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Co-location of fisheries and offshore wind farms: Current practices and enabling conditions in the North Sea

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ABSTRACT

Current expansion in offshore wind farm (OWF) development is resulting in increased spatial conflicts with other uses. In the North Sea, marine spatial planning (MSP) processes include co-existence strategies, with co-location between fisheries and offshore wind farms often discussed. However, current legal regulations and the lack of adequate scientific evidence to document economic viability of proposed passive gears, coupled with uncertainties regarding the implementation approach, continue to limit progress in developing co-location solutions. We synthesized current regulations and practices relevant to offshore wind farms and fisheries and conducted spatial-temporal overlap analysis of pot and trap fisheries targeting crustaceans in offshore wind farms to understand their potential for co-location. Our results showed the largest potential for co-location of pot and trap fisheries targeting crustaceans is located in OWFs that already exist or will be constructed until 2030. We also identified 1) gaps in fisheries and (OWF) regulations and 2) sector challenges that hindered the successful implementation of fisheries and offshore wind farm co-location. We discuss and recommend enabling conditions, including more science-based evidence on socio-economic and ecological viability of passive fisheries in offshore areas. Experiments on pot and trap gear safety and spillover evidence of artificial reef effects (AREs) are needed to inform the implementation of new safety distances and economically beneficial passive fisheries. Finally, we highlight needs for new insurance regimes and straightforward funding provision to support transitions to co-location and absorb the shocks from mobile fisheries displacement.

1. Introduction

Global energy transition towards clean, renewable and sustainable energy is characterized by substantial expansion in Offshore Wind Farm (OWF) development [34,87]. This expansion is expected to see a jump in growth of installed offshore wind energy capacity from 19 GW in 2018 to about 78 GW in 2030 and 215 GW by 2050 [35], which translates into vast offshore wind spatial requirements. There is evidence of adverse socio-economic and ecological effects of OWF expansion on fisheries [2,7,40,43,46]. Area closures have resulted in fishing effort displacements, longer steaming distances to and from fishing grounds, increasing operating costs and reduced fishing opportunities [26,82].

It has been established that OWF infrastructure modifies and even transforms habitats, which might function as artificial reefs in previously sand-dominated areas [12,18,25]. Nonetheless, there is only scant scientific evidence to make tangible conclusions on how the new infrastructure impacts fish abundance, distribution and diversity [7,15,71]. Even where long-term studies have identified large juvenile populations of relevant target species (e.g., such as from Leonhard et al. [45]), there are uncertainties as to whether these juveniles will continue to inhabit the area. On the other hand, some long-term studies (exceeding 6 years) have concluded that the artificial reef structures offered by OWFs are large enough to support fish species with a preference for rocky habitats [72]. The longevity of artificial reef effects

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(AREs) and their relevance for economically important species for fishers at the population scale remains debated [7,23,24,30,82]. This means for OWF and fisheries, trade-offs are often unclear and may result in huge imbalances between sectors, even intensifying negative impacts [69].

There have been calls for new management strategies to better implement tradeoff decisions that support the sustainability of OWFs and fisheries [46,58]. In the North Sea, co-location has been discussed and is being implemented [9,11,32,39,71,69,89]. In the Netherlands, 'area passports' with new guidelines are being implemented to designate specific areas for co-location [47]. In the UK, co-location has been promoted and implemented [57], often lacking buffer distances around OWF turbines. In Germany, safety distances up to 150 m from the outer buffers of wind farm areas have been implemented to support co-location with passive fisheries [17].

Despite these efforts, implementation is still not supported by clearly defined frameworks that address concerns and challenges. No new insurance regimes have been implemented despite calls by fishers [75]. Cost coverages for loss and damages of fishing in OWF areas remain undefined despite lasting concerns[54]. Guidelines on economic compensations are unchanged despite calls for sound economic analysis to define compensations [1,52]. The economic and technical feasibility of pot fisheries which has been promoted as an option for co-location with OWFs has not been widely explored. Furthermore, current governance practices and regulations governing co-location of fisheries and OWF differ across countries. They range from various definitions of buffer zones, as well as strict fisheries prohibitions to mutual agreements [81,82]. As outlined by Schupp et al. [63], the application of co-location currently lacks cooperation and synergies between users and pays no particular attention to accommodating individual user needs. Provisioning and functional dimensions such as monitoring and environmental data, providing safety and sharing infrastructure, do not exist. Successful co-location requires planning goals and strategies to be aligned, and implementing policies that clearly reflect the rights and responsibilities of each user [63].

To this end, our study aims to 1) identify global co-location solutions, 2) synthesize current regulations and practices in the greater North Sea, and 3) explore the potential of pot fisheries targeting crustaceans in the vicinity of OWFs. We first conducted a structured literature review to understand global solutions and explored grey literature on existing legal and regulatory mechanisms governing co-location implementation and practice for the North Sea region. To understand the potential for pot fishery co-location, we conducted a spatial analysis of pot and trap fisheries targeting crustaceans in OWF vicinity. The above resulted in the identification of OWF areas with the highest potential for pot fishery co-location, as well as regulations required to support co-location implementation.

2. Materials and Methods

2.1. Global co-location solutions

A structured literature review of studies relevant to co-location of OWF and fisheries was conducted in June 2022 using Web of Science and Scopus bibliographic databases. We used the search string (Query) to return 40 articles on the Web of Science core collection and 393 articles on Scopus. To test the comprehensiveness of the search strategy, we conducted a scoping search to compare results from iterations of the search string against a prior defined test library for six known relevant publications. All six articles were retrieved in the final search string confirming its functionality. Searches were also performed in June and July across relevant organizational and institutional websites and data repositories to collect more literature. Retrieved articles were transferred to EndNote and duplicates removed. Articles were systematically assessed based on four-step exclusion criteria. First, we used time relevance to exclude publications published before 2010, coinciding with the first significant growth in OWF developments [65,88]. In the second stage, we screened titles and abstracts and excluded publications whose study outcomes do not relate to fisheries and OWF multi-use. Third, full texts were screened to exclude tertiary studies and include only primary and secondary publications. For the last phase, we excluded publications that did not report on at least two of five defined themes. The themes were developed from review of six publications of known relevance. Themes included theories of, advantages and concerns of, and barriers and recommendations for co-location (Table 1). We later screened the bibliographies of our final list of publications to identify new publications based on the exclusion criteria.

2.2. Co-location practices in the greater North Sea

To identify current co-location practices in the North Sea, we reviewed legal and regulatory mechanisms relevant to the interaction of fisheries and OWF development. Searches were conducted for grey literature, legal and regulatory text across government, organizational and institutional websites and data repositories (Annex A) of seven North Sea countries (United Kingdom, Germany, The Netherlands, Belgium, Sweden, Denmark and Norway). Searches captured national and sectoral policies, regulations and strategies relevant to fisheries and OWFs. Searches were performed between June 2022 and March 2023, as our paper sought to capture current developments. From the data collected, we analyzed regulations on safety distances, restrictions and permissions, impact assessment, compensations and insurances.

Analysis of safety distances related to buffers employed around individual structures or wind farm areas at different stages of OWF development (construction, operation and maintenance). Impact assessments included environmental and socio-economic impact assessments of offshore development on fish and fisheries. Assessments included Environmental Impact Assessment (EIA) or Strategic Environmental/Impact Assessment (SEA/SIA). SEA/SIA are assessments carried out during planning procedures to describe and evaluate the environmental impact of plans for decision-making, including planning alternatives. EIA are mandatory assessments relevant for approval of OWF development in planned areas. EIAs identify, describe and assess the significant impacts of a project on other related activities and ecosystems. We also analyzed the nature of compensations for fishers affected by OWF development and insurance regimes to cover accidents and other liabilities related to fishing in OWF areas.

Finally, we reviewed current practices of OWF and fishery co-location to understand where they are currently happening and how they are being implemented. As document sources did not provide all the information required, we sought expert information from the various countries to support and validate the information gathered. We identified six experts through national and sector websites who are working on MSP, ocean management, fisheries, and OWF. Informal online interviews were conducted with these six experts to validate and fill

Table 1
Five themes used to extract information from publications.

Theme	Definition	Examples
Theories	The terms used to explain the need or potential for fisheries and OWF co-location	The potential for fisheries to benefit from AREs
Advantages	Advantages are the benefits of fisheries and OWF co-location, including	Improved catches due to stock assemblages at OW foundations
Concerns	The negative effects or impacts of offshore development on fisheries	Spatial restrictions reducing economic viability of fishing
Barriers	Barriers represent factors that prevent successful implementation of co-location	Fear of safety and navigation OWFs
Recommendations	Proposals to address identified barriers.	Sharing technical data such as foundations types

information gaps.

2.3. Passive gear fisheries in the vicinity of OWF

For our study, we used the latest OWF data from 4COffshore [dataset] (June 2023) and STECF fisheries-dependent information [dataset] [41] from 2013 to 2021 to conduct our analysis. For OWF data, we used ArcGIS Pro [22] to filter for only OWF polygons in the ICES Greater North Sea. We then removed irrelevant OWFs and grouped relevant OWFs under 3 development scenarios (Table 2). We dissolved OWF polygons based on 'Name' and 'WindfarmId' to remove duplicated polygons.

For fisheries data, we employed R [51] and R Packages to filter our fishery data. Packages included data.table, dplyr, sp, and sf [8,21,50]. We filtered data for only pots and traps (FPO) targeting crustaceans (CRU) in the Greater North Sea subregion (region 27.4. A, 27.4. B, 27.4. C). We excluded fisheries data for the year 2014 and 2021, as the UK did not provide data for those years. We did this to prevent the skewing of subsequent analysis. We summed up fishing days across four fishing quarters per year for each ICES rectangle. We then calculated the mean fishing days for each ICES rectangle between 2014 and 2020. Each ICES rectangle has a resolution of 0.5 × 1 -degree (made up of 2 c-squares of resolution 0.5 ×0.5 and unique cscode). See Github for code used and link to data.

We exported our fishing data to ArcGIS Pro [22] for spatial representation and analysis. To identify overlaps between fishing days and OWFs, we intersected ICES rectangles with OWF polygons for all three scenarios. For each OWF scenario, we summed up the size of all individual OWF areas overlapping fishing effort and their corresponding mean fishing days. We did this for each North Sea country to identify differences in OWF overlaps and fishing days. We estimate the co-location potential as the fishing days for ICES rectangles overlapping present and planned OWFs. Fishing effort for each ICES rectangle remains unchanged across all OWF scenarios.

3. Results

3.1. Global baseline for co-location solutions

Our structured literature review resulted in 22 case studies from 18 publications. From our themes (Table 1), we identified six scientific theories, six advantages, six concerns, 16 barriers and 18 recommendations for co-location. We grouped barriers and recommendations under five subthemes (Economic, ecological, social, technical and regulatory) due to the number of topics identified.

From our review, the six scientific theories identified to influence co-location were spatial conflicts, artificial reef effects, effort displacement, cumulative impacts/effects and tradeoffs. The theories discussed in most case studies were spatial conflicts (13) and artificial reef effects (12).

Table 2
OWFs grouped under three development scenarios. OWF classifications are based on 4COffshore wind farm status and commissioning dates.

Scenario	Wind Farm Classification
Present areas (Until 2023)	• OWFs 'Fully Commissioned' and 'Partial Generation/ Under Construction' • Wind Farms areas with starting dates before 31.12.2023
Mid-term areas (Until 2030)	• OWFs 'Under Construction', 'Pre-Construction', 'Consent Authorized', 'Consent Application Submitted', 'Concept/ Early Planning' with no starting dates or with starting dates before 31.12.2030 • OWFs Development Zones with starting dates before 31.12.2030
Long-term areas (After 2030)	• 'Development Zones' with no starting dates • 'Development Zones' with starting dates after 31.12.2030
Removed data	• OWFs 'Cancelled', 'Decommissioned', 'Dormant' or 'Failed proposal'

For advantages of fisheries and OWF co-location (Fig. 1), 64% (n = 14) of the case studies attributed increased marine biodiversity and integrity as an advantage of co-location. In total, 55% (n = 12) of the case studies also discussed that co-location provides better economic conditions to fishers. For concerns of co-location (Fig. 1), the lack of spatial access ranked highest and was discussed in 73% (n = 16) of the case studies. This is followed by reduced marine biodiversity and integrity, discussed in 68% (n = 15) of the case studies. About 41% (n = 9) of the case studies discuss that OWF co-location worsens the economic conditions of fishers.

For barriers to co-location (Fig. 2), insufficient ecological data and research was the most discussed barrier in 86% of case studies (n = 19). This was followed by a lack of financing and fear of safety and navigation, which were discussed in 59% (n = 13 each) of case studies. The lack of alternative livelihoods and the lack of consideration of traditional fisheries integration were the least discussed barriers. Each was discussed in 5% of the case studies (n = 1 each). Early/better participation and information sharing were the most discussed recommendations (Fig. 3) for co-location implementation (77% of studies, n = 17). This was followed by the availability of technical data and feasibility research (n = 16) and improved environmental assessment (n = 16). Skills training (n = 4) was the least discussed recommendation for co-location implementation (Fig. 3).

3.2. Co-location regulations and practices in the greater North Sea

Grey literature from official national and institutional homepages indicates fundamental differences in co-location regulations and practices among countries. We identified three main topics relevant for fisheries and OWF co-location. These include safety regulations and insurances, financial support and compensations, and impact assessments for offshore licensing. We treat these topics from the perspective of different countries to understand what guidelines exist if any, and how they are being implemented.

3.2.1. Safety regulations and insurances

Safety distances differ for OWFs during construction, maintenance and operation phases. During construction and maintenance phases, countries adopt similar safety distances of 500 m radius around offshore installations as defined by the UNCLOS [80]. In this 500 m radius, co-use is prohibited, except for vessel navigation. During operation, however, safety distances vary grossly, from the absence of defined safety zones to safety zones up to 500 m. Within all operational safety zones, countries apply different regulations to define fisheries restrictions and

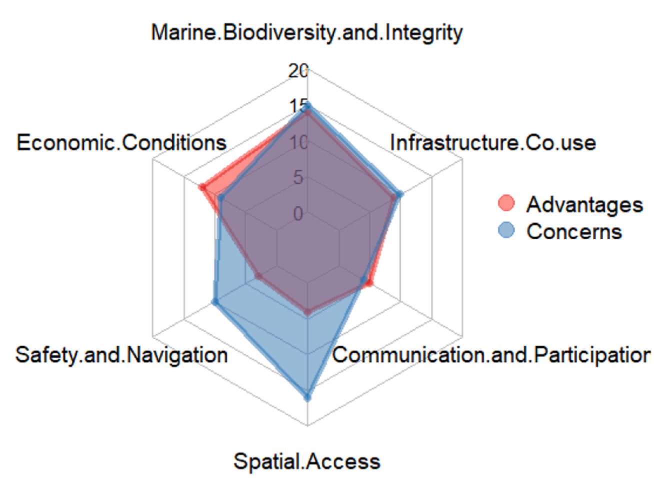

Fig. 1. Advantages and concerns of co-location of fisheries and OWF discussed in the 22 case studies. Case studies discussed more than one advantage and concern.

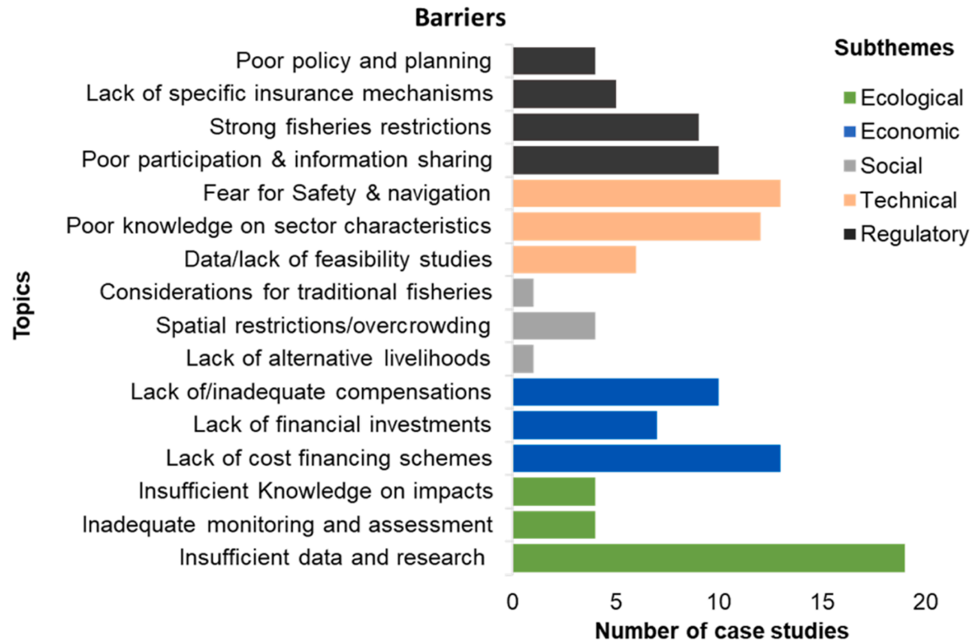

Fig. 2. Number of studies that discuss the literature on barriers to co-location implementation grouped under different themes. Some articles discuss more than one topic or subtheme.

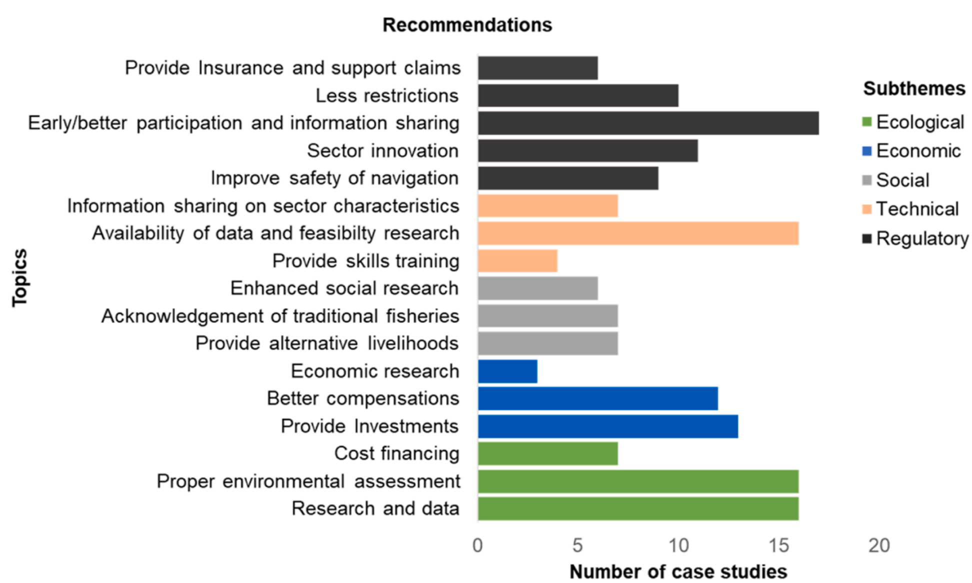

Fig. 3. Number of studies that discuss the literature on recommendations for co-location implementation grouped under different subthemes.

permissions relating to fishing gears, vessel lengths and passage regulations (Table 3). The UK, Sweden, Denmark, and Norway have no defined statutory safety zones around offshore installations during operation. Nonetheless, safety zones may be applied on a case-by-case basis (Table 3). In the UK and Sweden, the developer may apply for a 50 m safety or exclusion zone around each wind farm pile. In the Netherlands and Germany, safety distances are being developed, and some are already implemented [16,47]. Safety distances during operation are established around individual OWF structures, as occurs in the UK and Sweden. Germany and the Netherlands apply a mix of both methods. In the Netherlands, ‘area passports’ of 500 m safety zones around entire areas with 250 m maintenance zone around each monopile and both sides of infield cables are being implemented to allow for passive fisheries in offshore areas [47]. In Germany, a 150 m buffer is employed around individual structures, with passive gear co-location possible outside the buffer area [16]. In Norway and Denmark, individual agreements have been implemented to allow mobile bottom contacting fishing within safety areas over export cables, as alternate compensations for loss of fishing grounds [14]. With the new Belgian Marine Spatial Plan for 2020–2026 (Royal Decree MSP-2020), passive fishery is allowed in the Noordhinder North and South wind farm areas (Zones 2 and 3). Additionally, separate safety distances around export cables apply, often implementing up to 200 m buffers on each side of cables and pipelines.

There are no specific insurances for fishing in OWF areas. In the Netherlands, the regular protection and indemnity provided by insurance companies is sufficient for the specific circumstances of working in an OWF. In Sweden, no specific insurance regimes exist, but the general insurance regimes for fishing should apply to operations inside wind farms.

Table 3
Current co-locations practices in the Greater North Sea, including safety distances and restrictions, environmental assessments, fisheries compensations and insurances, as well as cases of co-location implementation.

Country	Operational Safety Distances and Permissions	Assessments related to fisheries and sector participation	Fisheries compensations	Fisheries Examples
UK	1. No mandatory safety zones during operation 2. Developer may apply for 50 m permanent safety zone around each structure 3. Conditional fishing over export cables (based on individual agreements with offshore developers)	1. SEA with fishing and changes to fish community, damage to benthic species, fish /marine mammal sensitivity to disturbances and contamination 2. Considerations for fisheries sector overlaps, impacts and conflicts (SEA) 3. EIA includes sustainability appraisal and formal consultations with fishers for data and identification of mitigation measures	1. Compensations after all residual impacts have not been avoided 2. Compensations related to offshore fouling that may impact fisheries	Dredging and Demersal Otter Trawl of Scallops at East (Moray Firth OWD) European lobster fisheries in Westermost Rough
Sweden	1. No mandatory safety zones 2. Developer may apply for a 50 m exclusion zone around each wind farm (current practice)	1. SEA and Sustainability assessment based on MSP and Swedish Environmental Code 2. EIA on environmental impacts including feedback/recommendations on impact mitigation on fisheries through non-statutory contacts between fisheries originations and developers	1. Negotiated compensations for fisheries in areas of assumed loss of income	
Denmark	1. No mandatory safety zones 2. 'Cable protection zones' covering entire wind farm area and 200 m buffer along each side of export cable 3. Conditional bottom trawling along cable lines based on defined agreements	1. SEA as defined within MSP 2. EIA of predetermined sites including worst-case scenarios and cumulative impacts including on commercial fisheries	1. Monetary and non-monetary compensations 2. Negotiated compensations for documented permanent or temporal losses at different OW life cycle	1. Bottom trawling over export cables connecting Horns Rev 2 offshore and Danish Westcoast
Belgium	1. No defined safety zones 2. Conditional passive gears may be permitted	1. SEA as described in the MSFD 2. EIS submitted by application to MUMM and further EIA on sectors and ecology, including fisheries	1. No compensations apply	1. Passive gear fisheries in Noordhinder North & South
Germany	1. 150 m from the outer buffer during operation to allow for passive fisheries 2. Transit of smaller fishing vessels, subject to weather conditions and restricted top speed	1. SEA as defined within MSP 2. EIA according to BSH and based on SEA to include likely significant impacts on fish and measures to avoid, mitigate and compensate	1. No direct compensations apply 2. Wind Energy Act allocates 5% of funds from offshore bids to support environmentally friendly fishing	1. 2cases of passive fisheries within OWF near Helgoland
Norway	1. No defined safety zones 2. May be up to 500 m (decided by the Norwegian Coastal Association (NCA) 3. Fishing allowed in cable areas with close cooperation between cable owners and fishers.	1. SEA and SIA on all planned activities as defined by MSP and offshore energy act 2. Specific assessment on fisheries impact (SIA) (exemption for pilot projects) 3. EIA on fisheries impact mitigation measures during construction and operation	1. Compensations for economic losses due to seizure of grounds 2. Compensations for lost fishing time due to longer distances or damage to objects if recorded and brought ashore	1. Trawling by Shrimp fisheries along cable lines
Netherlands	1. 'Passport areas' (500 m around each wind farm area for 2nd generations of wind farms) 2. 250 m fisheries multi use safety zone around monopiles and both sides of infield cables and export cables 3. Experimental passive gear fisheries in spaces between safety zones 4. Transit of vessels allowed when bottom-disturbing gear is visible above waterline	1. SEA based on MSP and National Environmental Management Act 2. SEA includes considerations for fishery ground preservation & impact on fish 3. EIA including environmental impact on fish and marine mammals (noise mitigation) during development phase 4. EIA includes socio-economic and safety impact on fisheries during construction and operationalization	1. Conditional compensations based on appeal related to experienced adverse effects from another lawful use if losses extend beyond normal risk	1. Opening of OWEZ, Amalia and Luchterduinen wind farms for transit for vessels up to 24 m and for sport hand line fisheries and (experimental) pot fisheries. 2. Experimental pot fisheries in OWF plot Borssele II (Rozemeijer et al., 2023 in prep)

3.2.2. *Financial support and compensations*

Regulations on compensations for fishers related to OWF development exist for the Netherlands, Denmark, the UK, Sweden and Norway, whereas they are missing in Germany and Belgium. Where regulations exist, compensations are paid for economic losses from temporal or permanent seizure of grounds at different stages of offshore development. In places like Denmark, fishers are also compensated for lost time and cost of longer sailing distances to new grounds [14,5]. For compensation payments due to economic loss, regulations often require evidence of recorded losses to be provided. In the UK, this requires evidence of catches for the last 3 years, whereas in Denmark, compensations are paid based on logbook evidence for between two to ten years, supported by interviews with fishers. In Norway, compensations cannot be claimed seven years after losses have occurred, whereas claims of equipment damage require damaged objects to be retrieved, recorded and brought ashore to initiate compensation processes. In some countries, negotiations may be done between the individual fisher or fisher organizations and the authorities or wind developers. In Sweden, regulations require that compensations are negotiated between the fishers and the offshore developer in areas of assumed income losses whereas in the Netherlands, claims for compensations are negotiated with the Ministry of Infrastructure and the Environment. Financial compensations may be paid in lump sums or fixed annual sums depending on the country. In the Netherlands, a financial formula exists for determining the amount to be paid [6]. Non-monetary compensations may also be negotiated between fishers and developers. Example of such compensation is bottom trawling over export cables connecting Horns Rev 2 offshore and Danish West Coast [36,14]. In Germany, no compensations exist so far, but 5% of the OWF licensing fees are dedicated to support fisheries. The application of this fund is currently under discussion.

3.2.3. Impact Assessments for offshore licensing

Both SEAs and EIAs are conducted in relation to OWFs and fisheries. Where plans are likely to have significant effects on the environment, the EU MSP directive (2014/89/EU) subject plans to environmental assessments [20]. Environmental assessments for OWFs and fisheries occur as defined in the SEA Directive (2001/42/EU) and other directives such as the Birds and Habitats Directive (2009/147/EC and 92/43/EEC). SEAs involve environmental assessments and socio-economic impact analysis of proposed plan areas to identify overlap, potential conflicts and impacts of allocated areas for OWF on ecosystems, uses and activities [17]. For fisheries and OWF development, this includes changes to fish communities, damages to benthic species and other disturbances, as well as the potential social and economic impact on the fishing sector prior to offshore area designations in national marine spatial plans [17].

EIA requirements and processes for OWF development are far more diverse. In the UK, as a result of devolution of governance, EIA application and consenting processes differ between England, Wales, Scotland and Northern Ireland. In Scotland and Northern Ireland for instance, a pre-application process may require a screening opinion if requested by the developer, and is provided by the responsible national agencies [19,77]. In England, the Marine Management Organization (MMO) provides a similar screening opinion, but EIA is only mandatory for projects exceeding 100 MW. In Norway, EIA exceptions are provided for pilot and demonstrative projects [69]. In general, EIAs often account for both socio-economic and ecological impact assessments and are carried out prior to construction and installation, but not afterwards. In Germany it includes monitoring of fish before, during and after construction [17]. In the UK and Norway, legislations exist for formal consultations with fishers, including data from fishers to help in sustainability appraisal and identify mitigation measures [49,75]. In Sweden, consultations for EIA are non-statutory and may happen at the discretion of the developer. Consultations with fisheries include opinions on the likely significant impacts on fish and suggestions on measures to avoid, mitigate and compensate for negative impacts.

3.3. Patterns of passive gear fisheries in the vicinity of OWF

On an ICES statistical rectangle (1 degree longitude x 0.5 degree latitude), our results indicate a high spatial overlap of pots and traps fishery targeting crustaceans, predominantly brown crabs (*Cancer pagurus*; also known as edible crab) and European lobsters (*Homarus gammarus*) with operational and planned (until 2030) OWF areas (Fig. 4). Further analysis (Table 4) shows that the highest fishing effort (on average 351 fishing days) is concentrated in currently operational OWFs despite having the smallest OWF area (4460 km^2). Fishing effort

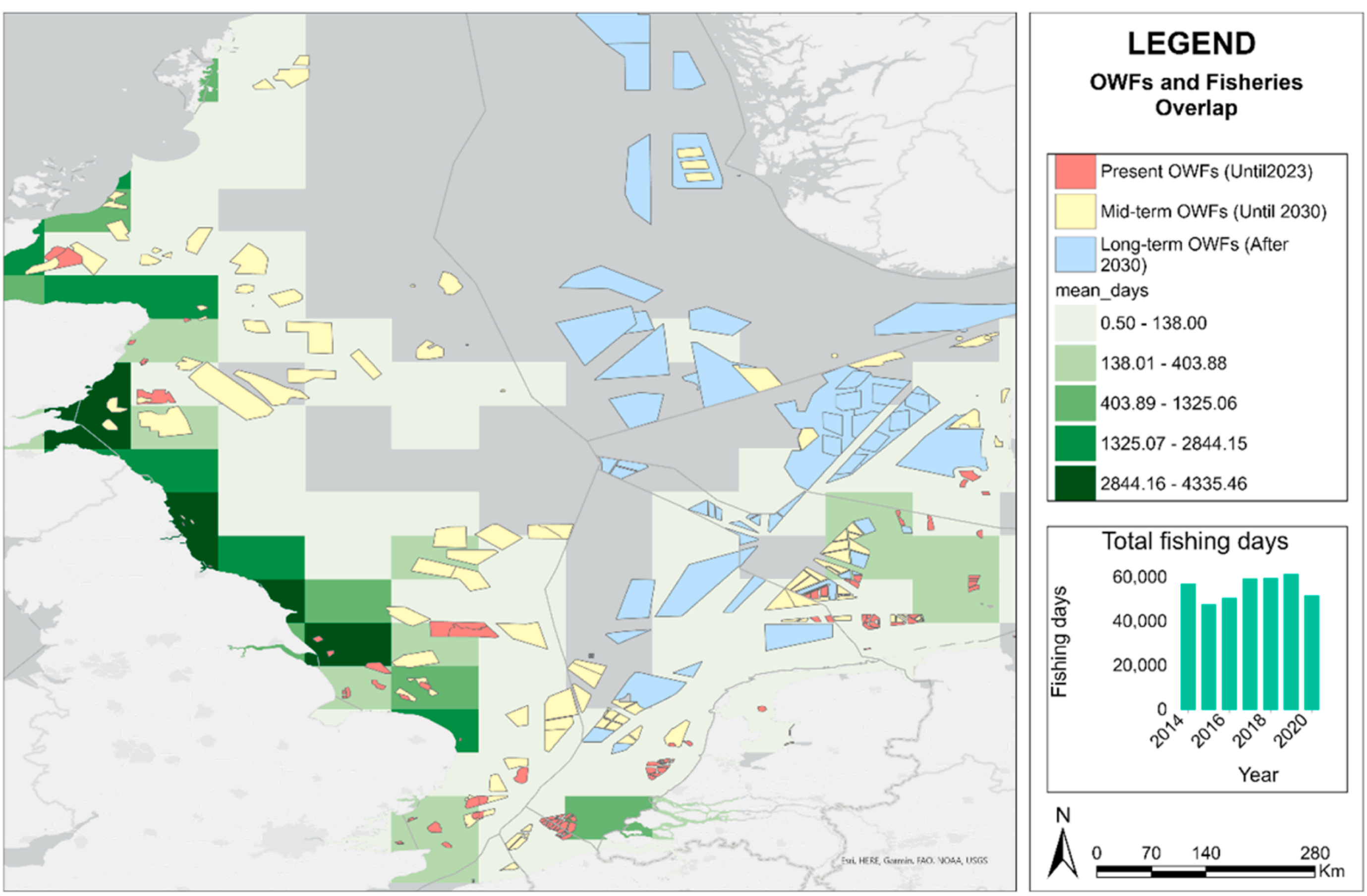

Fig. 4. Mean fishing effort for pots and traps targeting crustaceans within the EEZ of seven North Sea countries based on STECF data between 2013 and 2020. OWF areas are grouped under three development scenarios.

Table 4
OWF areas overlapping pot and trap fishing effort targeting crustaceans and corresponding fishing days for three development scenarios in seven North Sea EEZs. Fishing efforts are represented by mean fishing days (MFDs).

	Present scenario		Mid-term scenario		Long-term scenario		NATIONAL MFD
	OWF area (km^2)	MFD	OWF area (km^2)	MFD	OWF area (km^2)	MFD	
UK	2722	806	13980	440	-	-	703
Germany	759	109	1575	103	1574	48	81
Sweden	-	-	-	-	-	-	-
Netherlands	626	121	1628	14	5177	26	56
Norway	-	-	-	-	1389	1	
Denmark	175	66	571	22	7867	27	37
Belgium	178	118	255	5	-	-	166
Total	4460		18008		16008	-	

in the future (OWFs after 2030) will continue to decrease rapidly. The lowest fishing efforts (on average 28 fishing days) are in long-term OWFs, which has the biggest overlap areas (18078 km^2). In presently operational OWFs, UK has the largest OWF area (2772 km^2) overlapping with fishing effort. The average fishing effort is in this area is 674 fishing days. This is followed by OWFs in Germany and the Netherlands, although the Netherlands have higher fishing efforts (98 mean fishing days) in OWF areas than Germany (85 mean fishing days). A similar trend is recorded for the mid-term scenario (Table 4). In the long-term scenario (After 2030), Denmark and the Netherlands have the biggest OWF areas, in rectangles with relatively low fishing effort. In Sweden, the planned OWFs after 2030 will not be implemented in areas with current fishing activities (where current fishing effort is zero).

4. Discussion

4.1. Science-based evidence for global co-location implementation

Discussions for fisheries co-location with OWF are now gaining prominence, however, case stories about their implementation are still rare. Our review revealed that although theories of spatial conflicts and artificial reef effects are driving co-location solutions, the lack of ecological data, research and feasibility studies prevent their implementation. This matters because some fishers already oppose OWF development, with concerns that offshore development will lead to reduced catch quality [40] and economic collapse due to displacement [1,26,42]. Moreover, proposals for fisheries and OWF co-location have been met with skepticism from both OWF developers and fisheries. Fishers' concerns regard fear of safety and the economic viability of alternate proposed gears to mobile gears, as well as lack of trust for the offshore developers [53]. For offshore developers, concerns have been raised regarding the lack of clear demonstration of added value and absence of risk to support fisheries' co-location [62]. These challenges persist also because global multi-use options rarely integrate fisheries' co-location. Integrations have predominantly focused on multi-use with aquaculture [10,27,33,38,85,86] and in some cases marine conservation [29,37,68,90]. In the US, conversations have been more favorable towards recreational fisheries as a means to support tourism and promote OWF development [74,13,67,66]. In Asia, non-monetary options for co-existence between OWF and local fisheries to support societal balance have been explored [42,48,64]. Similarly, in Europe and US, there are ongoing discussions around social concerns, stakeholder preferences, attitudes and perceptions regarding fisheries and OWF co-location [52,74,28,31,44,62]. All the above research provides first hand insights into possible socio-economic conditions necessary to enable fisheries and OWF co-location, as well as ensuring a balance of OWF development with societal and biodiversity needs [83]. The North Sea region provides scientific evidence to support fishery co-location in OWF areas due to strong spatial overlaps [46,71,69]. Scientific evidence has even gone further to define target species including brown crab, Lobster, Shellfish [58,57,78,79] and specific passive gears including crab-pot-strings anchored with Bruce anchors [61,59,60]. It is important to note that, differences in spatial, temporal, social, and ecological characteristics of global oceans mean that translating evidence of co-location potential from one site to another remains impractical [57]. While the potential contributions of reef effects on fish and fisheries remain a topic of scientific discussion, other relevant issues such as the potential impacts of climate change on anticipated reef effects and target species are less discussed [84].

4.2. Enabling conditions for passive fisheries in OWF vicinity in the North Sea

The potential for co-location lies in operational and planned OWFs before 2030. In these areas, we recorded higher fishing effort for pots and traps targeting crustaceans in relatively smaller OWF areas. Additionally, OWFs that will be implemented after 2030 are mostly far from the coast where little fishery occurs. For presently operational and planned OWFs by 2030, guidelines and regulations, particularly on safety and navigation are urgently required. This is important to regulate fishing practices, ensure safety and build developer and fishers confidence. Regulations will particularly be important for the UK, Germany and the Netherlands where we observe high fishing effort in present and mid-term OWF scenarios. In the same countries, vast OWF areas are planned for development by 2030 highlighting the need for co-location [39,46,70,74]. Further studies are required to access the co-location potential of other gears in future OWFs (after 2030 scenario). Especially in Denmark and the Netherlands because they have high areas of planned OWFs before and after 2030 overlapping minimal fishing effort for pots and traps. Given the limited spatial detail in the fishing effort data used for this study, further research incorporating finer-scale fishing effort or habitat information are essential to thoroughly evaluate (or fully assess) the potential for passive gear co-location in offshore wind farms.

4.2.1. Experimental research

Despite proposals for fisheries and OWF co-location especially across the North Sea region, we identified knowledge gaps that hinder successful implementation. For instance, the ecology, production and spillover potential of identified resources such as edible crabs and European lobsters attributed to artificial reefs of offshore foundations are not fully understood. The potential for co-location of other commercially important species that are likely to be affected by offshore development such as flatfish [3] have not been studied. The safety and technical feasibility of fishing with passive gears like pots and traps in OWF vicinity has not been sufficiently tested. Moreover, safe potting distances from OWFs and the impacts of adverse weather conditions on gear stability, loss, damages and retrieval needs to be investigated.

A handful of experimental research on brown crabs and European lobster caught with passive gears exist. Roach [55,56] found changes in European lobster and brown crab populations within similar time frames for different offshore development stages. Strietman et al. [73] reports that economically viable fishing for North Sea crab in OWFs would be more successful further North off the coast with better habitat conditions. Results of experimental local spill-over assessment by Stelzenmüller et al. [69] illustrate that brown crab fishery in OWF areas serves as an economically viable option to lower the susceptibility of risks of potentially displaced fishing activities. The above studies provide important contributions to understanding the ecological aggregation and economic potential in different areas and distances. Rozemeijer et al. [61,59,60] assessed the stability and mobilization of crab-pot-strings anchored with Bruce anchors in offshore under different weather conditions. They resolve that crab-pot-strings are sufficient but need to be fixed to the seabed with normal anchors. Their results are vital for undertaking safe use of pots and traps in OWF areas.

4.2.2. Safety and Insurance

We identified that safety and navigation is a key barrier to co-location implementation. In addition, insurance regimes for operation within OWF areas remain mostly unclear. For fishers and developers, this lack of clarity on liabilities regarding safety of fishing within OWF vicinity slowed down co-location practices [9,26]. Additionally, the deficiency in knowledge on whether current insurance regimes for fishers enable them to fish within OWF areas continues to deter fishers from fishing within OWF vicinity. While in some places it is assumed that current premiums should be valid for fishers to operate within OWF areas, other places have no concrete information on the adequacy of existing premiums or cost of new premiums to fish in OWF areas.

The absence of adequate evidence to suggest that pot and trap fishing and other forms of passive gears can safely operate within OWF areas, also taking into account weather and oceanographic conditions, needs to be tackled. In OWF areas, it is possible for accidents of gear loss and snagging to occur, resulting in damages to offshore cables and other infrastructure. Aside the designated safety zones and navigation conditions, operational protocols for managing residual impacts from gear retrieval, weather limits and fisheries liaison plans need to be established.

In the Dutch North Sea, mitigatory measures including new insurances, attention to weather conditions and seasonal variability, as well as attention to vessel equipment and coordination with developers have been proposed through risk assessment for pot fisheries [61,59,60]. In addition, new safety developments as part of license application procedures are already being implemented to allow for fisher's coordination with OWF operators [4](Staatscourant, 2021). Therefore, the Netherlands is a good example for other North Sea states in terms of safety and insurance for co-location practices.

4.2.3. Compensations and financing co-location solutions

While compensations are important for fishers, our results indicate that compensation regulations are not often clearly defined. Non-existent compensation mechanisms, loopholes and complexity in compensation regulations hampers co-location efforts [1,52]. Knowledge gaps exist on who should be compensated, and how compensations should be determined and distributed [52,53]. In some national regulations, questions on compensation are partly answered, leaving gaps that may result in unfair compensations. For instance, demonstrations of economic losses to merit compensations need to account for other factors aside differences in value of landings prior to offshore development. For instance, in cases where disruptions may result in longer travel distances or change in fishing practices, compensation payments should account for these new developments. Determination of who pays or finances compensations is often a challenge for parties involved. Companies and developers are often reliant on government subsidies to become operational and may have difficulty in supporting compensation funds to fishers. In cases like the above, uncertainties may arise. Fisher funds have been advocated as a viable approach to ensure that appropriate and long-term compensations are available to fishers [52,75]. Compensation funds may include special resource pools from government programs as planned in Germany and already exist within the oil and gas sector in the US and UK. Additionally, non-financial compensation mechanisms need to be explored, either as an alternative to the unavailability or adequacy of compensation funds or to ensure that displaced commercial mobile bottom fishing can safely occur within OWF areas. So far, trawling along export cables represents non-financial compensation options implemented between fishers and offshore developers.

In places like the UK and US, transitions from commercial to recreational fisheries, and training fishers in their off-season to support offshore development activities have occurred. This represents an alternative strategy to the transitioning from active to passive fisheries, which would require huge financial commitments and the absence of financial mechanisms to support high-cost transitions such as vessels and gear modifications needs to be addressed.

5. Conclusions

OWF development will have a huge impact on European and North Sea mobile fisheries, but bears some potential for co-locating passive gear fisheries in the vicinity of OWFs. Places like the Netherlands are already seeing the decline in small-scale fisheries, potentially due to conservation measures, hike in fuel prices, Brexit and OWF development. Successful case studies of passive fisheries for brown crabs and European lobsters with pots and traps have been recorded in the UK, Germany and the Netherlands. Nonetheless, adequate scientific evidence of potential ecological and economic benefits is required. New regulatory guidelines on safety of fishing and navigation within OWFs and an understanding of potential risks are required. Clarity on insurance regimes and liabilities, as well as financial support for smooth transitions and adequate compensations for impacted fisheries are needed. The largest potential for co-location of passive gear fisheries is located in OWFs that already exist or will be constructed until 2030. Any legal and security frameworks should therefore be developed quickly to support a transition of the fishing sector. Future technological advancements in OWF development, climate change and the EU political situation will have an impact on the spatial and temporal requirements of fisheries and OWFs. For now, proactive and bottom-up mechanisms are needed in the course of MSP to enable sustainable co-location of fisheries and OWF development.

CRediT authorship contribution statement

Prince Owusu Bonsu: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft. **Vanessa Stelzenmüller:** Conceptualization, Funding acquisition, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Jonas Letschert:** Data curation, Methodology, Visualization, Writing – review & editing. **Jennifer Rehren:** Methodology, Writing – review & editing. **Katherine Yates:** Methodology, Validation, Writing – review & editing. **Jon C. Svendsen:** Writing – review & editing. **Jörg Berkenhagen:** Validation, Writing – review & editing. **Marcel Rozemeijer:** Writing – review & editing. **Thomas Kerkhove:** Investigation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no competing financial interests or personal relationships that have appeared to influence the work reported in this paper.

Data Availability

Fisheries data from the STECF has been referenced in the paper and is accessible. Offshore wind farms data from 4 C Offshore is a property of the Thünen Institute for Sea Fisheries and is treated as confidential. Reference to fisheries data have been provided in this paper and is accessible.

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Annex A. List of Organizations and Institutions Accessed

Germany

Das Bundesministerium für Umwelt, Naturschutz, nukleare Sicherheit und Verbraucherschutz (BMUV).

Das Bundesministerium der Justiz (BMJ).

Das Bundesamt für Seeschifffahrt und Hydrographie (BSH).

Belgium

The Federal Ministry for the Economy (FPS Economy).

Exercice Technique Appliqué Au Moniteur Belge (ETAAMB).

Royal Belgian Institute of Natural Sciences.

Federal Public Service for Public Health, Food Chain Safety and Environment.

Norway

Norwegian Government Security and Service Organisation (regjeringen).

Ministry of Petroleum and Energy.

Ministry of Climate and Environment.

Norwegian Ministry of Foreign Affairs information foundation (Lovdata).

Norwegian Directorate of Fisheries.

Norwegian Institute of Marine Research.

The Norwegian Water Resources and Energy Directorate (NVE).

Bergen Offshore Wind Centre (BOW).

Denmark

The Ministry of Environment of Denmark.

The Danish Energy Agency (DEA).

Danish Ministry of Climate, Energy and Utilities.

Sweden

Swedish Agency for Marine and Water Management.

Swedish Energy Agency.

UK

Marine management Organization.

Department for Business, Energy & Industrial Strategy (as existed before).

Fisheries Liaison with Offshore Wind and Wet Renewables Group (FLOWW).

SeaFish.

Welsh Government (Marine and Fisheries).

Scottish Marine Directorate.

Department of Agriculture, Environment and Rural Affairs (Northern Ireland).

The Netherlands

Ministry of Economic Affairs and Climate Policy.

Ministry of Infrastructure and Water Management.

Noordzeeloket.

Overheid (Official Government Publications).

Parlementaire Monitor.

Wageningen University & Research.

Maritime Research Institute Netherlands (MARIN).

Netherlands Enterprise Agency.

Wind Water and Works.

Others

Global Wind Energy Council.

Wind Europe.

International Energy Agency.

Enerdata.

EU MSP Platform.

Access to European Union law.

European Commission.

European Market Observatory for Fisheries and Aquaculture Products.

References

[1] K.A. Alexander, T. Potts, T.A. Wilding, Marine renewable energy and Scottish west coast fishers: exploring impacts, opportunities and potential mitigation, Ocean Coast. Manag. 75 (2013) 1–10, https://doi.org/10.1016/j.ocecoaman.2013.01.005.

[2] I. Anggriani, L.P. Adnyani, N. Millah, The effect of wind turbine on sea flow, J. Phys.: Conf. Ser. 1490 (1) (2020), 012035, https://doi.org/10.1088/1742-6596/1490/1/012035.

[3] L. Barbut, B. Vastenhoud, L. Vigin, S. Degraer, F.A.M. Volckaert, G. Lacroix, The proportion of flatfish recruitment in the North Sea potentially affected by offshore windfarms, ICES J. Mar. Sci. 77 (3) (2019) 1227–1237, https://doi.org/10.1093/icesjms/fsz050.

[4] Bekendmaking houdende een verbod zich te bevinden binnen de veiligheidszones van windenergiegebied Borssele in de Noordzee (2021). ⟨https://zoek.officielebekendmakingen.nl/stcrt-2021-13511.html⟩.

[5] Bekendtgørelse af lov om fremme af vedvarende energi, (2020). ⟨https://www.retsinformation.dk/eli/lta/2020/125⟩.

[6] Beleidsregel nadeelcompensatie Infrastructuur en Waterstaat 2019, (2019). ⟨https://wetten.overheid.nl/BWBR0010692/2020-12-18⟩.

[7] L. Bergström, F. Sundqvist, U. Bergström, Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community [Article], Mar. Ecol. Prog. Ser. 485 (2013) 199–210, https://doi.org/10.3354/meps10344.

[8] R.S. Bivand, E. Pebesma, V. Gomez-Rubio. Applied spatial data analysis with R, Second edition ed..,, Springer,, 2013. ⟨https://asdar-book.org/⟩.

[9] Blyth-Skyrme, R. (2010). Options and opportunities for marine fisheries mitigation associated with wind farms (Final report for Collaborative Offshore Wind Research Into the Environment contract FISHMITIG09, Issue. L. COWRIE Ltd.

[10] B.H. Buck, G. Krause, T. Michler-Cieluch, M. Brenner, C.M. Buchholz, J.A. Busch, R. Fisch, M. Geisen, O. Zielinski, Meeting the quest for spatial efficiency: progress and prospects of extensive aquaculture within offshore wind farms, Helgol. Mar. Res. 62 (3) (2008) 269–281, https://doi.org/10.1007/s10152-008-0115-x.

[11] N. Christie, K. Smyth, R. Barnes, M. Elliott, Co-location of activities and designations: a means of solving or creating problems in marine spatial planning? [Article]. Mar. Policy 43 (2014) 254–261, https://doi.org/10.1016/j.marpol.2013.06.002.

[12] J.W.P. Coolen, W. Lengkeek, S. Degraer, F. Kerckhof, R.J. Kirkwood, H. J. Lindeboom, Distribution of the invasive Caprella mutica Schurin, 1935 and native Caprella linearis (Linnaeus, 1767) on artificial hard substrates in the North Sea: separation by habitat [Article], Aquat. Invasions 11 (4) (2016) 437–449, https://doi.org/10.3391/ai.2016.11.4.08.

[13] T. Dalton, M. Weir, A. Calianos, N. D'Aversa, J. Livermore, Recreational boaters' preferences for boating trips associated with offshore wind farms in US waters, Mar. Policy 122 (2020), 104216, https://doi.org/10.1016/j.marpol.2020.104216.

[14] Danish Energy Agency. (2018). Offshore Wind and Fisheries in Denmark. In.

[15] J. Dannheim, L. Bergström, S.N.R. Birchenough, R. Brzana, A.R. Boon, J.W. P. Coolen, J.C. Dauvin, I. De Mesel, J. Derweduwen, A.B. Gill, Z.L. Hutchison, A. C. Jackson, U. Janas, G. Martin, A. Raoux, J. Reubens, L. Rostin, J. Vanaverbeke, T. A. Wilding, S. Degraer, Benthic effects of offshore renewables: Identification of knowledge gaps and urgently needed research [Review], Ices J. Mar. Sci. 77 (3) (2020) 1092–1108, https://doi.org/10.1093/icesjms/fsz018.

[16] Das Bundesamt für Seeschifffahrt und Hydrographie. (2021). *Annex to the Spatial Planning Ordinance for the German exclusive economic zone in the North Sea and in the Baltic Sea dated 19 August 2021- unofficial translation*. Germany.

[17] Das Bundesamt für Seeschifffahrt und Hydrographie. (2021). *Environmental Report on the Spatial Plan for the German Exclusive Economic Zone in the North Sea*. Retrieved from ⟨https://www.bsh.de/EN/TOPICS/Offshore/Maritime_spatial_planning/Maritime_Spatial_Plan_2021/_Anlagen/Downloads/ROP_2021/Environmental_Report_North_Sea.pdf?__blob=publicationFile&v=5⟩.

[18] S. Degraer, D.A. Carey, J.W.P. Coolen, Z.L. Hutchison, F. Kerckhof, B. Rumes, J. Vanaverbeke, Offshore wind farm artificial reefs affect ecosystem structure and functioning: A synthesis, Oceanography 33 (4) (2020) 48–57.

[19] Department of Agriculture Environment and Rural Affairs. (2018). Draft Marine Plan for Northern Ireland. Belfast Retrieved from ⟨https://www.daera-ni.gov.uk/articles/marine-plan-northern-ireland⟩.

[20] Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning, (2014). ⟨http://data.europa.eu/eli/dir/2014/89/oj⟩.

[21] Dowle, M., & Srinivasan, A. (2023). data.table: Extension of 'data.frame'. In ⟨https://CRAN.R-project.org/package=data.table⟩.

[22] Esri. (2021). ArcGIS Pro. In (Version 2.9.0) ⟨https://www.esri.com/en-us/home⟩.

[23] A.B. Gill, S. Degraer, A. Lipsky, N. Mavraki, E. Methratta, R. Brabant, Setting the context for offshore wind development effects on fish and fisheries [Article], Oceanography 33 (4) (2020) 118–127, https://doi.org/10.5670/oceanog.2020.411.

[24] A. Gimpel, K. Werner, F.D. Bockelmann, H. Haslob, M. Kloppmann, M. Schaber, V. Stelzenmüller, Ecological effects of offshore wind farms on Atlantic cod (Gadus morhua) in the southern North Sea, Sci. Total Environ. 878 (2023), 162902, https://doi.org/10.1016/j.scitotenv.2023.162902.

[25] M. Glarou, M. Zrust, J.C. Svendsen, Using Artificial-Reef Knowledge to Enhance the Ecological Function of Offshore Wind Turbine Foundations: Implications for Fish Abundance and Diversity, J. Mar. Sci. Eng. 8 (5) (2020) 332. ⟨https://www.mdpi.com/2077-1312/8/5/332⟩.

[26] M. Gray, P.-L. Stromberg, D. Rodmell, *Chang. Fish. Pract. UK a Result Dev. Offshore Wind. – Phase* 1 (Revis.) (2016). ⟨https://www.thecrownestate.co.uk/media/2600/final-published-ow-fishing-revised-aug-2016-clean.pdf⟩.
[27] R. Griffin, B. Buck, G. Krause, Private incentives for the emergence of co-production of offshore wind energy and mussel aquaculture, Aquaculture 436 (2015) 80–89, https://doi.org/10.1016/j.aquaculture.2014.10.035.
[28] C. Haggett, T.T. Brink, A. Russell, M. Roach, J. Firestone, T. Dalton, B.J. McCay, Offshore wind projects and fisheries conflict and engagement in the United Kingdom and the United States, Oceanography 33 (4) (2020) 38–47, https://doi.org/10.5670/oceanog.2020.404.
[29] L. Hammar, D. Perry, M. Gullström, Offshore wind power for marine conservation, Open J. Mar. Sci. 6 (1) (2016) 66–78, https://doi.org/10.4236/ojms.2016.61007.
[30] T. Hooper, M. Austen, The co-location of offshore windfarms and decapod fisheries in the UK: Constraints and opportunities, Mar. Policy 43 (2014) 295–300, https://doi.org/10.1016/j.marpol.2013.06.011.
[31] T. Hooper, M. Ashley, M. Austen, Perceptions of fishers and developers on the co-location of offshore wind farms and decapod fisheries in the UK, Mar. Policy 61 (2015) 16–22, https://doi.org/10.1016/j.marpol.2015.06.031.
[32] T. Hooper, C. Hattam, M. Austen, Recreational use of offshore wind farms: Experiences and opinions of sea anglers in the UK [Article], Mar. Policy 78 (2017) 55–60, https://doi.org/10.1016/j.marpol.2017.01.013.
[33] C.T. Huang, F. Afero, C.W. Hung, B.Y. Chen, F.H. Nan, W.S. Chiang, H.J. Tang, C. K. Kang, Economic feasibility assessment of cage aquaculture in offshore wind power generation areas in Changhua County, Taiwan, Aquaculture 548 (13) (2022), 737611, https://doi.org/10.1016/j.aquaculture.2021.737611.
[34] International Energy Agency. (2019). World Energy Outlook 2019. ⟨https://www.iea.org/reports/world-energy-outlook-2019⟩.
[35] International Renewable Energy Agency. (2019). FUTURE OF WIND: Deployment, investment, technology, grid integration and socio-economic aspects (A Global Energy Transformation paper, Issue.
[36] J. Carl B. Nielsen Horns Rev. 3 Offshore Wind Farm. Commer. Fish. 2014.⟨https://ens.dk/sites/ens.dk/files/Vindenergi/commercial_fisheries_v4.pdf⟩.
[37] H.I. Jager, R.A. Efroymson, R.A. McManamay, Renewable energy and biological conservation in a changing world, Biol. Conserv. 263 (2021), 109354, https://doi.org/10.1016/j.biocon.2021.109354.
[38] H.M. Jansen, S. Van Den Burg, B. Bolman, R.G. Jak, P. Kamermans, M. Poelman, M. Stuiver, The feasibility of offshore aquaculture and its potential for multi-use in the North Sea [Article], Aquac. Int. 24 (3) (2016) 735–756, https://doi.org/10.1007/s10499-016-9987-y.
[39] Kafas, A. (2017). *Offshore wind and commercial fisheries in the East Coast of Scotland.* ⟨https://maritime-spatial-planning.ec.europa.eu/media/12372⟩.
[40] A. Kafas, P. Donohue, I. Davies, B.E. Scott, Displacement of existing activities, *Offshore Energy Mar. Spat. Plan.* (2017) 88–112, https://doi.org/10.4324/9781315666877.
[41] Kovšars, M., Maurizio, G., Adamowicz, M., Zanzi, A., & Zeynep, H. (2022). *Fisheries landings & effort: data by c-square.* ⟨http://data.europa.eu/89h/00ae6659-ddde-4314-a9da-717bb2e82582⟩.
[42] A. Kularathna, S. Suda, K. Takagi, S. Tabeta, Evaluation of co-existence options of marine renewable energy projects in Japan, Sustainability 11 (10) (2019), 2840, https://doi.org/10.3390/su11102840, 26.
[43] S.S. Kulkarni, D.J. Edwards, A bibliometric review on the implications of renewable offshore marine energy development on marine species [Article], Aquac. Fish. 7 (2) (2022) 211–222, https://doi.org/10.1016/j.aaf.2021.10.005.
[44] T. Laskowicz, The perception of polish business stakeholders of the local economic impact of maritime spatial planning promoting the development of offshore wind energy, Sustain. (Switz.) 13 (12) (2021) 6755, https://doi.org/10.3390/su13126755.
[45] S.B. Leonhard, C. Stenberg, J. Støttrup, M.V. Deurs, A. Christensen, J. Pedersen, Fish benefits from offshore wind farm development. In *Danish offshore wind - key environmental issues – a follow-up*, Danish Energy Agency,, 2013, pp. 31–45.
[46] J. Letschert, N. Stollberg, H. Rambo, A. Kempf, J. Berkenhagen, V. Stelzenmüller, The uncertain future of the Norway lobster fisheries in the North Sea calls for new management strategies [Article], Ices J. Mar. Sci. 78 (10) (2021) 3639–3649, https://doi.org/10.1093/icesjms/fsab204.
[47] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2020). Handreiking gebiedspaspoort Borssele. Retrieved from ⟨https://www.noordzeeloket.nl/publish/pages/188385/handreiking-gebiedspaspoort-borssele.pdf⟩.
[48] H. Obane, Y. Nagai, K. Asano, Assessing the potential areas for developing offshore wind energy in Japanese territorial waters considering national zoning and possible social conflicts, Mar. Policy 129 (2021), 104514, https://doi.org/10.1016/j.marpol.2021.104514.
[49] Orsted. (2021). Fisheries Communication and Outreach Plan. Corporate Fisheries Communication and Outreach Plan. ⟨https://www.boem.gov/oil-gas-energy/appendix-b⟩.
[50] E. Pebesma, Simple Features for R: Standardized Support for Spatial Vector Data, R. J. 10 (1) (2018) 439–446, https://doi.org/10.32614/RJ-2018-009.
[51] R Core Team, *R: A language and environment for statistical computing.* In (Version 2021.9.2.382), R Foundation for Statistical Computing,, 2021. ⟨https://www.R-project.org/⟩.
[52] K. Reilly, A.M. O'Hagan, G. Dalton, Attitudes and perceptions of fishermen on the island of Ireland towards the development of marine renewable energy projects [Article], Mar. Policy 58 (2015) 88–97, https://doi.org/10.1016/j.marpol.2015.04.001.
[53] K. Reilly, A.M. O'Hagan, G. Dalton, Moving from consultation to participation: A case study of the involvement of fishermen in decisions relating to marine renewable energy projects on the island of Ireland [Article], Ocean Coast. Manag. 134 (2016) 30–40, https://doi.org/10.1016/j.ocecoaman.2016.09.030.
[54] Rijksoverheid. (2018). *Review on risk assessment on transit and co-use of offshore wind farms in dutch coastal Water* . (bijlage bij 29675,nr.191). Tweede Kamer der Staten-Generaal Retrieved from ⟨https://www.parlementairemonitor.nl/9353000/1/j9vvij5epmj1ey0/vkomhgf09gzv⟩.
[55] Roach, M. (2015). *Westermost Rough Fish & Shellfish Monitoring Report 2015; Including Comparison to Baseline Data 2013 A study conducted for DONG Energy*.
[56] M. Roach, *West. Rough. Offshore Wind Farm Shellfish Surv.* 2017 (2020), https://doi.org/10.13140/RG.2.2.15450.57289.
[57] M. Roach, A. Revill, M.J. Johnson, S. Degraer, 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, Ices J. Mar. Sci. 79 (4) (2022) 1175–1186, https://doi.org/10.1093/icesjms/fsac040.
[58] M. Roach, M. Cohen, R. Forster, A.S. Revill, M. Johnson, The effects of temporary exclusion of activity due to wind farm construction on a lobster (Homarus gammarus) fishery suggests a potential management approach [Article], Ices J. Mar. Sci. 75 (4) (2018) 1416–1426, https://doi.org/10.1093/icesjms/fsy006.
[59] M.J.C. Rozemeijer, R. Cramer, B. Deetman, A. Korving, Defining a haul-out indicator for removal of crab-pot-strings in Offshore Windfarms under anticipated adverse weather conditions, W. M. Research.,, 2022, https://doi.org/10.18174/576836.
[60] Rozemeijer, M.J.C., Cramer, R., Deetman, B., & Korving, A. (2022). An overview and conclusion concerning the use of Bruce anchors to anchor crab-pot-strings in Prinses Amalia Offshore Windpark. Summarising report https://doi.org/10.18174/576750.
[61] M.J.C. Rozemeijer, C. Chun, R. Cramer, A. Korving, C. Meeldijk, Assessing the stability and mobilisation of crab-pot-strings anchored with Bruce anchors under different marine conditions, W. M. Research,, 2021. ⟨https://edepot.wur.nl/560823⟩.
[62] M.F. Schupp, A. Kafas, B.H. Buck, G. Krause, V. Onyango, V. Stelzenmüller, I. Davies, B.E. Scott, Fishing within offshore wind farms in the North Sea: Stakeholder perspectives for multi-use from Scotland and Germany, J. Environ. Manag. 279 (10) (2021), 111762, https://doi.org/10.1016/j.jenvman.2020.111762.
[63] M.F. Schupp, M. Bocci, D. Depellegrin, A. Kafas, Z. Kyriazi, I. Lukic, A. Schultz-Zehden, G. Krause, V. Onyango, B.H. Buck, Toward a common understanding of ocean multi-use [Article], Article 165, Front. Mar. Sci. 6 (APR) (2019), https://doi.org/10.3389/fmars.2019.00165.
[64] Shyam Kularathna, A.H.T., Takagi, K. (2018). Takagi Factors behind local acceptability of marine renewable energy projects and perceived preferences of possible Co-existence options: Case study of marine renewable energy development in Nagasaki, Japan. 2018 OCEANS - MTS/IEEE Kobe Techno-Oceans OCEANS - Kobe.
[65] Global Wind Energy Council. (2022). GWEC | GLOBAL OFFSHORE WIND REPORT 2022.
[66] T. Smythe, D. Bidwell, G. Tyler, Optimistic with reservations: The impacts of the United States' first offshore wind farm on the recreational fishing experience, Mar. Policy 127 (2021), 104440, https://doi.org/10.1016/j.marpol.2021.104440.
[67] T. Smythe, D. Bidwell, A. Moore, H. Smith, J. McCann, Beyond the beach: Tradeoffs in tourism and recreation at the first offshore wind farm in the United States, Energy Res. Soc. Sci. 70 (2020), 101726, https://doi.org/10.1016/j.erss.2020.101726.
[68] N.A. Steins, J.A. Veraart, J.E.M. Klostermann, M. Poelman, Combining offshore wind farms, nature conservation and seafood: Lessons from a Dutch community of practice, Mar. Policy 126 (2021) 104371, https://doi.org/10.1016/j.marpol.2020.104371.
[69] V. Stelzenmüller, A. Gimpel, H. Haslob, J. Letschert, J. Berkenhagen, S. Bruning, Sustainable co-location solutions for offshore wind farms and fisheries need to account for socio-ecological trade-offs [Article], Article 145918, Sci. Total Environ. 776 (12) (2021), https://doi.org/10.1016/j.scitotenv.2021.145918.
[70] V. Stelzenmüller, J. Letschert, A. Gimpel, C. Kraan, W.N. Probst, S. Degraer, R. Döring, From plate to plug: The impact of offshore renewables on European fisheries and the role of marine spatial planning [Article], Article 112108, Renew. Sustain. Energy Rev. 158 (2022), https://doi.org/10.1016/j.rser.2022.112108.
[71] V. Stelzenmüller, R. Diekmann, F. Bastardie, T. Schulze, J. Berkenhagen, M. Kloppmann, G. Krause, B. Pogoda, B.H. Buck, G. Kraus, Co-location of passive gear fisheries in offshore wind farms in the German EEZ of the North Sea: A first socio-economic scoping [Article], J. Environ. Manag. 183 (2016) 794–805, https://doi.org/10.1016/j.jenvman.2016.08.027.
[72] C. Stenberg, J.G. Støttrup, M. van Deurs, C.W. Berg, G.E. Dinesen, H. Mosegaard, T. M. Grome, S.B. Leonhard, Long-term effects of an offshore wind farm in the North Sea on fish communities, Mar. Ecol. Prog. Ser. 528 (2015) 257–265, https://doi.org/10.3354/meps11261.
[73] Strietman, W.J., Deetman, B., Rozemeijer, M.J.C., & Kunz, M.C. (2023). De commerciële haalbaarheid van passieve visserij op Noordzeekrab in windparken voor de Hollandse kust. Een verkenning naar de potentiële kosten en opbrengsten (No. 2023–026 ed.). Wageningen Economic Research. https://doi.org/https://doi.org/10.18174/585893.
[74] T.S. ten Brink, T. Dalton, Perceptions of commercial and recreational fishers on the potential ecological impacts of the Block Island Wind Farm (US) [Article] (Article), Front. Mar. Sci. 5 (NOV) (2018) 439, https://doi.org/10.3389/fmars.2018.00439.
[75] The Fishing Liaison with Offshore Wind and Wet Renewables Group. (2014). FLOWW Best Practice Guidance for Offshore Renewables Developments: Recommendations for Fisheries Liaison.

[76] The Norwegian Water Resources and Energy Directorate. (2013). Offshore wind power in Norway: Strategic Environmental Assessment. Oslo. Retrieved from https://publikasjoner.nve.no/diverse/2013/havvindsummary2013.pdf.
[77] The Scottish Government. (2014). Scotland's National Marine Plan. Edinburgh Retrieved from ⟨https://www.gov.scot/binaries/content/documents/govscot/publications/strategy-plan/2015/03/scotlands-national-marine-plan/documents/00475466-pdf/00475466-pdf/govscot%3Adocument/00475466.pdf⟩.
[78] L. Tonk, M.J.C. Rozemeijer, Ecol. brown crab (Cancer pagurus) Prod. Potential Passiv. Fish. Dutch Offshore Wind Farms (2019), https://doi.org/10.18174/496176.
[79] L. Tonk, M.J.C. Rozemeijer, Passive fisheries of brown crab (Cancer pagurus) and European lobster (Homarus gammarus) in Dutch offshore wind farms. With reflections on its feasibility as a form of multi-use in offshore wind farms, W. M. Research,, 2022 https://doi.org/10.18174/576744.
[80] United Nations Convention on the Law of the Sea, (1982). ⟨https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf⟩.
[81] G. Van Hoey, F. Bastardie, S. Birchenough, A. De Backer, A. Gill, S. Koning, S. Hodgson, S. Mangi Chai, J. Steenbergen, E. Termeer, S. Burg, N. Hintzen, Overv. Eff. Offshore Wind Farms Fish. Aquac. – Final Report. (2021) doi/10.2826/63640.
[82] S. Vandendriessche, K. Hostens, W. Courtens, E. Stienen, Fisheries activities change in the vicinity of offshore wind farms, in: S. Degrear, R. Brabant, B. Rumes (Eds.), Environmental impacts of offshore wind farms in the Belgian part of the North Sea: Learning from the past to optimise future monitoring programmes, Royal Belgian Institute of Natural Sciences, 2013, pp. 80–85.
[83] E.A. Virtanen, J. Lappalainen, M. Nurmi, M. Viitasalo, M. Tikanmäki, J. Heinonen, E. Atlaskin, M. Kallasvuo, H. Tikkanen, A. Moilanen, Balancing profitability of energy production, societal impacts and biodiversity in offshore wind farm design, Renew. Sustain. Energy Rev. 158 (2022), 112087, https://doi.org/10.1016/j.rser.2022.112087.
[84] H.E.E. Voet, C. Van Colen, J. Vanaverbeke, Climate change effects on the ecophysiology and ecological functioning of an offshore wind farm artificial hard substrate community [Article] (Article), Sci. Total Environ. 810 (2022), 152194, https://doi.org/10.1016/j.scitotenv.2021.152194.
[85] C.V.C. Weiss, B. Ondiviela, X. Guinda, F. del Jesus, J. Gonzalez, R. Guanche, J. A. Juanes, Co-location opportunities for renewable energies and aquaculture facilities in the Canary Archipelago, Ocean Coast. Manag. 166 (2018) 62–71, https://doi.org/10.1016/j.ocecoaman.2018.05.006 [Article; Proceedings Paper].
[86] L. Wever, G. Krause, B.H. Buck, Lessons from stakeholder dialogues on marine aquaculture in offshore wind farms: Perceived potentials, constraints and research gaps, Marine Policy 51 (2015) 251–259, https://doi.org/10.1016/j.marpol.2014.08.015.
[87] Wind Europe. (2019). *Our energy, our future: How offshore wind will help Europe go carbon-neutral*.
[88] Wind Europe. (2020). *Offshore Wind in Europe: Key trends and statistics* 2020.
[89] K.L. Yates, D.S. Schoeman, C.J. Klein, Ocean zoning for conservation, fisheries and marine renewable energy: Assessing trade-offs and co-location opportunities [Article], J. Environ. Manag. 152 (2015) 201–209, https://doi.org/10.1016/j.jenvman.2015.01.045.
[90] Y. Zhang, C. Zhang, Y.C. Chang, W.H. Liu, Y. Zhang, Offshore wind farm in marine spatial planning and the stakeholders engagement: Opportunities and challenges for Taiwan, Ocean Coast. Manag. 149 (2017) 69–80, https://doi.org/10.1016/j.ocecoaman.2017.09.014.