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An analysis of fishers' concerns and knowledge gaps relating to offshore wind development in Norway

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Abstract

Norway is planning large-scale offshore wind development, aiming for 30 GW installed capacity by 2040, while emphasizing co-existence with fisheries. However, the impacts on marine ecosystems and fishing operations remain uncertain. This study investigates the information needed to promote coexistence and identify knowledge gaps. The research involved in-depth interviews with fishers in three Norwegian offshore wind areas, a national media survey of stakeholder opinions, and a literature review on offshore wind farm effects on fisheries. Key concerns from the fishing industry were explored, along with their local ecological knowledge. The study highlights critical knowledge gaps regarding offshore wind farm impacts on fish and fisheries in Norway. The paper concludes with recommendations to promote co-existence between offshore wind and fishing industries, aiming to minimize potential negative effects on fisheries while supporting renewable energy goals.

Keywords: offshore wind development; fisheries; co-existence; knowledge gaps; fishing industry concerns

Introduction

Human activities have significantly increased greenhouse gas emissions, impacting climate and marine ecosystems. To mitigate these effects, there is an urgent need for clean, renewable energy technologies. Offshore wind turbines are a promising solution, with bottom-fixed turbines used in Europe since the 1990s. Norway, with large marine areas and extensive wind resources, is an emerging player in offshore wind. Most offshore areas are too deep for bottom-fixed turbines, but floating wind turbine technology provides the potential for deep-water wind farms.

The expansion of offshore wind into these areas creates challenges, as existing maritime industries, like fisheries, already utilize much of the space. Careful planning is needed to balance renewable energy development with the needs of other sectors.

The Norwegian Water Resources and Energy Directorate (NVE) has been mapping areas for offshore wind since 2009. In 2010, NVE identified 15 potential sites, and ongoing evaluations led to recommendations for 20 new areas in April 2023 to support Norway's target of 30 GW of offshore wind energy by 2040. The selection process considered technical suitability, wind conditions, potential conflicts with other activities (such as fisheries and shipping), and grid connection possibilities. While Norway's Ocean Energy Act (2010) does not directly address co-existence, Norwegian policies strongly emphasize balancing offshore wind development with maritime sectors, especially fisheries.

The Northeast Atlantic hosts some of the world's most productive fisheries (FAO 2024), vital for food security and the economy. Fisheries are crucial for Norway's coastal communities and international trade. In 2023, Norway exported 1.5 million tonnes of seafood from wild-caught fisheries, totaling NOK 43.3 billion (https://en.seafood.no/), and contributing up to 1% of GDP. Sustainable fisheries are also important for climate goals, having a much lower CO_2 footprint than beef, pork, and poultry (Winther et al. 2020). A shift to diets including fisheries and aquaculture is suggested to help meet climate targets (Hoegh-Guldberg et al. 2019, Costello et al. 2020).

Given this priority, it is crucial that fishers themselves contribute to defining what credible and legitimate co-existence looks like in practice. Our research bridges a knowledge gap by incorporating local fisher knowledge, or local ecological knowledge (LEK) (Silvano and Valbo-Jørgensen 2008). By regularly interacting with the natural environment, fishers accumulate extensive knowledge about both the physical aspects (such as tides, temperatures, wind, currents, and seasonal variations) and biological aspects (such as fish behaviour, fish distribution, spawning, and feeding grounds) of their fishing habitat, including bottom substrate and shipwrecks (Murray et al. 2006, Farr et al. 2018). This experiential knowledge enables fishers to provide valuable information regarding the location and design of offshore wind farms (OWFs) to minimize impacts on fisheries and reduce the overall environmental footprint of offshore wind development.

OWFs can create artificial reef-like environments, altering habitats and attracting fish species. OWFs introduce noise and may also affect water currents, waves, and sediment transport. Additionally, underwater cables can generate

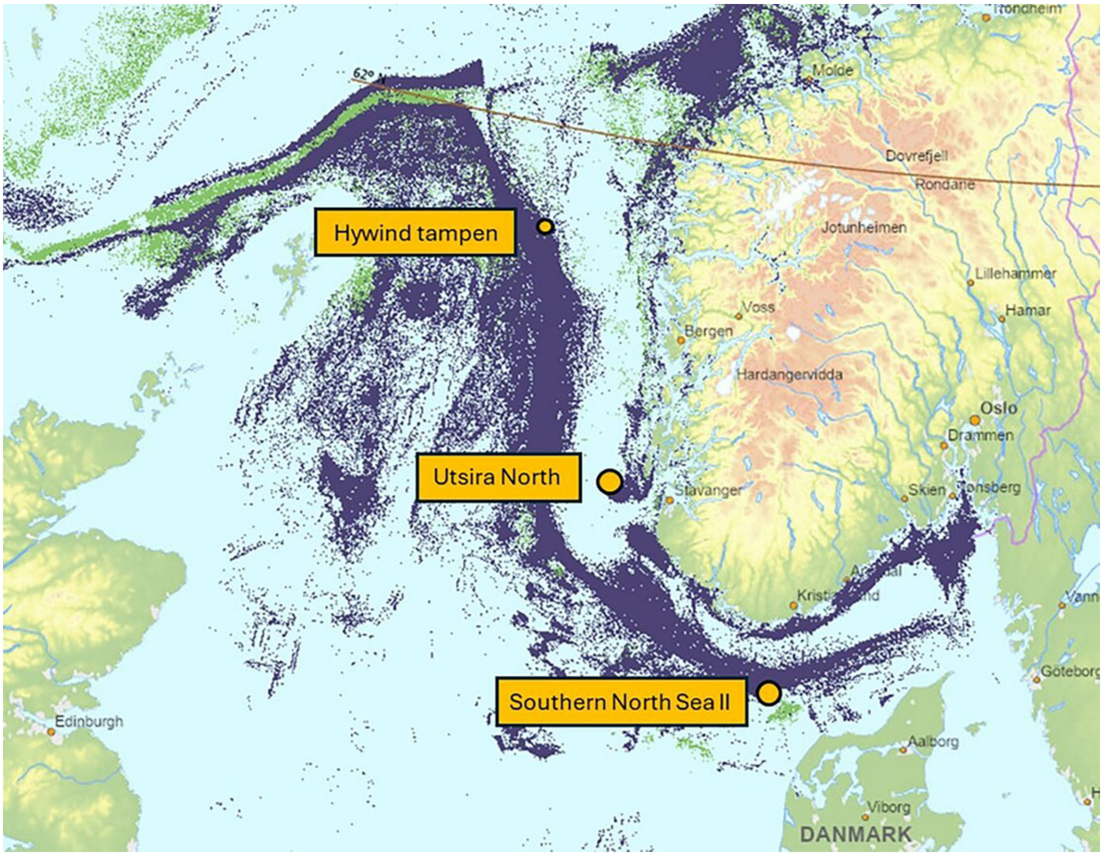

Figure 1. Location of the three wind farm areas (not to scale) in relation to fishery activity of Norwegian vessels over 15 m (2018–2022) in the North Sea, Southern Norway, and adjacent waters. Dots represent commercial fishing activity. Detailed maps are in Fig. S5a–c. Data from the Norwegian Directorate of Fisheries.

electromagnetic fields that influence marine species. These effects have been studied extensively (Galparsoro et al. 2022, Hogan et al. 2023, Wang et al. 2024, and Gill et al. 2025), and understanding them is essential for developing mitigation strategies.

Hywind Tampen, Southern North Sea II, and Utsira North are Norwegian OWF areas that will be the focus of this study. These areas overlap with historical fishing areas and fish spawning grounds. Southern North Sea II, the first commercial area for offshore wind under the Offshore Energy Act, was auctioned in 2024. Utsira North is in the process of being opened.

Hywind Tampen, Norway's first OWF, is a legal part of the petroleum sector, with its own unique licensing process under the Petroleum Act. Norway is a major fossil fuel exporter, and its petroleum and gas sector accounts for 25% of the country's CO2 emissions. To meet climate goals, Norway wants to power its fossil fuel sector with offshore wind energy. Thus, many more of the OWF to come will likely be licensed through the Petroleum Act.

This study aims to explore the interaction between OWFs and fisheries in Norway. Specifically, we will identify fishers' concerns about OWF establishment, focusing on three specific case studies (described above) (Fig. 1). We will also review existing LEK and assess how it is being utilized in the co-existence process. Ultimately, we seek to understand the challenges and opportunities in balancing offshore wind development with fisheries, in terms of spatial conflicts and ecological impact. Challenges related to socio-economic and legal regulations are beyond the scope of this study.

Fishers' LEK and concerns were assessed through interviews, as well as a review of opinion articles and responses from fishermen's organizations to governmental hearings. Additionally, a literature review was conducted to evaluate the direct effects of OWF on fisheries resources, comparing scientific research with fishers' concerns and identifying knowledge gaps.

Methods

Fisheries information

Interviews with fishers

In 2022, the Norwegian fishing fleet consisted of 5503 vessels, of which 456 (8%) were >15 m and suitable for offshore fishing, potentially conflicting with the three OWF sites in this project (Fiskeridirektoratet, n.d.). In April 2022, twenty-four experienced skippers from vessels operating near the planned wind farms were selected for semi-structured interviews (for more details, see supplementary and Table S1). The interviewees were selected based on recommendations from an advisory group, which included experienced fishermen from various gear groups, as well as input from local fishers and data from the Directorate of Fisheries, including AIS records. We selected vessels that had fished regularly in the North Sea and near the three OWF sites.

Table 1. Number of interviews (*n*) per fishery and per OWF.

Fishery	Target species	OWF area	Vessel length (m)	*n*
Offshore gillnet fishery	Saithe, hake, cod, haddock	HYT, SN	27–56	8
Offshore trawl fishery	Saithe, hake, cod, haddock	HYT	35–76	6
Deep water (Bottom trawl)	Shrimp	UTS	27–36	2
Offshore sandeel fishery (Bottom trawl)	Sandeel	SN	69–78	2
Pelagic trawl and purse seine fisheries	Herring, mackerel	HYT, UTS, SN	67–78	2
Offshore Longline Fishery	Ling, tusk	HYT	39–58	2
Demersal fish with Danish Seine	Cod, saithe, haddock, hake	HYT, SN	35–58	2

HYT, Hywind Tampen; UTS, Utsira North; and SN, Southern North Sea II. Target species: Saithe (*Pollachius virens*), hake (Merluccius merluccius), cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), shrimp (*Pandalus borealis*), sandeel (*Ammodytes* spp.), herring (*Clupea harengus*), mackerel (*Scomber scombrus*), ling (*Molva molva*), and tusk (*Brosme brosme*).

The selected vessels represented all the main fisheries that may conflict with the three OWF sites in this study. We grouped the vessels based on target species, fishing gear, and fishing area and season (Table 1).

We respected interviewees' privacy preferences, omitting sensitive information like specific fishing grounds. Most fishers used electronic devices to record their activities, which they referenced during interviews. We employed a semi-structured interview method, covering twelve topics in four main areas: fishing practices, fish distributions, physical characteristics of OWF sites, and opinions on OWF development and co-existence with fisheries (Supplementary Table S1). Responses were used to create detailed drawings of wind farm sites, highlighting features important to fisheries. Concerns about OWF development emerged, particularly during discussions about experiences with similar structures and views on co-existence.

The answers were compiled to summarize the interviewees' opinions and concerns, with severity levels (low, medium, high) counted for each identified concern

Catch statistics for the wind farm areas

Fisheries catch statistics were used to corroborate and supplement the information from interviews about the most important commercial fish species caught in the three OWF areas (see Supplementary for details). These data contributed to the development of the drawings (Figs. 2–4) and descriptions of the OWF areas.

Information from fisheries representatives

We also reviewed responses from fisheries organizations to public consultations by the Norwegian Ministry of Energy (Supplementary 8).

Media review

We analyzed Norwegian media coverage of offshore wind and fisheries by searching for op-ed articles using Google Advanced Search with the terms 'Fisheries∗ AND offshore wind∗ AND (op-ed article∗ OR debate∗ OR opinion∗)' in Norwegian, from 1 January to 31 December 2022. To avoid skewing the sample size by including the same authors opinions or stories published in multiple articles, interviews, duplicates, and irrelevant pieces were excluded. We also searched the fisheries newspaper, Fiskeribladet, and included relevant articles. The op-eds were categorized into six groups: fishing industry representatives, politicians, scientists, environmental organizations, offshore wind developers, and others (e.g. private citizens). Nine topics were subjectively selected based on the concerns that were raised by the fishermen in the interviews and commonly discussed in the literature and media. In addition, we aimed to investigate perceptions towards knowledge gaps and research needs among the different groups. One person then assessed all the articles and made an evaluation on whether the authors' views were positive, negative, or neutral on key topics:

- Offshore wind development.
- Faster development of offshore wind.
- Need for consideration of environmental and ecosystem effects.
- Need for consideration of fisheries effects.
- Need for better spatial planning.
- Need for more research on environmental and ecosystem effects.
- Need for more research on fisheries effects.
- Need for better dialogue between the stakeholders.
- Fishing opportunities inside the wind farm.

Literature review

To get an overview of the scientific effort and address fishermen's concerns, we searched Web of Science with the terms 'offshore wind' AND (fish∗ OR invertebrate∗). We included all papers published before January 2024 (last search 03.06.2024). We checked whether papers covered the effects of offshore wind on fisheries activities and/or resources (fish and crustaceans) based on the abstract. Additionally, we reviewed which papers provided original data and, if needed, the full text. For each paper, we checked if it fell into one or more of the following categories:

- Reports on societal impacts.
- Reports on approaches for impact assessment and management.
- Reports on potential environmental impacts of OWF.
- Reports on interactions with coexisting industries: Fisheries.
- Reports on interactions with coexisting industries: Other.
- Reports primary biological data on fish (including catches).
- Reports primary biological data on crustacea (including catches).
- Reports primary data on fisheries activity and revenue.
- Reports related effects.

Our analysis was strictly limited to papers from the initial search criteria. To maintain consistency and avoid citation bias, we excluded additional papers cited within the primary

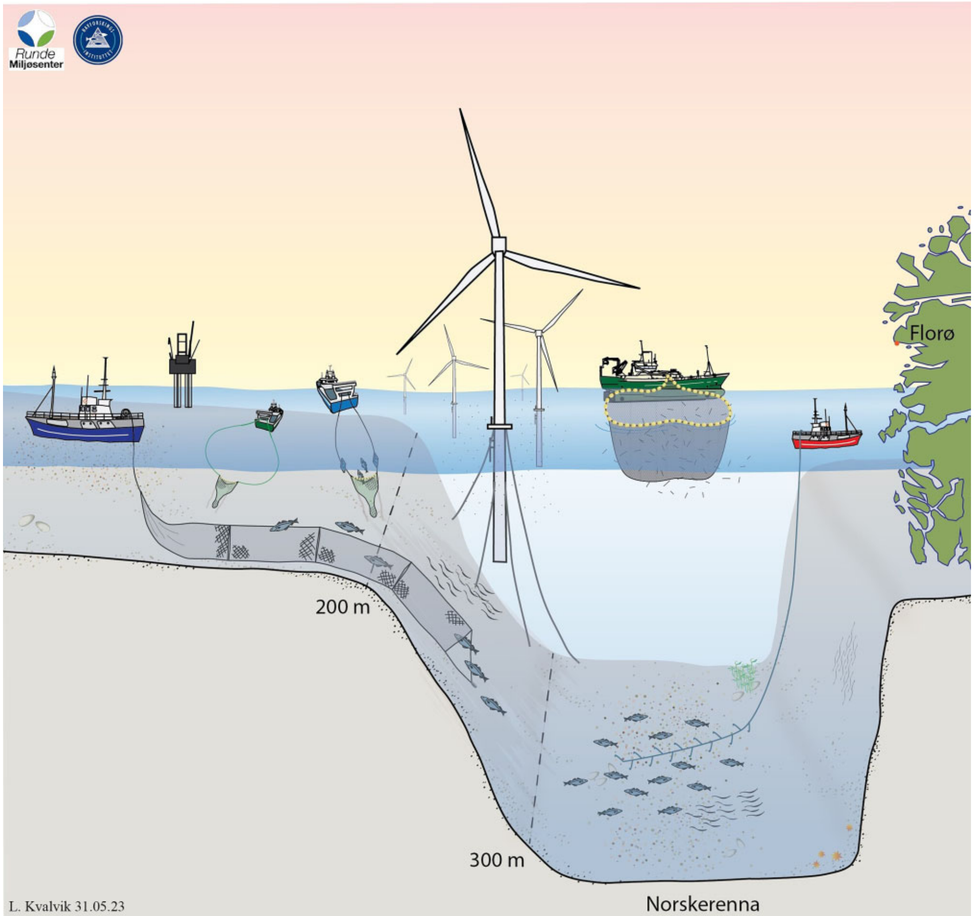

Figure 2. Hywind Tampen OWF. The figure is an artistic impression based on information from skippers and from the Norwegian Directorate of Fisheries. Illustration by L. Kvalvik, based on original sketches by N. R. Hareide.

sources. This approach ensures our results are not disproportionately influenced by papers reporting original findings and preserves the integrity of our systematic review process.

Results

Site descriptions and site-specific concerns

The interviews with fishermen provided insight into fishing practices and catches in the OWF areas. Fishers shared detailed knowledge on target and bycatch species, related to fishing banks, depths and season, including the location of spawning grounds. They also shared knowledge on bottom conditions, tides, and seasonal changes in weather conditions and their impact on catch success (see Supplementary Fig. S2).

Hywind Tampen

Hywind Tampen is located on the western slope of the Norwegian Trench, at the eastern edge of the 'Tampen' fishing bank (61°16′38″N-61°23′17″N, 2°12′54″E-002°18′28″E) (Fig. 1, Supplementary Fig. S3). The depth is 240–290 m, consisting of clay and sand, with strong north-westerly currents. Installation of the floating OWF began in April 2022 and was completed in August 2023, covering 22 km^2 with 11 turbines and 88 MW capacity (Equinor report 2019).

Fisheries along the western slope in this region target saithe (*Pollachius virens*), cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), and ling (*Molva molva*), while the trench area includes hake (*Merluccius merluccius*), ling and tusk (*Brosme brosme*), and pelagic species such as mackerel (*Scomber scombrus*), herring (*Clupea harengus*), blue whiting (*Micromesistius poutassou*) and Norway Pout (*Trisopterus esmarkii*). Further west, in shallower waters (<200 m, 'Tampen' fishing bank), there are cod spawning grounds. Commercial catches, summed for 2018–2021, show the largest catches were blue whiting (240 tonnes), herring (163 tonnes), saithe (116 tonnes), Argentine (*Argentina silus*) (115 tonnes), and mackerel (6 tonnes), with landings varying between years (Supplementary Table S2).

Fisheries include gillnet, bottom trawl, pelagic trawl, longline, and Danish seine, with gillnetters, trawlers, and longliners focusing on the western slope (Fig. 2).

Interviewees mentioned a direct conflict between the OWF placement and bottom trawl fisheries, reporting overlap with trawling lanes along the slope (e.g. Supplementary Fig. S4). For gillnet fisheries west of Hywind Tampen, fishers mentioned the risk of nets drifting into the OWF area due to strong currents and soft bottom conditions, making it difficult and potentially dangerous to fish close to the OWF. Pelagic trawl, purse seine, longline, and Danish seine fishers are concerned about loss of fishing area but are less affected due to more control of their gear.

In response to public consultations for this OWF, fisheries organizations stated that Hywind Tampen is an important spawning and foraging area for fish, vulnerable to OWF de-

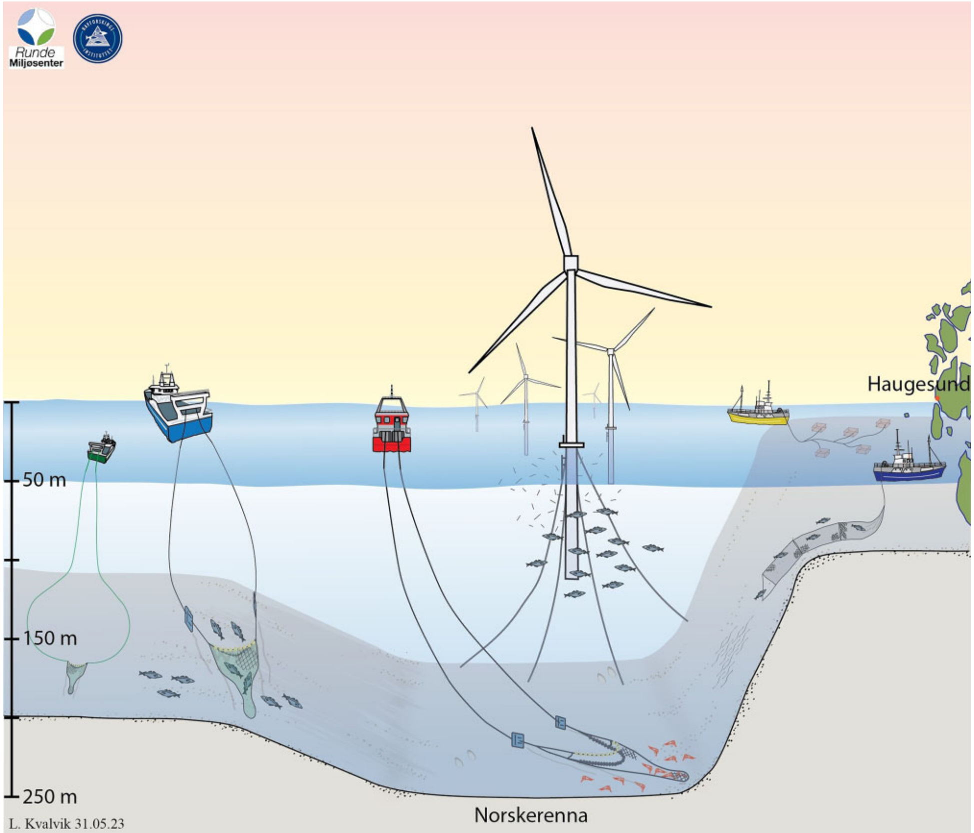

Figure 3. Utsira North OWF. The figure is based on information from skippers and from the Norwegian Directorate of Fisheries. Illustration by L. Kvalvik, based on original sketches by N. R. Hareide.

velopment, with insufficient knowledge on the biological consequences (Supplementary 8). They noted that it is a historical fishing ground. The organizations requested the wind turbines be positioned parallel to the slope and moved further north to reduce interference with fishing activity. The Norwegian Directorate of Fisheries made the same request, but it was not accepted.

Utsira North

The Utsira North OWF site is in the deepest part of the Norwegian trench (59°00′01″N, 4°14″02″E), with depths over 100 m (Fig. 1, Supplementary Fig. S3). The substrate is soft bottom and clay. Fishers report weaker currents compared to Hywind Tampen. Utsira North will host floating turbines with 1380–1500 MW capacity, covering 429 km^2 based on a 3.5 MW/km^2 requirement (according to the Norwegian Ministry of Petroleum and Energy). The area supports diverse fisheries, including bottom trawl for shrimp, hake, saithe, and cod, pot fishing for Norway lobster, and pelagic fisheries for species like herring (Fig. 3). Landings data from 2018 to 2021 shows major catches of herring (41.5 tonnes), mackerel (37 tonnes), Norway pout (16 tonnes), saithe (6 tonnes), and horse mackerel (4 tonnes) (Supplementary Table S3).

The interviews indicated that fishers do not foresee much conflict with the planned OWF, but highlighted that expansion to the upper slope or further south in the trench would cause significant conflict (Supplementary Fig. S5b). Fishing activity is higher on the slopes than the deeper parts of the trench, but there is a commercial fishery for shrimp in the deep part of the trench along the most southern part of Norway—an area identified for future development. In response to public consultations, fisheries organizations and the Directorate of Fisheries recommended moving the wind farm area further north and east to avoid conflicts also if the area is expanded, but this was not acted upon (Supplementary 8 and Fig. S6).

Southern North Sea II

The Southern North Sea II OWF site is located between Denmark and Norway (59°13″29″N-56°28″13″N, 4°26″54″E-5°29″51″E) at a depth of 50–60 m with sandy and fine gravel sediment. As of October 2024, it is still in the licensing process. Bottom-mounted turbines are expected due to the shallow depth. A 1400–1500 MW capacity is planned. The most important commercial fisheries in this area are bottom trawl fisheries for sandeel and gillnet and Danish seine fisheries for cod, haddock, and saithe (Fig. 4). Landings data from 2018 to 2020 show sandeel (6329 tonnes) as the largest catch, followed by haddock (47.6 tonnes), whiting (38.5 tonnes), gurnards (9.6 tonnes), and herring (8.7 tonnes) (Supplementary Table S4).

Sandeels (*Ammodytes* spp.) play a crucial ecological role in marine ecosystems and serve as vital raw material for the European fishmeal industry. Fishers and their organizations have expressed concerns regarding potential impacts of OWFs on the benthic environment, which is critical for sandeel populations. They worry that bottom-mounted turbines could cause significant sediment resuspension, creating plumes spanning several kilometres (Vanhellemont and Ruddick 2014). Suspended sediment clouds could harm sandeel populations by impairing gill function, potentially leading to asphyxiation. Altered sedimentation could change the benthic substrate,

Figure 4. Southern North Sea II OWF. The figure is based on information from skippers and from the Norwegian Directorate of Fisheries. Illustration by L. Kvalvik, based on original sketches by N. R. Hareide.

impacting sandeel burrowing and spawning. Fisheries organizations and the Directorate of Fisheries requested that the OWF be moved northeast to avoid important fishing grounds, a request that was followed (Supplementary 8 and Figs. S5c and S6).

General concerns of fishers relating to OWF development

The interviewed fishermen's concerns about OWF development emerged naturally during discussions across all topics (Supplementary Table S1) and were further elaborated through experiences fishing near similar structures, as well as personal opinions on OWF development and co-existence. Interview responses were carefully documented to summarize interviewees' views on the impact of OWF development and its integration with fisheries. Six general concerns regarding OWF development were highlighted in the interviews (Table S1). We classified each concern as high, low, or medium severity based on how many of the interviewees commented on each concern. The concerns are ranked by importance in Table 2, with detailed comments provided below.

Table 2. The concerns of interviewed fishermen in relation to OWF in general, ranked by the proportion of interviewees who considered the concern of low, medium, or high severity.

Concern (%)	Low concern	Medium concern	High concern
1. Loss of fishing grounds			100
2. Involvement of the fishing industry in the process			100
3. Effects on spawning grounds		10	90
4. Effects of noise		20	80
5. Rescue/safety concerns		30	70
6. Lack of knowledge of ecosystem	10	30	60

1. Loss of fishing grounds

All interviewees expressed concern about the loss of fishing areas, noting that OWF zones are much larger than those used by the oil and gas industry. When asked about alternative fishing grounds, all fishers believed no new grounds are available, as many are already exploited or closed, e.g. to protect spawning. A related concern is the need for detours to avoid OWF areas, which reduce fishing efficiency and increase fuel consumption, negatively impacting both costs and the environment.

2. Involvement of the fishing industry in the process

All interviewed fishers stated that the fishing industry has not been adequately involved in OWF planning. They noted a general lack of knowledge and understanding about fisheries and the environment. Establishing forums to manage the relationship between fisheries and the offshore wind industry is seen as essential.

3. Effects on spawning grounds

Interviewees expressed concern about pollution of fish spawning areas and disruption of habitats and sediment, particularly for herring and sandeel. Herring spawn on gravel,

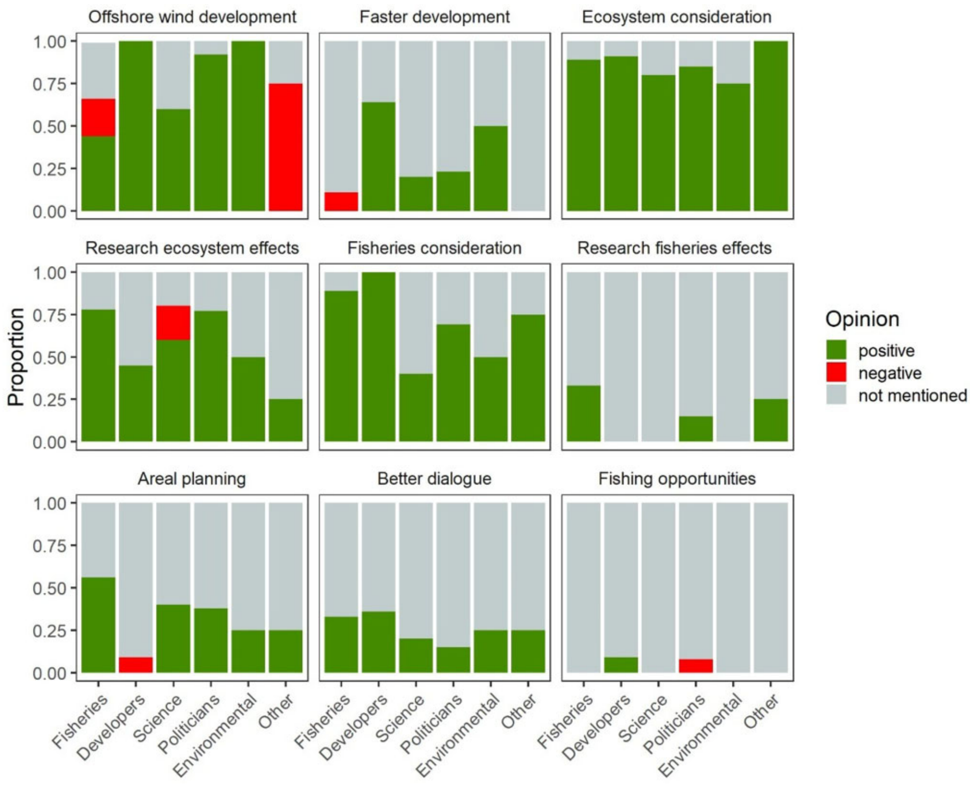

Figure 5. Results from the analysis of Norwegian national media coverage of co-existence. Selected op-ed articles were categorized into 6 interest groups, including the fishing industry (fisheries), offshore wind developers (developers), science, politicians, environmental organizations, and an ‘other’ group mainly represented by private persons.

while sandeel use sandy substrates for spawning, feeding, and shelter. The Viking Bank, an important sandeel spawning and fishing ground, has seen a decline in sandeel populations, which interviewees attribute to possible pollution or changes in sediment caused by the oil industry.

4. Effects of noise

All fishermen had experienced that noise from fishing vessels and gear can affect fish behaviour and scare fish away. They also reported that seismic surveys influence fish behaviour, raising concerns that noise from OWFs could have similar effects. Interviewees were particularly worried that noise from OWFs could alter migration routes, especially for herring, which have been observed changing swimming direction when disturbed by fishing or seismic vessels.

5. Rescue/safety concerns

Fishers raised concerns about rescue operations for OWF-related incidents, especially for vessels drifting into OWF areas, questioning the availability of nearby rescue vessels and helicopters. Most expected a 500-m security zone around turbines, with some suggesting flexibility. They also highlighted the risk of entanglement with floating turbine mooring lines, particularly for trawlers and gillnetters in adverse weather, which could lead to capsizing.

6. Lack of knowledge about effects on ecosystems

All interviewees expressed concern about the lack of knowledge regarding the effects of OWFs on the ecosystem, particularly on small pelagic fish species like herring, Norway pout, and sandeels. They worry that disturbances to these key species in the food chain could lead to their disappearance.

Fishing close to offshore installations, and opinions of OWF development and co-existence with fisheries

All interviewees had experience fishing around fixed installations like oil rigs and pipelines, where vessels are restricted to a 500-m distance. However, bottom trawlers often approach within 300–370 m when towing gear in a circle around the rigs. Fishers report high catch rates near platforms and pipelines, and purse seine skippers fish as close as possible in good weather. In bad weather, they may fish as far as 4–5 nautical miles (7–9 km) away.

Skippers did not have a general design suggestion for better co-existence with fisheries. They believe the best approach is to study fishing activity and work closely with local fishers to develop OWF design that minimally impacts their operations.

Media review

A total of 86 op-ed articles were identified, with 46 meeting the review criteria (see Fig. 5). Authors were diverse, with the most contributions from politicians ($n = 13$) and offshore wind developers ($n = 11$), followed by fishing industry representatives ($n = 9$), scientists ($n = 5$), and environmental organizations ($n = 4$). Overall, the attitude towards offshore wind was mostly positive, with developers and environmental groups supporting faster development. However, some fishermen and the ‘other’ group ($n = 4$) expressed negative views. Most articles emphasized ecosystem effects and the need for more research, while fisheries considerations were seen as important but secondary. Few articles discussed OWF impacts on fisheries, and less attention was given to spatial planning and dialogue. Only two articles addressed fishing opportunities in-

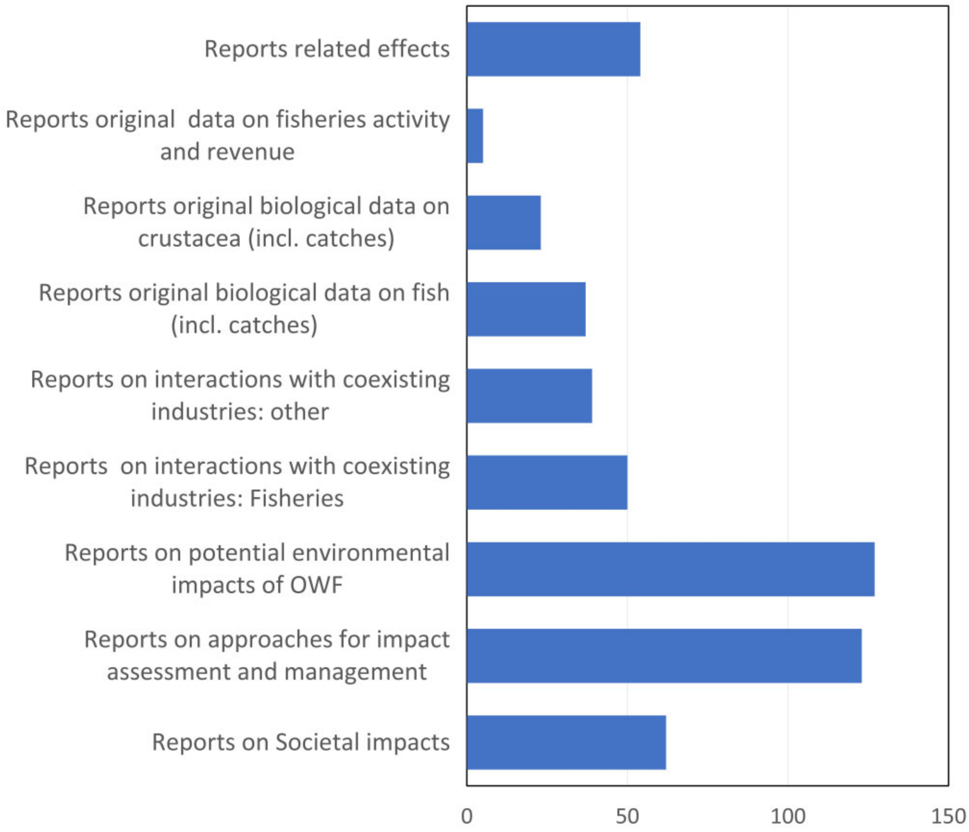

Figure 6. Bar chart showing the number of studies that addressed each of the nine chosen categories within a total of 316 studies found in a literature search of literature up to December 2023. Search was done in Web of Science with search terms: 'offshore wind' AND (fish* OR invertebrate*). Note that a single article can show up in several categories.

side wind farms, with differing opinions from developers and politicians.

Literature review

The literature review on OWF effects on fishery resources identified 596 unique records, with 318 papers categorized into nine non-exclusive groups (Fig. 6). Over 100 publications addressed environmental effects, but only 40 focused on fisheries impacts. Of 52 studies with original data on fisheries, only five included fishery activity and revenue data. None of the studies compared fishing activity and commercial catch success before and after OWF development.

While commercial catch success was not reported, experimental studies show higher-value catches in areas temporarily or permanently closed for fishing. One study off the UK coast found that lobster catches inside an OWF increased after its development but decreased once the area was reopened for fishing (Roach et al. 2022). Landings and catch per unit effort (LPUE/CPUE) remained stable in the year following the OWF construction.

Wilber et al. (2022) conducted a seven-year BACI study at the Block Island Wind Farm, examining CPUE changes for various species in a scientific fisheries survey. Results were mostly inconclusive, with only a few species showing significant differences between the wind farm and reference sites during construction and operation. These findings emphasize the complexity of assessing OWF impacts and the need for long-term, multi-site research. Experimental studies may not reflect economically viable fisheries, highlighting the need for data on actual fishing activity and CPUE to assess OWF impacts.

Dunkley and Solandt (2022) showed a 77% decrease in bottom contacting mobile gear within most UK OWF areas, except for one area where fishing activity increased due to turbine arrangement. Stelzenmüller et al. (2021) observed increased vessel activity of crab fishers in German waters following OWF development, and linked it to higher crab availability, though landing data was lacking. A model by Scheld et al. (2022) predicted a 3%–15% decrease in catch and a 1%–5% increase in economic costs for the American surfclam fishery after OWF development. Recreational fishermen reported mixed effects, with a consistent decline in tope (*Galeorhinus galeus*) catches post-construction (Hooper et al. 2017).

Discussion

Our aim was to reveal the conditions of co-existence that are important for the fisheries sector and to show how LEK of fishers can provide important insights into the development of a new offshore wind sector in Norway.

The Norwegian Government emphasizes co-existence between offshore wind development and fisheries due to several key factors. Legally, the Ocean Energy Act of 2010 mandates that investments in ocean energy must align with the interests of fisheries, recognizing the economic and cultural significance of fishing to coastal communities and the national economy. Early offshore wind development in 2010 faced backlash due to overlap with fishing grounds, highlighting the need for a collaborative approach. In 2023, a multi-directorate process was introduced to identify offshore wind areas with minimal conflict, involving the Norwegian Directorate of Water Resources and Energy (NVE), Norwegian Environment Agency, Directorate of Fisheries, and expert groups including fishers' organizations, wind farm developers, research institutions, and environmental groups. The entire process was made publicly available online. This strategy, deemed successful, credible, and legitimate by fisheries representatives, aims to balance both industries while minimizing environmental impacts.

Spatial conflict

Norwegian fishers are deeply concerned about the loss of fishing grounds due to OWF development, especially since they believe no new viable fishing areas are available. The area closed to fishing is expected to be much larger than the OWF itself, with buffer zones and safety considerations. Estimates for Norway's 30 GW target suggest a footprint of 4000 to 26 000 km^2, but uncertainty about these figures, with some studies indicating even larger areas (Adams and Keith 2013, Miller and Kleidon 2016), intensifies concerns. Loss of fishing grounds is a global issue, also highlighted in studies from the British Isles (Alexander et al. 2013, Reilly et al. 2015, Gray et al. 2016). Additional challenges include reduced profitability from increased fuel consumption from detours and ecological risks associated with the displacement of fishing activities (Püts et al. 2023). The need for long-term data on fishing effort and distribution is crucial to assess the impact of fishing displacement (de Groot et al. 2014, Stelzenmuller et al. 2020, Hogan et al. 2023). This is particularly challenging for nearshore areas where smaller vessels often lack vessel monitoring systems (Gray et al. 2016).

Involvement of fisheries in the development of OWFs

Interviewed fishers expressed concern about their lack of involvement in the OWF development process, which aligns with our Norwegian media review findings, where 'better dialogue' was rarely mentioned by stakeholders. The fishing industry's dissatisfaction with the Hywind Tampen OWF planning highlights this issue, as their concerns were reportedly ignored (Titlestad 2024).

Specific concerns at the Hywind Tampen site included spatial overlap with trawling lanes (Supplementary Fig. S4). Fishers requested a shift in the wind farm's location to minimize this overlap, but the request was not accepted. This has forced trawlers to fish in more limited areas, avoiding cod spawning grounds and the OWF by fishing at depths between 200 and 225 m. Although Hywind Tampen construction proceeded without addressing these concerns, the Southern North Sea II site was adjusted to protect sandeel fishing grounds.

To mitigate negative effects, early consultation with fisheries is critical (Alexander et al. 2013, Reilly et al. 2015), but this is often lacking (Stelzenmüller et al. 2020, European Court of Auditors 2023), leading to distrust (Gray et al. 2016). Fishers' LEK is frequently undervalued (Ames et al. 2002; Sjostrom et al. 2021), despite its potential to enhance OWF design and placement (Hogan et al. 2023). Recent initiatives in Norway, like the 'Dreiebok' guidebook, and a similar effort in Ireland (Seafood/ORE Engagement in Ireland—A Summary Guide), aim to foster co-existence between fisheries and offshore wind. The recommendations are clear: It is important that the interests and knowledge of the fishing industry are considered before decisions on location and development are made, thus, dialogue and information sharing should begin immediately after an area has been opened for offshore wind and before specific sites are allocated to developers. This is important to establish an overview of (i) potential fishing activities and interests within the designated offshore wind areas, (ii) to map knowledge about spawning and nursery areas, migration routes as well as bottom substrate, and biotopes within these areas (fishers LEK combined with research), (iii) to present preliminary plans from offshore wind stakeholders (both wind farms and associated infrastructure), and (iv) to facilitate dialogue on a coexistence strategy. The important thing is that these guides are used. Despite Norway's political aim of developing OWFs in co-existence with fisheries, our study reveals a significant gap between this goal and the current reality, with fishers expressing concerns about lack of early involvement in OWF planning and potential loss of fishing grounds. The industries have agreed that wind farms should not be developed in important spawning and fishing areas and that necessary consideration should also be given to migration routes for important stocks (such as Norwegian spring-spawning herring, cod, capelin, and sandeel). However, fishers are worried that wind farm development via the Petroleum Act will not follow the same promising policies as the 20 areas identified within the process under the Offshore Energy Act.

Environmental impact of OWFs

Fishers and scientists share concerns about OWF environmental impacts, particularly noise, and disturbance to spawning grounds. While many studies discuss these impacts, few provide original data on effects on fishery resources or activities (Fig. 5; Wilber et al. 2022, Methratta 2024). Noise from OWFs can affect fish and crustacean behaviour (e.g. Slabbekoorn et al. 2010, Popper and Hawkins 2019, Nousek-McGregor et al. 2016, Kühn et al. 2023), but knowledge gaps remain (Popper et al. 2022). Chronic noise on land has been shown to restructure wildlife communities (Kok et al. 2023), and similar effects may occur in marine ecosystems. OWF development may also impact spawning habitats, particularly for herring and sandeel, through sediment resuspension and changes in bottom structure (Vanhellemont and Ruddick 2014, Hogan et al. 2023).

The literature review highlights a lack of BACI studies on OWF impacts on fishery resources. Limited data suggests that OWFs are likely to affect fishery activities, with impacts depending on how the OWF influences target species populations and fishing ground accessibility. Given the potential species- and area-specific nature of these effects, careful study during OWF development is essential to understand and mitigate impacts on local fisheries.

Practicalities of co-location of OWF and fisheries

The interest to develop fisheries inside OWF is weak. Fishers are concerned about safety near wind farms (Gray et al. 2016), while the offshore wind industry shows little interest in multi-use solutions without clear benefits (Schupp et al. 2021). A UK study shows reduced fishing activity with bottom-contacting mobile gears in OWF areas, with some exceptions (Dunkley and Solandt 2022). More research is needed on fishing operations inside OWFs (Bonsu et al. 2024). Passive gear is less problematic than active gear, and floating OWFs pose greater challenges (Wright et al. 2023, Thatcher et al. 2024). Excluding fisheries from OWFs may increase environmental and CO_2 footprints due to lower catch rates in less favorable fishing grounds and longer distances to alternative fishing grounds, but comprehensive assessment is hindered by knowledge gaps. Sustainable integration requires ongoing multidisciplinary research and stakeholder collaboration.

Conclusions

To achieve sustainable co-existence, it is crucial to integrate fishers' LEK into OWF development processes, address knowledge gaps regarding OWF impacts on fisheries and marine ecosystems, and design OWFs that minimize displacement of fishing activities while ensuring safety and efficiency for both industries. By genuinely integrating fisheries' concerns and expertise, Norway's offshore wind industry can secure a broader social license to operate, paving the way for truly sustainable energy development that harmonizes with historically established and socio-economically important maritime industries like fisheries.

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Authors contribution

A.C.U-P.: conceptualization, funding acquisition, supervision, project administration writing original draft, writing review and editing. K.M.: conceptualization, analysis of fisheries data, writing and editing. K.d.J.: conceptualization, writing and editing, responsible for literature review. M.T.: conceptualization, writing and editing, responsible for media review. D.J.D.: conceptualization, writing and editing. N.R.H.: conceptualization, writing and editing, responsible for interview with fishers and analysis of fisheries data.

Supplementary material

Supplementary data is available at *ICES Journal of Marine Science* online.

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Data availability

The data underlying this article are available in the article and in its online supplementary material. The interview data in this article cannot be shared publicly due to the privacy of individuals that participated in the study. The data will be shared on reasonable request to the corresponding author.

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