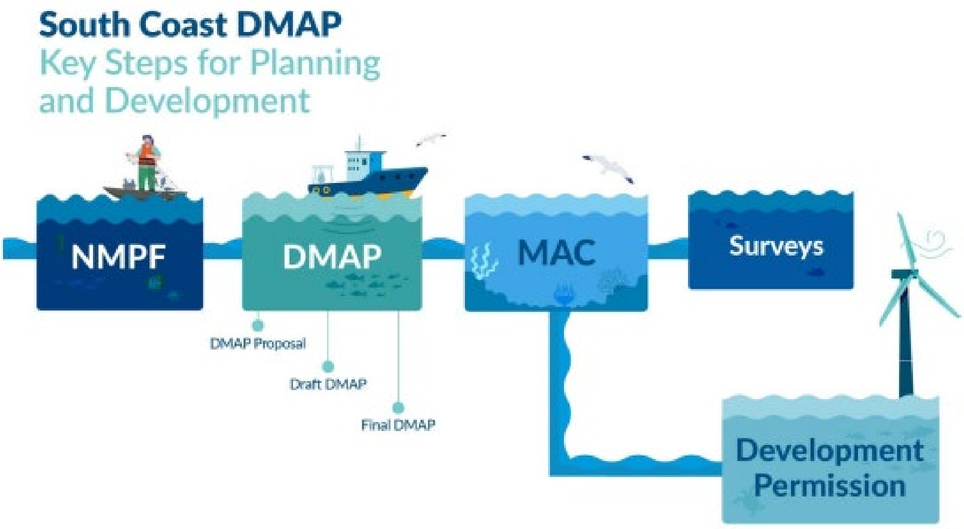

Figure 4.2. Structure of offshore wind farm planning instruments in Ireland (SC-DMAP, 2024).

Depending on spatial concretisation, measures to avoid or mitigate impacts from one use to another use may therefore vary and become more spatially explicit within different planning instruments (Figure 4.1 and 4.2). Traditionally, a top-down approach has been applied in policy cycles in spatial planning. Incorporating a feedback mechanism such as stakeholder working groups and communication processes (see section 4.2.5.2) can facilitate a better-informed policy cycle for all levels of involvement (Figure 4.3). As well the policy cycle needs at each level of concretization support from level specific scientific advice (Cormier et al. 2017) and risk assessment (Cormier & Kannen 2019).

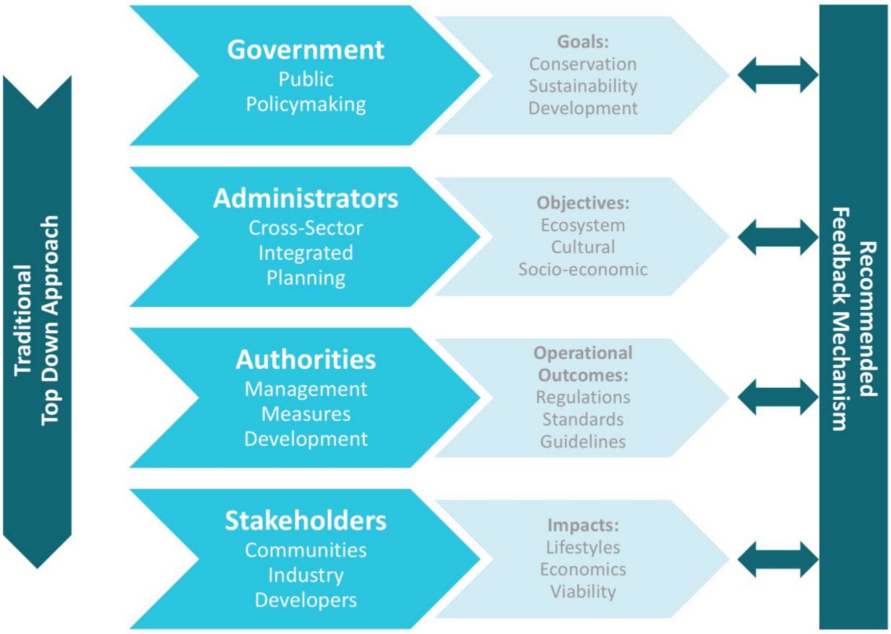

Figure 4.3: Adaptation of the meta-logic policy cycle including stakeholders and a recommended feedback mechanism for communication through representatives of each of the mentioned groups (M. Arrigan, based on Cormier et al. 2017).

4.2.4 Political objectives from offshore wind and fisheries driving MSP

Offshore wind farming has been a significant driver for some of the early maritime spatial plans in Europe, in particular in the Netherlands and for the first spatial plan for the German EEZ in 2009 (Kannen 2014). At that time, it became obvious that the number of requests for wind farm project approvals required guidance from a more strategic large-scale planning perspective to guide administrative project approval procedures for single projects. Since then, political priorities concerning marine renewables have significantly increased. National targets should not be viewed in isolation and on a national level, but rather in the context of climate and energy policy targets and obligations at EU level (e.g. EU Green Deal of 2019, EU Offshore Renewable Energy Strategy of 2020 and Commission Communication Delivering on the EU offshore renewable energy ambitions, COM/2023/668 of 2023) and agreements for the North Sea region (Esbjerg/Ostende declarations). UK and Norway, even though not being EU Member States, are also part of transnational political agreements and contribute for example to transnational targets for offshore wind within the Ostend Declaration (see below).

At the EU level, the European Green Deal, the EU's central framework for climate and energy policy since 2019, formulates ambitious climate targets: By 2030, net greenhouse gas emissions are to be reduced by 55% compared to 1990 levels and the share of renewable energy across the EU is to be increased to at least 32% by 2030. Climate neutrality is to be achieved by 2050 (COM/2019/640; COM/2019/640 Annex). These targets are implemented in a legally binding manner in the EU Climate Law (Regulation (EU) 2021/1119). The EU Climate Law legally obliges the Member States to take the necessary measures and revise their national energy and climate plans for 2021-2030 in line with the objectives of the EU Climate Law.

Regarding the expansion of offshore wind energy, the EU strategy for harnessing the potential of offshore renewable energy for a climate-neutral future (EU Offshore Renewable Energy Strategy, SWD(2020) 273 final) forms an overarching framework. This specifies the goal of increasing offshore wind energy capacity from around 12 GW (in 2020) to at least 60 GW in 2030 and 300 to 400 GW in 2050, as well as generating at least 1 GW by 2030 and 40 GW by 2050 from other marine energy sources (e.g. waves, currents, tides) and new technologies (floating wind, floating solar). These targets were increased once again by the EU Member States in January 2023 in the light of energy security and energy independence. The new (non-binding) targets envisage an installed capacity for the generation of renewable offshore energy of around 111 GW by 2030 and around 317 GW by 2050 for all European sea basins (COM(2023) 668 final). To maximise its impact, the EU strategy for offshore renewable energy goes beyond a narrow definition of energy production and addresses broader issues such as access to maritime space, regional and international cooperation, industrial and employment dimensions, and technology transfer from the lab to the field in research projects. (COM/2020/741). In addition to climate neutrality, the war in Ukraine has made energy security and energy independence strong drivers for the expansion of (marine) renewable energies.

The Renewable Energy Directive (RED) is the main legal instrument for implementing these targets at EU level. The latest version of the Renewable Energy Directive (RED III, Directive (EU) 2023/2413) came into force on 20 November 2023. The directive formulates the goal to increase the share of renewable energy in the EU's gross final energy consumption to at least 42.5% by 2030. In order to achieve this target, the EU Member States - among other things – have to accelerate the authorisation procedures for renewable energy installations and the grid infrastructure. The pan-European industry association WindEurope assumes that Europe will install new wind power capacity totalling 260 GW in the period 2024-2030, of which 200 GW should be in the EU-27. This would be an average of 29-33 GW per year if the EU wants to achieve its climate and energy targets for 2030 (WindEurope 2024).

These political objectives are also part of transnational cooperation agreements, specifically the Vilnius Declaration for the Baltic Sea (April 2024) which addresses energy security, and the Ostend Declaration from April 2023, in which the energy ministers of nine countries (Belgium, Denmark, France, Germany, Ireland, Luxembourg, Norway, the Netherlands and the United Kingdom (UK)) agreed on political targets for offshore wind energy for the extended North Sea region (including the Celtic Sea and parts of the Atlantic coast). These are significantly higher than those formulated in the EU 2020 Strategy. With the inclusion of Norway and the United Kingdom, the Ostend Declaration also goes beyond the scope of the European Union energy goals. The common goal is to expand offshore wind energy from the current 30 GW to around 120 GW in the North Sea by 2030. By 2050, the total capacity of offshore wind energy is to be increased to at least 300 GW and the North Sea is to be developed as 'Europe's green power plant' (Table 4.2, Figure 4.4).

Table 4.2: Energy goals as declared in the Ostend declaration (Source: own table based on numbers as provided in the Ostend Declaration of Energy Ministers in 2023)

Country	Current	Until 2030	After 2030
Belgium	2,26 GW	6 GW	8 GW by 2040
Denmark	2,7 GW	min. 5,3 GW	Up to 35 GW by 2050
France	1 GW	min. 2,1 GW	4.6 to 17 GW by 2050
Germany	8,5 GW	min. 26,4 GW	66 GW by 2045
Ireland	< 0,1 GW	min. 5 GW	20 GW by 2050
Norway	< 0,1 GW	min. 3 GW	Up to 30 GW by 2050
The Netherlands	4,7 GW	about 21 GW	Studies for 50 GW in 2040 and 72 GW in 2050
UK	13,9 GW	Up to 50 GW	n. a.

A visual impression of the spatial extend of the politically envisioned offshore wind farm development is provided in Figure 4.4. It needs to be understood, that the coloured areas in Figure 4.4, in particular the development zones, will not be fully occupied by wind farms, but serve as areas in which wind farms might be built from a planning perspective, but these would cover only parts of the development zone area. The map therefore visually overestimates the spatial impact.

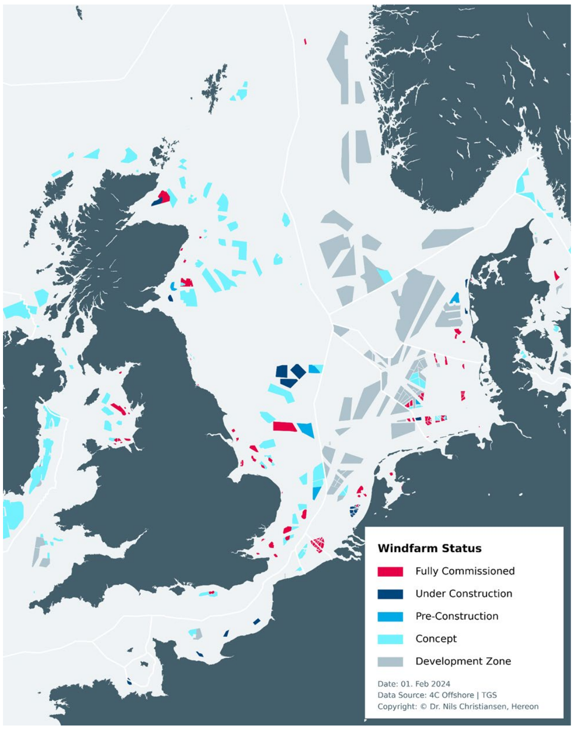

Figure 4.4: Overview of potential offshore wind farm development in the wider NorthSea area (N. Christiansen, Hereon)

Overall, political agreements and co-operation structures exist in the North Sea region to expand offshore wind energy, including an integrated offshore energy grid. Together with environmental policies for the marine environment - specifically the MSFD, the Birds and Habitat Directives and the Restoration Directive from 2024 - spatial competition for fisheries is going to ever more increase if all of these policies are implemented.

Fisheries are controlled and managed via the Common Fisheries Policy (CFP, Regulation (EU) No. 1380/2013). The stated aim of the CFP is to ensure that fishing and aquaculture activities contribute to long-term environmental, economic and social sustainability. In line with the European Green Deal and the Biodiversity Strategy 2030, fisheries in the EU are subject to the precautionary principle to limit the negative impact of fishing activities on the marine ecosystem. The CFP sets out rules for fisheries management, including authorised catches for regional stocks. However, the CFP regulations do not contain any explicitly defined localised and spatially delimited rights for fisheries that restrict other uses such as the expansion of offshore wind energy. In addition, areas used for fishing are mostly not defined statically and are therefore difficult to designate in terms of specific places in maritime spatial planning. However, some cases of zoning for fisheries exist (Zaucha et al. 2024). There are varying degrees of integration of fisheries and planning policies at the national level, leading to greatly variable roles of MSP in supporting sustainable fisheries overall (Ramieri et al., 2024).

Overall, offshore wind farms in many countries exclude fisheries (particularly bottom trawling), but fishing activities rarely provide constraints to the construction of offshore wind farms. Fisheries (mostly bottom trawling) may therefore lose traditional fishing areas with the expansion of offshore wind energy, as they do from existing and potential restrictions in protected areas. This is likely to be exacerbated by the impacts of climate change on target species and associated uncertainties, as well as innovative tool and process requirements, for anticipatory and adaptive planning (Queiros et al., 2021).

An exemplary case of the intersection between offshore renewable energy projects and fisheries can be observed at Dogger Bank. This site is currently the focus of the largest wind energy initiative, which coincides with a historically significant fishing ground spanning 17,600 km² in the North Sea. Renowned for its plaice and sndeel fisheries, this region is actively fished by over 178 vessels utilizing both pelagic and demersal trawling methods (Figure 4.5).

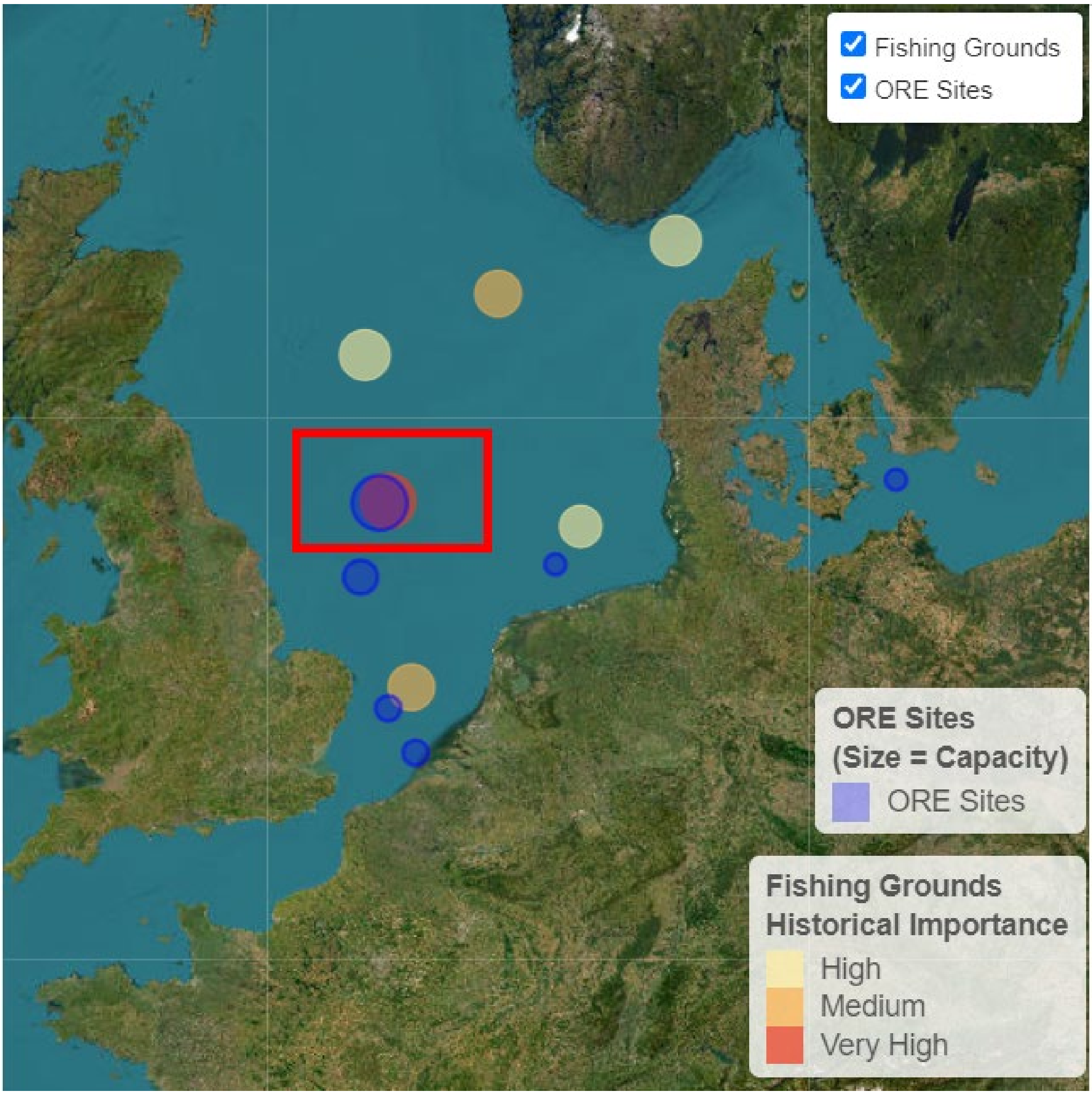

Figure 4.5: Overlap of offshore wind farm areas and fisheries (Source: Anthony B. Ndah, extracted from The European Offshore Renewable Energy Impact Assessment Dashboard - under development), Data sources: Offshore Renewable Energy Sites from WindEurope Database. (Official offshore wind farm statistics), 4C Offshore (Technical specifications and project details), RenewableUK (Industry data and project updates); Fishing Grounds: ICES Data Portal (Fishing grounds and activity data), EU Fishing Fleet Register (Fleet and vessel information), EMODnet (Marine observation and fisheries data)

In an attempt to meet potentially competing policy objectives such as climate change mitigation and adaptation, biodiversity protection and sustainable seafood production (as envisaged e.g. by the European Green Deal, see https://mspgreen.eu/maritime-green-deal/), many discussions in MSP now focus on co-use options, e.g. allowing some forms of fishing within windfarms such as use of passive gears.

4.2.5 Impact of Offshore Wind Farms on Fisheries from a spatial planning perspective

Given that political priorities currently focus on the expansion of offshore wind farms, spatial competition for the same area is the most direct conflict between offshore wind farms and fisheries to be addressed by MSP. Importantly, spatial competition can relate to fishing activities per se but also fisheries resources, such as spawning and nursery areas or fishing grounds.

An overview of conflicts and options for prevention and mitigation is provided by the European MSP Platform in its fact sheet "Conflicting interests study: Offshore Wind and Commercial Fisheries". It reasons that similar spatial requirements form the main source of conflict between offshore wind farms and especially small-scale fisheries and family businesses due to the fact that both sectors have similar spatial requirements, including specific depth ranges, sediment types, and proximity to the coast. According to the fact sheet, important fish habitats are also often preferred sites for offshore wind farm construction. In situations where there is no direct spatial competition between offshore wind and fisheries, offshore wind farms can still be a barrier to fisheries, making it more expensive and time-consuming to travel around them to reach important fishing grounds. Spatial conflicts between offshore wind farming and fisheries become more acute in situations where seas are busy and where other constraints, most notably nature conservation, restrict alternative location options for either sector. Conflicts may also become more acute when climate change impacts affect the spatial distribution of fish stocks, requiring fishers to adjust their activities but potentially finding their adaptive capacity restricted by the presence, or impacts, of other sea uses.

Kruse et al. (2024) investigated different future trajectories of the social-ecological system of German plaice fisheries concerning spatial fishery restrictions (in 2025, 2030, and 2040), economic, and ecological change, as well as different management targets in 2030. Assuming different scenarios of area closures for fisheries in offshore wind farms and in marine protected areas the proportions of areas with high profitability declined continuously across spatial scenarios dropping by almost half as more areas became inaccessible for fishing. The identified spatial heterogeneity, however, also opens pathways for MSP in fisheries, potentially including installations of wind farms outside the most profitable fishing areas, offering recommendations for installation designs that enhance fisheries' benefits or providing options for less invasive fishing practices (Stelzenmüller et al. 2021) to potentially mitigate use conflicts among sectors. In summary, the study highlights those spatial restrictions coupled with unforeseen climate change impacts, will ultimately determine the adaptive capacity of existing fisheries and their ability to withstand future changes.

Many countries do not allow navigation in and near wind farms for safety reasons except for maintenance vessels, although there is increasing openness to allow some forms of fisheries in some countries. Key argument for prohibiting vessels entering wind farm areas is the fear of accidental damage to turbines and cables and ship collisions with turbines, and particularly damage to subsea cables from bottom trawling (European MSP Platform). Also, in countries where no legal ban exists (e.g. UK), trawling may not take place because liability and safety issues and specifically lack of insurance coverage for damages to gear or vessels inside wind farms prevent fishers from entering the wind farm array (Gill et al. 2020). Furthermore, safety concerns lead to establishment of safety zones (usually 500 m around turbine arrays) around offshore wind farms and general restrictions for vessel traffic including fishing vessels. During offshore wind farm construction fishing may be totally excluded from the area and these restrictions may remain in place also during operation. Some countries (e.g. the Netherlands and Germany) have changed their policies to some degree and adapted regulation in a sense, that they allow some types of (fishing) vessels (in Germany up to 24 m length and subject to good weather conditions and restricted top speed) to navigate in safety zones and through (some) wind farm areas, thereby reducing travel costs for fishers to reach some fishing grounds and enabling passive fisheries in safety zones.

Passive fisheries methods, including the use of fixed fishing gear (e.g., pots, traps and longlines), may be used within wind farms or within the safety zones and may profit from habitats supporting increased abundances of large crustaceans for example, thereby offering new chances for some types of fisheries. For example, in the Netherlands, the MSP Decree provides that passive fishing may be permitted in some specific renewable energy zones. However, as Van Hoey et al. (2021) state, it seems not entirely clear how navigational access to these zones for the purpose of passive fishing is in line with the prohibition on navigation within wind farms. Also, the Netherlands is currently investigating the possibility of modifying the current rules and applying pilot projects, e.g. permitting recreational and commercial fishing using passive gear within offshore wind farms (Van Hoey et al. 2021).

However, the effective closures of wind farm areas for fisheries may force fishers to reallocate their fishing effort to alternative sea areas. This might imply stronger competition with other fishers already active in those areas, using previously less impacted sensitive habits, and could risk catching vulnerable elements of the stock (Gill et al. 2020). Economically, such spatial displacement can increase operational costs. For example, Chaji & Werner (2023) identified four main economic areas of concern relating to the impacts of offshore wind on the fishing industry, including (1) fishing industry fuel expenditures; (2) fishing industry revenues, income, and livelihoods; (3) the cost of insurance; and (4) impacts on fishing support businesses. Socially, exclusion and displacement may threaten fisher livelihoods and the socio-cultural existence of fishing communities (European MSP Platform). However, only locational aspects can be addressed by spatial planning instruments and approval procedures. Other mitigation options (e.g. financial support for adaptation, economic structures of the fishing sector) require other policy instruments. In Denmark for example in accordance with the Fisheries Act from 2014, compensation may be payable to fishers with respect to documented losses resulting from offshore wind farm construction (Van Hoey et al. 2021).

4.2.5.1 Mitigation options from a (spatial) planning perspective

From the perspective of spatial competition, the following generic types of measures are available as mechanisms to mitigate and manage spatial conflicts between offshore wind farms and fisheries, both in terms of fishing activity and supporting fish stocks as a resource:

- Spatial and/ or temporal separation of both activities, e.g. by using zoning approaches to provide planning security for both sectors, or restricting other activities during wind farm construction;
- Combination of both activities within the same place (co-use or multi-use of space) including appropriate wind farm design (e.g. larger distances between turbines to allow space for manoeuvring or nature-inclusive design to support specific habitats to support specific stocks). This includes technical measures such as protection of cables and wind farm infrastructure and/or change of fishing techniques;

In general, any mitigation measures require a trade-off analysis considering legal and political objectives for both sectors, fisheries and offshore wind farming (and possibly other affected economic sectors as well as marine conservation), economic feasibility for both affected sectors and socio-cultural considerations (e.g. impact on fishing communities). Active participation of both sectors, including also planners, and collaboration are required in the design of appropriate and workable mitigation measures, ideally in a co-design approach that goes beyond mere consultation (Morf et al., 2019).

Recognising the political nature of MSP, the power of the sectors and their lobbying capacities play a significant role in decision-making and strategic policy decisions within MSP. In some countries, fisheries is seen as a sector in decline, which weakens its position in trade-off assessments (e.g. Lewin et al. 2023). Some countries are also traditionally more fisheries focused than others, which affects the relative status and political weight of the sector. In contrast, marine renewables, and in particular offshore wind, is a sector with currently significant political, financial and industrial power, supported by its fundamental relevance for national economies and energy security. As a first step, MSP therefore needs to recognise such inherent power asymmetries. It then needs to use appropriate tools to ensure the planning process is perceived as fair and that fishing communities are among the beneficiaries of the plan in the sense of social sustainability (e.g. Saunders et al., 2020). Ultimately, however, the role MSP can realistically play in mitigating the impacts of offshore wind farming on fisheries is limited, not least because plans rarely refer to social or socio-economic concerns. Although the Latvian plan refers to employment issues in fisheries, social well-being has been used as a frame of reference in only a few current European MSP plans (Zaucha et al., 2024).

While the legal status of fisheries may vary among countries, there are several reasons why fisheries may find themselves in a weak position legally as well as strategically/politically. As indicated in a large-scale set of interviews with coastal fishers in Germany as part of the German research project SeaUseTip and focus group meetings with local coastal fishers in the project CoastalFutures of the research mission sustainMare of the German Marine Alliance (DAM) this is particularly relevant for local small-scale fisheries, which often are less professionally organised than industrial fisheries, requiring consideration of local specifics of fishing fleets, their community structure and their socio-economic and cultural status in local communities in planning and management. Establishing appropriate communication between planning authorities, fishers and wind industry, but also among fishers themselves is therefore an important element to properly address fisheries needs within offshore wind farm planning and identify appropriate prevention and/or mitigation options.

The European MSP Platform lists a number of measures which may help to prevent conflicts between offshore wind farms and fisheries. These are to:

- ensure consideration of impacts already in high-level policies
- acknowledge fishers in the MSP planning process and draw on fishers' knowledge to co-create a (fisheries) evidence base
- choose suitable offshore wind farm locations taking into account (and where possible avoid) nursing and spawning grounds and the most profitable fishing grounds in spatial planning and
- use spatial planning and regulations in approval procedures to favour synergies and co-existence including co-use options

These prevention actions are linked with mitigation of impacts by;

- providing the foundation to allow, under certain conditions, some types of fishing in offshore wind farms,
- allowing fishing vessels to transit offshore wind farms
- align where possible construction phases with fisheries seasons and
- consideration of technical solutions wherever technically and economically feasible

MSP can also encourage and support collaborative agreements between fisheries and the offshore wind farm industry, in particular in areas where there is flexibility concerning the locations of wind farms. Adaptive decision-making and adapting regulations over time based on coordinated research is a long-term approach to mitigate impacts that arise from the development of one sector onto another sector. For example, changes in risk perception and different wind farm design may make it more likely that some types of fishing will be allowed in offshore wind farms in the future. Also, a move towards more environmentally friendly fishing practices because of pressure on fisheries from ecosystem management and a fundamental shift within the industry, including an overall reduction in fleet sizes may support adaptive solutions. However, this requires regular communication within and between the sectors, between sectors and spatial planning authorities and accompanying research stimulating adaptive solutions.

4.2.5.2 Instruments from a (spatial) planning perspective

Instruments to mitigate impacts from offshore wind farming on fisheries are:

- Zoning/area designation;
- Multi-use approaches, specifically co-use of areas between fisheries and offshore wind farms;
- Fisheries sector engagement and

- Compensation
- Other measures

Current European MSP plans include multiple spatial and non-spatial provisions to enhance the sustainability of fisheries, although the role MSP can play greatly varies from country to country. A common limitation is the lack of information especially on small-scale fisheries, including their spatial distribution (Ramieri et al., 2024).

For all instruments and types of measures applied, local and regional specificities such as types of fishing, metiers, fleets, and traditions need to be taken into account, e.g. the specifics of coastal and offshore fisheries and of bottom trawling vs. demersal, pelagic and passive fishing. Any affected fishing community will have specific resilience and adaptive capacities which need to be understood and kept in mind (Stelzenmueller et al. 2024). The results from Stelzenmueller et al. (2024) strongly suggest that the adaptive capacity of fisheries' social-ecological systems is based on the experience and knowledge of community members and their ability to characterise pertinent conditions, community sensitivities, adaptive strategies, and decision-making processes. The development of adaptation strategies in fisheries (which are required to mitigate impacts from offshore wind farms on fisheries) therefore needs to build on the knowledge of all relevant actors in the respective social-ecological system, including with respect to data and indicator selection/development (Lauerburg et al. 2020 referred to in Stelzenmueller et al. 2024). Participative and collaborative approaches to developing and/or adapting mitigation solutions are therefore essential.

4.2.5.2.1 Zoning/Area designation

Zoning, commonly understood as area designation, has various functions in MSP, including – albeit rarely in current plans – the explicit promotion of co-existence or multi-use. Area designations usually make "positive" provisions in the sense of explicitly encouraging rather than prohibiting any activities outright (Zaucha et al. 2024). The most common designation is a priority area that focuses on single sector or activity. Yet, despite similar terminology used by different countries, the meaning and legal consequences of these designations differ. Area designations can be supplemented by regulations that ensure that priority use is not impeded by any other use and that the priority use itself adheres to specific rules (e.g. temporal restrictions on pile driving for offshore wind) (Zaucha et al. 2024).

Positive area designations for fisheries include fishing zones, which are quite common in Mediterranean plans. This reflects both the scale of these MSP plans (territorial waters and EEZ) and the regional economic importance of fisheries, in particular, small-scale coastal fisheries (Zaucha et al. 2024). Specific examples include:

- Italian and Finnish maritime spatial plans identify areas where small-scale fishery is particularly significant and define several spatial measures for its sustainable development, including coexistence with other sectors, such as tourism and nature protection (similarly in Poland for some local plans, i.e. for lagoons)
- In French plans, fishing has to be carefully considered in terms of co-existence with priority uses.
- The German EEZ plan includes a reservation area for Norwegian lobster and the plan for the state of Mecklenburg-Vorpommern includes a fisheries protection zone but otherwise assumes fishing can occur anywhere unless expressly excluded.
- Maritime spatial plans for Belgium, the Netherlands, Estonia, Sweden, and the UK specify elements of co-existence.

Zoning has long been contentious among fishers as they have traditionally followed the resource and relied on the freedom to fish anywhere in the sea. Despite existing and prospective positive area designations for fisheries, displacement of fishing activities as a result of area closures and subsequent concentration of fishing in non-wind farm areas will still occur. Also, meaningful zoning depends on the availability of independent data, i.e. where fishing occurs in time and space, the location of spawning and nursery areas and how fishing practices, and with this spatial fishing patterns, have changed over time.

Climate change is likely to have an impact on zoning options. Presently, it is still difficult to accurately assess how fish stocks may shift in time and space, and how this may affect different fisheries and their ability to access mobile resources. Climate change is also likely to affect hydrodynamic structures and wider habitats, with large-scale offshore wind farm expansion as envisaged in current political priorities contributing to these changes.

The implication of these changes and associated uncertainties is that zoning should not be seen as static. To the best degree possible, MSP should anticipate the impacts of climate change on commercially exploited species (fished and farmed) and any spatial displacement this may entail (Ramieri et al., 2024). This may entail a shift in MSP practice towards more climate-smart planning, which may include more dynamic and adaptive zoning provisions (Frazao-Santos et al., 2024). However, it also has to be recognised that offshore wind farms are built for a lifetime of at least 25 years and will increasingly become the backbone of European energy production. Zoning therefore needs to balance more static planning provisions with more dynamic options in order to future-proof both offshore wind farming and fisheries as much as possible.

4.2.5.2.2 Multi-Use approaches

Multi-use describes various forms of coexistence between ocean users, characterised by different levels of spatial and temporal overlap and varying levels of compatibility and mutual dependency. The most intense form of multi-use is when uses take place in the same area, at the same time, with shared services and with shared infrastructure. Co-existence, co-use or co-location (used interchangeably here) all refer to uses or activities taking place in the same space at the same time, most often without shared infrastructure or functions (Schupp et al., 2019). Guyot-Téphany et al. (2024) formally define multi-use as the "co-location of complementary activities at sea, their clustering, or their combination", and understand multi-use as joint use of maritime resources by several users in geographical proximity, with the aim of increasing efficiency.

Co-use and its positive and negative impacts on fishers is also discussed under ToR a.i.i in section 2.2 in this report. However, co-use can be of benefit to fishers either in terms of retaining access to an area for fishing, for passage, or in terms of dedicated management of fish stocks (e.g. spawning and nursery habitats, refuges) leading to potential spill-over effects. Maritime spatial plans can support these different forms of co-use or multi-use in their area designations, but also in the general rules and principles that accompany area designations. Encouraging MSP plans to zone for multi-use or explore innovative concepts such as mariparks (designed to provide the basic physical infrastructure for multi-use, such as anchors, docking facilities, maintenance, other relevant technologies) could support the practical implementation of co-use. The aim should be to de-risk investment in multi-use and create viable business cases that can contribute to transformation, moving away from sector-specific single-use activities, and making licence procedures easier for multi-use (Ramieri et al., 2024). Operational implementation is best done through co-design, or by having co-use options checked by the affected actors to ensure operability, for example concerning maintenance and safety operations for offshore wind farms and fishing activities. A science-based risk assessment is required (Cormier & Kannen 2019) as well as trustful communication among authorities and sectors, in order to come to accepted trade-off decisions within administrative planning.

Offshore wind farms can contribute to increases in the biomass of fishery resources in their vicinity (Stelzenmüller et al. 2021). Such spill-over effects can then be exploited in the vicinity of wind farms especially through passive fishing, as for lobster and crab (Bonsu et al. 2024; Gimpel et al. 2020). However, the potential of wind farms to increase lobster populations depends on the design of the wind farms (Van Hoey et al. (2021) referring to Hooper & Austen (2014)). Also, co-location of wind farms and fisheries is mostly mentioned in relation to static gear such as pots, but not in relation to static gears aimed at finfish, such as gillnets (Van Hoey et al., 2021).

Co-use of fisheries and offshore wind farms can also be supported by design measures that stimulate the development of specific habitats in offshore wind farms. Specifically, offshore wind farms can contribute to artificial reef effects through the introduction of hard structures (Pardo et al. 2023). Including supporting ecological elements in the development phase of an offshore wind farm through such eco-design offers settlement opportunities for reef-building species (e.g. mussels or oysters), which in turn can attract other organisms. Also, erosion protection of wind turbines can be designed in a way that it serves as a habitat for various living organisms allowing certain species to find shelter in spaces between the scour protection and attracting other species and predators (Lengkeek et al. 2017). Other reef structures could also be installed directly on turbine towers or foundations, such as "fish hotels", which TenneT has attached to a transformer platform. However, the statics of such measures must always be considered, which is why in many cases they cannot be retrofitted and should be considered from the outset during project planning. In any case, additional artificial reefs can be created between the individual turbines, for example by laying out stones, concrete blocks, dead wood, mussel shells or other special objects (Hermans et al. 2020).

From a fisheries perspective these types of co-location solutions could to some extent mitigate the loss of fishing opportunities. They could also be explored in MSP processes and facilitated through spatial planning and regulation procedures (Stelzenmüller et al., 2022). Nonetheless, a number of obstacles present themselves.

Artificial reef effects may conflict with nature conservation perspectives that might anyhow be sceptical of "artificial" habitat construction. Using such artificially created habitats for fishing might even more create opposition and resistance from nature conservation as these groups might look at such measures as an ecological enhancement of wind farm areas, but not one to be commercially used. Utilising spill-over effects or allowing passive gear fishing in offshore wind farms also conflicts with nature conservation objectives to reduce fishing pressure generally. Using artificially constructed habitats to support passive types of fisheries will also require appropriate incentives in the regulatory process or in auctions for wind farm areas; the same applies to allowing access to (licensed) fishing vessels into offshore wind farms. Lastly, while passive gear fishing can seem an obvious replacement for other locally traditional fisheries, the success of passive gear alternatives depends on a range of socio-economic factors, such as a well-structured and well-developed marketing strategy that focuses on regionality or the dissemination of recipes in cooperation with the catering industry (Gimpel et al., 2020). Some countries are already taking an integrated approach to fisheries, embedding the whole supply chain in (mostly sub-national) marine spatial planning (Ramieri et al., 2024). In addition to environmental sustainability, considering the broader value chain and community livelihoods in the sense of a fair and just transition are aspects MSP should consider.

A study by Bonsu et al. (2024) has investigated the possibility of co-use of fisheries in or on the edge of offshore wind farms as well as current practices and framework conditions in the North Sea. According to the authors, the lack of sufficient scientific evidence for the economic viability of the proposed passive fishing gear, as well as uncertainties regarding implementation, are proving to be barriers to the development of co-use solutions. Their results show that the largest potential for co-location of crustacean pot fisheries is in offshore wind farms that already exist or will be built by 2030. Enabling conditions promoting this type of co-use include more scientific evidence on the socio-economic and environmental viability of passive fisheries in offshore areas. A positive factor is that stakeholders in the North Sea are generally receptive to the joint use of fisheries and offshore wind farm development, indicating awareness of the challenges and chances of this transformation. Although only on a limited empirical basis, stakeholders also expect positive effects of offshore wind farms on cod and North Sea crab abundance.

Barriers to implementing co-use of fisheries and offshore wind farms also relate to the current legal basis, the implementation of safety regulations and the definition of minimum requirements for fishing vessels to engage in gillnet or trap fishing in offshore wind farm areas (capacity, quotas, technical equipment), the introduction of a licensing procedure, and a scoping exercise for financial subsidies for the establishment of companies would be prerequisites for establishing (passive) fishing in wind farm areas (Bonsu, 2024).

Barriers to transforming fisheries specifically relate to financial aspects. For example, converting the current bottom-trawling fishery to passive fishing requires new or refurbished vessels, which entails considerable investment costs. In particular, coastal small-scale fishers would need more expensive and larger vessels, as most offshore wind farms are too far offshore for smaller boats. In addition, insurance issues play a vital role in such a transition to manage economic risks in case of emergencies and accidents with cables and other wind farm or ship infrastructure.

Theoretically, also pelagic fisheries in wind farms generally can be made possible, however, this would require solving questions of insurance and design, e.g. larger distances between turbines (which could be dealt with in regulations in maritime spatial plans, approval procedures and auction design). On the other hand, reducing the number of turbines within a wind farm area by increasing the distances between turbines may result in lower levels of electricity production within the same area or alternatively in even larger area requirements for wind farms when installed capacities are expected to stay at currently envisaged levels. Technological innovation in turbine development may however provide new options in this respect in the longer term.

4.2.5.2.3 Conflict mitigation and fisheries sector engagement

If MSP is understood as an adaptive approach that is essentially multi-sector planning to optimize the use of maritime space (Kyriazi, 2018), conflict management and the promotion of synergy are at the core of the planning process. Participation, engagement and co-design are essential for the development of mitigation options that are technically, economically, politically, socially and ecologically feasible and supported by all relevant stakeholders including MSP planners.

When designing co-use, a key question is how much disadvantage each player is willing to accept at each stage of the co-use process (Gee & Mikkelsen, 2023). Tools to calculate trade-offs, such as compatibility matrices, can be useful in this context, as are participatory processes, alternative dispute resolution, formal allocation rules (such as game theory), and — as an ultimate resort — litigation (Kyriazi, 2018; Schupp et al., 2019).

If co-use is still in the early stages, MSP can provide a platform for different actors to explore opportunities. If co-use has already reached a level of maturity, MSP can proactively support its implementation, e.g. by designing multi-use zones or identifying locations with least constraints for combined uses.

As explored in previous sections, mitigation may not be possible within the boundaries of MSP mechanisms. The MSP process is, therefore, also essential for identifying and recommending additional supporting measures that could help resolve a conflict but are outside the remit of planners — such as technical measures or measures related to licensing. The ideal process then also identifies the actors that need to be brought to the table to agree such measures and ensure they are implemented (Gee & Mikkelsen, 2023).

Mitigative strategies need to respond to precise situations and contexts based on consideration of:

- how activities are in conflict with each other,
- compensation for displaced activities,
- how other levels of planning (e.g. licensing) or sectoral strategies can be used to mitigate spatial conflicts, and
- temporal/spatial management for non-permanent activities.

To develop suitable planning and mitigation options, offshore wind farm planning should actively involve the different fisheries sectors from the beginning, ideally employing a co-design approach (Morf et al., 2019). Co-design, understood here as the active involvement of stakeholders in the design of planning solutions, has become an important tool for policy makers in many fields, and is employed to engage with stakeholders and wider publics to find solutions to complex problems and to ensure that policies have the necessary support (Urquhart et al., 2023). Well managed co-design approaches are transparent, participative, collaborative and inclusive, ideally based on shared decision-making and process responsibility. There are many advantages to participatory and collaborative processes, including generating a broad knowledge and evidence base, improved understanding of the issues at hand, recognition of different interests and values, fair and equitable representation of all relevant sectors and stakeholders, joint ownership of planning solutions, as well as intangible process benefits such as learning, mutual understanding and trust-building (Ehler & Douvere 2009). At the same time, co-design presents a number of challenges, such as building trust between stakeholders and policymakers, overcoming traditional modes of evidence-based policy making, accessing hard-to-reach groups, getting discussions to move beyond the general to the specific, and recognising that co-design takes time and is resource-intensive (Urquhart et al., 2023).

In the context of offshore wind farm planning, co-design approaches should leverage fishers' knowledge of preferred fishing areas, significant target species and other sector-specific needs and expectations. They should identify the potential conflicts that may arise from displacement and reduced areas available for fishing. Last not least, they should also consider the impacts of climate change on fisheries and the implications this may have for fishing opportunities generally. In Finland for example, dedicated workshops have taken place with small-scale fishers to identify expected climate change impacts and how this might affect fishing activities in the medium term (Arki et al., 2024). This knowledge can then be introduced to broader spatial planning processes, e.g. to anticipate future fishing patterns, in order to make appropriate location decisions for other sea uses.

More generally, collaboration and negotiation are also prerequisites for reaching agreement on reasonable and feasible compensation measures. Together, these elements allow the establishment of a strong foundation for defining mitigation options.

Successful planning and stakeholder engagement require specialized human resources with relevant experience and local expertise. For an effective co-design process, it is also essential to define in detail the timing and methods for stakeholder involvement, optimizing the cost-benefit ratio. Different forms of participation and stakeholder engagement can be used (Table 4.3), but only the high level of involvement will allow the development of a true co-designed plan, as well as more consensual mitigation measures. Consequently, consensus-building and negotiation-based methods will increase the level of acceptance and reduce implementation-related opposition. Effective engagement in fisheries management requires inclusive and well-structured processes. Capacity-building initiatives should be promoted across all sectors to enable equitable participation, particularly for less organized groups like small-scale fisheries. Key sectors must be adequately represented to prevent exclusion, while managing expectations realistically to uphold commitments. Reviewing past engagement experiences helps refine approaches and improve outcomes. Additionally, participatory processes should be guided by impartial, experienced teams to ensure transparency and efficiency. A clear communication mechanism should be established, allowing stakeholders to provide feedback, raise concerns, and resolve disputes effectively.

In Ireland, there is an example of proactive engagement at the forward planning stage of offshore wind development. A Seafood/ORE Working Group was established to facilitate discussion on matters arising from the interaction of the Irish seafood and offshore renewable energy industries, to promote and share best practice, and to encourage liaison with other sectors in the marine environment.

Table 4.3. Methods for Stakeholder Participation and Engagement (adapted from Bouamrame 2006).

Participation Method	Description	Level of Stakeholder Involvement	Common Tools
Communication	Management team shares information without seeking feedback.	No active involvement.	Videos, brochures
Information	Information is provided for stakeholders to react or take a stance.	Passive reaction or stance-taking.	Presentations, seminars, info sessions
Consultation	Gathering stakeholder opinions to ensure they are considered.	Low	Meetings, workshops, interviews
Dialogue	Equal interaction among parties to understand perspectives and find solutions.	Low/Medium	Meetings, workshops
Consensus-Building	Developing a shared position among stakeholders for presentation to authorities.	Medium/High	Meetings, workshops
Negotiation	Equal decision-making power between stakeholders and management.	High	Meetings, workshops
Dispute Resolution Mechanism (DRM)	Tool for resolving disagreements between stakeholders.	High	DRM process, meetings

4.2.5.2.4 Compensation

Proper communication structures may also help to identify impact mitigation measures outside the administrative and legal scope of spatial planning such as **compensation schemes**. For example, van Hoey et al. (2021) refer to the North Sea Dialogue in the Netherlands resulting in the North Sea Agreement (NSA), which was signed by all parties, however not by the fisheries organizations, who did not agree with the final agreement. For fisheries, the implementation of the NSA will result in a decrease in fishing grounds due to offshore wind farm and nature conservation area expansion. The fishers will be compensated through a Transition Fund, which will be used to develop a decommissioning scheme to adapt the Dutch fleet in size to suit the remaining space for fisheries and to finance sustainability innovations for the vessels that do not opt for decommissioning. This example shows chances as well as difficulties in participatory communication processes.

Referring to Alexander et al. (2013), Hoey et al. (2021) also state that diverging ideas may exist within the fishing sector on what proper compensation for loss of fishing grounds due to offshore wind farm expansion should look like. As Alexander et al. (2013) note, fishers on the Scottish west coast were not in favour of compensation by means of stimulating or investing in alternative livelihoods for affected fishers, reasoning that for fishing communities in rural areas, alternative employment opportunities are not always available. Therefore, fishers preferred that compensation instead should focus on the long-term wellbeing of the fisheries communities, for instance, by investing in local education opportunities (Alexander et al. 2013). Alternatively, compensation can be considered beyond monetary measures. As mentioned in a stakeholder comment in this workshop the creation of new fishing grounds by seeding would be an alternative approach.

Also, there might be different opinions between wind farm developers and fishers on who is eligible for compensation (Gray et al. 2005, referred to in Van Hoey et al. 2021). Should this only be those fishers directly fishing within the planned wind farm area or include those that might be affected by increased fishing pressure in other areas when the total amount of available fishing grounds decreases?

Where possible compensation for disruption and displacement of fishing activities should be evidence-based. Difficulties arise when considering inshore fishing vessels and vessels under 12m where there is a lack of vessel tracking evidence (VMS/AIS data). This may result in a reliance on qualitative data or voluntary means of vessel tracking. An example of a project that could be adapted for vessels operating in offshore wind areas of interest is the installation of bespoke VMS instruments on selected vessels <12m in Ireland (iVMS project).

These examples show that the involvement of local fishing communities and regional specificities need to be considered in planning and management (see also Stelzenmueller et al. 2024 from an adaptive capacity perspective), requiring development of dedicated communication structures and cross-sectoral dialogues at local levels as much (or even more) as on national or European levels. A cascade of dialogues from high-level policy-making to local levels including among the various levels may be required to mitigate impacts from offshore wind farms on fisheries (and other sectors). At high-level policies, this also includes better alignment between sectoral policies, specifically between the CFP and marine renewable policies and taking marine environmental policy into account as well, which intertwines with both, fisheries and marine renewables. The development of standardized consultation and compensation processes for all EU Member States as proposed by Van Hoey et al. (2021) might therefore not be sufficient to address real-world complexities in the interaction of offshore wind farms, fisheries and other sectors (including nature conservation).

4.2.5.2.5 Other measures

Other measures may relate to turbine array design and cabling (NYSERDA 2022). Inter-array and external grid connections pose considerations for the operability of fishing vessels within an array and along cable routes outside the wind farm. Interactions between cables and fishing gear create risk to the vessel, crew, and cables alike (apart from effects of the electromagenetic field). Impact minimization measures for cabling include, but are not limited to (NYSERDA 2022):

- designing cable routes to maximize the potential for responsible cable burial
- optimizing grid connection and inter-array cable layouts that account for existing fishing activity, including minimizing the amount of cable laid
- laying power cables using the method that causes the least damage to the seabed
- laying high voltage direct current (HVDC) cable with opposing electrical currents alongside each other and with sufficient burial
- planning cable location and directionality with delineation of cable locations on charts
- considering removal of cables in case of decommissioning
- bundling cables in corridors to reduce spatial disturbance

4.2.6 Recommendations

Table 4.4 Describes recommendations derived from the analysis of maritime spatial planning (MSP) and planning systems including subordinated planning instruments such as approval procedures and political context. The table is structured around rationales and divided into policy recommendations (relating to specific mitigation options such as zoning and co-use), procedural recommendations (relating to the policy and planning process) and recommendations for science.

Rationale	Recommendation Level		
	Policy	Procedural	Scientific
Appropriate zoning approaches and co-use of areas are the main instruments that could support mitigation of impacts from offshore wind farms onto fisheries in maritime spatial planning and subordinate planning processes	Include planning policies, regulations and incentives that support fishers as well as wind farm operators in spatial plans and approval procedures;	Include appropriate fisher engagement plans to allow co-design and/or co-defining compensation measures;	Provide relevant information to support the co-design process, e.g. maps of fishing grounds habitats, spawning and nursery grounds, key species distribution, in a clear and easily understood language for all involved (non-scientific) stakeholders.
From the perspective of MSP any conflict between two sectors is one of spatial competition. In addition, spatial pressures on any of these sectors may also stem from any other sectors (in particular fisheries is also under spatial pressure from restrictions in protected areas, but also from an increasing amount of underwater cables), therefore the respective sector may experience a sum of cumulated spatial competition and pressure		Include cumulative impact assessments in SEA of maritime spatial plans;	Develop frameworks and methods for operational use in (spatial) cumulative impact assessments in SEA;

Rationale	Recommendation Level		
	Policy	Procedural	Scientific
Area closures may come with displacement of fishers and re-allocation of fishing activities, increasing competition in remaining fishing areas and associated economic and socio-cultural impacts as well as ecological risks		Include analysis of the spatial heterogeneity of profitable fishing grounds along with scenario trajectories which may support MSP in adapting zoning approaches to mitigate economic impacts on fisheries; If chosen as a political option in fisheries policy, compensation (either monetary or in the form of providing alternative fishing areas) should be based on evidence where possible and must be tailored to the specific fishing community and their specific local setting, and might have to extend beyond directly affected fishers.	Provide scenario analyses to predict the impacts of the different re-allocation options and maximise the trade-offs between the different activities.
Current political priorities (at European and national levels) strongly support offshore windfarm development	Addressing unavoidable conflicts between offshore wind farms and fisheries depends on their recognition and principal consideration in high-level policies;	Include socio-economic and socio-cultural impact/risk assessments in planning (either as separate assessments or as part of the SEA)	Provide frameworks, approaches and tools for operational use of socio-economic and socio-cultural risk assessments;
Given restrictions in offshore wind farms, in particular for bottom trawling, mitigation measures for the sector and political as well as financial support to adaptation of the sector is required (new fishing techniques and new forms of operation, significant investments in boats, gears and infrastructure), in particular for local small-scale fisheries	Adaptations within fisheries policies (including the CFP) and aligning the CFP and national fisheries policies better with MSP; Adaptions in the EMFF to provide financial support mechanisms for such a transition;	Recognising conflicts and support for adaptation of fisheries in high-level policies as a prerequisite for policy adaptations considering existing economic structures, economic context and increasing restrictions from conservation management onto fisheries prohibiting the sector to adapt by own resources; Integrate MSP evidence requirements into existing fisheries data collection programmes	Encourage and incentivise research, trials and use-cases to build an evidence base to support adaptation in fishing; Test the ecological effects (e.g., impact on communities, target species) and socio-economic effects (e.g., CPUE) of different co-use possibilities and other management measures that could enhance fishery yields (e.g., gear efficiency, artificial reef implementation, seafood certification).

Rationale	Recommendation Level		
	Policy	Procedural	Scientific
Co-use is an opportunity for fisheries which may support survival of parts of fishing communities, diversify fishing activities and mitigate to some extend the loss of fishing grounds	Co-use should be specifically explored in MSP processes and facilitated through spatial planning and regulation procedures; Consider appropriate incentives in the regulatory process and in auctions for wind farm areas and eventually access to (licensed) fishing vessels in these areas in maritime spatial plans and approval procedures	Encourage co-use of fisheries and wind farms at political level, e.g. in legislation. Incentivise feasibility studies on co-use options.	Facilitate co-designed trials and use-cases to build an evidence base to support co-use.
For all offshore renewable impacts on fisheries consider differentiation of types of fishing, metiers as well as regional and local specifics of fishing communities.		Secure proper stakeholder engagement and develop regular communication mechanisms throughout all stages of the planning process; Include analysis of the specific resilience and adaptation capacities for each specifically affected fishing community including recognition of experience and knowledge of community members;	

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Annex 2: Resolution

2024/WK/HAPISG13 A **Workshop to Compile Evidence on the Impacts of Offshore Renewable Energy on Fisheries and Marine Ecosystems** (WKCOMPORE), chaired by Andreas Kannen, Germany; Jan Vanaverbeke, Belgium; and Katell Hamon, Netherlands; will be established and will meet at ICES HQ, Copenhagen, Denmark, 3–7 February 2025.

WKCOMPORE will use the outputs of the ICES ORE Part One, Part Two and Part Three groups[1] as the primary sources of material to address the following:

a) To review, summarise and compile evidence on the impacts of offshore renewable energy (ORE) on fisheries and marine ecosystems[2] to address the following topics (Science Plan codes: 2.1, 2.2, 2.7, 7.3):
    i. The data and resources available for the analysis of the economic and social impacts of ORE developments on the fisheries sector, and on that basis:
        i. Summarise the known and projected economic and social impacts of existing and planned offshore renewable developments (on fisheries, at métier and fleet levels). Potential trade-offs between negative economic impacts on fisheries and positive economic impacts of the ORE sector should be considered;
        ii. Summarise the sources of information available, methods that may be applied, and further data and information required, to address the economic and social impacts of ORE on fishers;
    ii. The known ecological impacts of ORE developments and their intensity (severe, medium, limited, unknown) on main commercial fish species for the areas listed above and at population levels (positive and negative impacts) looking at the different phases of ORE development (survey, construction, operation, decommissioning). A specific case study on the effects on recruitment of western Baltic herring and of the effects on harbour porpoises should be developed;
    iii. How changes on hydrodynamic conditions produced by ORE may change the food availability to filter-feeders and influence phytoplankton primary production;
    iv. The ways artificial structures could influence the colonization of new areas by species, both indigenous and non-indigenous species. Based on data available for other structures (e.g. oil & gas), and from other locations (e.g. US);
    v. The ways in which pelagic species (especially commercial fish species) may react to dynamic cables suspended in the water column (floating wind);
    vi. Recommendations for next steps to define methodologies to model cumulative impacts of offshore wind on commercial fisheries (temporary, permanent) and the possibility to adopt mitigation measures;
    vii. Options for mitigation measures, good practices, and spatial planning for ORE developments and their strengths, weaknesses, implications and uncertainties. Priorities for research and monitoring related to these options.

b) To ensure, in the compilation to evidence described in ToR 'a', that the level of detail presented, data used, approaches taken, treatment of knowledge gaps and uncertainty, conclusions drawn, and references to evidence are, as far as possible, consistent.

c) To identify and report on recommendations and future work required to help address areas of uncertainty, data quality/ availability and the implementation of ORE applicable assessment methods.

[1] The 'Part' groups developed expert reviews and analyses of the impacts of offshore renewable energy on fisheries and marine ecosystems in 2024 and 2025. The Part One group addressed ToR 'a' i, the Part Two group addressed ToR 'a' vi & vii, and the Part Three group addressed ToR 'a' ii, iii, iv, and v.

[2] With a focus on the Celtic Sea, Greater North Sea and Baltic Sea ecoregions.

WKCOMPORE will report by 14 April 2025 for the attention of ACOM and SCICOM.

Supporting information

Priority	High, in response to a special request from DGMARE on the impacts of offshore renewable energy on fisheries and marine ecosystems.
Scientific justification	Rapid and large-scale offshore ORE development is underway. The ICES ORE Roadmap highlights the necessity to engage in assessing the fisheries and ecosystem impacts of ORE developments. The compilation and review of data and information and methods required to respond to the special request from DGMARE will advance ICES capacity to advance the science prioritised in the ICES ORE Roadmap and to identify priorities for ORE research.
Resource requirements	Secretariat support.
Participants	Scientific leadership will be provided by the leads of the Part One, Part Two and Part Three groups as well as many members of existing Expert Groups who have been contributing to the Part groups. Expected participation is 20-25 experts. Participants join the workshop at national expense. If the number of requests to participate exceeds the meeting space available ICES reserves the right to refuse participants. Choices will be based on previous engagement with the Part One, Two and Three groups, and the experts' relevant qualifications for the Workshop
Secretariat facilities	Secretariat support and meeting room [breakout rooms TBC].
Financial	Partial funded by a special advice request from DGMARE.
Linkages to advisory committees	ACOM and SCICOM.
Linkages to other committees or groups	HAPISG, HUDISG, IEASG, WGECON, WGSOCIAL, WGOWDF, WGMBRED, WGORE, WGMPAS, WGSFD , WGCEAM, WGMPCZM
Linkages to other organizations	EC, GNSBI

Annex 3: Lookup table of expected state changes

Table A3.1: General "lookup table" indicating an expected effect of expected state changes caused by the installation, operation and decommissioning of fixed offshore wind installations on population characteristic and response trait.

Population characteristic	Trait	Sediment resuspension	Sediment deposition	Colonisation of hard substrate (at monopile)	Sediment/nutrient/contaminant fluxes	Changed sediment seabed-water column (stratifaction, mixing)	Turbulent wakes	Changed thermal stratification	Wind wakes	Changed energy emissions/ environment (noise)	Changed light cues
Altered aggregation	Behavioural plasticity	0	0	x	0	0	0	0	0	x	0
Changed colonisation	Behavioural plasticity	x	0	x	x	0	0	0	0	0	0
Changed feeding patterns	Behavioural plasticity	x	x	0	0	0	x	x	0	0	0
Larval dispersal (passive or active)	Behavioural plasticity	x	x	0	0	0	0	0	0	0	0
Physiological damage	Behavioural plasticity	0	0	0	0	0	0	0	0	x	0
Predator-prey interactions	Behavioural plasticity	x	x	0	0	0	0	0	0	x	0
Recruitment (survival of the juveniles)	Behavioural plasticity	x	0	0	0	0	0	0	0	0	0
Reproduction	Behavioural plasticity	0	0	0	0	x	0	0	x	x	0
Altered aggregation	Diet specialisation	0	0	x	0	0	0	0	0	0	0
Altered migration	Diet specialisation	0	0	x	0	0	0	0	0	0	0
Changed feeding patterns	Diet specialisation	0	0	x	x	x	x	x	0	0	0
Predator-prey interactions	Diet specialisation	0	0	x	x	x	0	0	0	0	0
Recruitment (survival of the juveniles)	Diet specialisation	0	0	0	x	x	x	0	x	0	0
Reproduction	Fecundity	0	0	0	x	0	0	0	0	0	0
Changed feeding patterns	Feeding behaviour	x	x	0	0	0	0	0	0	0	0

Population characteristic	Trait	Sediment resuspension	Sediment deposition	Colonisation of hard substrate (at monopile)	Sediment/nutrient/contaminant fluxes	Changed sediment seabed-water column (stratifaction, mixing)	Turbulent wakes	Changed thermal stratification	Wind wakes	Changed energy emissions/ environment (noise)	Changed light cues
Predator-prey interactions	Feeding behaviour	x	x	0	0	0	0	0	0	0	0
Recruitment (survival of the juveniles)	Feeding behaviour	x	0	x	0	0	0	0	0	0	0
Altered aggregation	Feeding mode	0	0	x	0	0	0	0	0	0	0
Changed feeding patterns	Feeding mode	x	x	x	0	0	0	0	0	0	0
Predator-prey interactions	Feeding mode	x	x	x	0	0	0	0	0	0	x
Predator-prey interactions	Feeding time	0	0	0	0	0	0	0	0	0	0
Altered distribution	Habitat dependence/Resilience to habitat alteration	0	0	x	0	x	x	0	0	0	0
Predator-prey interactions	Habitat dependence/Resilience to habitat alteration	0	0	0	0	0	0	x	0	0	0
Recruitment (survival of the juveniles)	Habitat dependence/Resilience to habitat alteration	0	x	0	x	x	x	0	x	0	0
Changed colonisation	Habitat selection/spawning location	x	0	0	0	0	0	0	0	0	0
Larval dispersal (passive or active)	Habitat selection/spawning location	0	0	x	0	0	x	0	x	0	0
Recruitment (survival of the juveniles)	Habitat selection/spawning location	0	0	0	0	0	0	0	0	x	0
Reproduction	Habitat selection/spawning location	x	x	x	0	0	x	0	0	0	0
Altered migration	Migration behaviour (or migrating pattern)	x	0	x	0	0	0	0	0	x	0
Changed colonisation	Migration behaviour (or migrating pattern)	x	0	0	0	0	0	0	0	0	0
Altered distribution	Oxygen tolerance	0	0	0	x	0	0	0	0	0	0

Population characteristic	Trait	Sediment resuspension	Sediment deposition	Colonisation of hard substrate (at monopile)	Sediment/nutrient/contaminant fluxes	Changed sediment seabed-water column (stratifaction, mixing)	Turbulent wakes	Changed thermal stratification	Wind wakes	Changed energy emissions/ environment (noise)	Changed light cues
Reproduction	Oxygen tolerance	0	0	0	x	0	0	0	0	0	0
Larval dispersal (passive or ac-tive)	Salinity tolerance	0	0	0	0	x	0	x	0	0	0
Altered aggregation	Sensory adaptations	0	0	0	0	0	0	0	0	0	0
Altered distribution	Sensory adaptations	0	0	0	0	0	0	0	0	x	0
Altered migration	Sensory adaptations	0	0	0	0	0	0	0	0	x	0
Changed feeding patterns	Sensory adaptations	x	0	0	0	0	0	0	0	0	x
Larval dispersal (passive or ac-tive)	Sensory adaptations	x	0	0	0	0	0	0	0	0	0
Predator-prey interactions	Sensory adaptations	x	0	0	0	0	0	0	0	x	0
Altered distribution	Thermal tolerance	0	0	0	0	0	0	x	0	0	0
Larval dispersal (passive or ac-tive)	Thermal tolerance	0	0	0	0	x	0	x	0	0	0
Predator-prey interactions	Trophic level	0	0	0	0	0	x	0	x	0	0
Predator-prey interactions	Trophic level	0	0	0	0	0	x	0	x	0	0
Predator-prey interactions	Trophic level	0	0	0	0	0	x	0	x	0	0

Annex 4: Impact narrative

Table A4.1: Lookup table with impact narrative for the causal pathways between expected state changes caused by pressures of fixed offshore wind in operation and the response trait modes.

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Sensory adaptations	Vision	Predator-prey interactions	-1	Species that rely primarily on vision for hunting or detecting prey may be at a disadvantage in visually disturbed environments, as reduced visibility can impair their ability to locate and capture prey, thereby disrupting predator-prey interactions.	0		0		0		0		0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Sensory adaptations	Smell and taste	Predator-prey interactions	0		0		0		0		0		0
Sensory adaptations	Mechanosense (Lateral line)	Predator-prey interactions	0		0		0		0		-1	Species that primarily rely on their lateral line may be impacted by noise, as it can interfere with water movement and infrasound, impairing their ability to detect prey and disrupting predator-prey interactions.	0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction, mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Sensory adaptations	Electrosense and magnetosense	Predator-prey interactions	-1	Species that primarily rely on electroreception may be at a disadvantage in environments with high concentrations of suspended particles, as these particles can scatter or dampen electric fields, impairing the species' ability to detect prey and affecting predator-prey interactions.	0		0		0		-1	Species that primarily rely on electroreception may be impacted by noise or EMFs. These can interfere with electrical fields and infrasound, impairing species ability to detect prey cues and disrupting predator-prey interactions.	0
Sensory adaptations	Hearing	Predator-prey interactions	0		0		0		0		-1	Species that primarily rely on hearing may be impacted by noise, impairing their ability to detect prey and disrupting predator-prey interactions.	0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Sensory adaptations	Vision	Altered distribution	0		0		0		0		0		0
Sensory adaptations	Smell and taste	Altered distribution	0		0		0		0		0		0
Sensory adaptations	Mechanosense (Lateral line)	Altered distribution	0		0		0		0		-1	Species that primarily rely on their lateral line may be impacted by noise, as it can interfere with water movement and infrasound, affecting their distribution.	0
Sensory adaptations	Electrosense and	Altered distribution	0		0		0		0		-1	Species that primarily rely on electroreception may be impacted by noise or EMF, as it can interfere with electrical fields and infrasound, affecting their	0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
	magnetosense											distribution; magnetosensitive species may be diverted from typical movement routes.	
Sensory adaptations	Hearing	Altered distribution	0		0		0		0		-1	Species that primarily rely on hearing may be impacted by noise, affecting their distribution.	0
Sensory adaptations	Vision	Larval dispersal (passive or active)	-1	Larvae that primarily rely on vision for feeding may be at a disadvantage in visually disturbed environments, as reduced visibility could hinder their ability to locate food, potentially impacting their distribution.	0		0		0		0		0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Sensory adaptations	Smell and taste	Larval dispersal (passive or active)	0		0		0		0		0		0
Sensory adaptations	Mechanosense (Lateral line)	Larval dispersal (passive or active)	0		0		0		0		0		0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Sensory adaptations	Electrosense and magnetosense	Larval dispersal (passive or active)	-1	Larvae that primarily rely on electroreception for feeding may be at a disadvantage in visually disturbed environments, as suspended particles can interfere with electric field detection by scattering or dampening signals, impairing their ability to locate food.	0		0		0		0	Larvae that primarily rely on magnrtooreception for orientiation or migrations may be diverted away from normal movement paths.	0
Sensory adaptations	Hearing	Larval dispersal (passive or active)	0		0		0		0		0		0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Habitat selection/spawning location	Pelagic spawners	Reproduction	0		0		0		-1	Pelagic spawners may be negatively affected by turbulent wakes, as their eggs could be exposed to increased energy from waves and water movement.	0	Pelagic spawners may be negatively affected by noise causing reproductive adults to move away	0
Habitat selection/spawning location	Demersal spawners	Reproduction	-1	Demersal eggs may become covered by sediment, which can negatively impact reproduction by hindering egg development or fertilization.	1	The colonisation of OWF structures may create additional spawning habitats for demersal spawners, potentially enhancing their reproductive success.	0		0		0	Demersal spawners may be negatively affected by noise causing reproductive adults to move away or reproductive vocalisations to be affect	0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Habitat selection/spawning location	Egg hider	Reproduction	-1	Demersal eggs may become covered by sediment, which can negatively impact reproduction by hindering egg development or fertilization.	1	The colonisation of OWF structures may create additional spawning habitats for demersal spawners, potentially enhancing their reproductive success.	0		0		0	Demersal eggs may be exposed to underwater noise or EMF impacts on development.	0
Habitat selection/spawning location	Egg guarders	Reproduction	-1	Demersal eggs may become covered by sediment, which can negatively impact reproduction by hindering egg development or fertilization.	1	The colonisation of OWF structures may create additional spawning habitats for demersal spawners, potentially enhancing their reproductive success.	0		0		0	Demersal eggs may be exposed to underwater noise impacts or EMF on development.	0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction, mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Habitat selection/spawning location	Viviparous	Reproduction	0		0		0		0		0		0
Habitat selection/spawning location	Pelagic spawners	Recruitment (survival of the juveniles)	0		0		0		0		0	Pelagic eggs may be exposed to underwater noise or EMF impacts on development, depending on how long they remain in the area	0
Habitat selection/spawning location	Demersal spawners	Recruitment (survival of the juveniles)	0		0		0		0		0		0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Habitat selection/spawning location	Egg hider	Recruit-ment (survival of the ju-veniles)	0		0		0		0		0		0
Habitat selection/spawning location	Egg guarders	Recruit-ment (survival of the ju-veniles)	0		0		0		0		0		0
Habitat selection/spawning location	Viviparous	Recruit-ment (survival of the ju-veniles)	0		0		0		0		0		0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Habitat selection/spawning location	Pelagic spawners	Larval dispersal (passive or active)	0		0		0		-1	Pelagic spawners may be negatively affected by turbulent wakes, as their eggs could be exposed to increased energy from waves and water movement.	0	Pelagic larvae may be exposed to underwater noise affecting movement and orientation	0
Habitat selection/spawning location	Demersal spawners	Larval dispersal (passive or active)	0		-1	The predation risk at colonized OWF structures may be higher for demersal spawners.	0		0		0	Demersal species larvae may be exposed to underwater noise affecting movement and orientation	0
Habitat selection/spawning location	Egg hider	Larval dispersal (passive or active)	0		-1	The predation risk at colonized OWF structures may be higher for demersal spawners.	0		0		0	Pelagic larvae may be exposed to underwater noise affecting movement and orientation	0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Habitat selection/spawning location	Egg guarders	Larval dispersal (passive or active)	0		-1	The predation risk at colonised OWF structures may be higher for demersal spawners.	0		0		0	Pelagic larvae may be exposed to underwater noise affecting movement and orientation	0
Habitat selection/spawning location	Viviparous	Larval dispersal (passive or active)	0		0		0		0		0		0
Feeding behaviour	Solitary	Recruitment (survival of the juveniles)	-1	Species that rely primarily on their own sensory abilities may be at a disadvantage under turbidity from resuspension, as they cannot benefit from group dynamics for orientation.	0		0		0		0		0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Feeding behaviour	Group feeders	Recruit-ment (survival of the ju-veniles)	0		0		0		0		0		0
Feeding behaviour	Solitary	Predator-prey interactions	0		0		0		0		0		0
Feeding behaviour	Group feeders	Predator-prey interactions	-1	In a visually disturbed envi-ronment, the encounter rate with prey may be lower for group-feeding species com-pared to solitary feeders, as visual impairments can dis-rupt group coordination	0		0		0		0		0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Behavioural plasticity (i.e., migration shifts and habitat switching)	Low	Recruitment (survival of the juveniles)	-1	Species with low behavioural plasticity may struggle to adapt to changing environmental conditions, potentially affecting their recruitment success.	0		0		0		0		0
Behavioural plasticity (i.e., migration shifts and habitat switching)	High	Recruitment (survival of the juveniles)	0		0		0		0		0		0
Behavioural plasticity (i.e., migration shifts	Low	Reproduction	0		0		-1	Species with low behavioural plasticity may struggle to	0		0	Species with low behavioural plasticity may struggle to adapt to the masking of reproductive signals in one or more modalities	0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
and habitat switching)								adapt to changing en-vironmental conditions, potentially affecting re-production.					
Behavioural plasticity (i.e., migra-tion shifts and habitat switching)	High	Reprodu ction	0		0		0		0		0		0
Behavioural plasticity (i.e., migra-tion shifts	Low	Predator -prey interacti ons	-1	Species with low behavioural plasticity may struggle to adapt to changing environ-mental conditions,	0		0		0		0	Species with low behavioural platicity may struggle to adapt to the masking of predator cues in one or more modalities	0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)		Changed light cues (notes)
and habitat switching)				potentially affecting predator-prey interactions.										
Behavioural plasticity (i.e., migration shifts and habitat switching)	High	Predator-prey interactions	0		0		0		0		0		0	
Behavioural plasticity (i.e., migration shifts and habitat switching)	Low	Altered distribution	0		0		0		0		-1	Species with low behavioural plasticity may struggle to adapt to changing environmental conditions, potentially affecting their distribution.	-1	Species with low behavioural plasticity may

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
													struggle to adapt to changing environmental conditions, potentially affecting their distribution.

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
Behavioural plasticity (i.e., migration shifts and habitat switching)	High	Altered distribution	0		0		0		0		0		0
Behavioural plasticity (i.e., migration shifts and habitat switching)	Low	Larval dispersal (passive or active)	-1	Species with low behavioural plasticity may struggle to adapt to changing environmental conditions, potentially affecting their distribution.	0		0		0		0		0
Behavioural plasticity (i.e., migration shifts	High	Larval dispersal (passive or active)	0		0		0		0		0		0

Traits	Modes	Population characteristic	Sediment resuspension (cat)	Sediment resuspension (notes)	Colonisation of hard substrate (at monopile) (cat)	Colonisation of hard substrate (at monopile) (notes)	Changed sediment seabed-water column (stratifaction. mixing) (cat)	Changed sediment seabed-water column (stratifaction, mixing) (notes)	Turbulent wakes (cat)	Turbulent wakes (notes)	Changed energy emissions/ environment (noise) (cat)	Changed energy emissions/ environment (noise) (notes)	Changed light cues (notes)
and habitat switching)													

Annex 5: Cumulative Sum landings

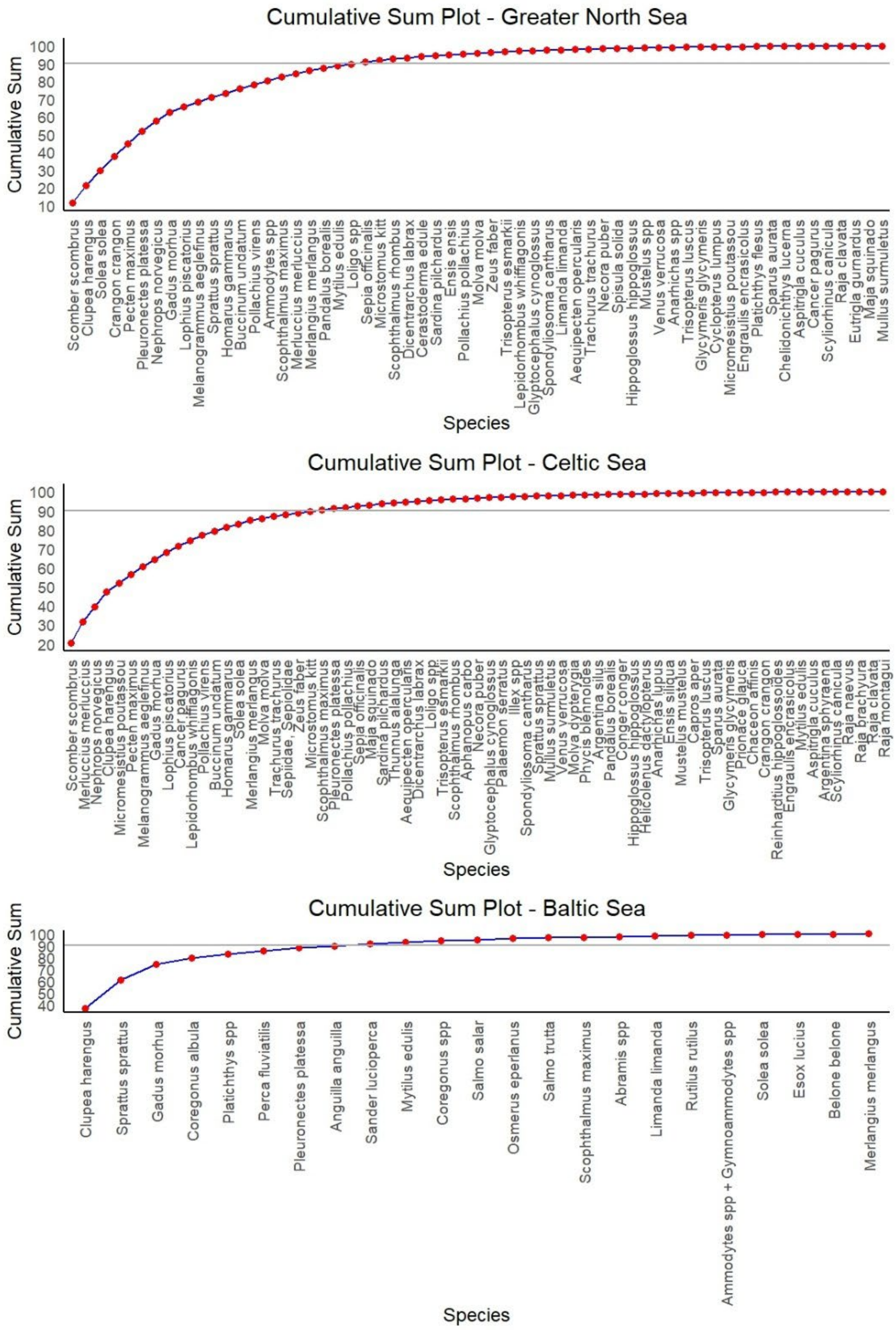

Figure 1: Cumulative sums (%) of total landings (1000 €) by species and regions with a respective cut off value indicating a 90 % contribution. Data have been extracted from (ICES 2022).

ICES. EU request for advice on developing appropriate lists for Descriptor 3 (commercially exploited fish and shellfish,) reporting by EU Member States under MSFD Article 17 in 2024. In Report of the ICES Advisory Committee, 2022. ICES Advice 2022, sr.2022.15, https://doi.org/10.17895/ices.advice.21332967. In, 2022

Annex 6: Species trait list

				Behavioral plasticity (e.g., migration shifts and habitat switching, diet shifts)					Diet specialization					Fecundity						Feeding behavior					Feeding mode								Feeding time				
Species	English nar	Taxa	Reg	ehavioral_plasticity	behavioral_plasticity	Source_behavioral plasticity	Comments_behavioral plasticit	plasticity	alist_diet	alist_diet	e_diet specialization	nents_diet specialization	diet	-1000 eggs)	ate (1000-1e+5 eggs)	> 1e+5 eggs)	e_fecundity	nent_fecundity	fecundity	y	feeders	e_feeding behavior	Comments_ feeding iour	feeding_behavior	ores	ivores	ores	ivores	vores	_feeding mode	nents_feeding mode	feeding_mode	l	nal	e_feeding time	nents_feeding time	feeding_time
Ammodytes spp	Sandeels(=Sandlanc	Fish	North Sea	3	1	Expert judgement	Spawning sit	4	4	0	Beukhof et al., 2019; F		4	0	4	0	Beukhof e	The Beukl	4	0	4	Sparholt 2015		4	0	0	0	4	0	Beukhof e	Ammodyt	4	4	0	Winslade 1	Activity is	4
Clupea harengus	Atlantic herring	Fish	North Sea	3	1	Expert judgement	Spawning sit	4	3	1	Froese et al., 2024		4	0	4	0	Froese an	Only value	4	0	4	Dickey-Cd	judged on	4	0	0	0	3	1	Froese et	Main food	4	4	0	Dickey-Collas et al. 2		4
Gadus morhua	Atlantic cod	Fish	North Sea	1	3	Expert judgement	Associated	4	0	4	Beukhof et al., 2019		4	0	0	4	Beukhof e	The Beukl	4	2	2	Hislop et a	General sc	4	2	2	0	0	0	Beukhof e	Main food	4	3	1	Hislop et a	Based on	4
Crangon crangon	Common shrimp	Invertebrate	North Sea	0	4	Expert judgement		4	0	4	Expert judgement		4	1	3	0	Bilgin, Sabri, and Osm		4	4	0	Expert judgement		4	1	1	1	0	1	Expert judgement		4	1	3	Pihl, Leif, and Rutger		4
Pecten maximus	Great Atlantic scallo	Invertebrate	North Sea	4	0	Expert judgement		4	4	0	Tillin, H. M., et al. "Ch		4	0	0	4	Le Pennec M, Pauga		4	4	0	Expert judgement		4	0	0	0	4	0	Tillin, H. M., et al. "Ch		4	2	2	Expert judgement		4
Lophius piscatorius	Angler(=Monk)	Fish	North Sea	2	2	Expert judgement	Habitat spec	4	4	0	Beukhof et al., 2019; F		4	0	0	4	Beukhof e	The Beukl	4	4	0	Ellis & Velasco 2015		4	4	0	0	0	0	Beukhof e	Main food	4	4	0	Ellis & Vel	Based on	4
Nephrops norvegicus	Norway lobster	Invertebrate	North Sea	4	0	Expert judgement		4	0	4	Tillin, H. M., et al. "Ch		4	3	1	0	Nichols J, Bennett D,		4	4	0	Expert judgement		4	1	3	0	0	0	Tillin, H. M., et al. "Ch		4	0	4	Chapman CJ, Rice A		4
Melanogrammus aeglefi	Haddock	Fish	North Sea	1	3	Expert judgement		4	0	4	Beukhof et al., 2019		4	0	1	3	Beukhof e	The Beukl	4	0	4	Hislop et a	judged on	4	0	4	0	0	0	Beukhof et al., 2019		4	3	1	Hislop et a	Based on	4
Merlangius merlangus	Whiting	Fish	North Sea	0	4	Expert judgement		4	3	1	Beukhof et al., 2019; F		4	0	0	4	Beukhof e	The Beukl	4	0	4	Expert judg	judged on	4	3	0	0	1	0	Beukhof e	Main food	4	3	1	Hislop et a	Based on	4
Merluccius merluccius	European hake	Fish	North Sea	0	4	Expert judgement		4	3	1	Beukhof et al., 2019; F		4	0	0	4	Beukhof e	The Beukl	4	4	0	Heessen &	judged on	4	3	1	0	0	0	Beukhof e	Main food	4	0	4	Heessen &	demersal	4
Pleuronectes platessa	European plaice	Fish	North Sea	2	2	Expert judgement	Soft bottom	4	4	0	Beukhof et al., 2019		4	0	0	4	Beukhof e	The Beukl	4	4	0	Goldsmith	judged on	4	0	4	0	0	0	Beukhof et al., 2019 a		4	4	0	Goldsmith	Full grown	4
Homarus gammarus	European lobster	Invertebrate	North Sea	3	1	Expert judgement	Needs rocky	4	0	4	Expert judgement		4	0	4	0	Ellis CD, Knott H, Da		4	4	0	Expert judgement		4	1	3	0	0	0	Expert judgement		4	1	3	Smith IP, Collins KJ,		4
Buccinum undatum	Whelk	Invertebrate	North Sea	3	1	Expert judgement		4	0	4	Tillin, H. M., et al. "Ch		4	1	3	0	Valentinsson D (2002		4	4	0	Expert judgement		4	1	3	0	0	0	Tillin, H. M., et al. "Ch		4	2	2	Expert judgement		4
Pollachius virens	Saithe(=Pollock)	Fish	North Sea	1	3	Expert judgement		4	2	2	Beukhof et al., 2019; F		4	0	0	4	Beukhof e	The Beukl	4	0	4	Hislop et a	judged on	4	3	0	0	1	0	Froese et	Main food	4	2	2	Hislop et a	Based on	4
Scomber scombrus	Atlantic mackerel	Fish	North Sea	0	4	Expert judgement		4	0	4	Beukhoff	It is assum	4	0	1	3	Beukhof e	The Beukl	4	0	4	Ellis & Hee	judged on	4	1	1	0	2	0	Froese et	Main food	4	2	2	Ellis & Hee	feeding du	4
Scophthalmus maximus	Turbot	Fish	North Sea	2	2	Expert judgement	Soft bottom	4	2	2	Beukhof e	Conflicting	4	0	0	4	Beukhof e	The Beukl	4	4	0	Velasco e	judged on	4	0	2	0	2	0	Beukhof e	Conflicting	4	4	0	Velasco e	Based on	4
Solea solea	Common sole	Fish	North Sea	2	2	Expert judgement	Soft bottom	4	4	0	Froese et al., 2024		4	0	3	1	Beukhof e	The Beukl	4	4	0	Rijnsdorp	"Adults oc	4	0	4	0	0	0	Froese et	Main food	4	0	4	Rijnsdorp et al. 2015		4
Sprattus sprattus	European sprat	Fish	North Sea	0	4	Expert judgement		4	4	0	Beukhof et al., 2019; F		4	0	4	0	Froese an	Only value	4	0	4	Dickey-Cd	judged on	4	0	0	0	4	0	Froese et	Main food	4	4	0	Dickey-Collas et al. 2		4
Pandalus borealis	Northern prawn	Invertebrate	North Sea	0	4	Expert judgement		4	0	4	Tillin, H. M., et al. "Ch		4	1	3	0	Expert judgement		4	4	0	Expert judgement		4	1	1	1	0	1	Tillin, H. M., et al. "Ch		4	2	2	Expert judg	2/2 = no in	4
Mytilus edulis	Blue mussel	Invertebrate	North Sea	4	0	Expert judgement		4	4	0	Expert judgement		4	0	0	4	Expert judgement		4	4	0	Expert judgement		4	0	0	0	4	0	Expert judgement		4	2	2	Riisgård H	depending	4
Loligo spp	Common squids nei	Invertebrate	North Sea	2	2	Expert judgement	Might benefi	4	0	4	Expert judgement		4	0	4	0	Coelho, M. L., et al. "F		4	4	0	Expert judgement		4	3	1	0	0	0	Pierce, G. J., et al. (19		4	2	2	Sauer W, Lipiński M (		4
Clupea harengus	Atlantic herring	Fish	Celtic Sea	2	2	Expert judgement		4	3	1	Froese et al., 2024		4	0	4	0	Froese an	Only value	4	0	4	Dickey-Cd	judged on	4	0	0	0	3	1	Froese et	Main food	4	2	2	Dickey-Collas et al. 2		4
Gadus morhua	Atlantic cod	Fish	Celtic Sea	1	3	Expert judgement		4	0	4	Beukhof et al., 2019		4	0	0	4	Beukhof e	The Beukl	4	2	2	Expert judgement		4	2	2	0	0	0	Beukhof e	Main food	4	0	4	Hislop et a	Based on	4
Nephrops norvegicus	Norway lobster	Invertebrate	Celtic Sea	4	0	Expert judgement		4	0	4	Tillin, H. M., et al. "Ch		4	3	1	0	Nichols J, Bennett D,		4	4	0	Expert judgement		4	1	3	0	0	0	Tillin, H. M., et al. "Ch		4	0	4	Chapman CJ, Rice A		4
Lepidorhombus whiffiag	Megrim	Fish	Celtic Sea	2	2	Expert judgement	Soft bottom	4	4	0	Beukhof et al., 2019		4	0	2	2	Froese an	Values fro	4	4	0	Velasco e	judged on	4	0	4	0	0	0	Beukhof et al., 2019		4	4	0	Velasco e	Based on	4
Lophius piscatorius	Angler(=Monk)	Fish	Celtic Sea	2	2	Expert judgement	Habitat spec	4	4	0	Beukhof et al., 2019; F		4	0	0	4	Beukhof e	The Beukl	4	4	0	Froese et	"It lies half	4	4	0	0	0	0	Beukhof e	Main food	4	4	0	Ellis & Vel	Based on	4
Pecten maximus	Great Atlantic scallo	Invertebrate	Celtic Sea	4	0	Expert judgement		4	4	0	Tillin, H. M., et al. "Ch		4	0	0	4	Le Pennec M, Pauga		4	4	0	Expert judgement		4	0	0	0	4	0	Tillin, H. M., et al. "Ch		4	2	2	Expert judgement		4
Melanogrammus aeglefi	Haddock	Fish	Celtic Sea	1	3	Expert judgement		4	0	4	Beukhof et al., 2019		4	0	1	3	Beukhof e	The Beukl	4	0	4	Hislop et a	judged on	4	0	4	0	0	0	Beukhof et al., 2019		4	3	1	Hislop et a	Based on	4
Merlangius merlangus	Whiting	Fish	Celtic Sea	1	3	Expert judgement		4	3	1	Beukhof et al., 2019; F		4	0	0	4	Beukhof e	The Beukl	4	0	4	Expert judgement		4	3	0	0	1	0	Beukhof e	Main food	4	3	1	Hislop et a	Based on	4
Merluccius merluccius	European hake	Fish	Celtic Sea	0	4	Expert judgement		4	3	1	Beukhof et al., 2019; F		4	0	0	4	Beukhof e	The Beukl	4	4	0	Heessen &	judged on	4	3	1	0	0	0	Beukhof e	Main food	4	0	4	Heessen &	demersal	4
Cancer pagurus	Edible crab	Invertebrate	Celtic Sea	4	0	Expert judgement	Needs rocky	4	0	4	Tillin, H. M., et al. "Ch		4	0	0	4	Bennett, 1995		4	4	0	Expert judgement		4	1	3	0	0	0	Tillin, H. M., et al. "Ch		4	1	3	Skajaa et al., 1998		4
Micromesistius poutass	Blue whiting(=Pouta	Fish	Celtic Sea	0	4	Expert judgement		4	1	3	Beukhof et al., 2019; F		4	0	4	0	Froese an	All values	4	0	4	Hislop et a	judged on	4	1	0	0	3	0	Beukhof e	Main food	4	4	0	Hislop et a	Based on	4
Microstomus kitt	Lemon sole	Fish	Celtic Sea	2	2	Expert judgement	Soft bottom	4	4	0	Beukhof et al., 2019; F		4	0	3	1	Froese an	Only value	4	4	0	Goldsmith	judged on	4	0	4	0	0	0	Beukhof et al., 2019 a		4	3	1	Froese et al., 2024		4
Buccinum undatum	Whelk	Invertebrate	Celtic Sea	3	1	Expert judgement		4	0	4	Tillin, H. M., et al. "Ch		4	1	3	0	Valentinsson D (2002		4	4	0	Expert judgement		4	1	3	0	0	0	Tillin, H. M., et al. "Ch		4	2	2	Expert judg	2/2 = no in	4
Homarus gammarus	European lobster	Invertebrate	Celtic Sea	4	0	Expert judgement	Needs rocky	4	0	4	Expert judgement		4	0	4	0	Ellis CD, Knott H, Da		4	4	0	Expert judgement		4	1	3	0	0	0	Expert judgement		4	1	3	Smith IP, Collins KJ,		4
Molva molva	Ling	Fish	Celtic Sea	0	4	Expert judgement		4	0	4	Beukhof et al., 2019		4	0	0	4	Froese an	Values fro	4	4	0	Hislop et a	judged on	4	2	1	0	1	0	Froese et	Main food	4	3	1	Hislop et a	Based on	4
Pollachius virens	Saithe(=Pollock)	Fish	Celtic Sea	0	4	Expert judgement		4	2	2	Beukhof et al., 2019; F		4	0	0	4	Beukhof e	The Beukl	4	0	4	Hislop et a	judged on	4	3	0	0	1	0	Froese et	Main food	4	2	2	Hislop et a	Based on	4
Scomber scombrus	Atlantic mackerel	Fish	Celtic Sea	0	4	Expert judgement		4	0	4	Beukhof e	It is assum	4	0	1	3	Beukhof e	The Beukl	4	0	4	Ellis & Hee	judged on	4	1	1	0	2	0	Froese et	Main food	4	2	2	Ellis & Hee	feeding du	4
Scophthalmus maximus	Turbot	Fish	Celtic Sea	2	2	Expert judgement		4	2	2	Beukhof e	Conflicting	4	0	0	4	Beukhof e	The Beukl	4	4	0	Velasco e	judged on	4	0	2	0	2	0	Beukhof e	Conflicting	4	4	0	Velasco e	Based on	4
Sepiidae, Sepiolidae	Cuttlefish, bobtail sq	Invertebrate	Celtic Sea	3	1	Expert judgement	Needs benth	4	0	4	Expert judgement		4	4	0	0	Rodrigues et al., 2011		4	4	0	Expert judgement		4	2	2	0	0	0	Expert judgement		4	1	3	Yau, 1994	dawn and	4
Solea solea	Common sole	Fish	Celtic Sea	2	2	Expert judgement	Soft bottom	4	4	0	Froese et al., 2024		4	0	3	1	Beukhof e	The Beukl	4	4	0	Froese et	"Adults oc	4	0	4	0	0	0	Froese et	Main food	4	0	4	Rijnsdorp	Based on	4
Trachurus trachurus	Atlantic horse mack	Fish	Celtic Sea	0	4	Expert judgement		4	0	4	Beukhof et al., 2019; F		4	0	1	3	Froese an	Values fro	4	0	4	Ellis 2015	judged on	4	1	2	0	1	0	Froese et	Main food	4	4	0	Ellis 2015		4
Zeus faber	John dory	Fish	Celtic Sea	0	4	Expert judgement		4	4	0	Beukhof et al., 2019		4	0	4	0	Pecuchet	The Pecu	4	4	0	Froese et	"Found in	4	4	0	0	0	0	Beukhof et al., 2019		4	2	2	Froese et	Solitary pr	4
Anguilla anguilla	European eel	Fish	Baltic Sea	4	0	Expert judgement	Obligatory hc	4	0	4	Beukhof et al., 2019; F		4	0	0	4	Froese an	Only one v	4	4	0	Walker & E	judged on	4	0	2	0	0	2	Beukhof e	Main food	4	4	0	Walker & E	based on	4
Clupea harengus	Atlantic herring	Fish	Baltic Sea	2	2	Expert judgement		4	3	1	Froese et al., 2024		4	0	4	0	Froese an	Only value	4	0	4	Dickey-Cd	judged on	4	0	0	0	3	1	Froese et	Main food	4	4	0	Dickey-Collas et al. 2		4
Coregonus albula	Vendace	Fish	Baltic Sea	0	4	Expert judgement	Only at very l	4	4	0	Froese et al., 2024		4	0	4	0	Froese an	Values fro	4	0	4	Froese et al	Feeds on	4	0	0	0	4	0	Froese et	Main food	4	2	2	Froese et	Zooplankt	4
Gadus morhua	Atlantic cod	Fish	Baltic Sea	1	3	Expert judgement	Associated	4	0	4	Beukhof et al., 2019		4	0	0	4	Beukhof e	The Beukl	4	4	0	Hislop et a	judged on	4	2	2	0	0	0	Beukhof e	Main food	4	3	1	Hislop et a	Based on	4
Perca fluviatilis	European perch	Fish	Baltic Sea	2	2	Expert judgement		4	2	2	Froese et al., 2024		4	0	3	1	Froese an	Values fro	4	4	0	Froese et	Diurnal fee	4	0	2	0	2	0	Froese et	Main food	4	4	0	Froese et	Based on	4
Platichthys spp	European flounder	Fish	Baltic Sea	2	2	Expert judgement		4	4	0	Beukhof e	Based on	4	0	0	4	Froese an	Values fro	4	4	0	Goldsmith	judged on	4	0	4	0	0	0	Beukhof e	Based on	4	4	0	Goldsmith	"They feed	4
Pleuronectes platessa	European plaice	Fish	Baltic Sea	2	2	Expert judgement		4	4	0	Beukhof et al., 2019		4	0	0	4	Beukhof e	The Beukl	4	4	0	Goldsmith	judged on	4	0	4	0	0	0	Beukhof et al., 2019 a		4	4	0	Goldsmith	Full grown	4
Sprattus sprattus	European sprat	Fish	Baltic Sea	0	4	Expert judgement		4	4	0	Beukhof et al., 2019; F		4	1	3	0	Froese an	Only value	4	0	4	Dickey-Cd	judged on	4	0	0	0	4	0	Froese et	Main food	4	4	0	Dickey-Collas et al. 2		4

			Habitat dependence/Resilience to habitat alteration					Habitat selection/spawning location							
Species	English nar	Taxa	alists_habitat	alists_habitat	e_habitat dependence	nents_habitat dependenc	habitat_dependence	c spawners	rsal spawners	ider	uarders	rous	e_habitat selection	nents_habitat selection	habitat_selection
Ammodytes spp	Sandeels(=Sandlanc	Fish	3	1	Froese at	Based on	4	0	4	0	0	0	Pecuchet	The Pecu	4
Clupea harengus	Atlantic herring	Fish	3	1	Heessen e	The deper	4	0	4	0	0	0	Froese et	No inform	4
Gadus morhua	Atlantic cod	Fish	0	4	Froese at	substrate	4	4	0	0	0	0	Pecuchet	The Pecu	4
Crangon crangon	Common shrimp	Invertebrate	0	4	Expert judgement		4	0	0	0	4	0	Expert judgement		4
Pecten maximus	Great Atlantic scallo	Invertebrate	0	4	Expert judgement		4	4	0	0	0	0	Tillin, H. M., et al. "Ch		4
Lophius piscatorius	Angler(=Monk)	Fish	0	4	Froese at	"Occurs o	4	4	0	0	0	0	Pecuchet	The Pecu	4
Nephrops norvegicus	Norway lobster	Invertebrate	4	0	Rice AL, Chapman C		4	0	0	0	4	0	Expert judgement		4
Melanogrammus aeglefi	Haddock	Fish	2	2	Froese at	"Adults ar	4	4	0	0	0	0	Pecuchet	The Pecu	4
Merlangius merlangus	Whiting	Fish	2	2	Froese at	"More co	4	4	0	0	0	0	Pecuchet	The Pecu	4
Merluccius merluccius	European hake	Fish	0	1	Froese at	Deep wate	1	4	0	0	0	0	Pecuchet	The Pecu	4
Pleuronectes platessa	European plaice	Fish	2	2	Froese at	"Adults liv	4	4	0	0	0	0	Pecuchet	The Pecu	4
Homarus gammarus	European lobster	Invertebrate	3	1	Expert judgement		4	0	0	0	4	0	Expert judgement		4
Buccinum undatum	Whelk	Invertebrate	1	3	Expert judgement		4	0	0	4	0	0	Expert judgement		4
Pollachius virens	Saithe(=Pollock)	Fish	0	4	Heessen e	"Saithe liv	4	4	0	0	0	0	Pecuchet	The Pecu	4
Scomber scombrus	Atlantic mackerel	Fish	0	4	Heessen e	"In shelf w	4	4	0	0	0	0	Froese et al., 2024		4
Scophthalmus maximus	Turbot	Fish	0	4	Froese at	"Adults liv	4	4	0	0	0	0	Pecuchet	The Pecu	4
Solea solea	Common sole	Fish	4	0	Heessen e	Sole are b	4	4	0	0	0	0	Pecuchet	The Pecu	4
Sprattus sprattus	European sprat	Fish	1	0	Froese at al.	Usually ir	1	4	0	0	0	0	Pecuchet	The Pecu	4
Pandalus borealis	Northern prawn	Invertebrate	0	4	Expert judgement		4	0	0	0	4	0	Expert judgement		4
Mytilus edulis	Blue mussel	Invertebrate	4	0	Expert judgement		4	4	0	0	0	0	Expert judgement		4
Loligo spp	Common squids nei	Invertebrate	0	4	Expert judgement		4	0	0	4	0	0	Expert judgement		4
Clupea harengus	Atlantic herring	Fish	3	1	Heessen e	The deper	4	0	4	0	0	0	Froese et	No inform	4
Gadus morhua	Atlantic cod	Fish	0	4	Froese at	"Widely dis	4	4	0	0	0	0	Pecuchet	The Pecu	4
Nephrops norvegicus	Norway lobster	Invertebrate	4	0	Rice AL, Chapman C		4	0	0	0	4	0	Expert judgement		4
Lepidorhombus whiffiag	Megrim	Fish	3	1	Froese at	"Adults oc	4	4	0	0	0	0	Pecuchet	The Pecu	4
Lophius piscatorius	Angler(=Monk)	Fish	0	4	Froese at	"Occurs o	4	4	0	0	0	0	Pecuchet	The Pecu	4
Pecten maximus	Great Atlantic scallo	Invertebrate	0	4	Expert judgement		4	4	0	0	0	0	Tillin, H. M., et al. "Ch		4
Melanogrammus aeglefi	Haddock	Fish	2	2	Froese at	"Adults ar	4	4	0	0	0	0	Pecuchet	The Pecu	4
Merlangius merlangus	Whiting	Fish	2	2	Froese at	"More co	4	4	0	0	0	0	Pecuchet	The Pecu	4
Merluccius merluccius	European hake	Fish	4	0	Froese at	Marine; de	4	4	0	0	0	0	Pecuchet	The Pecu	4
Cancer pagurus	Edible crab	Invertebrate	3	1	Expert judgement		4	0	0	0	4	0	Expert judgement		4
Micromesistius poutass	Blue whiting(=Pouta	Fish	0	4	Froese at	Marine; ba	4	4	0	0	0	0	Pecuchet	The Pecu	4
Microstomus kitt	Lemon sole	Fish	3	1	Froese at	"Lives mo	4	4	0	0	0	0	Pecuchet	The Pecu	4
Buccinum undatum	Whelk	Invertebrate	1	3	Expert judgement		4	0	0	4	0	0	Expert judgement		4
Homarus gammarus	European lobster	Invertebrate	3	1	Expert judgement		4	0	0	0	4	0	Expert judgement		4
Molva molva	Ling	Fish	3	1	Froese at	"Occurs m	4	4	0	0	0	0	Pecuchet	The Pecu	4
Pollachius virens	Saithe(=Pollock)	Fish	0	4	Heessen e	"Saithe liv	4	4	0	0	0	0	Pecuchet	The Pecu	4
Scomber scombrus	Atlantic mackerel	Fish	0	4	Heessen e	"In shelf w	4	4	0	0	0	0	Froese et al., 2024		4
Scophthalmus maximus	Turbot	Fish	0	4	Froese at	"Adults liv	4	4	0	0	0	0	Pecuchet	The Pecu	4
Sepiidae, Sepiolidae	Cuttlefish, bobtail sq	Invertebrate	0	4	Expert judgement		4	0	0	4	0	0	Expert judgement		4
Solea solea	Common sole	Fish	4	0	Heessen e	Sole are b	4	4	0	0	0	0	Pecuchet	The Pecu	4
Trachurus trachurus	Atlantic horse mack	Fish	0	4	Heessen e	"The wide	4	4	0	0	0	0	Pecuchet	The Pecu	4
Zeus faber	John dory	Fish	0	4	Froese at	Marine; br	4	4	0	0	0	0	Pecuchet	The Pecu	4
Anguilla anguilla	European eel	Fish	0	4	Froese at	"Inhabits a	4	4	0	0	0	0	Pecuchet	The Pecu	4
Clupea harengus	Atlantic herring	Fish	3	1	Heessen e	The deper	4	0	4	0	0	0	Froese et	No inform	4
Coregonus albula	Vendace	Fish	3	1	Froese at	Open wate	4	0	4	0	0	0	Froese et	No inform	4
Gadus morhua	Atlantic cod	Fish	0	4	Froese at	"Widely dis	4	4	0	0	0	0	Pecuchet	The Pecu	4
Perca fluviatilis	European perch	Fish	0	4	Froese at	"Inhabits a	4	0	4	0	0	0	Pecuchet	The Pecu	4
Platichthys spp	European flounder	Fish	2	2	Froese at	Based on	4	4	0	0	0	0	Pecuchet	The value	4
Pleuronectes platessa	European plaice	Fish	2	2	Froese at	"Adults liv	4	4	0	0	0	0	Pecuchet	The Pecu	4
Sprattus sprattus	European sprat	Fish	0	4	Froese at	Marine; br	4	4	0	0	0	0	Pecuchet	The Pecu	4

	Migration behavior (or migrating pattern)						Oxygen tolerance					Salinity tolerance				
Species	nal migration	age migration	gration	e_migration	nents_migration	migration	ia-sensitive	ia-tolerant	e_oxygen tolerance	nents_oxygen tolerance	oxygen	tolerance	tolerance	e_salinity tolerance	nents_salinity tolerance	salinity
Ammodytes spp	2	0	2	Expert opinion Thüne		4	4	0	Kaschner,	Based on	4	4	0	Kaschner,	Based on	4
Clupea harengus	2	2	0	Froese et	Herring sc	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Gadus morhua	4	0	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Crangon crangon	2	2	0	Expert judgement		4	0	4	Expert judgement		4	4	0	Expert judgement		4
Pecten maximus	0	0	4	Tillin, H. M., et al. "Ch		4	3	1	Artigaud, Sébastien, e		4	0	4	Johnson MP, Lordan		4
Lophius piscatorius	1	0	3	Heessen e	Informatio	4	0	4	Kaschner, K., Kesner-		4	0	4	Kaschner, K., Kesner-		4
Nephrops norvegicus	0	0	4	Tillin, H. M., et al. "Ch		4	1	3	Baden, Susanne P., L		4	0	4	Expert judgement		4
Melanogrammus aeglefi	4	0	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Merlangius merlangus	0	4	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Merluccius merluccius	0	1	3	Heessen e	Informatio	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Pleuronectes platessa	1	3	0	Froese et	Based on	4	4	0	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Homarus gammarus	0	1	3	Smith I, Jensen A, Co		4	0	4	Zheng C, Zhao Q, Li B		4	0	4	Expert judgement		4
Buccinum undatum	0	0	4	Tillin, H. M., et al. "Ch		4	2	2	Expert judg	2/2 becau	4	0	4	Expert judgement		4
Pollachius virens	4	0	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	0	4	Kaschner, K., Kesner-		4
Scomber scombrus	4	0	0	Froese et	Annual sp	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Scophthalmus maximus	0	4	0	Heessen e	Informatio	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Solea solea	0	4	0	Froese et	Based on	4	2	2	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Sprattus sprattus	4	0	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Pandalus borealis	2	2	0	Expert judgement		4	0	4	Pillet, Marion, et al. "E		4	0	4	Allen, J. A. "On the bi		4
Mytilus edulis	0	0	4	Expert judgement		4	1	3	Artigaud, Sébastien, e		4	4	0	Expert judgement		4
Loligo spp	1	3	0	Expert judgement		4	0	4	Pörtner, Hans-Otto, a		4	4	0	Pörtner, Hans-Otto, a		4
Clupea harengus	2	2	0	Froese et	Herring sc	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Gadus morhua	4	0	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Nephrops norvegicus	0	0	4	Tillin, H. M., et al. "Ch		4	1	3	Baden, Susanne P., L		4	0	4	Expert judgement		4
Lepidorhombus whiffiag	0	0	4	Froes et a	Poor data	4	4	0	Kaschner, K., Kesner-		4	0	4	Kaschner, K., Kesner-		4
Lophius piscatorius	4	0	0	Heessen e	Informatio	4	0	4	Kaschner, K., Kesner-		4	0	4	Kaschner, K., Kesner-		4
Pecten maximus	0	0	4	Tillin, H. M., et al. "Ch		4	3	1	Artigaud, Sébastien, e		4	0	4	Expert judgement		4
Melanogrammus aeglefi	4	0	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Merlangius merlangus	0	4	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Merluccius merluccius	0	1	3	Heessen e	Informatio	4	0	4	Kaschner, K., Kesner-		4	0	4	Kaschner, K., Kesner-		4
Cancer pagurus	1	3	0	Nichols et al., 1982		4	0	4	Bradford, S. M., and A		4	3	1	Wanson et al., 1983		4
Micromesistius poutass	0	0	4	Froese et	Informatio	4	2	2	Expert judgement		4	0	4	Kaschner, K., Kesner-		4
Microstomus kitt	0	0	4	Jennings, S., et al. (19		4	4	0	Kaschner, K., Kesner-		4	0	4	Kaschner, K., Kesner-		4
Buccinum undatum	0	0	4	Tillin, H. M., et al. "Ch		4	2	2	Expert judgement		4	0	4	Expert judgement		4
Homarus gammarus	0	1	3	Smith I, Jensen A, Co		4	0	4	Zheng C, Zhao Q, Li B		4	0	4	Expert judgement		4
Molva molva	0	4	0	Heessen e	Informatio	4	4	0	Kaschner, K., Kesner-		4	0	4	Kaschner, K., Kesner-		4
Pollachius virens	4	0	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	1	3	Kaschner, K., Kesner-		4
Scomber scombrus	4	0	0	Froese et	Annual spa	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Scophthalmus maximus	0	4	0	Heessen e	Informatio	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Sepiidae, Sepiolidae	3	1	0	Jones and Richardso		4	0	4	Expert judgement		4	0	4	Guerra, 1992; Rodrigu		4
Solea solea	0	4	0	Froese et	Based on	4	2	2	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Trachurus trachurus	4	0	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	0	4	Kaschner, K., Kesner-		4
Zeus faber	4	0	0	Maravelias, 2007 "Se		4	0	4	Kaschner, K., Kesner-		4	0	4	Kaschner, K., Kesner-		4
Anguilla anguilla	0	4	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Clupea harengus	2	2	0	Froese et	Herring sc	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Coregonus albula	4	0	0	Froese et	Anadromo	4	4	0	Kaschner, K., Kesner-		4	0	4	Kaschner, K., Kesner-		4
Gadus morhua	4	0	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Perca fluviatilis	0	0	4	Froese et	Based on	4	0	4	Froese et al.	Appears t	4	4	0	Froese et al.	Freshwate	4
Platichthys spp	0	4	0	Froese et	Based on	4	0	4	Based on Platichthys		4	4	0	Kaschner,	Based on	4
Pleuronectes platessa	1	3	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4
Sprattus sprattus	4	0	0	Froese et	Based on	4	0	4	Kaschner, K., Kesner-		4	4	0	Kaschner, K., Kesner-		4

	Sensory adaptations								Trophic level						Thermal tolerance					
Species		and taste	line	c and magnetic	g	Source_sensory adaptation	nents_sensory adaptatio	sensory	y consumer	datry consumer	predator	e_trophic level	nents_trophic level	tl	thermal tolerance	m_thermal tolerance	_thermal tolerance	e_thermal tolerance	nents_thermal tolerance	thermal
Ammodytes spp	3	0	0	0	1	Expert judgment		4	0	4	0	Froese et	3.3	4	0	0	4	Kaschner,	Prefered t	4
Clupea harengus	2	0	0	0	2	Expert judgment		4	0	4	0	Froese et	3.4	4	0	4	0	Kaschner, K., Kesner		4
Gadus morhua	1	1	1	0	1	Expert judgment		4	0	4	0	Froese et	4.1	4	0	4	0	Kaschner, K., Kesner		4
Crangon crangon	2	2	0	0	0	Expert judgment		4	0	4	0	Expert judgement		4	0	4	0	Kaschner, K., Kesner		4
Pecten maximus	2	0	2	0	0	Expert judgment	non selec	4	4	0	0	Tillin, H. M., et al. "Ch		4	0	4	0	Kaschner, K., Kesner		4
Lophius piscatorius	2	0	2	0	0	Expert judgment	Lures prey	4	0	0	4	Froese et	TL=4.5 ba	4	0	4	0	Kaschner, K., Kesner		4
Nephrops norvegicus	2	2	0	0	0	Expert judgment		4	0	4	0	Expert judgement		4	0	4	0	Kaschner, K., Kesner		4
Melanogrammus aeglefi	2	0	0	0	2	Expert judgment		4	0	4	0	Froese et	4	4	0	4	0	Kaschner, K., Kesner		4
Merlangius merlangus	4	0	0	0	0	Expert judgment		4	0	4	0	Froese et	4.4	4	4	0	0	Kaschner, K., Kesner		4
Merluccius merluccius	4	0	0	0	0	Expert judgment		4	0	4	0	Froese et	4.4	4	4	0	0	Kaschner, K., Kesner		4
Pleuronectes platessa	2	0	1	0	1	Expert judgment		4	0	4	0	Froese et	3.2	4	0	0	4	Kaschner, K., Kesner		4
Homarus gammarus	0	2	0	0	2	Expert judgment		4	0	4	0	Expert judgement		4	0	4	0	Kaschner, K., Kesner		4
Buccinum undatum	0	4	0	0	0	Expert judgment		4	0	4	0	Expert judgement		4	0	4	0	Kaschner, K., Kesner		4
Pollachius virens	2	0	0	0	2	Expert judgment		4	0	4	0	Froese et	4.3	4	0	4	0	Kaschner, K., Kesner		4
Scomber scombrus	3	0	1	0	0	Expert judgment		4	0	4	0	Froese et	3.6	4	4	0	0	Kaschner, K., Kesner		4
Scophthalmus maximus	2	0	1	0	1	Expert judgment		4	0	0	4	Froese et	TL=4.4, b	4	0	4	0	Kaschner, K., Kesner		4
Solea solea	2	0	1	0	1	Expert judgment		4	0	4	0	Froese et	3.2	4	0	4	0	Kaschner, K., Kesner		4
Sprattus sprattus	3	0	0	0	1	Expert judgment		4	0	4	0	Froese et	3	4	4	0	0	Kaschner, K., Kesner		4
Pandalus borealis	2	2	0	0	0	Expert judgment		4	0	4	0	Expert judgement		4	4	0	0	Kaschner, K., Kesner		4
Mytilus edulis	0	0	4	0	0	Expert judgment	non selecti	4	4	0	0	Expert judgement		4	4	0	0	Kaschner, K., Kesner		4
Loligo spp	2	1	0	0	1	Expert judgment		4	0	4	0	Expert judgement		4	4	0	0	Kaschner,	Prefered t	4
Clupea harengus	2	0	0	0	2	Expert judgment		4	0	4	0	Froese et	3.4	4	0	4	0	Kaschner, K., Kesner		4
Gadus morhua	1	1	1	0	1	Expert judgment		4	0	4	0	Froese et	4.1	4	0	4	0	Kaschner, K., Kesner		4
Nephrops norvegicus	2	2	0	0	0	Expert judgment		4	0	4	0	Expert judgement		4	0	4	0	Kaschner, K., Kesner		4
Lepidorhombus whiffiag	2	0	1	0	1	Expert judgment		4	0	4	0	Froese et	4.3	4	0	4	0	Kaschner, K., Kesner		4
Lophius piscatorius	2	0	2	0	0	Expert judgment		4	0	0	4	Froese et	TL=4.5, ba	4	0	4	0	Kaschner, K., Kesner		4
Pecten maximus	2	0	2	0	0	Expert judgment	non selecti	4	4	0	0	Tillin, H. M., et al. "Ch		4	0	4	0	Kaschner, K., Kesner		4
Melanogrammus aeglefi	2	0	0	0	2	Expert judgment		4	0	4	0	Froese et	4	4	0	4	0	Kaschner, K., Kesner		4
Merlangius merlangus	4	0	0	0	0	Expert judgment		4	0	4	0	Froese et	4.4	4	4	0	0	Kaschner, K., Kesner		4
Merluccius merluccius	4	0	0	0	0	Expert judgment		4	0	4	0	Froese et	4.4	4	4	0	0	Kaschner, K., Kesner		4
Cancer pagurus	0	2	0	0	2	Expert judgment		4	0	4	0	Expert judgement		4	0	0	4	Kaschner, K., Kesner		4
Micromesistius poutass	2	1	1	0	0	Expert judgment		4	0	4	0	Froese et	4.1	4	4	0	0	Kaschner, K., Kesner		4
Microstomus kitt	2	0	1	0	1	Expert judgment		4	0	4	0	Froese et	3.2	4	0	0	4	Kaschner, K., Kesner		4
Buccinum undatum	0	4	0	0	0	Expert judgment		4	0	4	0	Expert judgement		4	0	4	0	Kaschner, K., Kesner		4
Homarus gammarus	0	2	0	0	2	Expert judgment		4	0	4	0	Expert judgement		4	0	4	0	Kaschner, K., Kesner		4
Molva molva	2	0	1	0	1	Expert judgment		4	0	4	0	Froese et	4.4	4	0	0	4	Kaschner, K., Kesner		4
Pollachius virens	2	0	0	0	2	Expert judgment		4	0	4	0	Froese et	4.3	4	0	4	0	Kaschner, K., Kesner		4
Scomber scombrus	4	0	0	0	0	Expert judgment		4	0	4	0	Froese et	3.6	4	4	0	0	Kaschner, K., Kesner		4
Scophthalmus maximus	2	0	1	0	1	Expert judgment		4	0	0	4	Froese et	TL=4.4, b	4	0	4	0	Kaschner, K., Kesner		4
Sepiidae, Sepiolidae	2	1	0	0	1	Expert judgment		4	0	4	0	Expert judgement		4	4	0	0	Kaschner,	Prefered t	4
Solea solea	2	0	1	0	1	Expert judgment		4	0	4	0	Froese et	3.2	4	0	4	0	Kaschner, K., Kesner		4
Trachurus trachurus	3	0	1	0	0	Expert judgment		4	0	4	0	Froese et	3.7	4	0	4	0	Kaschner, K., Kesner		4
Zeus faber	4	0	0	0	0	Expert judgment		4	0	0	4	Froese et	TL=4.5, ba	4	4	0	0	Kaschner, K., Kesner		4
Anguilla anguilla	2	2	0	0	0	Expert judgment		4	0	4	0	Froese et	3.6	4	4	0	0	Kaschner, K., Kesner		4
Clupea harengus	2	0	0	0	2	Expert judgment		4	0	4	0	Froese et	3.4	4	0	4	0	Kaschner, K., Kesner		4
Coregonus albula	3	0	0	0	1	Expert judgment		4	0	4	0	Froese et	3.1	4	0	0	4	Kaschner, K., Kesner		4
Gadus morhua	1	1	1	0	1	Expert judgment		4	0	4	0	Froese et	4.1	4	0	4	0	Kaschner, K., Kesner		4
Perca fluviatilis	3	1	0	0	0	Expert judgment		4	0	4	0	Froese et	4.4	4	0	4	0	Kaschner, K., Kesner		4
Platichthys spp	2	0	1	0	1	Expert judgment		4	0	4	0	Froese et	TL 3.3, bas	4	0	4	0	Kaschner,	Prefered t	4
Pleuronectes platessa	2	0	1	0	1	Expert judgment		4	0	4	0	Froese et	3.2	4	0	0	4	Kaschner, K., Kesner		4
Sprattus sprattus	3	0	0	0	1	Expert judgment		4	0	4	0	Froese et	3	4	4	0	0	Kaschner, K., Kesner		4

Annex 7: Summary of key evidence from list of references

The list of references (Annex 7) provides the evidence to support the trait-based analysis in ToR aii (section 3.2). Annex 7 builds on a literature list compiled as part of a systematic review study by Gill et al. (2024), which established a knowledge base for assessing the effects of offshore wind farms on commercial fisheries populations and stocks. Since the scope of ToR aii was broader than that of the Gill et al. (2024) study, a supplementary literature search was conducted using broader search terms in relation to the potential effects of offshore wind on fisheries species. The Working Group on Offshore Wind Developments and Fisheries (WGOWDF) used Web of Science, Google Scholar and the Tethys renewable energy database to identify potentially relevant sources. These were then reviewed and compiled, and the relevant evidence was extracted to support ToR aii. This extracted list of references was categorised using an adapted DPSIR (Driver-Pressure-State-Impact-Response) framework (Oesterwind et al., 2016) from the perspective of the fisheries resources. In this context, a *driver* is defined as a societal need, with key drivers being the demand for food (fisheries) and the need for renewable energy. *Pressures* (e.g., electromagnetic fields) are attributes that alter the natural environment and were specified based on Table 3.1 in the general introduction of ToR a. *State* (e.g., prey availability) refers to the condition of an ecosystem component, either biotic or abiotic, while *impacts* (e.g., changes in fish abundance) represent the effects of a state change resulting from a pressure. The tabulated list of literature highlights the sources and the relevant evidence and each source is assigned either a pressure or state or impact category or multiple where there is more than one piece of evidence. Below the table, the full list of references is provided.

Oesterwind, D., Rau, A., Zaiko, A. (2016). Drivers and pressures – Untangling the terms commonly used in marine science and policy. Journal of Environmental Management. Volume 181, pp. 8-15. https://doi.org/10.1016/j.jenvman.2016.05.058.

Gill, A.B., Bremner, J., Vanstaen, K., Blake, S., Mynott, F. and Lincoln, S. (2025), Limited Evidence Base for Determining Impacts (Or Not) of Offshore Wind Energy Developments on Commercial Fisheries Species. Fish Fish, 26: 155-170. https://doi.org/10.1111/faf.12871

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
PRESSURES				
Abrasion of sediment by seabed disturbance				
Welzel, M.; Schendel, A.; Schlurmann, T.; et al.	Volume-Based Assessment of Erosion Patterns around a Hydrodynamic Transparent Offshore Structure	2019	This study examines erosion patterns around a hydrodynamic transparent (jacket) offshore foundation under combined waves and currents. Empirical formulas quantify scour depth and sediment loss, with findings aligning well with field data. Erosion intensity peaked at 1.25 times the structure's footprint, with a total scour extent of 2.1–2.8 times, defining the environmental impact of the structure on marine habitats.	Abrasion of sediment by seabed disturbance
Change in sediment composition				
Braeckman, U.; Lefaible, N.; Brunis, E.; and Moens, T.	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Empirical Evidence Inspiring Priority Monitoring, Research and Management	2020	Ch 6: a three year study in the North Sea indicated a trend for sediments to become finer and organically enriched 'very close' to jacket foundations, with concomitant effects on the abundance, diversity and species composition of macrofauna.	Change in sediment composition, STATE CHANGE
Jammar, C.; Reynes-Cardona, A.; Vanaverbeke, J.; Lefaible, N.; Moens, T.; Braeckman, U.	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Progressive Insights in Changing Species Distribution Patterns Informing Marine Management	2024	Ch 2: inside 2 offshore wind farms in the North Sea higher macrobenthos abundance, species richness and diversity were recorded in sediments with small grain size and higher total organic matter content. Although sea surface temperature and Atlantic Multidecadal Oscillation index (SST and AMO) were significant predictors of macrobenthic diversity, abundance, and species richness no clear patterns could be identified. It remains important to incorporate local environmental variability along with climate predictors such as SST and AMO.	Change in sediment composition, STATE CHANGE
Nene, L; Ulrike, B; Tom, M	Effects of Wind Turbine Foundations on Surrounding Macrobenthic Communities	2018	Within very close samples, fining and enrichment of the sediment was detected together with higher macrofaunal densities, diversity and shifts in communities. In contrast, effects around monopile-based foundations were less pronounced and a significant difference in community composition only was found between both distances.	Change in sediment composition, STATE CHANGE
Reubens, J; Alsebai, M; Moens, T	Expansion of small scale changes in macrobenthic community inside an offshore windfarm	2016	No significant differences in abiotic factors were observed between the two distances. All samples were characterized by coarse sediments, with a low mud and total organic matter content. Macrobenthic densities on the other hand differed significantly between the two distances. Densities and number of species were higher for the far samples compared to the close samples. The latter were dominated by Urothoe brevicornis and Gastrosaccus spinifer, while Bathyporeia elegans and Spiophanes	Change in sediment composition, STATE CHANGE

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
			bombyx were more important in far samples.	
Reubens, J; Eede, SV; Vincx, M	Monitoring of the effects of offshore wind farms on the endobenthos of soft substrates: Year-0 Bligh Bank and Year-1 Thorntonbank	2009	Sediment characteristics at Thorntonbank and Goote Bank remain consistent with 2005, with medium sand, low mud, and organic content. Macrobenthos densities and biomass vary, but species richness is low, dominated by Nephtys cirrosa and Spiophanes bombyx. Community composition shifted between 2005 and 2008, but no significant differences were found within each year. A transition from the N. cirrosa to the O. limacina – G. lapidum community was observed. The impact of the first six windmills on endobenthos was minimal or undetectable in the first year, with natural variations playing a larger role. Future monitoring should adjust sampling locations to better assess effects near the windmills.	Change in sediment composition, STATE CHANGE
Wilding, T.	Effects of Man-Made Structures on Sedimentary Oxygenation: Extent, Seasonality and Implications for Offshore Renewables	2014	Artificial structures, including MREDs, may cause quite major sedimentary changes but this evidence suggests that these effects will be of limited spatial scale and, where phytodetrital accumulations occur, are only likely to be detrimental in oxygen-deficient sediments	Change in sediment composition
Hydrological changes				
Ajmi, S.; Boutet, M.; Bennis, A.; et al.	Numerical Study of Turbulent Wake of Offshore Wind Turbines and Retention Time of Larval Dispersion	2023	Predicted OWFs impacts of foundation type, flow velocity, flow direction, and release type on larval dispersion.	Change in water current
Broström, G	On the influence of large wind farms on the upper ocean circulation	2008	Modelling showed large wind farms exert a significant disturbance on the wind speed in the vicinity of the installation. The size of the wind wake is an important factor and the predicted upwelling is sufficient to affect the local ecosystem.	Change in water current, Change in stratification

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Burchard, H.; Hüttmann, F.; Janssen, F.; et al.	Effects of Wind Farm Foundations on the Water Exchange between North Sea and Baltic Sea - A First Careful Assessment Derived from the QuantAS-Off Project	2008	Baltic Sea inflow events are more complex and variable than previously thought. Local simulations used to quanitfy mixing because of turbines. Indicates that wind farms, depending on location, can influence the exchange between North Sea and Baltic Sea but too complicated to provide estimates.	Change in water current, Change in stratification
Cazenave, P.; Torres, R.; Allen, J.	Unstructured Grid Modelling of Offshore Wind Farm Impacts on Seasonally Stratified Shelf Seas	2016	Monopiles locally increase turbulence, but the effects dissipate rapidly and remain near-field. Velocity reductions occur in wakes, with increases around monopile sides. On a larger scale, the dynamic shelf sea adjusts within tens of kilometers, showing little to no impact on overall circulation.	Change in water current, Change in stratification
Chen, Changsheng; Zhao, Liuzhi; Lin, Huichan; He, Pingguo; Li, Siqi; Wu, Zhongxiang; Qi, Jianhua; Xu, Qichun; Stokesbury, Kevin; Wang, Lu;	Potential impacts of offshore wind energy development on physical processes and scallop larval dispersal over the US Northeast shelf	2024	Tidal currents interacting with monopiles create complex horizontal flow shear patterns. Stratification influences flow around wind turbines, with mixing effects mostly confined to the wind farm area. Monopile-fluid interactions intensify offshore subtidal flows, forming mesoscale eddies that transport scallop larvae offshore, where eddies enhance larval retention.	Change in water current, Change in stratification
Christiansen, M.; Hasager, C.	Wake Effects of Large Offshore Wind Farms Identified from Satellite SAR	2005	Wind speed decreases by 8–9% immediately downstream of wind turbine arrays, with recovery to within 2% of the free stream velocity over 5–20 km, depending on factors like wind speed and atmospheric conditions.	Change in water current
Floeter, J; van Beusekom, JEE; Auch, D; Callies, U; Carpenter, J; Dudeck, T; Eberle, S; Eckhardt, A; Gloe, D; Hänselmann, K; Hufnagl, M; Janssen, S; Lenhart, H; Möller, KO; North, RP; Pohlmann, T; Riethmüller, R; Schulz, S; Spreizenbarth, S; Temming, A; Walter, B; Zielinski, O; Möllmann, C	Pelagic effects of offshore wind farm foundations in the stratified North Sea	2017	The survey provides empirical indication that an OWF with 80 foundations decreases the local summer water column stratification. This effect may also extend into its surrounding area by approximately half the diameter of an ambient tidal excursion. Furthermore, there are indications that an OWF in a tidally affected stratified sea creates a stirring effect, with local upwelling cells at its sides	Change in water current, Change in stratification

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Integral Consulting Inc	An Assessment of the Cumulative Impacts of Floating Offshore Wind Farms	2021	Changes in wind stress were found to be largest inside the wind farm call areas, though wake effects seemed to persist in the lee of the wind farms. Changes in ocean circulation were described via changes in sea surface temperature and the underlying density structure. A 10-15% change was inferred in upwelled volume transport and resulting nutrient flux to the euphotic zone. The impact of these changes on the phytoplankton productivity, while expected to be present, is currently unknown and beyond the scope of this study.	Change in water current, Change in stratification
Miles, J.; Martin, T.; Goddard, L.	Current and Wave Effects around Windfarm Monopile Foundations	2017	The mean water flow reduces downstream of the pile, but returned to background levels by 8.3 (pile diameters) D downstream of the pile. Turbulence peaked at 1.5 D from the pile centre, and subsequently decayed. Velocity magnitudes at the side of the pile were up to 1.35 times greater than background flow rates. Wave velocities reduced immediately down-wave of the pile, but returned quickly to background levels (by 1.65 to 3.5 D of the pile centre). Wave velocities at the side of the pile increased up to 1.66 times the background level.	Change in water current
O'Dor, RK; Adamo, S; Aitken, JP; Andrade, Y; Finn, J; Hanlon, RT; Jackson, GD;	Currents as environmental constraints on the behavior, energetics and distribution of squid and cuttlefish	2002	Distinctive activity patterns indicated that tidal currents were key environmental influences, as important as temperature, diel cycles and foraging. Cuttlefish were diurnal, relatively inactive and spent their time within benthic boundary layers, hovering near or under structures. Squid, in contrast, were continuously active, seeking out particular current regimes to conserve energy using slope soaring tactics previously seen in Loligo forbesi. In the high current GBR site, squid concentrated in the boundary layers of floating 'squid aggregating devices' (SADs).	Change in water current
Raghukumar, K.; Nelson, T.; Jacox, M.; et al.	Projected cross-shore changes in upwelling induced by offshore wind farm development along the California coast	2023	The introduction of wind turbines primarily affects wind stress curl-driven upwelling, with little change observed in coastal upwelling. When cast in terms of metrics for upwelling strength and nutrient flux to the euphotic zone, a decrease in upwelling was seen on the nearshore side of the simulated wind farm, which was mostly offset by increases in upwelling on the offshore side of the wind farm. A pronounced cross-shore structure in changes to upwelling was observed, in excess of natural variability, while integrated changes indicated more modest changes in total upwelling. The consequences of these changes in physical upwelling structure on the ecosystem are currently unknown and could potentially form future areas of investigation that could also include an assessment of fisheries and socio-economic effects	Change in water current, Change in stratification

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Schultze, L.; Merckelbach, L.; Horstmann, J.; Raasch, S.; Carpenter, J.	Increased Mixing and Turbulence in the Wake of Offshore Wind Farm Foundations	2020	The loss of stratification within the wake of a single OWF structure was observed for the first time in the field, which enabled a qualitative characterisation of the disturbed flow downstream. The turbulent wake of a structure is narrow and highly energetic within the first 100 m, with the dissipation of turbulent kinetic energy well above background levels downstream of the structure.	Change in water current, Change in stratification
Schultze, V.	Natural variability of turbulence and stratification in a tidal shelf sea and the possible impact of offshore wind farms	2018	Shallow shelf seas strongly influenced by tidal motion, impact the additional turbulence generated by offshore wind farms should be further investigated. The additional forcing being supplied to the water column and, more specifically, to the thermocline by turbine foundations could locally drive turbulence to levels significantly above those observed in a natural environment. This enhanced mixing could lead to higher scalar fluxes across stratification, possibly affecting its stability and leading to the erosion of the thermocline in the vicinity of the turbine foundations, which could have further reaching implications on biological productivity.	Change in water current, Change in stratification
Siedersleben, S.	Numerical Analysis of Offshore Wind Farm Wakes and their Impact on the Marine Boundary Layer	2019	The wakes of large offshore wind farms clusters are longer than 100 km associated with changes in the sensible and latent heat flux. The net impact depends on the inversion height and the temperature gradient between sea surface temperature and air temperature.	Change in water current; Change in stratification
Electromagnetic fields				
Albert, L.; Maire, O.; Olivier, F.; et al.	Can artificial magnetic fields alter the functional role of the blue mussel, Mytilus edulis?	2022	Experimental evidence that artificial magnetic fields do not significantly impair the feeding behaviour of blue mussels at the intensities explored.	Electromagnetic fields
Gill, A.; Huang, Y.; Gloyne-Philips, I.; et al.	COWRIE 2.0 Electromagnetic Fields (EMF) Phase 2: EMF Sensitive Fish Response to EM Emissions from Sub-sea Electricity Cables of the Type used by the Offshore Renewable Energy Industry	2009	Study provides evidence that benthic elasmobranch species can respond to the presence of EMF that is of the type and intensity associated with sub-sea cables. The response is not predictable and appears to be species specific and perhaps individual specific, meaning that some species and their individuals are more likely to respond by focussing movement within the zone of EMF.	Electromagnetic fields

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Gill, Andrew B; Taylor, H.	The Potential Effects of Electromagnetic Fields Generated by Cabling Between Offshore Wind Turbines Upon Elasmobranch Fishes: Research Project for Countryside Council for Wales	2001	Study demonstrated a differential effect on behavioural response of dogfish to simulated electric fields emitted by prey and those from undersea power cables. The benthic shark, S. canicula, avoids electric fields of the maximum predicted to be emitted from undersea cables. The avoidance response was highly variable amongst individuals and had a relatively low probability of occurring in the conditions presented in these experiments. The same species individuals were attracted to current levels consistent with the predicted bioelectric field emitted by prey species.	Electromagnetic fields
Harsanyi, Petra; Scott, Kevin; Easton, Blair AA; de la Cruz Ortiz, Guadalupe; Chapman, Erica CN; Piper, Althea JR; Rochas, Corentine MV; Lyndon, Alastair R	The Effects of Anthropogenic Electromagnetic Fields (EMF) on the Early Development of Two Commercially Important Crustaceans, European Lobster, Homarus gammarus (L.) and Edible Crab, Cancer pagurus (L.)	2022	Studied effects of EMF associated with OWF on early development stages of lobster and crab species. Provides evidence of biological effects of subsea cables on early life history of these species.	Electromagnetic fields
Hutchison, Z.; Sigray, P.; Gill, A.; et al.	Electromagnetic Field Impacts on American Eel Movement and Migration from Direct Current Cables	2021	Eels did respond to EMF; they moved faster and more purposefully	Electromagnetic fields
Jakubowska, Magdalena; Greszkiewicz, Martyna; Fey, Dariusz P.; Otremba, Zbigniew; Urban-Malinga, Barbara; Andrulewicz, Eugeniusz	Effects of magnetic fields related to submarine power cables on the behaviour of larval rainbow trout (Oncorhynchus mykiss)	2021	Early life stages of rainbow trout can detect and are attracted to artificial magnetic fields of a magnitude recorded in the vicinity of submarine cables, with no visible signs of stress (i.e. increased oxygen consumption).	Electromagnetic fields
Livermore, J; Truesdale, C; Ransier, K; McManus, MC;	Small effect sizes are achievable in offshore wind monitoring surveys	2023	Authors present a design of BAG experiments to detect and assess the impacts of offshore wind cable installation on American lobster. This design assures that a 10% change in catch after the implementation of offshore cables will be detectible at a 0.05 significance level.	Electromagnetic fields
McIntyre, A.; Janeski, T.; Garman, G.; et al.	Behavioral responses of subadult Atlantic Sturgeon (Acipenser oxyrinchus oxyrinchus) to electromagnetic and magnetic fields under laboratory conditions	2016	This study assessed the effects of M/EM fields from submarine HV cables on Atlantic Sturgeon behavior. The results indicate that exposure to these fields did not cause biologically significant changes in simple behaviors of sub-adult sturgeon. Their findings do not support the hypothesis that such fields negatively impact migrating or foraging wild Atlantic Sturgeon.	Electromagnetic fields

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Scott, K; Harsanyi, P; Easton, BAA; Piper, AJR; Rochas, CMV; Lyndon, AR	Exposure to Electromagnetic Fields (EMF) from Submarine Power Cables Can Trigger Strength-Dependent Behavioural and Physiological Responses in Edible Crab, Cancer pagurus (L.)	2021	EMF strengths of 250 μT were found to have limited physiological and behavioural impacts. Exposure to 500 μT and 1000 μT were found to disrupt the L-Lactate and D-Glucose circadian rhythm and alter THC. Crabs showed a clear attraction to EMF exposed (500 μT and 1000 μT) shelters with a significant reduction in time spent roaming. Consequently, EMF emitted from MREDs will likely affect crabs in a strength-dependent manner thus highlighting the need for reliable in-situ measurements.	Electromagnetic fields
Taormina, B.; Quillienn, N.; Lejart, M.; et al.	Characterisation of the Potential Impacts of Subsea Power Cables Associated with Offshore Renewable Energy Projects	2021	Subsea power cables generate electromagnetic frequencies (EMFs) that can influence marine organisms, potentially affecting species behavior and distribution. The operation of these cables can lead to localized temperature increases in the surrounding sediment, which may impact benthic communities. The installation and presence of subsea cables can modify the physical structure of the seabed, creating new habitats that may attract certain species. The report identifies significant knowledge gaps regarding the long-term ecological impacts of subsea power cables and recommends further research to assess their effects on marine ecosystems.	Electromagnetic fields
Introduction of artificial hard substrate				
Adgé, M; Lobry, J; Tessier, A; Planes, S	Modeling the impact of floating offshore wind turbines on marine food webs in the Gulf of Lion, France	2024	Trophic model proposing biomass and ecological indicators within floating offshore wind turbines.	Introduction of artificial hard substrate
Andersson, Mathias H; Öhman, Marcus C;	Fish and sessile assemblages associated with wind-turbine constructions in the Baltic Sea	2010	Fish and sessile communities were examined for vertical zonation. Common sessile organisms from the surface down to 3 m were filamentous green algae Cladophora sp., the red alga Ceramium tenuicorne and the barnacle Balanus improvisus. Further down (3–8 m), the blue mussel together with two species of red algae, Polysiphonia fucoides and Rhodochorton purpureum, dominated. The marine hydroid Laomedea loveni occurred in small numbers. Multivariate analysis revealed no significant difference between the assemblages. The sessile fauna on the foundation differed from that on the seabed transects. Beneath the foundation, a dense coverage of blue mussels was found as well as small turfs of red algae (P. fucoides, R. purpureum and Rhodomela confervoides); the opposite pattern occurred at 20-m	Introduction of artificial hard substrate, IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Bech, M; Frederiksen, R; Pedersen, J; Leonhard, SB	Infauna monitoring Horns Rev offshore wind farm. Annual status report 2004	2005	The commercially important bivalve Spisula solida constituted most of the biomass in 2001, about 30% in 2003 but only 3.3% in 2004. Recruitment of S. solida is often very irregular and this species has a preference to sediments of grain size 200-300 µm which might explain the decline in abundance. There was no significant difference in benthos community structure related to the distance from the wind turbine foundations in 2003 or in 2004. The main difference between the survey in 2001 and 2004 was the decline of the Pisione remota and Goniadella bobretzkii populations and the massive increase of the Goodallia triangularis population.	Introduction of artificial hard substrate
Bergman, M; Duineveld, G; Hof, P Van'T; ...	Impact of OWEZ wind farm on bivalve recruitment	2010	The possible impact of offshore wind on the macrobenthos community and recruitment of bivalves was explored. No differences were found between the densities of small-sized bivalve recruits in the wind farm and five reference areas. For the larger (older) recruits differences in densities were found only between reference areas. Of the larger recruits only Ensis spp. showed a significant difference in density between some survey areas.	Introduction of artificial hard substrate, STATE CHANGE
Bergman, Magda J. N. Ubels, Selma M. Duineveld, Gerard C. A. Meesters, Erik W. G.	Effects of a 5-year trawling ban on the local benthic community in a wind farm in the Dutch coastal zone	2015	No evidence was found that the species composition in the wind farm area relative to the reference areas had changed in the period between 2007 and 2011 after construction and closure to fisheries. The changes observed were mainly due to relatively small variations in species abundances.	Introduction of artificial hard substrate
Birklund, J.; Petersen, A.	Development of the Fouling Community on Turbine Foundations and Scour Protections in Nysted Offshore Wind Farm	2004	The hard substrate benthic community was dominated by mussels and barnacles with the biomass on the vertical foundations about ten times higher than on the stones. The biomass was uniform independent of direction (W, E, N and S) but declined with increasing depth. The community of macroalgae was dominated by red algae. The diversity and biomass increased with depth and was about two times higher on stones than on foundations. The biomass and abundance of invertebrates and the biomass of macroalgae on the shaft and stones was lower at the transformer station compared to the turbines.	Introduction of artificial hard substrate
Boutin, Kevin; Gaudron, Sylvie Marylene; Denis, Jérémy; Lasram, Frida Ben Rais;	Potential marine benthic colonisers of offshore wind farms in the English channel: A functional trait-based approach	2023	Offshore wind and oil and gas platforms communities were more similar to each other than to that of nearby hard substrates. The functional profile revealed that OWF colonisers were sessile, carnivore or suspension-feeding species ranging from 10 to 100 mm in size, with gonochoric reproduction, pelagic and planktotrophic larvae and a life span of less than 2 years or 5–20 years. Functional trait analysis revealed that during their intermediate stage of development, OWF benthic communities have a functional richness and diversity similar to those of hard substrate communities.	Introduction of artificial hard substrate

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Bunker, F.	Biology and Video Surveys of North Hoyle Wind Turbines 11th-13th August 2004	2004	OWFs act as artificial reefs, promoting sessile organism settlement and altering benthic communities. They provide new feeding and shelter opportunities for fish, potentially influencing species distribution and fisheries management.	Introduction of artificial hard substrate
Buyse, J.; De Backer, A.; Hostens, K.	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Progressive Insights in Changing Species Distribution Patterns Informing Marine Management	2024	Ch 3: Evidence from a wind farm in the North Sea suggests plaice is affected by the presence of wind farms, with the artificial hard substrate providing important habitat for individual plaice by increasing prey availability. The findings also suggest that wind farms may act as a refuge for plaice, potentially mitigating direct fishing mortality. There was no evidence that the increased prey availability leads to a better condition of plaice.	Introduction of artificial hard substrate
Buyse, J; Reubens, J; Hostens, K; Degraer, S; Goossens, J; De Backer, A	European plaice movements show evidence of high residency, site fidelity, and feeding around hard substrates within an offshore wind farm	2023	OWFs influence plaice movements, likely due to high food availability from hard substrates. Plaice use scour protection layers as feeding hotspots during the day and rest in surrounding sandy areas. Their high site fidelity suggests OWFs may offer seasonal protection from fishing, mainly in summer-autumn, but not during the winter spawning season when they leave the area.	Introduction of artificial hard substrate, IMPACT
Buyse, Jolien, Kris Hostens, Steven Degraer, Marleen De Troch, Jan Wittoeck, Annelies De Backer	Increased food availability at offshore wind farms affects trophic ecology of plaice Pleuronectes platessa	2023	No significant differences in overall condition and fecundity were found related to the presence of hard substrate. Larger individuals and a higher occurrence of females within the wind farm point to a potential refuge effect of the OWF due to the absence of fishing activities. They found evidence that OWFs act as artificial reefs for plaice by providing higher food abundances that are potentially easier to access than soft-sediment prey	Introduction of artificial hard substrate
Coates, D; Vanaverbeke, J; Rabaut, M; ...	Soft-sediment macrobenthos around offshore wind turbines in the Belgian Part of the North Sea reveals a clear shift in species composition	2011	Sediment samples taken at various distances from the scour protection system revealed two key trends: closer to the turbine, there was a lower median grain size and higher macrobenthic densities. The Southwest and Northeast gradients had high chlorophyll a concentrations, smaller grain sizes, and high densities of Lanice conchilega and Spiophanes bombyx, while the Southeast and Northwest gradients were dominated by the amphipod Monocorophium acherusicum. These species help stabilize soft substrates, indicating a shifting macrobenthic community.	Introduction of artificial hard substrate
Coates, DA; Deschutter, Y; Vincx, M; ...	Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea	2014	In this study from the North Sea, macrobenthic density and diversity increased in line with sediment enrichment close to turbines. Shifts in species dominance were detected with greater dominance of the ecosystem-engineer Lanice conchilega close to the foundation.	Introduction of artificial hard substrate

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
De Backer, A.; Buyse, J.; and Hostens, K.	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Empirical Evidence Inspiring Priority Monitoring, Research and Management	2020	Ch 7: in the North Sea, long term monitoring showed no change in fish and epibenthic communities between turbines. However, an increased number of hard substrate species suggested an expansion of the reef effect beyond the vacinity of the turbines.	Introduction of artificial hard substrate
De Backer, A.; Van Hoey, G.; Wittoeck, J.; Hostens, K.	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Getting ready for offshore wind farm expansion in the North Sea	2022	Ch 2: In this North Sea study, epibenthos and fish communities largely follow similar spatial distribution patterns with a clear distinction between the coastal and the offshore area. Locations inside the offshore wind farm concessions cluster nicely together with all non-concession locations confirming the conclusion from previous studies that epibenthos and fish assemblages on the soft sediments in between the turbines underwent no drastic changes.	Introduction of artificial hard substrate
De Troch, Marleen; Reubens, Jan T; Heirman, Elke; Degraer, Steven; Vincx, Magda;	Energy profiling of demersal fish: A case-study in wind farm artificial reefs	2013	In this study in the North Sea, energy profiling supported the statement that wind farm artificial reefs are suitable feeding ground for both cod and pouting. Sufficient energy levels were recorded and there is no indication of competition.	Introduction of artificial hard substrate
Degraer, S.; Brabant, R.; Vanaverbeke, J.	EDEN 2000: Exploring Options For A Nature-Proof Development of Offshore Wind Farms Inside A Natura 2000 Area	2023	Complex scour protection layers enhance biodiversity, while foundation type or material has little impact on fouling communities. *Buccinum undatum* and *Metridium senile* tolerate sediment burial up to 7 cm, but *Asterias rubens* and *Alcyonium digitatum* show increased mortality with deeper or prolonged burial. *M. senile* does not significantly affect overall fouling fauna but reduces *Actinothoe sphyrodeta* presence. Subtle, non-significant responses to electromagnetic fields were observed in sharks, squids, and lobsters.	Introduction of artificial hard substrate
Degraer, S.; Carey, D.; Coolen, J.; et al.	Offshore Wind Farm Artificial Reefs Affect Ecosystem Structure and Functioning: A Synthesis	2020	OWFs act as artificial reefs that can impact mobile fauna around them by increasing food availability.	Introduction of artificial hard substrate
Derweduwen, J, S. Vandendriessche, T. Willems & K. Hostens	The diet of demersal and semi-pelagic fish in the Thorntonbank wind farm: tracing changes using stomach analyses data	2012	Whiting's diet principally consisted of decapods. However, there is no direct link between consumption and availability because densities were virtually identical in the reference and fringe stations. The fullness index mostly showed that fish had fuller stomachs close to the wind turbines and at the borders of the concession area.	Introduction of artificial hard substrate

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Derweduwen, J.; Ranson, J.; Wittoeck, J.; and Hostens K.	Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded	2016	Ch 10: reports that in a North Sea wind farm the prey diversity and diet composition of lesser weaver and Dab were significantly influenced by the presence the turbines, which included more hard substrate epifauna.	Introduction of artificial hard substrate
Derweduwen, J.; Vandendriessche, S.; Willems, T.; Hostens, K.	Offshore Wind Farms in the Belgian Part of the North Sea: Heading for an Understanding of Environmental Impacts	2012	Ch6: Demonstrates importance of hard substratum prey (Jassa herdmani and Pisidia longicornis) in the diet of pouting.	Introduction of artificial hard substrate
Diembeck, D.	Populationsdynamik von kommerziell genutzten Fischarten in (durch Offshore-Windkraftanlagen) veränderter Ökosystemstruktur	2008	There is an urgent need for research into estimating the protective function of offshore wind farms in the form of artificial reefs. Future projects are necessary to answer the question of whether only fish from the surroundings congregate around the structures or whether a higher biomass production actually occurs. For further simulations with the FIWi model, an expansion of the individual-based model or a coupling with additional models, e.g. hydrodynamic models, is recommended. This could generate knowledge of the effect of bathymetry and sediment on the use of the habitat, as well as the effect of noise, electrical and magnetic fields during the operation of an offshore wind farm.	Introduction of artificial hard substrate, IMPACT
Gimpel, A; Werner, K M; Bockelmann, F-D; Haslob, H; Kloppmann, M; Schaber, M; Stelzenmuller, V	Ecological effects of offshore wind farms on Atlantic cod (Gadus morhua) in the southern North Sea.	2023	It seems likely that persistent favorable feeding conditions inside the OWFs would support local reproductive success of cod regardless of spawning taking place inside or outside the offshore wind farm.	Introduction of artificial hard substrate
Guarinello, Marisa L; Carey, Drew A	Multi-modal approach for benthic impact assessments in moraine habitats: a case study at the Block Island Wind Farm	2022	Assessment found no visual evidence of disturbance to the hard bottom habitats. Had undetected anchoring disturbance occurred, it is likely recolonization would have occurred in a similar time frame as where anchor furrows were detected, given proximity to mature faunal communities populations.	Introduction of artificial hard substrate
Hutchison Zoë, Monique LaFrance Bartley, Paul English, John King, Sean Grace, Boma Kresning, Christopher Baxter, Kristen Ampela, Mark Deakos, Anwar Khan	Benthic and Epifaunal Monitoring During Wind Turbine Installation and Operation at the Block Island Wind Farm, Rhode Island – Project Report	2020	The turbines have altered approximately 2,880 square meters of benthic habitat, accounting for 25–42% of the area impacted by two construction phases. While localized, the impact is significant, shifting from a sand habitat to one dominated by mussel aggregations, organic matter, sediment fines, and macrofaunal communities. Mussel growth is evident within turbine footprints and up to 90 m away but is absent in control sites.	Introduction of artificial hard substrate

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Jech, J.; Lipsky, A.; Moran, P.; et al.	Fish distribution in three dimensions around the Block Island Wind Farm as observed with conventional and volumetric echosounders	2023	We observed a consistent enhanced level of acoustic Sa within 130–160 m of the studied turbines, suggesting an attraction of fish. Although the acoustic data showed an increase in abundance within 160 m to individual turbines, the observed levels closer to the turbines did not rise above scattering levels at ranges further away.	Introduction of artificial hard substrate
Johnson, T.; van Berkel, J.; Mortensen, L.; et al.	Hydrodynamic Modeling, Particle Tracking and Agent-Based Modeling of Larvae in the U.S. Mid-Atlantic Bight	2021	Based on a modelling approach, offshore wind facilities could alter currents, temperature stratification, and wave heights. Models show slight shifts in larval settlement due to current changes, but the effects are not significant.	Change in water current, Change in stratification
Junquera Barbazán, P.; Sudjada, S.	Ecological design of scour protection for offshore wind power	2025	Experiments did not demonstrate a clear preference from any species for one particular scour protection design. This may be explained by the low number of replicates for this part of the study. The experiments highlighted the importance of scour protection measures , since they effectively prevented the wind turbine foundation against scouring, paticularly rocks scour protection.	Introduction of artificial hard substrate
Kerckhof, F.; De Mesel, I.; and Degraer, S.	Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded	2016	Ch 6: in a North Sea wind farm, 11 introduced and 2 cryptogenic species were recorded on turbine foundations. Of these, all but one were already known in the area. There is a risk that wind farms could substantially contribute to the spread of introduced species in the intertidal zone, but they are likely to only marginally contribute to their spread in the subtidal zone.	Introduction of artificial hard substrate
Kerckhof, F; Rumes, B; Degraer, S	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: a Continued move towards Integration and Quantification	2005	Ch 6: in the North Sea, natural hard substrate was shown to harbour a much higher number of species and also more unique species than the artificial ones and there were some differences in life traits.	Introduction of artificial hard substrate
Kerkhove, T. R.H.; Kapasakali D.; Kerckhof, F.; Degraer, S.	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Getting ready for offshore wind farm expansion in the North Sea	2022	Ch 5: in the North Sea shipwrecks were characterized by a higher epifaunal species richness compared to offshore wind farms. The differences in biodiversity between both structures may be attributed to the older age and the higher structural complexity of shipwrecks.	Introduction of artificial hard substrate

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Kingma, Enzo M; ter Hofstede, Remment; Kardinaal, Edwin; Bakker, Rebecca; Bittner, Oliver; van der Weide, Babeth; Coolen, Joop WP;	Guardians of the seabed: Nature-inclusive design of scour protection in offshore wind farms enhances benthic diversity	2024	It shows that SPL (scour protection layer) substrate type and substrate surface influences the biodiversity of benthic communities (NIDs). A significant positive relation between available substrate surface (pebble size) and taxonomic richness was found. Marble samples contained a higher prevalence of tube dwelling organisms, whereas concrete samples contained a relatively higher prevalence of free living, epi/endobiotic and crevice dwelling organisms	Introduction of artificial hard substrate
Krägefsky, S	Effects of the alpha ventus offshore test site on pelagic fish	2014	Some differences in feeding and presence both inside and outside of windfarm. Some issues in data collection that could influence results. The composition of pelagic fish species inside and outside alpha ventus is strongly congruent	Introduction of artificial hard substrate, IMPACT
Krone, R. and Krägefsky, S.	Effects of offshore wind turbine foundations on mobile demersal megafauna and pelagic fish research at the alpha ventus offshore wind farm	2013	After two years of installation following changes were obsereved: 1) substantially higher abundance of hard-substrate mobile species in comparison to reference area (paticularly edible crab), 2) higher abundance (attraction) of pelagic fish species, like pout and Atlantic Mackerel 3) reduced abundance of pelagic fish species during the constuction phase. However, mackerel had a higher proportion of empty guts within OWF in comparison to surrounging areas	Introduction of artificial hard substrate, IMPACT
Krone, R., Gutow, L., Brey, T., Dannheim, J. and Schröder, A.	Mobile demersal megafauna at artificial structures in the German Bight - Likely effects of offshore wind farm development	2013	5000 turbine foundations will provide habitat that increased the carrying capacity for additional stocks of C. pagurus, N. puber and T. bubalis by ca.25%, 165% and 121%, respectively, of the present soft bottom and wreck fauna within the entire German Bight.	Introduction of artificial hard substrate
Labourgade, P; Couturier, LIE; Bourjea, J; Woillez, M; Feunteun, E; Reubens, JT; Trancart, T	Acoustic telemetry suggests the lesser spotted dogfish Scyliorhinus canicula stays and uses habitats within a French offshore wind farm	2024	Acoustic telemetry was used to tag 31 lesser-spotted dogfish sharks and monitor them for one year. Most of the tagged sharks remained in the vicinity of the OWF post-release. This demonstrates site fidelity and seasonal residency. Individuals were mainly detected at the location of catch/release. The most frequent location was a monopile with a scour protection placed in soft sediment.	Introduction of artificial hard substrate
Langhamer, Olivia; Wilhelmsson, Dan;	Colonisation of fish and crabs of wave energy foundations and the effects of manufactured holes–a field experiment	2009	Field experiments revealed a significantly higher abundance of fish and crabs on foundations than on surrounding soft bottoms. Habitat complexity (holes) did not affect fish numbers but increased edible crab (Cancer pagurus) abundance. In contrast, spiny starfish (Marthasterias glacialis) declined, likely due to higher crab presence	Introduction of artificial hard substrate

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Lefaible, N.; Blomme, E.; Braeckman, U.; and Moens, T.	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Getting ready for offshore wind farm expansion in the North Sea	2022	Ch 3: comparison of hyperbenthic communities from inside and outside of 2 offshore wind farms in the northsea were inconsistent. Densities and diversity were greater inside of one of the wind farms than outside, consistent with the sediment enrichment hypothesis. But communities inside of the other wind farm were not significantly different from outside of it. This may be because the second wind farm was costructed more recently, and thus is comparitively "young".	Introduction of artificial hard substrate
Leonhard, SB; Stenberg, C; Støttrup, JG	Effect of the Horns Rev 1 offshore wind farm on fish communities: follow-up seven years after construction	2011	The spatial and temporal variability in the fish communities. New reef fish species established themselves in OWF. The present study indicates that wind farms represent neither a threat nor a direct benefit to sandeels. No significant changes in abundance of pelagic or demersal fish species different from the regional trend	Introduction of artificial hard substrate
Mavraki, N.; Braeckman, U.; Degraer, S.; Moens, T. and Vanaverbeke, J.	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Empirical Evidence Inspiring Priority Monitoring, Research and Management	2020	Ch 8: in the North Sea suspension feeding epifauna colonising turbine foundations slightly reduced local annual primary producers but were also an important resource for organisms of higher trophic levels, i.e. fish. The key role of scour protection was also highlighted, with high food web complexity and provision of a wide range of resources for epifauna and fish species identified in the area.	Introduction of artificial hard substrate
Mavraki, N; De Mesel, I; Degraer, S; Moens, T; Vanaverbeke, J;	Resource Niches of Co-occurring Invertebrate Species at an Offshore Wind Turbine Indicate a Substantial Degree of Trophic Plasticity	2020	Most of studied invertebrates at OWF in the North Sea are trophic generalists with susbtantial trophic plasticity, selecting different resources in different zones. Only Diadumene cincta was a trophic specialist that consumed suspended particulate organic matter independent of its zone of occurrence. Trophic plasticity appears an important mechanism for the co-existence of invertebrate species along the depth gradient of an offshore wind turbine.	Introduction of artificial hard substrate
Mavraki, Ninon; Braechman, U; Degraer, Steven; Moens, Tom; Vanaverbeke, Jan;	On the Food-Web Ecology in Offshore Wind Farms Areas: Lessons from 4 Years of Research	2020	This study examined OWF and hard substrate effects on food webs through field and lab studies. Colonizing species (Mytilus edulis, Jassa herdmani) drove carbon assimilation, reducing primary producer stocks and increasing complexity. Benthic and benthopelagic fish used OWFs as feeding grounds, while pelagic species showed limited reliance. OWFs appeared to favor trophic generalists. Jacket foundations had the highest carbon assimilation impact.	Introduction of artificial hard substrate

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Mesel, I De	Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species	2015	Clear vertical zonation in marine communities, with Telmatogeton japonicus dominating the splash zone, Semibalanus balanoides in the high intertidal, and a mussel belt in the low intertidal–shallow subtidal, In the deep subtidal, dominance by Jassa herdmani, Actiniaria spp., and Tubularia spp was observed. Ten non-indigenous species (NIS) were identified, with a higher proportion in the intertidal (8 out of 17 species) compared to the deep subtidal (2 out of 80 species).	Introduction of artificial hard substrate
Nogues, Quentin; Raoux, Aurore; Araignous, Emma; Chaalali, Aurelie; Hattab, Tarek; Leroy, Boris; Lasram, Frida Ben Rais; David, Valerie; Le Loc'h, Francois; Dauvin, Jean-Claude; Niquil, Nathalie	Cumulative effects of marine renewable energy and climate change on ecosystem properties: Sensitivity of ecological network analysis	2021	Potential (modelled) reef effects of OWF on fisheries species that offer refuge from climate change effects - indirect evidence. It is necessary to monitor keystone species to maintain the ecosystem properties before, during and after the exploitation of the offshore wind farm.	Introduction of artificial hard substrate
Redford, Michael; Rouse, Sally; Hayes, Peter; Wilding, Thomas A;	Benthic and fish interactions with pipeline protective structures in the North Sea	2021	The study provided evidence on the interaction of benthic and fish with pipelines so support decommissioning practices. Concrete mattresses are associated with higher abundance of grazers, decapods, suspension feeders and other fish in comparison with bare pipelines and rock dump.	Introduction of artificial hard substrate
Reubens, J.; Degraer, S.; Vincx, M.	The Ecology of Benthopelagic Fishes at Offshore Wind Farms: A Synthesis of 4 Years of Research	2014	Specific age groups of Atlantic cod and pouting were attracted to Windmill Artifiical Reefs (WARS) seasionally and show high site fidelity. Fish experienced growth when present at WARs and fed on dominant epifaunal prey species. Authors assume local scale production near WARs, but not expanded to regional scale. Authors recommend that no fisheries activites should be allowed inside offshore wind farms.	Introduction of artificial hard substrate, IMPACT
Reubens, J.T., Vandendriessche, S., Zenner, A.N., Degraer, S. and Vincx, M.	Offshore wind farms as productive sites or ecological traps for gadoid fishes? – Impact on growth, condition index and diet composition	2013	Based on the information of the current study no evidence was obtained to assume that the WARs act as an ecological trap for pouting (related to habitat quality). Length of pouting at the WARs was slightlylarger compared to individuals at the sandy areas, while no significant differences in condition were observed between sites. In addition, food was plentiful at the WARs and no restrictions relatedto sufficient food intake were encountered. Based on the measured proxies, fitness of pouting was even slightly better compared to thesandy areas (increased length and enhanced fullness index). Thismight be a first indication towards production (i.e. increased biomass) of pouting at the WARs.	Introduction of artificial hard substrate, IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Reubens, JT; Degraer, Steven; Vincx, Magda;	Aggregation and feeding behaviour of pouting (Trisopterus luscus) at wind turbines in the Belgian part of the North Sea	2011	Visual surveys of a single turbine indicated high abundance of pouting around a turbine foundation (22,000 individuals with a total biomass of 2700 kg). Stomach content analysis indicated that pouting were feeding on species that live on the turbine foundations, specifically Jassa herdmani and Pisidia longicornis.	Introduction of artificial hard substrate, IMPACT,
Stenberg, C; Stottrup, JG; van Deurs, M; Berg, CW; Dinesen, GE; Mosegaard, H; Grome, TM; Leonhard, SB	Long-term effects of an offshore wind farm in the North Sea on fish communities	2015	Species diversity was significantly higher close to the turbines. Overall, these results indicate that the artificial reef structures were large enough to attract fish species with a preference for rocky habitats, but not large enough to have adverse negative effects on species inhabiting the original sand bottom between the turbines.	Introduction of artificial hard substrate
ter Hofstede, R.; Driessen, F. M. F.; Elzinga, P. J.; Van Koningsveld, M.; Schutter, M.	Offshore wind farms contribute to epibenthic biodiversity in the North Sea	2022	Study shows that the epibenthic community at the scour protection in offshore wind farms is different from the community living at the surrounding seabed. Species abundance was found to be higher on the scour protection than on the surrounding seabed. The addition of scour protection results in a higher abundance and diversity of epibenthic species in offshore wind farms. The epibenthic community at the scour protection in offshore wind farms is different from the community in the surrounding seabed. Species abundance was higher on the scour protection with species typically associated with rocky habitat such as lobster and several fish species. Marine life can benefit from scour protection in OWFs as these provide hard substrate that otherwise would not be present in the area.	Introduction of artificial hard substrate, IMPACT
ter Hofstede, Remment; Witte, Sterre; Kamermans, Pauline; van Koningsveld, Mark; Tonk, Linda;	Settlement success of European flat oyster (Ostrea edulis) on different types of hard substrate to support reef development in offshore wind farms	2024	Applying suitable substrate in marine infrastructure promotes oyster reef development. Oyster larvae settlement preference differs per substrate type. Granite is conventionally used as scour protection and is suitable for oyster settlement. Oyster larvae settlement rates in a spatting pond are higher than in the natural environment.	Introduction of artificial hard substrate
Thatcher, H; Stamp, T; Moore, PJ; Wilcockson, D	Using fisheries-dependent data to investigate landings of European lobster (Homarus gammarus) within an offshore wind farm	2024	Landing per unit effort (LPUE) was found to be significantly higher at turbine locations where scour protection was present compared to those turbines where it was not. Predictions from modeling suggested LPUE was nearly 1.5× greater at turbines where scour protection was present. Significant differences in mean monthly and yearly LPUE were detected with this variation likely to reflect seasonal changes in lobster activity and the effect of introducing fishing into a previously unfished area. This work highlights the potential for fishing logbooks to be applied in fisheries management	Introduction of artificial hard substrate, IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
van Hal, R., Griffioen, A.B. and Van Keeken, O.A.	Changes in fish communities on a small spatial scale, an effect of increased habitat complexity by an offshore wind farm	2017	Fish abundance near the OWF turbines varied, with some days showing high concentrations and others an even distribution, indicating temporary use for shelter or feeding. Fish aggregation levels, observed via DIDSON, differed seasonally, with schools forming in April and individual fish or loose groups in summer. The wind farm structures had minimal impact on aggregation levels compared to seasonal or weather-related factors.	Introduction of artificial hard substrate
Wilber, Dara H.; Brown, Lorraine; Griffin, Matthew; DeCelles, Gregory R.; Carey, Drew A.	Offshore wind farm effects on flounder and gadid dietary habits and condition on the northeastern US coast	2022	Diets of benthic and benthopelagic predators were influenced by the introduction of hard structures in the area, as evidenced by the higher incidence of blue mussels and mysids in stomach contents. Their overall diet composition, however, did not differ from reference areas, indicating that the quality of foraging habitat near the wind farm was similar.	Introduction of artificial hard substrate
Zupan, M; Coolen, J; Mavraki, N; Degraer, S; Moens, T; Kerckhof, F; Lopez, LL; Vanaverbeke, J	Life on every stone: Characterizing benthic communities from scour protection layers of offshore wind farms in the southern North Sea	2024	The results demonstrate that abundant and diverse communities are present in all scour protection layers.	Introduction of artificial hard substrate
Introduction of synthetic and non-synthetic contaminants				
Wang, T; Zou, XQ; Li, BJ; Yao, YL; Li, JS; Hui, HJ; Yu, WW; Wang, CL	Microplastics in a wind farm area: A case study at the Rudong Offshore Wind Farm, Yellow Sea, China	2018	The plastic abundance in the wind farm area was lower than that outside the wind farm. The hydrodynamic effect was the main factor affecting the microplastic distribution. The presence of wind farm can increase the bed shear stress, increasing the ease of washing away microplastics adhered to the sediment.	Introduction of synthetic and non-synthetic contaminants
Introduction of underwater noise: continuous and impulsive				
Amaral, J.; Beard, R.; Barham, R.; et al.	Field Observations During Wind Turbine Foundation Installation at the Block Island Wind Farm, Rhode Island	2018	In situ measurements of pile driving noise particle acceleration levels in water were slightly above the behavioral sensitivity for the fishes considered in the frequency range 30 to 300 Hz. Hence, fishes may barely detect the particle motion during construction at 500 m range. Appears that the impact of construction will be more pronounced on fishes whose habitat is close to the seabed compared to fishes who spend most of their time in the water away from the seabed.	Introduction of Underwater noise: impulsive

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Bolle, L.; de Jong, C.; Bierman, S.; et al.	Shortlist Masterplan Wind - Effect of Piling Noise on Survival of Fish Larvae (pilot study)	2011	The laboratory setup was used in a pilot study, which aimed at determining the sound threshold for larval mortality. The study was limited to lethal effects on the larvae of one fish species: Experiments on different developmental stages of common sole (Solea solea) exposed to various levels and durations of piling noise, indicated that an effect of sound pressure exposure may occur, however lacking statistical significance, possibly due to sample size. No significant effects were observed in any of the three larval stages even cumulatively. The results of this study cannot be extrapolated to fish larvae in general, as interspecific differences in vulnerability to sound exposure may occur. However, this study does indicate that the previous assumptions and criteria may need to be revised.	Introduction of Underwater noise: impulsive
Bolle, LJ; Jong, CAF de; Blom, Ewout; Wessels, Peter W; van Damme, Cindy JG; Winter, HV;	Effect of pile-driving sound on the survival of fish larvae	2014	Realistic pile-driving sounds at different exposure levels and cumulatively showed that survival was not affected over a seven day (sole) or ten day (sea bass and herring) period.	Introduction of Underwater noise: impulsive
Bruintjes, Rick; Purser, Julia; Everley, Kirsty A; Mangan, Stephanie; Simpson, Stephen D; Radford, Andrew N;	Rapid recovery following short-term acoustic disturbance in two fish species	2016	Noise exposure affects fish behavior and physiology but dissipates quickly after the noise stops. Juvenile eels exhibited reduced anti-predator responses and increased ventilation rates, but these effects rapidly recovered within minutes. Similarly, seabass showed increased ventilation rates during noise exposure, with full recovery shortly after. While recovery times may vary by species, these findings suggest short-term noise impacts may be manageable for fish populations.	Introduction of underwater noise: continuous
Casper, B.; Halvorsen, M.; Carlson, T.; et al.	Onset of Barotrauma Injuries Related to Number of Pile Driving Strike Exposures in Hybrid Striped Bass	2017	Pile-driving causes barotrauma in striped bass	Introduction of Underwater noise: impulsive
Cones, Seth F.; Jezequel, Youenn; Ferguson, Sophie; Aoki, Nadege; Mooney, T. Aran	Pile driving noise induces transient gait disruptions in the longfin squid (Doryteuthis pealeii)	2022	In the West Atlantic, off the east coast of USA, pile-driving induced noise was shown to effect the swimming behaviour of squid.	Introduction of Underwater noise: impulsive
Corbett, William Thomas;	The behavioural and physiological effects of pile-driving noise on marine species	2018	This in-vitro study demonstrated that pile driving noise resulted in reduced feeding for Carcinus maenus crab and avoidance for pelagic fishes. Authors recommend mitigating pile driving noise.	Introduction of Underwater noise: impulsive

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Cresci, Alessandro, Guosong Zhang, Caroline M. F. Durif, Torkel Larsen, Steven Shema, Anne Berit Skiftesvik & Howard I. Browman	Atlantic cod (Gadus morhua) larvae are attracted by low-frequency noise simulating that of operating offshore wind farms	2023	Low frequency noise exposure did not affect swimming speed or turning behavior, it altered orientation: control larvae moved northwest, while exposed larvae moved toward the sound source. These findings suggest OW noise could influence fish dispersal, particularly in larval stages with limited mobility.	Introduction of underwater noise: continuous
De Backer, A.; Debusschere, E.; Ranson, J.; Hostens, K	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: a Continued move towards Integration and Quantification	2005	Ch3: during pile-driving associated with an offshore wind development in the North Sea there were increasing cases of swim bladder barotrauma in Atlantic cod with decreasing distance from impulse noise from pile-driving.	Introduction of Underwater noise: impulsive
Debusschere, E.; Hostens, K.; Adriaens, D.; et al.	Acoustic stress responses in juvenile sea bass Dicentrarchus labrax induced by offshore pile driving	2015	Acoustic stress responses from in situ experiments from the North Sea indicated that repeated exposure to impulsive sound from pile-driving can effect the fitness of European Sea Bass.	Introduction of Underwater noise: impulsive
Debusschere, E; De Coensel, B; Vandendriessche, S; Botteldooren, D; Hostens, K; Vincx, M; Degraer, S	In Situ Mortality Experiments with Juvenile Sea Bass (Dicentrarchus labrax) in Relation to Impulsive Sound Levels Caused by Pile Driving of Windmill Foundations	2014	In the North Sea, juvenile European sea bass exposed to pile-driving sounds at close range (45 m) experienced no immediate or delayed mortality compared to control groups, and no significan physiological harm. The in situ field experiment results align with previous laboratory studies, confirming minimal mortality impact from pile-driving sounds on juvenile fish.	Introduction of Underwater noise: impulsive
Halvorsen, M.; Casper, B.; Woodley, C.; et al.	Threshold for Onset of Injury in Chinook Salmon from Exposure to Impulsive Pile Driving Sounds	2012	Estimation of exposure conditions to impulsive sound can be used to manage the risk of physical injury to exposed juvenile Chinook salmon for any selected biological response weighted index value. Observed injuries ranged from mild hematomas at the lowest sound exposure levels to organ hemorrhage at the highest sound exposure levels.	Introduction of Underwater noise: impulsive
Han, DG; Choi, JW	Measurements and Spatial Distribution Simulation of Impact Pile Driving Underwater Noise Generated During the Construction of Offshore Wind Power Plant Off the Southwest Coast of Korea	2022	Sound exposure level and peak pressure level were lowest at 5 m above the seafloor, and higher at 3 and 7 m above the seafloor. Yellow croaker (L. polyactis) is one of the most abundant fish in the region where the OWF is located and a sound detection range between 0.1 to 1.0 kHz has been reported for closely related species. Physical damage to marine life due to anthropogenic noise should be carefully discussed through multidisciplinary assessments.	Introduction of Underwater noise: impulsive
Hawkins, A.D., Roberts, L. and Cheesman, S.	Responses of free-living coastal pelagic fish to impulsive sounds	2014	Responses to impulsive sounds by both sprat and mackerel occurred at relatively low sound levels, similar to those recorded at several kilometers distance from an operating pile driver or seismic airgun. Changes of depth for mackerel are less likely to have a negative impact than the dispersal of schools in sprat	Introduction of Underwater noise: impulsive

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
HDR Engineering Inc.	Underwater Acoustic Monitoring Data Analyses for the Block Island Wind Farm, Rhode Island	2019	Pile driving noise intensity higher than background noise within 20km around the OWF. Underwater sound levels were lower in deep waters and higher in shallow waters. Sound levels were also shown to be dependent upon the orientation of the pile to the recording sensor.	Introduction of Underwater noise: impulsive
Hynes, Hannah;	Acoustic monitoring of marine seismic survey impacts on fish and zooplankton in the northeast Newfoundland slope marine refuge	2024	This study provided evidence that fish at depths between 50 m and 350 m reacted to offshore seismic surveying within a 62 km horizontal radius. They descended and aggregated deeper in the water column. No observed effect on the abundance or behaviour of zooplankton. There were no significant measurable effects on fish or zooplankton from the single airgun coastal experiment. Mortality rates of zooplankton were also assessed using net sampling and dyeing methods in both coastal and offshore experiments, but no significant changes in zooplankton mortality were detected.	Introduction of Underwater noise: impulsive
Jezequel, Youenn; Cones, Seth; Jensen, Frants H.; Brewer, Hannah; Collins, John; Mooney, T. Aran	Pile driving repeatedly impacts the giant scallop (Placopecten magellanicus)	2022	Responses to pile driving (partial valve closures) were seen across all life stages (juveniles are most sensitive). Responses were dose-dependent and were not observed at a more distant site (50 m from source). Scallops did not show short-term (within days) and long-term (across days) habituation to pile driving events. Daily pile driving did not disrupt the scallops' circadian rhythm, but suggests serious impacts at night when valve openings are greater. Overall, results highlight concerns regarding the larger impact ranges of impending widespread offshore wind farm constructions on scallop populations.	Introduction of Underwater noise: impulsive
Jones, IT; Schumm, M; Stanley, JA; Hanlon, RT; Mooney, TA	Longfin squid reproductive behaviours and spawning withstand wind farm pile driving noise	2023	Reproductive behaviour of longfin squid was unaffected by pile driving noise compared to silent controls. It indicates that species with little opportunity to reproduce can tolerate intense stressors to secure reproductive success.	Introduction of Underwater noise: impulsive
Konow, T.	Measurement and Modelling of Underwater Acoustic Noise induced by Offshore Wind Turbines under the Effects of Varying Oceanic and Sea-State Conditions	2022	Results showed that environmental conditions alter the propagation and transmission of acoustic signals. Temperature and salinity determine the sound speed profile which determines sound propagation. The presence of surface waves also alters the propagation and transmission loss of acoustic signals. Sound pressure levels and transmission loss increased with the presence of wind forcing and strong waves at the surface.	Introduction of underwater noise: continuous
Kusel, E.; Weirathmueller, M.; Zammit, K.; et al.	Revolution Wind COP Appendix P3: Underwater Acoustic Modeling Analysis	2023	A quantitative model-based assessment of the sounds produced by pile driving of the monopile foundations. The aim was also to quantify the number of individual marine mammals and turtles to be affected by this sound and potentially distribed on their migration routes. For fish, exposure ranges were not calculated. Instead, the acoustic	Introduction of Underwater noise: impulsive

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
			distance to their regulatory thresholds were determined and reported.	
Leiva, Laura; Scholz, Sören; Giménez, Luis; Boersma, Maarten; Torres, Gabriela; Krone, Roland; Tremblay, Nelly	Noisy waters can influence young-of-year lobsters� substrate choice and their antipredatory responses	2021	Added tonal low-frequency noise in the environment have the potential to influence the behavior of early-life stages of European lobsters and highlights the importance of including key benthic invertebrates' community relationships in anthropogenic noise risk assessments	Introduction of underwater noise: continuous
Martin, B.; Zeddies, D.; MacDonnell, J.; et al.	Characterization and Potential Impacts of Noise Producing Construction and Operation Activities on the Outer Continental Shelf: Data Synthesis	2014	The baseline data (before construction) on underwater noise at two potential offshore wind-energy sites: Delaware Bay and Nantucket Sound. The study revealed that certain frequency bands and seasons showed higher sound levels than Welz curve predictions. Notable sound sources included anthropogenic noise from heavy shipping, storms, and biological activity from marine mammals and fish, with some events exceeding predicted levels.	Introduction of underwater noise: continuous (T0)
Mueller, C.	Behavioural Reactions of Cod (Gadus morhua) and Plaice (Pleuronectes platessa) to Sound Resembling Offshore Wind Turbine Noise	2007	Cod exhibited avoidance behavior when exposed to sounds resembling offshore wind turbine noise. Plaice (Pleuronectes platessa) showed no significant response. Conducted in a controlled tank, the research suggests turbine noise may cause habitat avoidance in cod but has little effect on plaice.	Introduction of underwater noise: continuous
Mueller-Blenkle, C.; McGregor, P.; Gill, A.; et al.	Effects of Pile-Driving Noise on the Behaviour of Marine Fish	2010	The range of received sound pressure and particle motion levels triggered behavioural responses in sole and cod. The results further imply a relatively large zone of behavioural response to pile-driving sounds in marine fish. However, some of our results point toward habituation to the sound.	Introduction of Underwater noise: impulsive
Nedwell, J.; Langworthy, J.; Howell, D.	Assessment of Sub-Sea Acoustic Noise and Vibration from Offshore Wind Turbines and its Impact on Marine Wildlife; Initial Measurements of Underwater Noise during Construction of Offshore Windfarms, and Comparison with Background Noise	2003	Ambient noise levels in shoals are high and vary more during the day due to ship movements. Marine mammals perceive more consistent noise, while fish experience greater variability. Piling noise caused strong avoidance in species and posing injury risks within 100 meters. Cable trenching and rock socket drilling also produced significant noise, detectable up to 7 km. Piling has major environmental impacts, especially on sensitive species, but mitigation measures like bubble curtains and acoustic monitoring can help reduce harm.	Introduction of Underwater noise: impulsive, Introduction of underwater noise: continuous

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Nedwell, J.; Parvin, S.; Edwards, B.; et al.	Measurement and Interpretation of Underwater Noise During Construction and Operation of Offshore Windfarms in UK Waters	2007	The environment within these operational windfarms was found to be on average about 2 dB noisier for fish, and no noisier for marine mammals, than the surrounding area. This is no more than variations which might be encountered by these animals during their normal activity. No evidence was found of noise levels that might have the capacity to cause marine animals to avoid the area.	Introduction of Underwater noise: impulsive, Introduction of underwater noise: continuous
Nedwell, J.; Turnpenny, A.; Lovell, J.; et al.	An Investigation into the Effects of Underwater Piling Noise on Salmonids	2006	No signs of trauma attributed to sound exposure were found in any fish. No increase in activity or startle response was seen to vibropiling. Noise at the nearest cages during impact piling reached levels at which salmon were expected to react strongly, but brown trout showed little reaction. Hearing of the brown trout was less sensitive than that of the salmon demonstrating the importance of using the correct species of fish as a model when assessing the effect of noise.	Introduction of Underwater noise: impulsive
Neo, Y.; Ufkes, E.; Kastelein, R.; et al.	Impulsive Sounds Change European Seabass Swimming Patterns: Influence of Pulse Repetition Interval	2015	Seismic shooting and offshore pile-driving generate significant noise that can negatively impact fish behavior. The pulse repetition interval (PRI) of these sounds can affect the extent and recovery of the behavioral changes. In this study, European seabass were exposed to four different PRIs, showing faster swimming, deeper diving, and tighter shoals at the onset of noise exposure. PRI influenced both immediate and delayed behavioral changes, but not recovery time. The study found that PRI affects behavioral impacts differently, and that acoustic metrics like SELcum may not fully predict noise impacts, emphasizing the need to consider sound temporal structure in impact assessments.	Introduction of Underwater noise: impulsive
Niu Fuqiang, Xie Jiarui, Zhang Xuexin, Xue Ruichao, Chen Benqing, Liu Zhenwen, Yang Yanming	Assessing differences in acoustic characteristics from impact and vibratory pile installation and their potential effects on the large yellow croaker (Pseudosciaena crocea)	2023	The effects of pile driving noise on populations of the large yellow croaker are evaluated based on field observations of the behavioural response of yellow croakers at different distances. The responses include both escape responses but also minor behavioural responses as change in swimming speed.	Introduction of Underwater noise: impulsive
Norro, A. and Degraer, S.	Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded	2016	Ch 3: operational sound emmited from an offshore wind farm in the North Sea increased underwater noise by about 20 dB re 1 micro Pa at frequencies below 3 kHz. Monopiles emitted significantly more sound than jacket foundations.	Introduction of underwater noise: continuous

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Paxton, A.; Voss, C.; Peterson, C.; et al.	Documenting fish response to seismic surveying and establishing a baseline soundscape for reefs in Onslow Bay, North Carolina	2018	The response of reef-associated fish to high-intensity was monitored, low-frequency sound created by repeated air-gun deployments from a seismic survey on the continental shelf of North Carolina. Although working with limited data, they provide evidence that during exposure to seismic noise, the prevailing pattern of heavy fish use of reefs during the evening was suppressed.	Introduction of underwater noise: continuous
Pérez-Arjona, I., Espinosa, V., Puig, V., Ordóñez, P., Soliveres, E., Poveda, P., Ramis, J., de-la-Gándara, F. and Cort, J.L.	Effects of offshore wind farms operational noise on Bluefin tuna behaviour	2014	Exposing tuna to wind turbine low frequency noise, main reactions are to high levels and long time exposures (i.e. 10-15 minutes). These reactions can be summarize as: i) position change in the water column of the fish school, ii) contraction of the school (avoidance) , iii) slight disorientation of some specimens and iv) increased speed. This behavior was repeatedly observed with longtime emission in absence of other noise sources, and emission levels ~165 dB ref 1mPa.	Introduction of Underwater noise: impulsive
Perrow, M.R., Gilroy, J.J., Skeate, E.R. and Tomlinson, M.L.	Effects of the construction of Scroby Sands offshore wind farm on the prey base of Little tern Sternula albifrons at its most important UK colony	2011	First evidence of indirect effect of wind farm construction on a seabird via its prey. Noise generated by pile driving thought responsible for the decline in young herring. Concomitant significant reduction in foraging success of Little terns. Circumstantial evidence of population response with unprecedented egg abandonment.	Introduction of Underwater noise: impulsive
Pine, MK; Jeffs, AG; Radford, CA	Turbine sound may influence the metamorphosis behaviour of estuarine crab megalopae	2012	In a laboratory experiment the median time to metamorphosis (TTM) for the megalopae of the crabs Austrohelice crassa and Hemigrapsus crenulatus was significantly increased by at least 18 h when exposed to either tidal turbine or sea-based wind turbine sound, compared to silent control treatments. Contrastingly, when either species were subjected to natural habitat sound, observed median TTM decreased by approximately 21–31% compared to silent control treatments, 38–47% compared to tidal turbine sound treatments, and 46–60% compared to wind turbine sound treatments. A lack of difference in median TTM in A. crassa between two different source levels of tidal turbine sound suggests the frequency composition of turbine sound is more relevant in explaining such responses rather than sound intensity. These results show that estuarine mudflat sound mediates natural metamorphosis behaviour in two common species of estuarine crabs, and that exposure to continuous turbine sound interferes with this natural process	Introduction of underwater noise: continuous

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Popper, A.; Halvorsen, M.; Casper, B.; et al.	Effects Of Pile Driving Sounds On Non-Auditory Tissues Of Fish	2013	Physoclistous fish were more sensitive to higher sound exposure levels than physosotomous fish. Major conclusions of this study are that: (a) For all species studied, onset of barotrauma effects did not occur until the SELcum was substantially above the current interim regulations. (b) Barotrauma injuries were not observed in a species without a swim bladder (hogchoker). (c) There were differences in the sound exposure level at which barotrauma appeared in fish. In the most sensitive tested species barotrauma was seen at an SELcum of 207 dB re 1 μPa2 ·s yielded from SELss 177 dB re 1 μPa2 ·s and 960 strikes. (d) The important metrics used to define the impulsive exposure incorporate how the energy accumulated. Three recommended metrics are: SELcum, SELss and the number of strikes. (e) Effects from exposure to pile driving sounds appear to be consistent across species, even when there are substantial differences in fish morphology, including in both physostomous and physoclistous fishes.	Introduction of Underwater noise: impulsive
Puig-Pons, V; Soliveres, E; Perez-Arjona, I; Espinosa, V; Poveda-Martinez, P; Ramis-Soriano, J; Ordonez-Cebrian, P; Moszynski, M; de la Gandara, F; Bou-Cabo, M; Cort, JL; Santaella, E	Monitoring of Caged Bluefin Tuna Reactions to Ship and Offshore Wind Farm Operational Noises	2021	The experiment confirmed that noisy stimuli can affect tuna behavior, but further research is needed to fully determine time and intensity thresholds, as well as the impact of turbine operational noise on bluefin tuna. Reactions were primarily triggered by high-power, low-frequency signals, including pure tones, broadband noises, and long exposure durations. Observed behaviors included changes in school position, increased activity, contraction and displacement of the school, occasional disorientation, and increased swimming speed. Repeated exposure required longer emissions to elicit similar reactions, suggesting that semi-captive bluefin tuna may have a high degree of adaptability to noise.	Introduction of underwater noise: continuous
Roberts, L; Cheesman, S; Breithaupt, T; ...	Sensitivity of the mussel Mytilus edulis to substrate-borne vibration in relation to anthropogenically generated noise	2015	Marine bivalve Mytilus edulis exposure to substrate-borne vibration under controlled conditions. Sinusoidal excitation by tonal signals at frequencies within the range 5 to 410 Hz were related to mussel size and to seabed vibration data produced by anthropogenic activities. Clear behavioural changes were observed in response to the vibration stimulus. Thresholds ranged from 0.06 to 0.55 m s−2 (acceleration, root mean squared), with valve closure used as the behavioural indicator of reception and response. Thresholds were shown to be within the range of vibrations measured in the vicinity of anthropogenic operations such as pile driving and blasting. The responses show that vibration is likely to impact the overall fitness of both individuals and mussel beds of M. edulis due to disruption of natural valve periodicity, which may	Introduction of Underwater noise: impulsive

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
			have ecosystem and commercial implications.	
Siddagangaiah, S.; Chen, C-F.; Hu, W-C.; et al.	Assessing the influence of offshore wind turbine noise on seasonal fish chorusing	2024	Results show the noise from a single turbine during the two-year monitoring period did not influence the seasonal fish chorusing	Introduction of underwater noise: continuous, Introduction of underwater noise: continuous
Siddagangaiah, S; Chen, CF; Hu, WC; Erbe, C; Pieretti, N	Influence of increasing noise at the offshore wind farm area on fish vocalization phenology: A long-term marine acoustical monitoring off the foremost offshore wind farm in Taiwan	2024	Offshore wind farm development project causes the elevation of low-frequency noise level. Elevated noise levels can potentially affect the fish vocalisation behavior. Reduced duration and intensity of fish chorus was observed in the noise-affected area. Long-term monitoring required to understand change in fish vocalization phenology.	Introduction of underwater noise: continuous, Introduction of underwater noise: continuous
Siddagangaiah, Shashidhar; Chen, Chi-Fang; Hu, Wei-Chun; Pieretti, Nadia	Impact of pile-driving and offshore windfarm operational noise on fish chorusing	2021	Two chorusing species cyclically repeating their chorus over a diurnal pattern at the windfarm site. When exposed to pile driving and operation noise, the two chorusing types behaved differently. This study also suggests the need to provide site and species-specific impact analyses of the pile driving and operating windfarm noise.	Introduction of Underwater noise: impulsive
Sigray, P; Andersson, MH	Particle motion measured at an operational wind turbine in relation to hearing sensitivity in fish	2011	Evidence of particle motion change in offshore environment. The results show that inferred mitigation techniques reduce the levels and decreases the power content of higher frequencies. These results suggest that mitigation has an effect and will reduce the effect ranges of impact on marine species, such as cod and plaice. Still, pressure variations might have an influence at larger distances, especially on fish with enhanced hearing sensitivity.	Introduction of Underwater noise: impulsive
Sigray, Peter; Linné, Markus; Andersson, Mathias H; Nöjd, Andreas; Persson, Leif KG; Gill, Andrew B; Thomsen, Frank	Particle motion observed during offshore wind turbine piling operation	2022	From an offshore piling event in the North Sea, the results show that inferred mitigation techniques reduce the particle motion levels significantly as well as decreasing the power content of higher frequencies. These results suggest that mitigation has an effect and will reduce the effect ranges of impact on marine species.	Introduction of Underwater noise: impulsive

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Song, Z.; Fu, W.; Li, H.; et al.	Evaluation of the influence of offshore wind farm noise on the fishes and dolphins in the Pearl River Estuary	2024	In situ measurements of pile driving and operational noise applied to modelled exposure levels for fish, estimated an impact zone of 12.8 m for fishes.	Introduction of Underwater noise: impulsive
Spiga, I., Caldwell, G.S. and Bruintjes, R.	Influence of Pile Driving on the Clearance Rate of the Blue Mussel, Mytilus edulis (L.)	2016	Results indicate that blue mussels are sensitive to pile driving and that pile driving can elicit increased clearance rates. Higher clearance rates of blue mussels could be an increase in active metabolism as a consequence of stress during pile driving. Shifts in physiological state and changes to clearance rate could risk resource limitations, i.e. a mismatch between energy expenditure and energy capture. Over a sustained period, this mismatch may have detrimental effects on fitness and implications for survival.	Introduction of Underwater noise: impulsive
Stanley, J.; Caiger, P.; Jones, I.; et al.	Behavioral effects of sound sources from offshore renewable energy construction on the black sea bass (Centropristis striata) and longfin squid (Doryteuthis pealeii)	2023	Evidence indicates that for C. Striata and D. pealeii, responses to sound are most likely to occur at the onset of noise, rapid habituation is expected, with some re-sensitization, and reproductive behaviors may be relatively resilient to noise stressors for semelparous species that have limited opportunity to reproduce.	Introduction of Underwater noise: impulsive
Stenton, C.; Bolger, E.; Michenot, M.; et al.	Effects of pile driving sound playbacks and cadmium co-exposure on the early life stage development of the Norway lobster, Nephrops norvegicus	2022	Effects of the pollutants anthropogenic sound (pile driving sound playbacks) and waterborne cadmium on larval and juvenile Norway lobster, Nephrops norvegicus, showed that pre-exposure to the combination of piling playbacks and 6.48 μg[Cd] L− 1 led to significant differences in the swimming behaviour of the first juvenile stage. Biomarker analysis suggested oxidative stress as the mechanism resultant deleterious effects, with cellular metallothionein being the predominant protective mechanism.	Introduction of Underwater noise: impulsive
van der Knaap, Inge; Slabbekoorn, Hans; Moens, Tom; Van den Eynde, Dries; Reubens, Jan	Effects of pile driving sound on local movement of free-ranging Atlantic cod in the Belgian North Sea	2022	The current study revealed that exposure to pile driving sounds at relatively close range of a few kilometres did not cause free-ranging cod to leave an area. We were able to show, however, several more subtle response patterns in their movement behaviour: they moved a couple of meters closer towards the scour-bed of the nearest turbine and also moved away from the sound source location. Spatial positioning before pile driving started suggested phonotactic approach behaviour in response to preparatory sounds at relatively large distances. Such changes in behaviour seem modest but can lead to changes in energy expenditure, which could potentially accumulate to population-level consequences.	Introduction of Underwater noise: impulsive

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
van der Knaap, Inge; Slabbekoorn, Hans; Winter, Hendrik V; Moens, Tom; Reubens, Jan	Evaluating receiver contributions to acoustic positional telemetry: a case study on Atlantic cod around wind turbines in the North Sea	2021	Exclusion of data from an acoustic positional telemetry receiver, that was positioned within the movement area of the individual fish, reduced the number of tag signals detected and the position accuracy of the set-up the most. Excluding the data from a single receiver caused a maximum of 34% positions to be lost per fish and a maximum increase in core area of 97.8%. Single-receiver data exclusion also caused a potentially large bias in the reconstruction of swimming tracks. By contrast, exclusion of a receiver that was deployed within 50 m from a turbine actually improved fish position accuracy, probably because the turbine can cause signal interference as a reflective barrier.	Introduction of underwater noise: continuous
Wang, Y.; Gong, K.; Xie, J.; et al.	Transcriptomic analysis of the response mechanisms of black rockfish	2024	Both offshore wind turbine underwater dominant frequency noise and on-site noise have varying degrees of impact on the metabolism and immune system of S. schlegelii.	Introduction of underwater noise: continuous
Zhang, Xuguang; Guo, Hongyi; Chen, Jia; Song, Jiakun; Xu, Kaida; Lin, Jun; Zhang, Shouyu	Potential effects of underwater noise from wind turbines on the marbled rockfish (Sebasticus marmoratus)	2021	Results showed that marbled rockfish (Sebastiscus marmoratus) has a lowest auditory threshold of 70 dB at 150 Hz, aligning with its communication range. Wind turbine noise overlaps this range, potentially masking acoustic signals.	Introduction of underwater noise: continuous
Loss of soft sediment, covered by scour protection				
Rudders, David; Mann, Roger L; Boresetti, Sarah; Munroe, Daphne; McCarty, Alexandra; Aponte, Reece; Sheehan, Ailey; Piper, Sohia; Tanaka, Hails; Dameron, Tom;	Resource monitoring for Atlantic surfclam (Spisula solidissima) at the Coastal Virginia Offshore Wind development site	2024	This surfclam survey observed relatively high total biomass and density of surfclams within and around the OW lease area in the USA; total biomass observed was more than double that observed in lease areas elsewhere in the central portion of the fishing stock. However, the surfclams collected in and around the lease were almost exclusively smaller than 120mm throughout the surveyed area, meaning that the exploitable biomass (the biomass of surfclams >120mm) was relatively low.	Loss of soft sediment, covered by scour protection
Sediment resuspension, transport and smothering				
Baeye, M; Fettweis, M	In situ observations of suspended particulate matter plumes at an offshore wind farm, southern North Sea	2015	Evidence of composition of suspended particles associated with turbines.	Sediment resuspension, transport and smothering
Brandao, I.; van der Molen, J.; van der Wal, J.	Effects of offshore wind farms on suspended particulate matter derived from satellite remote sensing	2023	No difference between wind farm and control areas in suspended particulate matter derived from satellite remote sensing.	Sediment resuspension, transport and smothering

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Forster, R.	The effect of monopile-induced turbulence on local suspended sediment pattern around UK wind farms	2018	Results show evidence that surface water within the plume or wake associated to monopiles within the Thanet OWF was enriched by over 40% in the concentration of suspended material. '-Plumes are caused by re-distribution of suspended sediment in the water column due to increased vertical mixing in the monopile wake. The Thames region experiences strong seasonal changes in turbidity and it is likely that benthic species and habitats existing at sites such as Thanet are adapted to rapid changes in sediment deposition and erosion.	Sediment re-suspension, transport and smothering
Ivanov, Evgeny; Capet, Arthur; De Borger, Emil; Degraer, Steven; Delhez, Eric J. M.; Soetaert, Karline; Vanaverbeke, Jan; Gregoire, Marilaure; Delhez, Eric J. M.; Soetaert, Karline; Vanaverbeke, Jan; Gregoire, Marilaure	Offshore Wind Farm Footprint on Organic and Mineral Particle Flux to the Bottom	2021	OSW farms have a significant effect on the sedimentation and deposition of TOC, increasing fluxes to the sediment by up to 50% within 5 km around monopiles	Sediment re-suspension, transport and smothering
van den Eynde, D.; Brabant, R.; Fettweis, M.; et al.	Monitoring of Hydrodynamic and Morphological Changes at the C-Power and Belwind Offshore Windfarm Sites - A Synthesis	2010	Monitoring of gravity-based foundations installed in the North Sea highlighted an substantial amount of sand was dredged, creating some pits. It appeared that more material was dredged and used than was expected. During backfill, most of the sediment was lost during disposal. Monitoring of these sand pits over several months showed that the sand pits are relatively stable and that no natural filling of the sand pits had occured.	Sediment re-suspension, transport and smothering
Vanhellemont, Q; Ruddick, K	Turbid wakes associated with offshore wind turbines observed with Landsat 8	2014	Increased suspended particulate matter concentration is found in the in-water wakes of offshore wind turbines and ships. The turbid turbine wakes are aligned with the direction of the tidal current.	Sediment re-suspension, transport and smothering
Multiple pressures				

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Bailey, L.; Dorrell, R.; Kostakis, I.; et al.	Monopile-induced turbulence and sediment redistribution form visible wakes in offshore wind farms	2024	Suspended particulate matter at the offshore wind farm showed inter-annual and intra-annual variation, however changes were consistent with waters located further away from the site, therefore variation was attributed to natural fluctuations rather than anthropogenic change. Colour changes extending in the direction of tidal flow were observed in monopile wakes for >90% of satellite scenes, formed due to elevated near surface water concentrations in suspended sediment. However, averaged water column showed no additional sediment was sourced in wakes, therefore suggesting the cause of visible plumes as a result of sediment distribution in the water column, instead of sediment erosion from monopile bases. Organic matter was consistent between water upstream of monopiles and within the corresponding wake, therefore plume formation was not related to material released by epifauna at the wind farm.	Sediment resuspension, transport and smothering, Change in water current
Creane, S.; Coughlan, M.; O'Shea, M.; et al.	Development and Dynamics of Sediment Waves in a Complex Morphological and Tidal Dominant System: Southern Irish Sea	2022	High-resolution, time-lapse bathymetry datasets, hydrodynamic numerical modelling outputs and various theoretical parameters were used to describe the morphological characteristics of sediment waves and their spatio-temporal evolution in the Irish Sea.	Change in water current, Sediment resuspension, transport and smothering
Dannheim, Jennifer; Beerman, Jan; Lacroix, Geneviève; De Mesel, Ilse; Kerckhof, Francis; Schon, Isa; Degraer, Steven; Birchenough, Silvana NR; Garcia, Clement; Coolen, Joop WP;	Understanding the influence of man-made structures on the ecosystem functions of the North Sea (UNDINE)	2018	The study revealed distinct spatial and temporal patterns in community structure and secondary production across man-made marine structures (MMSs), with biological traits remaining consistent over time. Energy flow analysis showed significant modifications in the upper parts of MMSs, where the highest production and biomass export to soft bottoms occurred. The EcoPath model demonstrated that offshore wind farms retain more carbon than oil and gas platforms, largely due to the presence of Mytilus edulis, a key contributor to carbon retention. Species composition on MMSs is shaped by constant propagule arrival and local survival of hard substrate species. Dispersal modeling indicated that Ostrea edulis larvae are limited to the southern half of the North Sea, while M. edulis and Patella vulgata have a wider dispersal range. MMSs serve as stepping stones, extending species' dispersal capacity and supporting genetic diversity for conservation and commercial species. However, increased connectivity may also facilitate the spread of non-indigenous and potentially invasive species across the North Sea.	Introduction of artificial hard substrate, Change in water current, IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Degraer, S.; Brabant, R.; Rumes, B.; Vigin, L.	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Attraction, avoidance and habitat use at various spatial scales	2021	Overview of the scientific findings of the Belgian offshore wind farm environmental monitoring programme based on data collected up to and including 2020. Increased densities of blue mussel Mytilus edulis were observed. Based on the 2020 dataset, no significant differences could be noted between impact and reference samples for both epibenthos and fish assemblages in both wind farms.	Change in sediment composition, Introduction of Underwater noise: impulsive, Introduction of artificial hard substrate, IMPACT, STATE CHANGE
Punzo, E; Pusceddu, A; Claudet, DJ	Ecological effects of offshore artificial structures at sea on macrobenthic and fish assemblages (NW Adriatic Sea)	2016	Both univariate and multivariate analyses showed different spatial patterns and temporal changes of macrozoobenthic communities surrounding the artificial structures. Using the results gathered from both hydroacoustic and fishing surveys around the three submerged structures, it has been reported that the abundance and biomass of fish close to the structures are higher than those in the open sea. Overall the results of my thesis highlighted the aggregation effect of the artificial structures under scrutiny on both the fish and macrobenthic assemblages.	Introduction of artificial hard substrate, Change in sediment composition, IMPACT
STATE CHANGES				
Causon, Paul D., Simon Jude, Andrew B. Gill, Paul Leinster	Critical evaluation of ecosystem changes from an offshore wind farm: producing natural capital asset and risk registers	2022	The UK Natural Capital Committee (NCC) methodology was intended to provide a framework through which trends in natural capital (NC) could be established and included within decision making processes. This critical evaluation of the NCC methodology demonstrated its limitations in assessing marine NC stocks associated with an OWF. A comprehensive asset register showing stocks of seabed and benthos NC could not be compiled using pre- and post-installation survey data as samples did not cover a large enough area.	STATE CHANGE
Colson, L; Braeckman, U; Moens, T	Effect of turbine presence and type on macrobenthic communities inside an offshore wind farm	2017	In this study from the North Sea, there were inconclusive results on the effects of offshore wind turbines on macrobenthic community structure.	STATE CHANGE
Coolen, Joop WP;	North Sea reefs: benthic biodiversity of artificial and rocky reefs in the southern North Sea	2017	In the North Sea macrobenthic invetebrates utilise wind turbines to colonise areas they cannot reach in one generation. Depth, location and habitat type had the greatest influence on reef community composition, but the relationship was non-linear for artificial reefs, with intermediate depths showing greatest species richness.	STATE CHANGE
De Backer, A; Hostens, K	Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: a Continued move towards Integration and Quantification	2017	Ch 5: there has been little change in soft sediment epibenthos and fish assemblages in offshore wind farms in the North Sea 6 years after the construction	STATE CHANGE

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Reubens, J.; Alsebai, M.; and Moens T.	Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded	2016	Ch 7: results from this study in the North Sea were inconsistent with other studies. Macrobenthic denstities and species richness were shown to be significantly greater as sites far from turbines than those close to turbines.	STATE CHANGE
Van Hoey, Gert; Coates, Delphine; Hostens, Kristian; Vincx, Magda;	The use of the Benthic Ecosystem Quality Index (BEQI) for the evaluation of the impact of the Thorntonbank wind farm on the soft-bottom macrobenthos	2011	The construction of 6 turbines disturbed the soft-bottom benthic community due to sand removal, sedimentation, and changes in currents. The opportunistic polychaete *Spiophanes bombyx* is abundant in the impacted area.	STATE CHANGE
Wang, Ting; Gao, Zhaoming; Ru, Xiaoshang; Wang, Xu; Yang, Bo; Zhang, Libin	Metabolomics for in situ monitoring of attached Crassostrea gigas and Mytilus edulis: Effects of offshore wind farms on aquatic organisms	2023	Crassostrea and Mytilus gill metabolomes were similar in the presence or absence of OWFs. Identification of metabolites discriminating the different area-types. Crassostrea and Mytilus metabolic pathways were significantly different in OWFs and marine ranches.	STATE CHANGE
IMPACTS				
Alexander, KA; Meyjes, SA; Heymans, JJ	Spatial ecosystem modelling of marine renewable energy installations: Gauging the utility of Ecospace	2016	At the whole ecosystem scale, species biomass was more likely to be affected by Artificial Reefs, whereas at the single installation scale, species biomass was more likely to be affected by Exclusion Zones. In both case studies, biomass changes were predicted to occur within the MRED installation areas rather than outside, suggesting that there is an effect of MRED installations. The model biomass results are likely to be overestimated and unreliable.	IMPACT
Ashley, M	The implications of co-locating marine protected areas around offshore wind farms	2014	Slight decline in flatfish landings and consistent landings of demersal fish after 2002, when OWF construction began. A steep decline was seen for crustacean landings in development areas between 2002 and 2005, followed by landings remaining steadier between 2005 and 2011. Nationally Nephrops landings increased and landings of crab remained consistent during this period. The presence of flatfish species in post-construction samples, both inside and outside the OWF may be due to anthropogenic effects or long term cycles. Natural decrease in sole and plaice appears to have occurred across the region. 8 years postconstruction habitat outside the OWF appears of greater benefit to flatfish species. Limited confidence in results.	IMPACT
Barbut, L; Vastenhoud, B; Vigin, L; Degraer, S; Volckaert, FAM; Lacroix, G	The proportion of flatfish recruitment in the North Sea potentially affected by offshore windfarms	2020	Based on modelling, study suggests that European plaice, common dab, and brill could be the most affected by OWFs, yet with local disparities across the North Sea.	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Barbut, Léo, Berthe Vastenhoud, Laurence Vigin, Steven Degraer, Filip A M Volckaert, Geneviève Lacroix	The proportion of flatfish recruitment in the North Sea potentially affected by offshore windfarms	2020	This modeling study examined the overlap between spawning grounds and OWFs and the contribution of OWF-origin settlers to nursery grounds for six flatfish species between 1997 and 2006. European plaice, common dab, and brill appeared most affected, with regional differences across the North Sea.	IMPACT
Berges, B.; van der Knaap, I.; van Keeken, O.; et al.	Strong site fidelity, residency and local behaviour of Atlantic cod (Gadus morhua) at two types of artificial reefs in an offshore wind farm	2024	Atlantic cod showed high fidelity to artificial reef sites for two types of reefs tested, they also resided and hid in artificial reefs for long periods of time. Authors suggest adding pipes for shelter was beneficial.	IMPACT
Bergström, L; Sundqvist, F; Bergström, U	Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community	2013	Increased densities of all piscivores studied, as well as the reef-associated species, were observed close to the turbine foundations in the first years of operation. The increase was attributed mainly to local changes in distribution rather than to immigration or increased local productivity. No effect on biodiversity was seen at larger scale of study. The results of monitoring before and after establishment of the wind farm indicated no major effects on benthic fish diversity and abundance compared to reference areas. Changes in the abundance of some species, as well as in community composition, were observed over time, but similar changes occurred in parallel in at least one of the reference areas.	IMPACT
Buyse, Jolien; Hostens, Kris; Degraer, Steven; De Backer, Annelies	Offshore wind farms affect the spatial distribution pattern of plaice Pleuronectes platessa at both the turbine and wind farm scale	2022	Sandy patches in between the rocks in the scour protection attract European plaice (4 times higher abundance compared to surrounding soft sediment), probably related to increased food abundance. At the wind farm scale, increased plaice abundance in one OWF suggests a refugium effect, though environmental conditions, fishing pressure, and foundation type may also play a role.	IMPACT
Choi, Y; Lee, HH; Oh, JK	Distribution of Fishes around the Offshore Wind Farm at the Southern Part of Yellow Sea by Trawl Net	2014	A total of 17 species were found at all four collection sites around an offshore wind farm, while 13 species were unique to one site. The wind farm's construction is expected to temporarily reduce fish in the area, but in the long term, species like Oplegnathus fasciatus and Sebastes shlegelli may increase due to the favorable environment created by the structures.	IMPACT
Claisse, Jeremy T; Pondella, Daniel J; Love, Milton; Zahn, Laurel A; Williams, Chelsea M; Williams, Jonathan P; Bull, Ann S;	Oil platforms off California are among the most productive marine fish habitats globally	2014	Concentrations of fish around oil platforms in California are higher than in any other analysed habitat, covering a diverse range of habitat types and geographic locations.	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Couperus, B.; Winter, E.; van Keeken, O.; et al.	Use of High Resolution Sonar for Near-Turbine Fish Observations (DIDSON) - WeSea 2007-002	2010	Using high resolution sonar, pelagic fish were shown to occur in greater concentrations close to turbines in an offshore wind farm in the Irish Sea, with densities a factor of 37 higher above the scour bed around monopiles than in open water between monopiles.	IMPACT
De Backer, A., Hostens K.	Soft Sediment Epibenthos And Fish Monitoring At The Belgian Offshore Wind Farm Area: Situation 6 And 7 Years After Construction	2018	No direct wind farm ('reef') effect, nor indirect fisheries exclusion effect, was observed for the soft-bottom epibenthos and demersal-benthopelagic fish assemblage in 2017. Species composition, species number, density and biomass (for epibenthos only) of the soft-bottom assemblage inside the OWFs were very similar compared to the assemblage in reference locations outside the OWFs. The species, originally inhabiting the soft sediments of both OWFs, remain to be dominant.	IMPACT
De Backer, A., Polet, H., Sys, K., Vanelslander, B., Hostens, K.	Fishing Activities In And Around Belgian Offshore Wind Farms: Trends In Effortand Landings Over The Period 2006-2017	2019	Presence of OWFs did not adversely affect fishing activity, plaice increased in several of the windfarms on the edges of the OWFs. Spatial changes in proportional LPUE of sole do not indicate a clear wind farm effect. For plaice however, more than 75% increase in proportional LPUE was observed, indicating an increased catch rate and a deviation of the general proportional trend around wind farms, where lower increases are observed. For plaice, LPUE seemed higher around some operational wind farms. As such, the relatively small loss of potential fishing grounds did not yet result in a real decrease of catches in the region.	IMPACT
Derweduwen, J.; Vandendriessche, S.; and Hostens, K.	Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded	2016	Ch 8: reports differences in fish and epibenthic communities between a North Sea wind and reference areas over a period from 2013-14.	IMPACT
Engell-Sørensen, K.	Possible Effects of the Offshore Wind Farm at Vindeby on the Outcome of Fishing	2002	It is not clear whether flatfish (especially turbot) migrate between the turbines during windy weather. It is therefore recommended that the investigation of the potential effects from electric cables and noise from wind turbines are concentrated to future offshore wind farms.	IMPACT
Gervelis, B.; Carey, D.	South Fork Wind Farm Atlantic Cod Spawning Survey	2020	Pre-construction hook and line assessment of cod spawning activity in the area where Deepwater Wind South Fork LLC would be constructing wind farms. Describes specific spawning activity in the area rather than effects.	IMPACT (T0)
Gervelis, Brian; Wilber, Dara H.; Brown, Lorraine; Carey, Drew A.	The Role of Fishery-Independent Bottom Trawl Surveys in Providing Regional and Temporal Context to Offshore Wind Farm Monitoring Studies	2023	There was no evidence that variation in catches near the OWF differed from regional trends in a way consistent with a detrimental impact of OSW farm operation.	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Gray, M., Stromberg, P-L., Rodmell, D.	Changes to fishing practices around the UK as a result of the development of offshore windfarms – Phase 1 (Revised).	2016	Although there was evidence of a small number of fishermen operating inside OSW farms, the key reason why they had not returned was heightened risk, perceived and actual, rather than changes to the ecosystem. The fishermen's responses to the questionnaires indicated that the main obstacles that limited the co-existence of fishing and offshore wind energy generation in the Eastern Irish Sea were: 1) The risks associated with turbines, cables, cable armouring and seabed construction debris to fishing inside OWFs; 2) Excessive disruption to fishing, loss of fishing gear and increasing steaming distances to fishing grounds caused by wind farm maintenance work; 3) A poor relationship and inadequate communication between fishermen and wind farm developers and their maintenance service companies; 4) The cumulative spatial encroachment of wind farms and MPAs on traditional fishing grounds.	IMPACT
Hal, R.V., Couperus, A.S., Fassler, S.M.M., Gastauer, S., Griffioen, B., Hintzen, N.T., Teal, L.R., Keeken, O.V. and Winter, H.V.	Monitoring- and Evaluation Program Near Shore Wind farm (MEP-NSW)	2012	The authors conclude that the reference areas were similar compared to OWE zones in abundance and average length of all species. Suggested that the wind farm did neither act as an attractant or deterrent. Differences in abundance and distribution of pelagic fish observed inside and outside the wind farm may therefore more likely be caused by natural migration and fish behaviour related factors such as temperature or food availability	IMPACT
Hansen, Kamilla Sande; Stenberg, Claus; Møller, Peter Rask	Smallscale distribution of fish in offshore windfarms	2012	Underwater video cameras assessed abundance of fish at 0, 25, and 50 m around wind turbine foundations in the Baltic Sea. Two-spotted gobies (G. flavescens) dominated in terms of numbers. The results suggest that OWFs in areas with homogeneous sand sediment have a higher impact on fish fauna compared to OWFs in areas with heterogeneous sediment.	IMPACT
Hintzen, Niels; Beukhof, Esther; Brunel, Thomas; Eweg, Annemiek; Hamon, Katell; de Koning, Susan; Mol, Arie; Steins, Nathalie	Exploring potential ecological impacts of different scenarios for spatial closures and fleet decommissioning for Dutch North Sea demersal fisheries	2021	The average condition of a fishing ground (relative benthic state) remains more or less stable under most of the scenarios.	IMPACT
Hoffmann, E.; Astrup, J.; Larsen, F.; et al.	Effects of Marine Windfarms on the Distribution of Fish, Shellfish and Marine Mammals in the Horns Rev Area	2000	No conclusive results and large variations in fish species abundance over 11 years of trawling surveys.	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Hoth, T; Dietrich, R; Huckstorf, V; Hartmann, M; Gloede, F; ...	Impacts on demersal fish communities in the North Sea based upon data from the first German offshore wind farm	2011	Study suggests that some fish species avoided the wind farm due to disturbance through running wind turbines. The main negative influences of wind turbines on fish are likely to be acoustic noise and vibrations by the turbine itself, and electromagnetic radiation of underwater cable connections. These influences may result in the disturbance of resident fish species and act as barriers to migrating fish	IMPACT
Huang, Ting-Chieh; Lu, Hsueh-Jung; Lin, Jia-Rong; Sun, Shih-Hsuan; Yen, Kou-Wei; Chen, Jing-Yi	Evaluating the Fish Aggregation Effect of Wind Turbine Facilities by using Scientific Echo Sounder in Nanlong Wind Farm Area, Western Taiwan	2021	In the joint surveys, we observed that the wind turbines had a relatively better fish aggregation effect than nearby neighboring wind towers and artificial reefs. The results of acoustic survey directly show a fish aggregation effect of the two wind turbines. The species and abundance information obtained by scuba diving within 20 m of the wind turbines also prove the aggregation effect, which includes fish hidden in the acoustic dead zone.	IMPACT
Hvidt, C.; Leonhard, S.; Klaustrup, M.; et al.	Hydro-Acoustic Monitoring of Fish Communities at Offshore Wind Farms	2006	No clear regional effects of the OWF were observed, as fish densities, biomass, and distributions showed no significant patterns across temporal or geographic variations. Abiotic factors like coarse sand influenced fish aggregations more than the wind farm itself. No local effects, such as increased fish densities near turbine foundations, were statistically evident, highlighting the challenges of accounting for high spatial and temporal variability in fish populations.	IMPACT
Kamermans, Pauline; Walles, Brenda; Kraan, Marloes; Van Duren, Luca A; Kleissen, Frank; Van der Have, Tom M; Smaal, Aad C; Poelman, Marnix;	Offshore wind farms as potential locations for flat oyster (Ostrea edulis) restoration in the Dutch North Sea	2018	Analysis showed that a number of wind farms in the Dutch section of the North Sea are suitable locations for development of flat oyster beds.	IMPACT
Khyria Swaleh Karama, Yoshiki Matsushita, Masahiro Inoue, Kenta Kojima, Kazuki Tone, Itsumi Nakamura, Ryo Kawabe	Movement pattern of red seabream Pagrus major and yellowtail Seriola quinqueradiata around Offshore Wind Turbine and the neighboring habitats in the waters near Goto Islands, Japan	2021	Red seabream and yellowtail released at the OWF showed low residence time (between 1 and 10 days) in the vicinity of the OWF and moved to the neighboring habitats. The study was based on the field experiments and acoutic tracking in winter and summer	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Parc eolien en mer de St Nazaire	Bilan annuel 2023 des études environnementales sur le parc éolien en mer de Saint-Nazaire	2024	The report includes findings from environmental monitoring programs conducted during the construction and operational phases of the offshore wind farm. These programs involve direct observations and studies on seabed flora and fauna, as well as research on fish and marine mammals. For instance, the report details how disturbed seabeds are gradually being recolonized by characteristic species and notes the "reef effect," where certain fish species are attracted to organisms accumulating on the wind turbine foundations. These insights are based on firsthand data collected through systematic environmental monitoring efforts.	IMPACT
Ramasco, V.	Glider study at Hywind Scotland	2022	The study found that zooplankton and fish biomass were higher closer to the wind park, particularly in weeks 3 and 4, with stronger fish schools showing more pronounced trends near the park. Zooplankton and fish peaking during the second half of the sampling campaign near the park suggest that the installations might boost zooplankton density. However, single fish showed lower densities near the park, and weak fish schools showed no clear trend with distance. The results indicate that the wind park may enhance primary and secondary production, leading to fish aggregations, but do not support the idea of a consistent increase in fish biomass over time. Instead, fish responses appear tied to natural phytoplankton blooms and subsequent trophic changes.	IMPACT
Raoux, A., Tecchio, S., Pezy, J.P., Lassalle, G., Degraer, S., Wilhelmsson, D., Cachera, M., Ernande, B., Le Guen, C., Haraldsson, M. and Grangeré, K.	Benthic and fish aggregation inside an offshore wind farm: Which effects on the trophic web functioning?	2017	This ecosystem-based approach of offshore wind farm impacts showed (1) an original control of the Courseulles-sur-mer site food web by pouting at the intermediate trophic levels, indicating a potentially “wasp-waist” controlled food web, (2) that the anticipated increase of mussel biomass after the offshore wind farm construction is predicted to lead to a food web dominated by detritivory, as hypothesized by Norling and Kautsky (2008), and (3) that the anticipated increase in benthic invertebrate and benthos feeding fish biomass, in response to the reef effect, is predicted to attract and benefit to apex predators, as hypothesized by Lindeboom et al. (2011) and Henkel et al. (2014). By combining the data collected on various ecosystem components, we determine in this study how the local food web structure and function may change 30 years after the installation of the offshore wind farm. The Ecopath models built in this study can thus be useful to interpret how other threats, such as climate change or restrictions of fisheries activities within the offshore wind farm limits, can further affect the trophic web structure and functioning. This study could be considered as a first step in using food web models to assess offshore	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
			wind farm impacts on the whole ecosystem.	
Reubens, J.T., Braeckman, U., Vanaverbeke, J., Van Colen, C., Degraer, S. and Vincx, M.	Aggregation at windmill artificial reefs: CPUE of Atlantic cod (Gadus morhua) and pouting (Trisopterus luscus) at different habitats in the Belgian part of the North Sea	2013	with seasonality, for both Atlantic cod and pouting. CPUE was highly enhanced (mainly in summer and autumn) at the WARs in comparison with the sandy bottom sites. Our results clearly indicate an aggregation effect of the WARs on pouting and Atlantic cod populations. This aggregation effect was also seen at the shipwrecks, but to a lesser extent. A third striking result of this study is the aberrant low CPUE rates in 2009 at the WARs for Atlantic cod compared to 2010–2011. This was notthe case atthe other habitats.As theWARs are relatively new structures (built in 2008) constructed in an area previously dominated by soft sediments, a construction effect is suggested to explain the variation in CPUE at the WARs between the different years for Atlantic cod	IMPACT
Roach, Michael	Interaction Between the Yorkshire Coast Static Gear Crustacean Fishery and Offshore Wind Energy Development	2019	Study highlighted that building an OWF has short-term effects (within 3 years) on the ecology of the lobster population and the commercial and non-commercial bycatch in the area, but also states that whilst these changes could be attributed to the construction and subsequent operation of the wind farm , it is more likely that the influence of the exclusion of fishing effort during the construction phase was the dominant factor.	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Roach, Michael; Revill, Andy; Johnson, Magnus J.	Co-existence in practice: a collaborative study of the effects of the Westermost Rough offshore wind development on the size distribution and catch rates of a commercially important lobster (Homarus gammarus) population	2022	Evidence of direct (positive) impact of OWF on lobster fishery, although the study recommends caution when extrapolating findings. The results here, whilst focused on a relatively small windfarm, can aid understanding the effects of OW development on the ecology of lobster populations and offer insight into positive interactions between industries. However, translating these results to other sites, fishery types and alternative lobster populations should consider differences in ecology, habitat and fishery management. Whilst effects were observed during the construction phase, these tended to be positive results to size structure and LPUE of lobsters in the windfarm site likely the result of exclusion of fishing effort due to safety concerns. Subsequent post-construction surveys have highlighted a return to trends that were observed in the pre-construction survey, indicating similar size structure and LPUE but increased CPUE of lobsters. The final year post-construction survey in 2019 followed the same trend as the pre-construction survey, indicating the size distribution of lobsters has not been affected by the operational phase of the windfarm	IMPACT
Scheld, Andrew M.; Beckensteiner, Jennifer; Munroe, Daphne M.; Powell, Eric N.; Borsetti, Sarah; Hofmann, Eileen E.; Klinck, John M.	The Atlantic surfclam fishery and offshore wind energy development: 2. Assessing economic impacts	2022	Over the longer-term, it is likely that the Atlantic surfclam industry will adjust to new conditions, by adapting to the constrains related to development of offshore wind energy, or failing to continue operations.	IMPACT
Schutter, M.; Dorenbosch, M.; Driessen, F.; et al.	Oil and gas platforms as artificial substrates for epibenthic North Sea fauna: Effects of location and depth	2019	Abundance and diversity of invertebrates and fish species found on or around eight Dutch and nine Danish oil and gas platforms. Species diversity was not significantly different between geographical clusters; however, average abundance was significantly higher on in the northern cluster. Invertebrate and fish communities did not change significantly with depth. However, depth zone was a significant clustering factor: communities closer to the seafloor (maximum depth minus 5m) were characterized by higher species diversity and species richness compared to communities found closer to the surface (<10m)	IMPACT
Shimada, Hideki; Asano, Kenji; Nagai, Yu; Ozawa, Akito	Assessing the Impact of Offshore Wind Power Deployment on Fishery: A Synthetic Control Approach	2022	With publicly available information on offshore wind farms and panel data on fishery production in Japan, there were no statistically significant effect of offshore wind power deployments on local fisheries. Although generalisation of findings requires caution because they are based on small-scale wind farms, results imply that such moderate-size wind projects may not harm local fisheries.	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Skerritt, DJ; Fitzsimmons, C; Polunin, NVC; ...	Investigating the impact of offshore wind farms on European Lobster (Homarus gammarus) and Brown Crab (Cancer pagurus) fisheries	2012	A smaller population of lobster was present within the demonstration wind farm site than at the inshore 'control', and the average size of lobster there within the wind farm was greater. A large population of crab, with a larger average size was also observed at the wind farm site. However, it remains unclear whether spatial variations in the shellfish populations are influenced by habitat differences or other physical properties, such as distance from shore, depth of water or temperature. Capture and recapture rates were very low within the wind farm site, which made the population modelling unfeasible there.	IMPACT
Slavik, K., Lemmen, C., Zhang, W., Kerimoglu, O., Klingbeil, K. and Wirtz, K.W.	The large-scale impact of offshore wind farm structures on pelagic primary productivity in the southern North Sea	2019	Epibenthic communities on offshore wind turbine foundations are frequently dominated by blue mussels (Mytilus edulis), a filter feeding bivalve. Model simulations indicate a non-negligible reduction in primary productivity of 8% within offshore wind farms and induced maximal increases of the same magnitude in daily productivity also far from the wind farms.	IMPACT
Stelzenmueller, Vanessa; Gimpel, Antje; Haslob, Holger; Letschert, Jonas; Berkenhagen, Joerg; Bruening, Simone	Sustainable co-location solutions for offshore wind farms and fisheries need to account for socio-ecological trade-offs	2021	North Sea, brown crab fishery in the vicinity of OWF could be economically viable and could lower the susceptibility to risk by diversifying fishing activities. The spill-over potentials of brown crabs differ according to the environmental setting of an OWF.	IMPACT
Stromp, Stephanie, Andrew M. Scheld, John M. Klinck, Daphne M. Munroe, Eric N. Powell, Roger Mann, Sarah Borsetti, Eileen E. Hofmann	Interactive Effects of Climate Change-Induced Range Shifts and Wind Energy Development on Future Economic Conditions of the Atlantic Surfclam Fishery	2023	There is potential that the range of Atlantic surfclams will continue to shift towards offshore wind energy lease areas. Atlantic surfclam fishery could be disrupted due to to combined pressures from competing ocean uses (quahog fishery, OWFs) and climate change. this will be a prediction as there are no direct OWF studies on surf clams (as only 8 turbines in the water in 3 areas).	IMPACT
Stromp, Stephanie;	The Influence of Range Shifts and Wind Energy on the Atlantic Surfclam (Spisula Solidissima) and Ocean Quahog (Arctica Islandica) Fisheries on the US Outer Continental Shelf	2023	Species overlap between surfclams and ocean quahogs is most prominent in the 40-55m depth range where size and density of surfclams declines with decreasing temperature, indicative of newly recruited populations in offshore, cooler waters. This analysis emphasizes the potential for economic disruption of fisheries and highlights the need for regulatory changes to allow mixed catches and landings.	IMPACT
Thatcher, H; Stamp, T; Wilcockson, D; Moore, PJ	Residency and habitat use of European lobster (Homarus gammarus) within an offshore wind farm	2023	Individuals were found to exhibit high residency to the tagging sites, with over half of tagged lobsters present at the tagging sites for 70% of the study period. Over 50% of all detections were recorded within 35 m of the scour protection. These results suggest that particular areas of habitat within fixed-turbine OWFs provide a suitable habitat for lobsters - likely the result of artificial reef effects arising from the addition of artificial hard substate into previously soft sediment dominated habitats.	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
van Deurs, M., Grome, T.M., Kaspersen, M., Jensen, H., Stenberg, C., Sørensen, T.K., Støttrup, J., Warnar, T. and Mosegaard, H.	Short- and long-term effects of an offshore wind farm on three species of sandeel and their sand habitat	2012	The results from an analysis on all species combined revealed a positive short-term effect on the densities of both juveniles and adults, which was consistent with a reduction in the fraction of silt+clay. In the long term, a negative effect on juveniles was found; however, this effect was neither consistent with the additional survey in 2009 nor the silt+clay fraction. Subsequent analysis at the species level revealed that the effects detected were driven by Hyperoplus lanceolatus, which dominated the study area in all years. Habitat quality was high in both the affected and control area throughout the study period.	IMPACT
van Hal, R.	Demersal Fish Monitoring Princess Amalia Wind Farm (No. C125/14)	2014	No significant effect of the wind farm on the total fish number per hectare was found. The number of target species (sole, plaice, dab, turbot, flounder, and brill) in the farm area was similar to regular surveys. Slightly more larger fish, including target species, were caught in the wind farm, it was concluded that this was likely due to differences in survey protocols rather than the wind farm's impact.	IMPACT
van Hal, Ralf	Roundfish Monitoring Princess Amalia Wind Farm	2013	Sprat and herring in PAWP were larger in length than those in the IBTS tows, however the collected data was too limited to explain this larger size. Only a single juvenile cod was caught in PAWP, but the tows are done in the middle between the monopiles, while other sources showed that cod aggregate close to the structures. There is no clear indication of a positive or a negative effect of the wind farm on the overall catches or on the target species of the IBTS that were found in the farm area: herring, sprat, whiting and cod. There is a suggestion of a positive effect of PAWP on the presence of greater sand-eel. The field work conducted as part of this study is too limited to draw statistically significant conclusions regarding the refugium function of the wind farm for roundfish.	IMPACT
Van Hoey, Gert; Bastardie, Francois; Birchenough, Silvana; De Backer, Annelies; Gill, Andrew; De Koning, Susan; Hodgson, Sophia; Chai, S Mangi; Steenbergen, Josien; Termeer, Emma;	Overview of the effects of offshore wind farms on fisheries and aquaculture	2021	Belgian Case Study: The refugium effect increased fish densities, such as Callionymus lyra and Pleuronectes platessa, due to fisheries exclusion and more food. Atlantic cod and pouting were attracted to OWFs for feeding, with no long-term growth impacts. Juvenile seabass showed temporary stress from pile driving, but no growth effects. Cod experienced swim bladder issues from pile driving. Danish Case Study: The EIA found minimal impacts on hydrography, seabed type, and water quality. Fish populations showed slight changes due to hard substrate, but no significant shifts in species. Harbour porpoise density was low, with noise impacts from pile driving. Crane collision risks were low, and sediment impacts on nearby reefs were minimal.	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Vandendriessche, S., da Costa, A.R. and Hostens, K.	Wind farms and their influence on the occurrence of ichthyoplankton and squid larvae	2016	Based on the data of 2010-2013, no clear evidence could be provided for positive impacts of wind farms on early life stages of fish and squid.	IMPACT
Vandendriessche, S.; Derweduwen, J.; Hostens, K.	Offshore Wind Farms in the Belgian Part of the North Sea: Selected findings from the baseline and targeted monitoring	2011	Ch5: Documents spatial and temporal migration patterns of cod in a windfarm	IMPACT
Vandendriessche, S.; Persoon, K.; Torreele, E.; Reubens, J. and Hostens, K.	Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded	2016	Ch 5: in this study on recreational fishing, less than 2% of anglers reported fishing in offshore wind farms in the North Sea largely due to the protection zones around wind farms and the lack of charter vessels travelling to wind farms.	IMPACT
Vandendriessche, S.; Ribeiro da Costa, A. M.; and Hostens, K.	Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Environmental impact monitoring reloaded	2016	Ch 9: the effects of a wind farm in the North Sea on fish eggs, fish larvae and squid larvae were studied. No significant effects were identified.	IMPACT
Waggitt, JJ; Cazenave, PW; Howarth, LM; Evans, PGH; van der Kooij, J; Hiddink, JG	Combined measurements of prey availability explain habitat selection in foraging seabirds	2018	The probability of encountering foraging seabirds was highest around fronts between mixed and stratified water. Prey were denser and shallower in mixed water, whilst encounters with prey were most frequent in stratified water. Therefore, no single measurement of increased prey availability coincided with the location of fronts.	IMPACT
Walls, R.; Pendlebury, C.; Lancaster, J.; et al.	Analysis of Marine Ecology Monitoring Plan Data from the Robin Rigg Offshore Wind Farm, Scotland (Operational Year 3): Chapter 1- Introduction and Executive Summary	2013	The study found no evidence that the construction and operation of the offshore wind farm caused significant changes in fish and benthic assemblages. Natural variability in mobile estuarine sand bank systems and environmental conditions likely influenced community composition, making it difficult to separate natural drivers from anthropogenic ones.	IMPACT, STATE CHANGE
Wang, Sheng V; Wrede, Alexa; Tremblay, Nelly; Beermann, Jan	Low-frequency noise pollution impairs burrowing activities of marine benthic invertebrates	2022	Low frequency noise negatively impacted the crustacean Corophium volutator, reducing bioturbation and luminophore burial depth. The effects on Arenicola marina and Limecola balthica were inconclusive, though A. marina showed variable bioirrigation rates, and L. balthica exhibited a potential stress response. These findings suggest risks to benthic macroinvertebrates and their ecosystem services.	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Wang, T; Yu, W; Zou, X; Zhang, D; Li, B; ...	Zooplankton community responses and the relation to environmental factors from established offshore wind farms within the Rudong coastal area of China	2018	Wind turbine foundations significantly reduced macrozooplankton quantity but had mixed biomass effects. Microzooplankton increased sharply in spring but declined in autumn. Postconstruction trends indicate eutrophication, with water temperature, oxygen, suspended matter, and pH as key factors. Suspended matter had opposing effects on macro- and microzooplankton, suggesting a shift toward smaller species.	IMPACT
Werner, KM; Haslob, H; Reichel, AF; Gimpel, A; Stelzenmüller, V	Offshore wind farm foundations as artificial reefs: The devil is in the detail	2024	There was evidence that the foundation type for offshore wind turbines can impact the density of cod. It was found that catch rates of Atlantic cod were significantly higher around monopiles with rock protection.	IMPACT
Wilber, D.H., Carey, D.A. and Griffin, M.	Flatfish habitat use near North America's first offshore wind farm	2018	Although flatfish abundance, size, and condition differed spatially near the Block Island Wind Farm and temporally between the baseline and operation time periods, these differences were not consistent with impacts from wind farm construction or operation. Flatfish abundance, size, and condition varied spatially and temporally. Seasonal variation in female winter flounder condition was consistent with spawning. Wind farm construction and operation were not associated with flatfish variability.	IMPACT
Wilber, Dara H; Brown, Lorraine J; Griffin, Matthew; Carey, Drew A;	American lobster Homarus americanus responses to construction and operation of an offshore wind farm in southern New England	2024	A BACI design found that the abundance of American lobster decline pre vs. post construction at both the impact and control locations. However, these findings cannot distinguish wind farm effects from regional shifts in lobster distributions to deeper, colder habitat.	IMPACT
Wilhelmsson, D	Aspects of offshore renewable energy and the alterations of marine habitats	2009	Field surveys and experiments indicate that offshore wind- and wave farms can boost local fish and decapod diversity. Reef structures up to 1 m high increase benthic fish, while single-entrance holes favor edible crabs (Cancer pagurus). However, added complexity may heighten predation pressure. Homarus gammarus and fish showed specific micro-habitat use, while filtering organisms (Mytilus and Balanus spp.) thrive on offshore structures. Substrate material and orientation influence epibenthic colonization, and wind turbines may alter nearby seabed habitats. Properly planned, ORED can benefit marine ecosystems, but it may also threaten conservation areas and species.	IMPACT
Winter, E.; Aarts, G.; van Keeken, O.	Cod and Sole Behaviour in an Offshore Wind Farm	2012	Sole appeared indifferent to the presence of OW structures, whilst dod had high individual variation in wind farm use. The presence of an offshore wind farm might be beneficial for cod.	IMPACT

Authors	Title	Publication Year	Key evidence and findings	Pressure-state-impact
Wood, Louisa E; Silva, Tiago AM; Heal, Richard; Kennerley, Adam; Stebbing, Paul; Fernand, Liam; Tidbury, Hannah J	Unaided dispersal risk of Magallana gigas into and around the UK: combining particle tracking modelling and environmental suitability scoring	2021	The OW industry is rapidly expanding and future risk from this unaided pathway for spread of Pacific oyster (M. gigas) may increase.	IMPACT
Wright, S.R., Lynam, C.P., Righton, D.A., Metcalfe, J., Hunter, E., Riley, A., Garcia, L., Posen, P. and Hyder, K.	Structure in a sea of sand: fish abundance in relation to man-made structures in the North Sea	2020	High densities of Atlantic cod (Gadus morhua L.), European plaice (Pleuronectes platessa L.), and thornback ray (Raja clavata L.) corresponded to increased abundance of structures. Whether fish actively seek structures or coincide with them is uncertain. This connection highlights the need for careful consideration in choosing decommissioning scenarios or other structural changes to these sites.	IMPACT

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Annex 8: Consolidated Report from the Review Group

Consolidated Report from the Review Group for the Workshop to Compile Evidence on the Impacts of Offshore Renewable Energy on Fisheries and Marine Ecosystems (WKCOMPORE)

Meeting: By Correspondence February–March 2025

Request: Review the outputs of WKCOMPORE, which will form the basis of the advice to EC-DGMARE on the socioeconomic impacts of ORE in fisheries

And to assess whether,

a) The report was complete and addressed the Terms of Reference.
b) Whether important points were missed or overlooked that are relevant to the request.
c) If the reviewers disagree with the conclusions that were made.

Background

The workshop to compile evidence on the impacts of offshore renewable energy on fisheries and marine ecosystems (WKCOMPORE) was set in response to a request to ICES on the socio-economic impacts of Offshore Renewable Energy (ORE) on fisheries and methodologies to model (cumulative) impacts in the Celtic Sea, Greater North Sea and Baltic Sea (ICES ecoregions).

The main objective of the request to ICES is to understand better the socio-economic impacts of large-scale ORE developments on the fisheries sector. The focus of the advice is on bottom-fixed offshore wind devices but evidence from floating wind and ocean energy (tidal, wave, etc.) can be considered where necessary.

More specifically, the request aims to address the following questions:

j) Assess data and resources available for the analysis of the economic[15] and social[16] impacts of ORE developments on the fisheries sector. On that basis:
k) Summarise the known and projected economic and social impacts of existing and planned offshore renewable developments (on fisheries, at métier and fleet levels). Trade-offs between negative economic impacts on fisheries and positive economic impacts of the ORE sector should be considered.;
l) Describe sources of information available, methods that may be applied, and further data and information required, to address the economic and social impacts of ORE on fishers.
m) Summarize the known ecological impacts of ORE developments and their intensity (severe, medium, limited, unknown) on main commercial fish species[17] for the areas listed above and at population levels (positive and negative impacts) looking at the different phases of ORE development (survey, construction, operation, decommissioning). A

[15] Focusing on economic impacts on fishers

[16] Identify priority impacts, but focus the assessment on employment of fishers

[17] species included in the ICES advice on list of Descriptor 3 species to support reporting by EU Member States under MSFD Article 17 (https://doi.org/10.17895/ices.advice.21332967

specific case study on the effects on recruitment of western Baltic herring and of the effects on harbour porpoises should be developed.

n) Provide recommendations for next steps to define methodologies to model cumulative impacts of offshore wind on commercial fisheries (temporary, permanent) and the possibility to adopt mitigation measures
o) Provide a review, based on the most recent literature, to describe how changes on hydrodynamic conditions produced by ORE may change the food availability to filter-feeders and influence phytoplankton primary production;
p) Provide a review, based on the most recent literature, of the ways artificial structures could influence the colonization of new areas by species, both indigenous and non-indigenous species. Based on data available for other structures (e.g. oil & gas), also from other locations (e.g. US), extrapolate how this colonization will affect ORE developments.
q) Provide a review, based on the most recent literature, of the ways in which pelagic species (especially commercial fish species) may react to dynamic cables suspended in the water column (floating wind);
r) List options for mitigation measures, good practices, and spatial planning for ORE developments and assess their strengths, weaknesses, implications and uncertainties. List priorities for research and monitoring related to these options

Note on Process

This report is a compilation of feedback from five experts. These experts, with diverse scientific backgrounds, are based in Norway, Germany, Spain, and the USA.

During the report's development by the WKCOMPORE authors, they decided to divide it into three sections. To ensure thorough review, an ICES Professional Officer directed the five experts to focus their feedback on these three sections, which each addressed different parts of the report's Terms of Reference, summarised here:

Part 1: Economic and social impacts of ORE on fisheries (questions a, b, & c of the request, ToR a.i.i and a.i.ii)

Part 2: Cumulative impacts assessment methods of ORE and mitigation measures (questions e & i of the request and ToRs a.v.i. and a.vii of WKCOMPORE)

Part 3: Review of the ecological, hydrographic, fisheries and select species impacts of ORE developments (questions d, f, g, & h of the request and ToR a.ii, a.iii, a.iv, a.v of WKCOMPORE ToR).

After each expert submitted their individual review, the Chair (of the review process) and an ICES Secretariat Professional Officer held separate meetings with two of the reviewers. These meetings aimed to discuss and combine the key points from all the reviews, creating a unified set of recommendations for the Advice Drafting Group (the team responsible for creating the final advice).

Summary

The review group reached a consensus that the submitted report demonstrated completeness and fulfilled the objectives delineated in the Terms of Reference. Furthermore, the reviewers generally concurred with the conclusions presented. Recommendations were made for the implementation of more rigorous and unambiguous language in specific sections. Detailed feedback has been provided to the authors via the ICES SharePoint platform. The subsequent sections of this Reviewer Report will focus on the identification of key omissions or oversights pertinent to the original request, organized according to Parts 1, 2, and 3 as previously defined.

Part 1

The thoroughness of the literature review in Part 1 highlights significant gaps in our current understanding. To gain a comprehensive perspective, it's essential to consider Parts 1, 2, and 3 collectively. While Part 1, focusing on the impacts of changing fishing spots for fishers, is of primary interest, it represents only a limited aspect of the broader picture. Although the Terms of Reference have been met, it's crucial to define the next steps. This includes outlining both short-term and long-term work that ICES can undertake, recognizing the vast diversity of system types involved. Notably, conducting scientific surveys within wind parks presents a challenge. In an ICES context, the work must be expanded to provide sensible advice. Exploring the availability of existing databases for immediate assistance is also necessary.

A critical aspect needing attention is the **understanding of fisheries interactions**, which is currently limited due to insufficient monitoring. The report must acknowledge this limitation and caveat its findings accordingly. Additionally, the **method for describing direct and indirect effects and deterioration is missing**, leaving a significant gap in the assessment. **Monitoring is key** to detecting changes, but this is only possible if monitoring requirements are adequately addressed. The report also **omits other indirect effects**, such as potential market changes, impacts on domestic seafood supply, and the role of fisheries in carbon mitigation. Finally, it's crucial to recognize that **consistent assessment methods** are as important as additional resources for accurately measuring changes over time.

Despite significant effort invested in Part 1, the Terms of Reference (ToRs) presented a fundamental challenge: they were, in essence, "unanswerable" due to the lack of detailed fleet-level economic impact data. Therefore, the report needs to begin by clearly explaining why the ToRs, as requested by DG MARE, could not be fully addressed with precise numerical data. We can provide a broad-scale response, but detailed figures are simply unavailable. This necessitates a clearer explanation of why tables with numerical impact data are absent. The authors' reliance on a literature review stems directly from this data scarcity. To emphasize this point, the report should be restructured from the outset to highlight the reasons for the data limitations.

The report offers a comprehensive overview of offshore wind farm (OWF) impacts, encompassing environmental, economic, and social aspects, and provides examples of assessment methodologies. However, the complexity of ecological impacts presents a challenge, as cause-effect chains are difficult to identify due to intricate interactions and site-specific ecosystem responses. Significant limitations exist, primarily due to data gaps. These gaps include the lack of quantitative estimates, in-situ observations of ecosystem changes, and sufficient knowledge of cause-effect chains related to direct and indirect effects. Furthermore, the relative contribution of direct versus indirect effects on a regional scale and cumulative impacts remains uncertain, as scientific evidence of cumulative effects is limited for certain impacts.

Finally, the social and economic impacts discussed in Part 1 should be further developed, with the support of the three ecoregions Expert Groups, who possess the necessary fisheries data to assemble existing information for assessing these immediate social and economic impacts.

Part 2

The report suggests several key recommendations for improving the understanding and management of offshore wind farm impacts. Firstly, data gaps and research needs should be consolidated into a visual timeline for clearer understanding and planning. Secondly, early scientist involvement is crucial, with integration into the wind park design phase before construction through EU Commission-led workshops.

Moving beyond business-as-usual practices is necessary, advocating for the adoption of best practices incorporating social science, philosophy of science, and sustainability, aiming for a “reverse engineered” vision of success in the North Sea based on data sharing and collaboration across the marine science, fisheries and renewable energy sectors.

Furthermore, enhanced stakeholder integration should be prioritized through collaborative research, multi-sector governance, and community engagement, drawing inspiration from successful EU project examples. It's essential to clarify responsibilities for integration, timelines, and funding sources. Stronger language should be considered for sensitive areas, with more definitive terms (for example “off-limits” or as appropriate in a legal sense) used for development near critically endangered species such as Baltic Proper harbour porpoises.

Mandatory monitoring is essential, with DG MARE leading the establishment of a systematic observation network for all wind farms, both new and existing, to effectively differentiate DWF-induced effects from natural variability.

Section 4.1.2 requires a table outlining the ecosystem models and their respective spatial resolution. Additionally, particular attention should be paid to areas where public awareness would be beneficial, and cause-and-effect relationships with selected activities should be clearly discussed.

The impact assessment process itself must be described in detail to illustrate its inherent challenges and the reasons for its infrequent application. Issues arise from the lack of detailed data in small geographical areas. The process is also lengthy, involving multiple stakeholders. Importantly, it reveals significant gaps in available data, underscoring the value of qualitative insights gathered from fishers.

To enhance the report, Section 4.2.1 should be synthesized by condensing its information into a revised introductory paragraph followed by five key points, providing a more focused and accessible overview. Furthermore, it is recommended to incorporate "best practices" related to wind fisheries, particularly those concerning lobster fisheries from the Northeast USA. Drawing upon the experience of the Bureau of Ocean Energy Management (BOEM) in the United States, the report should explore how they address the challenges posed by offshore wind development to the critically endangered Right Whales. Specifically, the report should highlight the interagency strategy employed by BOEM and NOAA, which aims to promote the recovery of endangered species while responsibly developing offshore wind energy, as detailed in the provided NOAA Fisheries media release. This inclusion would provide valuable insights into successful strategies for balancing renewable energy development with environmental protection.

Part 3

Data gaps are particularly prevalent for floating turbines and regions outside the North Sea, as research has predominantly focused on the North Sea and fixed wind turbines. To address these limitations, future research should prioritize process-oriented observations, modeling studies in diverse regions, and the socioeconomic impacts on fisheries.

The methodology employed in ToR a.ii demonstrates a novel assessment framework predicated on the ecological traits of 34 key fisheries species. This framework effectively establishes a linkage between offshore wind farm (OWF)-induced environmental state changes and corresponding population characteristics and response traits. The application of this assessment across the North Sea, Celtic Sea, and Baltic Sea, likely limited to fixed-foundation OWFs, underscores its potential utility.

It is recommended that future research initiatives expand the scope of this assessment framework to encompass additional ICES regions and extend its applicability to floating-foundation OWFs. Such an expansion would enhance the comprehensiveness of impact assessments and provide a more robust understanding of the ecological implications of diverse OWF deployments.

General Comments

Overall, the workshop report successfully fulfills its Terms of Reference mandate, but there are some key areas for improvement. The heading structure should be simplified to no more than three levels for better readability. To ensure clarity and consistency, avoid using acronyms such as CEA and instead spell out the full term "Cumulative Effects Assessment" throughout the report. The report would also benefit from the inclusion of more visuals, specifically a data overview table designed to be easily understood by policymakers, clearly outlining data, sources, and spatial resolution.

The report, while containing excellent individual components, suffers from **incomplete integration**, as these elements are not effectively woven together into a cohesive whole. Furthermore, claims regarding reduced fossil fuel dependency and greenhouse gas reduction **lack substantiation** and require proper referencing. If such references are unavailable, the report should instead focus on documenting development over time and outlining plans to meet stated targets.

Given the report's length of 334 pages, it's crucial to be transparent about the current state of knowledge to avoid giving the impression that all aspects of the topic are fully understood. Clearly state what is known, what is unknown, and what further information is required. In addition, identify potential collaborators for conducting comprehensive cumulative assessments. Finally, it is important to consider the credibility, legitimacy, and saliency of integrated assessments, as referenced in the WGMARS reports.

To effectively address the data gaps associated with offshore wind development, a **flat cooperation structure with the wind industry is essential**. Experience has demonstrated that **top-down control is counter-productive** to establishing sound management practices. Looking at the **big picture**, coordination with the wind farm industry should be pursued in alignment with the EU Commission's Corporate Sustainability Reporting Directive (CSRD). This is particularly relevant as companies with over 500 employees are now required to report on "double materiality," which necessitates a comprehensive understanding of both the financial and environmental impacts of their operations.

Conclusion

Based on the evaluation of available data, the reviewers have determined that the WKCOMPORE report has adequately addressed the objectives outlined in the Terms of Reference. The conclusions presented within the report are considered to provide a robust evidentiary basis for the subsequent development of advisory recommendations for DG MARE.

Annex 9: Feedback of Stakeholders on the ToRs

Stakeholder breakout group WKCOMPORE

Tuesday 4 February 2025 - Led by: Marloes Kraan

Approach

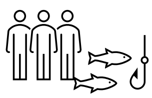
As the one-week workshop, WKCOMPORE aimed to finish the three subsection reports and integrate them whilst engaging with participants from science and interest groups (stakeholders), it was deemed important to have at least one sub session with the stakeholders separately. This would allow for more time to engage with them and to systematically gather and better understand their perspective to the TORs. Four stakeholders joined the sub session.

The goal of this sub session thus was: go through the TORs and collect relevant issues (evidence on impacts, concerns, views, questions) from the participants in relation to the four main topics of the TORs of the ICES advice request.

In order to so, the TORs were read out loud and shared in the chat. And the feedback was gathered per topic: 1) social and ecological impact of ORE on fisheries, 2) ecological impact, 3) cumulative impact and lastly, 4) spatial planning, mitigation measures and good practices. Per topic the participants would take turns and respond whilst their response was recorded on a shared screen so that they could see how it was noted down. The rough notes have been saved separately by the facilitator and were sent to the chairs of the three parts. They were requested to evaluate whether they had / were able to include the mentioned points or not and if not, why not. As a next step the rough notes were summarised in clear and concise points, grouped per topic, and shared in the plenary later that day. The resources shared by the stakeholders were sent to the chairs of the subsections for them to take along.

Issues

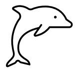
- Important to make a difference between fixed and floating wind poles & and differentiate between phases of construction
- Cables are also an issue
- Impacts: also think about risks, feedback loops (ecological impact has consequences for fisheries), scale (impact at local level), effects on land, value of quota
- Indirect effect: decrease efficiency, patchiness of resource, encroachment
- If look at ORE site – take fishing patters into account (15% in area – but perhaps whole trawl cannot be done anymore -> so 100% effect!)
- Historical landings – does not tell importance of current / future use (we know change is normal)
- Decommissioning – we have learnt from oil and gas. We do not know what will happen in 30 years



Social and economic impact of ORE on fisheries

Science for sustainable seas

Issues

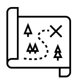


Ecological impacts

- There are many projects on potential impacts of ORE: The Problem is: not so much is known in fact. *What is known – is studied on a scale way smaller* than what is coming on us. There is a tipping point, with a point of no return
  - We are concerned about the ecological impact of ORE! greatest concern indirect conflict = effect environment and fish – effect for generations!
- the framing of research (done by some) is a big concern: a fish is not a fish. A study done on this scale is not conclusive.
- We are concerned about effect on pelagic species
- We are concerned about reproduction
- Also question what did we NOT see in a certain area?
- For western Baltic spring spawners: **research idea** – look at fishers logbooks
- What I miss is a structured lit review in the ecology section – make clear whatthe gaps are
- Environmental effect -> what is state of play on plastic particles? Abrasion of wings of wind mills?

Science for sustainable seas

Issues



Spatial planning, mitigation measures good practices

- Mitigation measures:
  - **think outside of the box here.** Often developers and regulators try to avoid and minimise – they tend to focus on what they need do in relation to the site. But for my fishery (clams) -> they *could* minimize impact if they seeded grounds outside the park in proportion to what we are loosing in the park.
  - If ORE has an impact on **something protected** (habitat or species) – need to avoid, reduce, mitigate or compensate – can we do that **for commercial species as well?**
  - If aggregation within wind energy area because of structure. **Can we minimize impact on that fishery by providing something for them to aggregate outside of wind park? Instead of compensating fishers?**

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Tradeoffs between negative economic impacts on fisheries and positive economic impacts of the ORE sector

- Strange that this is part of the request.
- Fishers are fishers for a reason and do not want to do something else
- Fishing is more than a job, it is heritage, culture, way of life, brings food
- There is no such thing as dry trade off here

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Feedback on the format

One of the participants expressed surprise at the beginning of the sub session that 'stakeholders' were set apart [fenced in] in this way, also because (s)he is also member to relevant ICES WGs, and participates in MIACO. Some of the participants also have a mixed background as scientist working for the industry or an NGO, so they questioned why they were set apart based on their affiliation. If only they (as all other participants) express their potential conflict of interest, there is no need for such separation. The facilitator understood the feedback, and said she would discuss this with the chairs of the meeting and with Marta Ballesteros (the new chair of WGENGAGE) to see how in ICES we can progress on this matter. At the end of the sub session all participants expressed that this session had been very useful and even though the principal question still stands, the sub session had been very valuable as it allowed enough time to express all known issues and concerns in relation to the TORs whilst also being able to engage with the other participants in a meaningful way.