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Wind and Fisheries

Desktop Study on the Coexistence

Between Offshore Wind and Fisheries in Sothern North Sea II

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Report no. 29-2022, NORCE Health and Society

Report title	Wind and Fisheries
Project No	105471
Institution	NORCE Health and Society
Client(s)	Vårgrønn, Agder Energi og Green Investment Group
Classification:	Open
Report No.	29-2022
No. of pages	49
Date of publ.:	June 2022
ISBN nr.	978-82-8408-241-7
CC-licence	CC BY 4.0
Citation	Austrheim, Dahlgren, Handberg, Hestetun, Haugland, Aslesen and Navrud (2022). Wind and Fisheries: Desktop Study on the Coexistence Between Offshore Wind and Fisheries in Sothern North Sea II. Report no. 29-2022, Norce Health and society.
Photo Credit	Dragan Mihajlovic, iStock, Agder Energi
Keywords	Offshore Wind Farms, Fisheries, Coexistence, Synergies

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Summary

The Norwegian Government has launched a major initiative to promote offshore wind power[1], in which bottom-fixed wind power will be developed in the Southern North Sea II (SN II) area. There is a low level of fishing activities in this area with varying catch sizes over the years. The activities consist nearly exclusively of bottom trawling of sandeel. The fishing industry has raised concerns about the development of offshore wind farms (OWFs), including risks for collision and hindrance for fishing vessels, negative impacts on fish stocks, and other ecosystem-wide effects. This report has conducted a data study and compiled existing literature on these topics to, based on best available science, assess how OWF development could affect fisheries in SN II, the possibilities for facilitating coexistence for these two industries, and potential synergies. While the development of OWFs in SN II has the potential to bring both positive and negative effects on the fisheries as well as the marine life in the area, the findings suggest that coexistence between the two industries is possible. Potential impacts, including noise, magnetic fields, turbidity, artificial reef and FAD effects, and no-fishing zones, have not been shown to adversely affect populations of commercially important fish at OWF developments in the North Sea. With the ongoing technology shift to larger turbines, the space between each turbine is increasing, which may reduce collision risk. Seafloor cables can also be sufficiently buried to reduce the risk of damage by demersal trawls. Furthermore, most types of passive fishing gear (except for drifting nets) and practices are less problematic to use in an OWF. Should, though, the construction of OWFs in SN II cause restrictions on the fishery activities in the area, it is likely to cause increased fishing in other areas, often referred to in the scientific literature as the displacement effect, indicating that the economic loss will be smaller than the estimated catch values. Notable knowledge gaps are regarding positive and negative long term cumulative impacts and regional effects, impact on primary production and carbon assimilation from changed upper ocean mixing and impact from floating wind farms (not relevant in SN II). We emphasise the importance of early and ongoing input from relevant stakeholders to address concerns and find optimal mitigation measures for minimising the OWF footprint in SN II during the different phases of OWF development.

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[1] https://www.regjeringen.no/en/aktuelt/major-initiative-to-promote-offshore-wind-power/id2900436/

Table of contents

1. Introduction

The consortium of Vårgrønn, Agder Energi, and Corio Generation has requested an overview of the state of knowledge (as well as current knowledge gaps) on the effects of offshore wind farms (OWFs) on fisheries. More specifically, the consortium seeks a local focus on the southern part of the North Sea, particularly the Southern North Sea II (SN II) area. NORCE is the R&D provider for this report, together with Menon Economics.

While the actual seafloor footprint of turbines may be small, offshore wind energy conversion installations (wind farms) can occupy large areas due to the network of moorings, cables, and associated safety zones. Concerns have been raised from fisheries regarding wind farm developments. Turbines and associated seafloor moorings (in the case of floating turbines) and cables constitute a risk for collision and hindrance for fishing vessels. Alternatively, measures such as exclusion or no-go zones deny fishers areas close to wind installations. Fishers are also concerned that fish will be negatively impacted by OWFs, which may reduce long-term fishing opportunities and the sustainability of the fish stocks.

There is a large and growing literature around the impact of wind power infrastructure on marine biology, including fish, their movements, and their availability to fishing vessels, as well as on legal challenges and implications from the introduction of wind power in waters previously dominated by other industries. There is also extensive literature on the coexistence between fisheries and other marine-based industries.

This report comprises two parts, a data and literature study, with the following four objectives:

- Examine current level, type, and value of fishing activity in the SN II area.
- Assessment of the effects of OWF development on fisheries and the marine habitat.
- Review of potential measures to facilitate coexistence between offshore wind and fisheries.
- Description of potential synergies between the two industries.

Figure 1**. Offshore wind farm, Flevoland, Holland.** ***Credit: iStock (user: Sjo).***

2. Methodological approach

2.1. Data study

To identify and quantify the marine activities in SN II, we have made use of geographical data on ship traffic, fishing activities, as well as catches. The geographical definition of the analysis area is SN II, as given by the Norwegian Energy Regulatory Authority (NVE) in their proposed study areas for offshore wind (NVE 2012)[2]. Information about ship movements is derived from AIS[3] and connected to ship information from Clarksons World Fleet Register. The AIS data is fetched from the Norwegian Coastal Administration (*Kystdatahuset*)[4]. The categorisation of ships into ship types is listed in the appendix. Fishing activities within the area are mapped through *Yggdrasil* by the Norwegian Directorate of Fisheries. Data on catches and catch values are based on fishers' reporting their landings to the register of the Norwegian Directorate of Fisheries ('landings- og sluttseddel-registeret').[5] We thus analyse data on catch values landed in Norway, meaning that catches in SN II landed in Denmark or other countries are not considered. The AIS data does not include all vessels under 15 meters length, but the catches include the smaller vessels as well. The data has been processed for our purposes, as described at the end of the appendix.

2.2. Literature study

The literature study comprises an overview of reports and findings on i) potential impacts of OWFs on fisheries and marine life, arranged thematically, then subject to an integrated assessment, ii) potential for coexistence of fisheries with OWF development in the SN II area, finally iii) possible synergy effects between the two industries. The study encompasses both scholarly articles and reports from organisations and industry. In addition to highlighting current knowledge, the review identifies relevant knowledge gaps. As the available literature comprises studies from different geographical areas, OWF developments and laboratory studies, the relevance of findings to the SN II area is assessed where appropriate, and potential mitigation measures and best practices are identified based on reviewed sources. Main findings and their applicability to SN II is summarised in the conclusion at the end of this report.

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[2] https://kartkatalog.geonorge.no/metadata/havvind/eebb5348-a2cf-44f2-a09f-7f715fcbdc08 [March 21, 2022]. See also https://www.regjeringen.no/no/dokumenter/hoyring-av-forslag-til-inndeling-av-dei-opna-omrada-i-utlysingsomrade-for-fornybar-energiproduksjon-til-havs/id2900420/?expand=horingsnotater

[3] Automatic identification system (AIS) is an autonomous tracking system that provides high resolution data on ship traffic. Ships of certain sizes, depending on ship type, is required to have AIS installed aboard: https://www.imo.org/en/OurWork/Safety/Pages/AIS.aspx [April 4, 2022]. In Norway all fishing vessels larger than 15 meters is required to have an AIS installed: https://havbase.kystverket.no/havbase_report/doc/AIS.pdf [April 4, 2022].

[4] Kystdatahuset, Norwegian Coastal Administration, v1.0.125: https://kystdatahuset.no/ [March 29, 2022].

[5] Available at www.fiskeridir.no/Tall-og-analyse/AApne-data/Fangstdata-seddel-koblet-med-fartoeydata [April 20, 2022]. Data described in more detail by Hopland & Aasheim (2022).

3. Activities in Southern North Sea II

The following provides an overview of the ship activities in SN II, defined by ship movements within the area (subchapter 3.2) and then, the types of fishing activities and the economic value of the catch (subchapter 3.3). Subchapter 3.1 first presents the area.

3.1. Southern North Sea II (SN II)

Southern North Sea II is one of two areas proposed by the Norwegian government for offshore wind development (Utsira North being the other).[6] The area is 2 591 km^2 and is located about 140 km from the Norwegian coast,[7] towards Scotland and on the border to the Danish economic zone, as shown in **Figure** 2. The two phases of the project are proposed at reaching a total of 3000 MW.

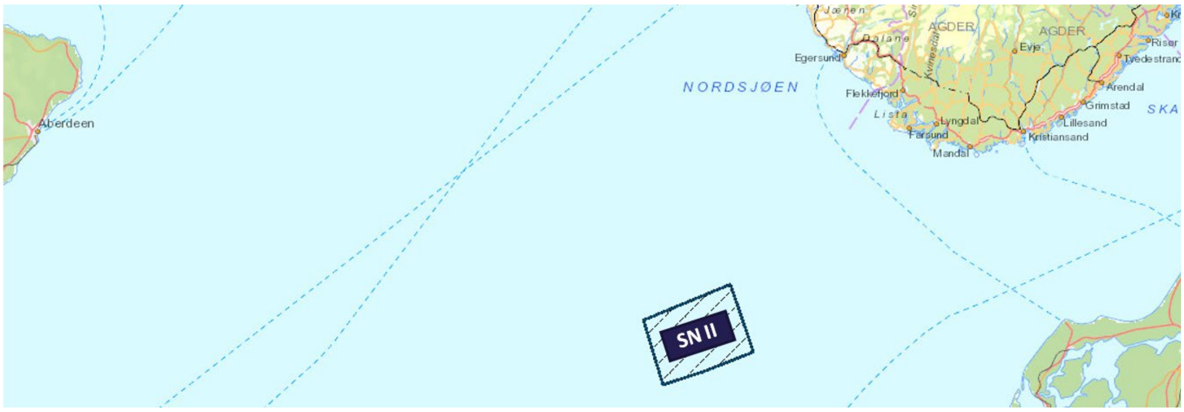

Figure 2**. Location of Southern North Sea II (SN II).** ***Source: The Norwegian Directorate of Fisheries (Yggdrasil).***

In this report, we use this definition of the SN II area. The Ministry of Petroleum and Energy is considering adjustments, which may reduce the area designated for OWF to accommodate fishing.[8] At the time of writing this report, the adjustments have not yet been decided, and hence no changes are made to the analysis area.

3.2. Ship traffic in SN II

Figure 3. shows the number of observations of ship traffic within the SN II area over the years 2013-2021 and is split into ship types. The figure shows that, measured by the number of observations,[9] offshore and other special vessels are most common in 2021, with about 6 400 observations. Cargo ships have the second-most observations with about 3 200. There are about 1 200 observations of fishing vessels. The dip in activities from particularly offshore supply vessels and other special

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[6] www.regjeringen.no/no/aktuelt/storstilt-satsing-pa-havvind/id2900436/ [May 4, 2022].

[7] https://www.regjeringen.no/contentassets/aaac5c76aec242f09112ffdceabd6c64/kgl.res-12.-juni-2020-opning-av-omrade-for-fornybar-energiproduksjon-til-havs.pdf [May 4, 2022].

[8] www.regjeringen.no/no/dokumenter/hoyring-av-forslag-til-inndeling-av-dei-opna-omrada-i-utlysingsomrade-for-fornybar-energiproduksjon-til-havs [May 4, 2022].

[9] The number of times a ship has entered the SN II area. This implies for instance that if a ship exits and re-enters the area briefly afterwards, it counts as two observations.

vessels in 2014 could be due to the start of the fall in oil prices in the summer and autumn of 2014. The fall in cargo and tanker ships in 2020 could be due to COVID-19. The number of observations increased from 2020 to 2021, but there are large fluctuations. It is not possible to interpret it as a trend, partly due to COVID-19. We return to fluctuations in fishing in subchapter 3.3.

The figure (and other figures in this subchapter) is based on AIS data, which to a lesser extent covers smaller vessels; typically, those smaller than 300 gross tonnage or 15 meters in length. Larger vessels are required to have AIS fitted. This is likely not a major issue of concern, as SN II is located 140 km from the coast, and smaller vessels typically sail closer to the coast. We return to this issue for fishing vessels in subchapter 3.3.

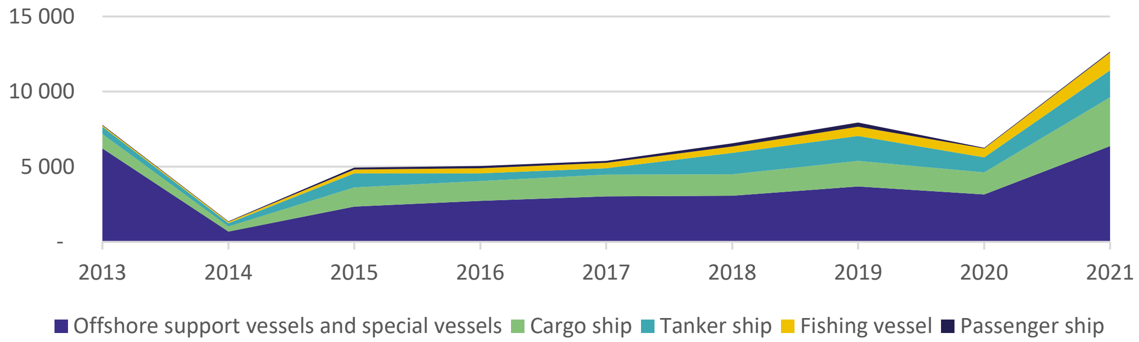

Figure 3. Number of observed ships in SN II over years and in ship types, including both Norwegian and foreign-owned ships. ***Source: Norwegian Coastal Administration (Kystdatahuset) and Clarksons World Fleet Register.***

The observations in the figure above treat a ship that conducts specific activities in the area, such as fishing, and a ship that barely touches the area, as equal observations. Figure 4. , therefore, indicates the times the different ship types have spent in SN II. The times are quite similar for most ship types: an average of 53 minutes for all types in 2013-2021. For passenger ships there are few observations, meaning that changes for a specific ship will have a strong effect on the average.

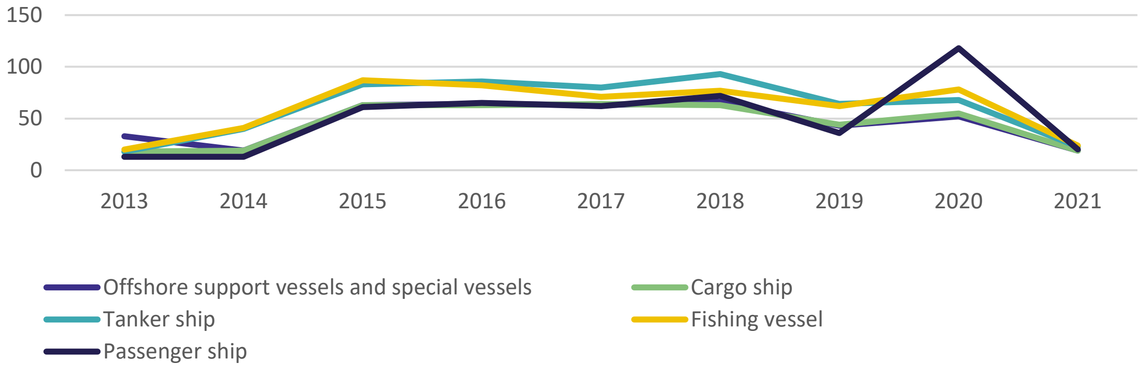

Figure 4. Average sailing time (minutes) in SN II over years and in ship types, including both Norwegian and foreign-owned ships. ***Source: Norwegian Coastal Administration (Kystdatahuset) and Clarksons World Fleet Register.***

Figure 5. shows that the time spent in the SN II area varies, but most (87 per cent) observations in the area are between 10 to 30 minutes. 5 per cent spent between 30 minutes and an hour in the

area, while 2 per cent spent one to two hours, and 1 per cent spent two to ten hours. Six observations spent more than ten hours in the area in 2021.

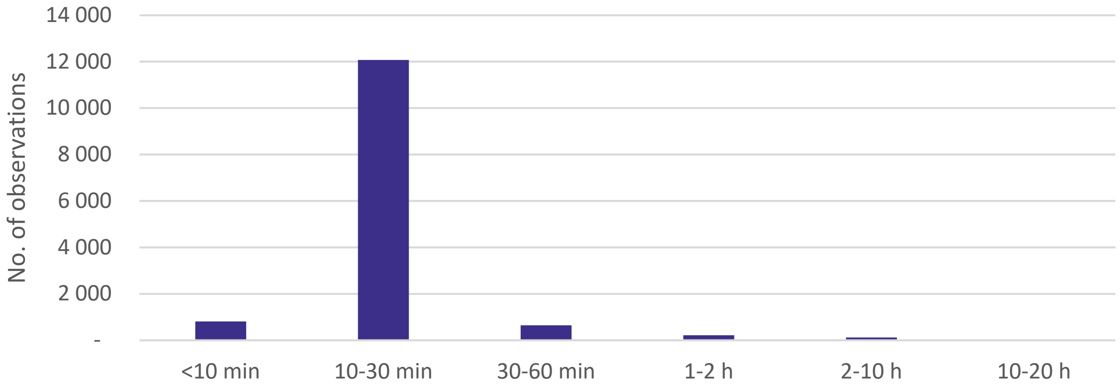

Figure 5. Distribution of time spent in SN II for each observation in 2021. ***Source: Norwegian Coastal Administration (Kystdatahuset).***

Table 1. provides an overview of the number of unique ships that were in the SN II area in 2021, categorised in finer ship types than in the figures above. In total, about one thousand ships were in the area at least once during 2021 (of about 12 000 observations). Among the ship types, general cargo ships, chemical and product tankers, and bulk carriers have the highest number of unique ships observed in 2021. The percentage of the ships that are registered in Norway is generally below half, and in total at about 20 per cent.

In sum, the AIS data reveal some marine activity in the area, mainly by non-Norwegian ships. There are several tanker and cargo ships in the area, likely in transit. This is also supported by the movements, as shown in the maps in the appendix (Figure 3). For offshore supply vessels and other special vessels, the movements could indicate some other activities (see Figure 4 in the appendix). Few passenger ships are passing through the area. For fishing vessels, there appears to be some activity. This is further explored in the next section.

Table 1. Number of unique ships, the percentage that is registered in Norway and the average sailings distance (km) in SN II in 2021.

Ship type	Unique ships	% registered in Norway	Average km sailed in SN II
Bulk Carrier	171	1 %	4,9
Chemical/Products Tanker	200	18 %	3,9
LNG Tanker	45	4 %	4,7
Anchor Handling Tug Supply	28	25 %	5,8
General Cargo Ship	326	9 %	5,8
Ro-Ro Cargo Ship	18	22 %	6,0
Fishing Vessel	75	31 %	3,4
Standby Safety Vessel	38	42 %	3,3
Container Ship (Fully Cellular)	10	0 %	8,1
Passenger/Cruise	1	0 %	5,2
Buoy Tender	18	28 %	4,8
Pipe Layer	13	23 %	5,4
Crew Boat	4	0 %	2,9
Live Fish Carrier (Well Boat)	1	100 %	9,9
Passenger/Ro-Ro Ship (Vehicles)	1	100 %	18,6
Unknown	76	0 %	4,4

Source: Norwegian Coastal Administration (Kystdatahuset) and Clarksons World Fleet Register.

3.3. Fishery activities in SN II

The subchapter above indicated that there are several observations of fishing vessels in the SN II area. In 2021, there were about 1 200 observations of fishing vessels in SN II, spending an average of 24 minutes in the area. **Figure 6.** shows the distribution of time spent: 37 per cent of the vessel observations spend less than 10 minutes in the area and another 37 per cent spend between 30 minutes and an hour. 13 per cent spend one to two hours, and 12 per cent spend two to ten hours. There are two observations of up to 20 hours in the area.

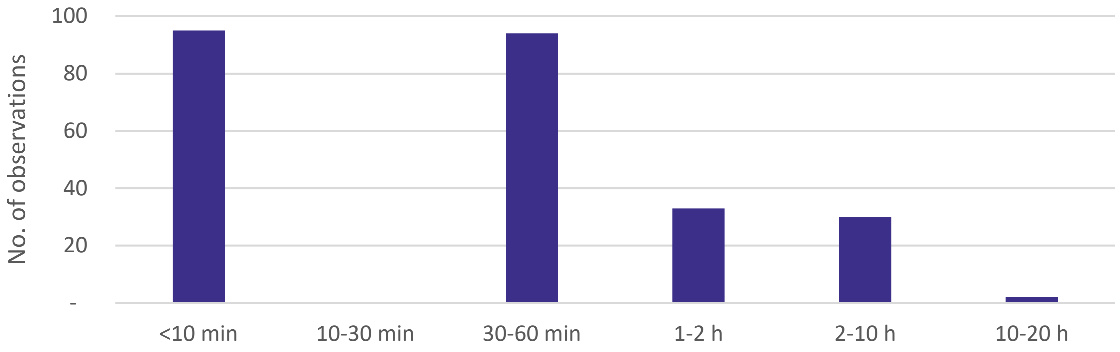

Figure 6. Distribution of time spent in SN II for each observation of fishing vessels in 2021. ***Source: Norwegian Coastal Administration (Kystdatahuset).***

The activities were conducted by 75 unique vessels. Figure 7. indicates the country of origin for these vessels. 36 per cent (27 vessels) are registered in Denmark, 31 per cent (23 vessels) are registered in Norway, and 21 (16 vessels) per cent are registered in the Netherlands. Other countries with vessels in the area are Germany (3), France (2), and the Faroe Islands, Ireland, UK, and Sweden (1 each).

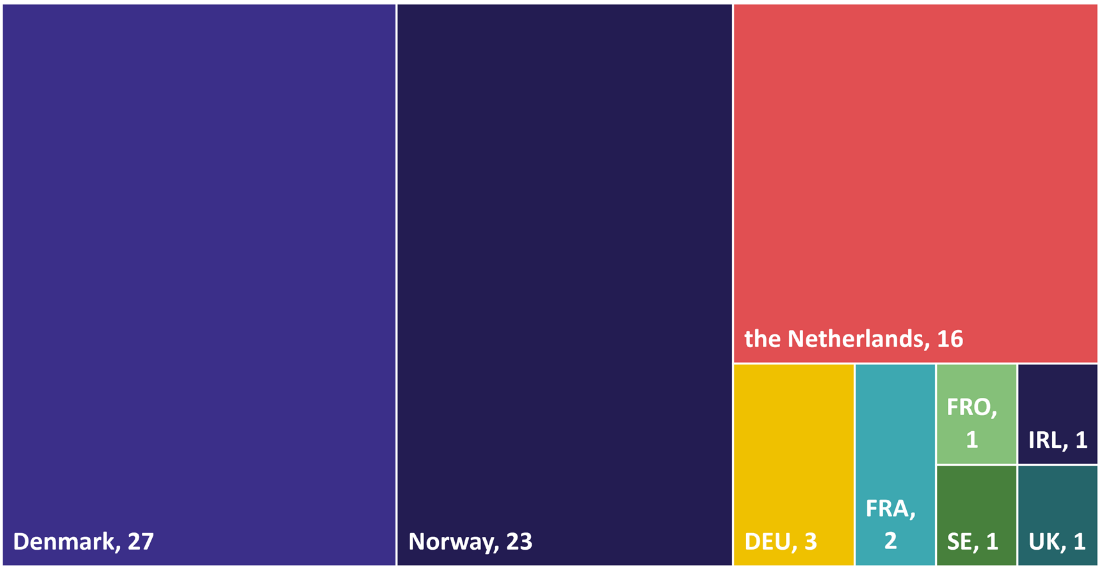

Figure 7. Number of ships in SN II in 2021, by country of origin. ***Source: Norwegian Coastal Administration (Kystdatahuset) and Clarksons World Fleet Register. DEU=Germany, FRA=France FRO= Faroe Islands, IRL=Ireland, SE=Sweden.***

Figure 8. summarises the sizes of the 75 vessels. Most of the fishing vessels (71 per cent) are between 30 and 70 meters long. There are also some larger vessels, with the largest being 86 meters long.

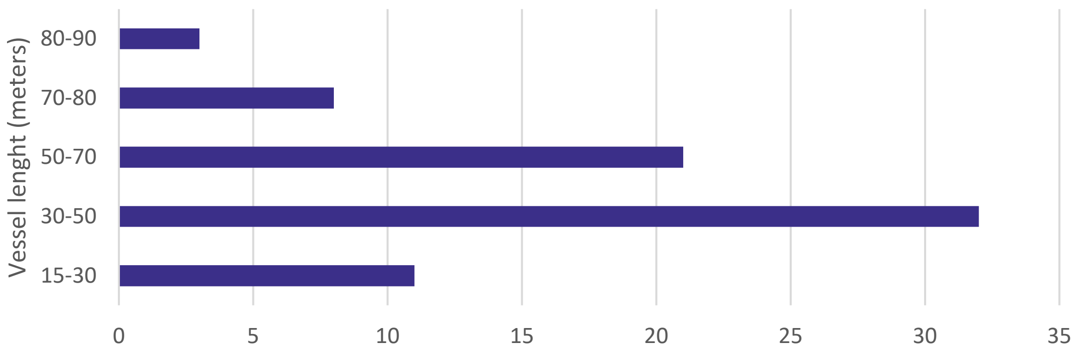

Figure 8. Number of vessels in SN II in 2021 by size (length in meters). ***Source: Norwegian Coastal Administration (Kystdatahuset) and Clarksons World Fleet Register.***

Not all fishing vessels observed in the SN II area are fishing. Figure 9. indicates limited registered fishing activities in the area in the time period 2011-2021. There has been fishing with line and hook in the Eastern part of the area in 2011, 2012 and 2013. These are different types of line fishing from a boat ('line', 'jukse', 'dorg'). Slightly north of the centre there have been some seine net fishing for plaice in 2013. Bottom and floating trawling for sandeel and herring has taken place over several years (2011-2020), and is still being conducted; mainly in areas touching the SN II area from the North-East and from the West, as shown in the figure below. Some seine fishing for sandeel has also been conducted in the North-East (2013). Finally, there has been some fishing for cod with fishing nets (2011) in the Eastern part and some in the North.

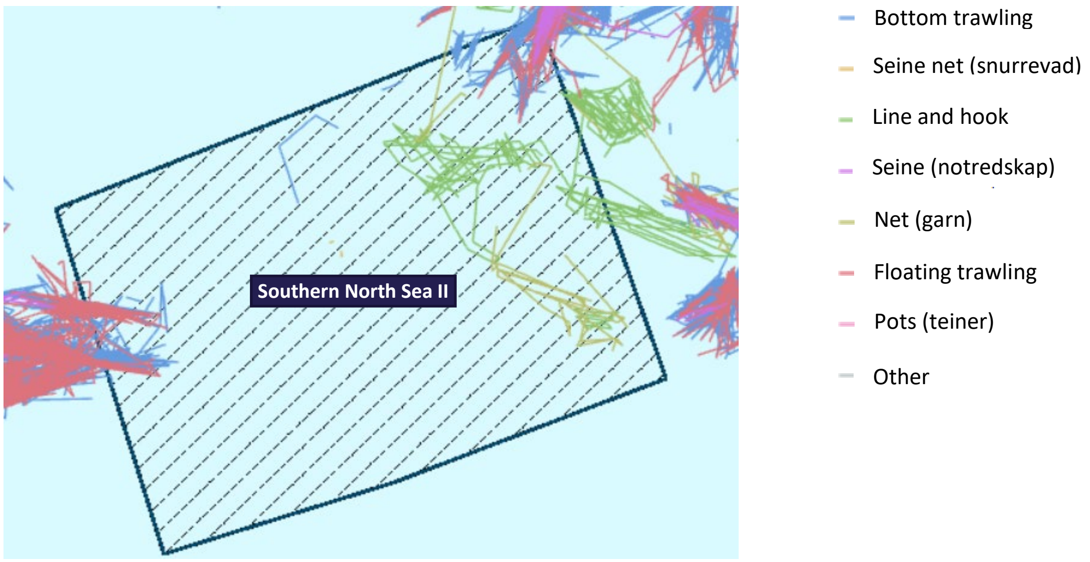

Figure 9. Fishery activities in the SN II area, after type of fishing gear, in 2011-2021. ***Source: The Norwegian Directorate of Fisheries (Yggdrasil).***

The activities summarised above are all conducted from the vessels. There is only one registered fixed gear activity; a long line from a point 14 km east of the area.

Figure 10. shows the Norwegian fishing activities in the area surrounding SN II in 2019 (most recent registration in Yggdrasil), compared to the fishing activities by foreign vessels in the same year. The figure indicates that foreign activities in the area are far larger than the Norwegian fishing activity.

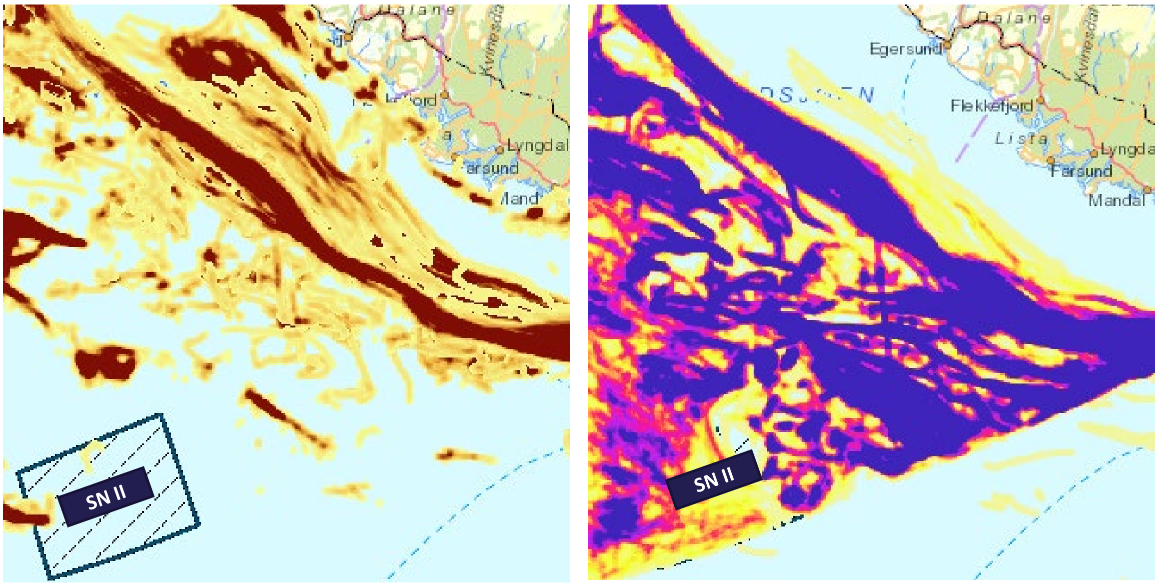

Figure 10. Fishery activities around the SN II area in 2019, by Norwegian (left) and foreign (right) fishing vessels. *Source: The Norwegian Directorate of Fisheries (Yggdrasil).*

The fishers' reporting of their landings provides information on catches and their values in given statistical areas. These areas are not identical to the SN II area, meaning that we have estimated the catches and catch values in SN II. This estimation is based on the distribution of sailing time (given by distance and speed) by the fishing vessels in SN II as a fraction of the total sailing time in the covered statistical areas. This is described in more detail in the appendix. The analysed catch values are the value of the catches that have landed in Norway, meaning that catches in SN II that have landed in Denmark or other countries are not considered.

Figure 11. shows the estimated total catch values in the SN II area for 2017-2020. There are large fluctuations in the values: from about NOK 120 000 in 2017 to about NOK 22 mill. in 2020. The large fluctuations are due to both the variation in estimated catch volumes (82 tonnes in 2017 and about 6 000 tonnes in 2020) and variation in prices[10]. At the time of writing this report, the prices, and thus the catch values, for 2021 have not yet been published by the directorate.

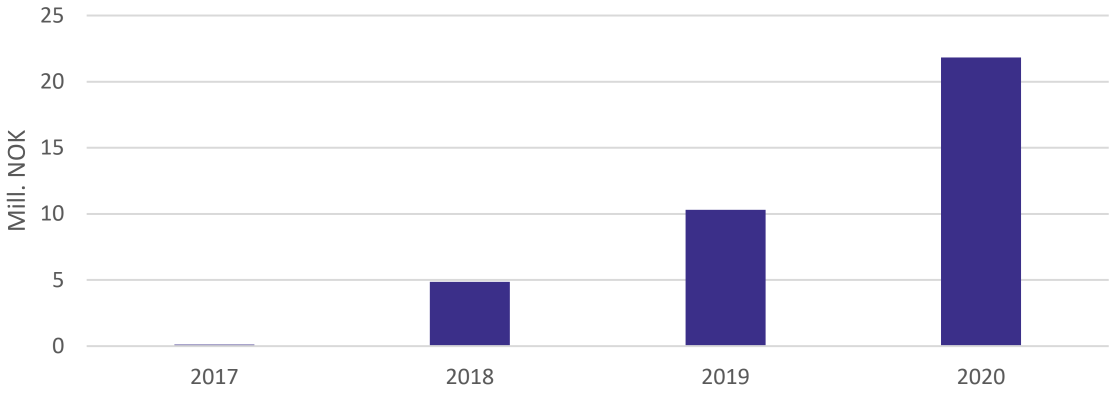

Figure 11. Estimated total catch values in SN II by year, from 2017 to 2020. Landings in Norway only. *Source: The Norwegian Directorate of Fisheries (landing message data).*

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[10] For tobis, the prices were NOK 1,50;, 2,20;, 3,00; and 3,60 per kg in 2017, 2018, 2019 and 2020, respectively.

The peak in 2020 matches the estimates by the Institute of Marine Research on the biomass of sandeel in the corresponding southern sandeel areas of the North Sea, as seen in Figure 12. (Johnsen 2021).

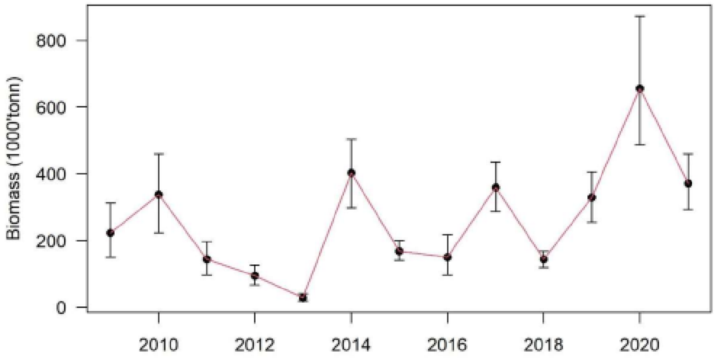

Figure 12. Estimated biomass (in 1000 tonnes) in the management areas 1-4 (except Nordgyden); average and 95% confidence interval. ***Source: Johnsen (2021: 18).***

As the number of fishing vessels in SN II is quite low, the activities and reported catches from a single ship and a single operation can strongly affect the estimated catch values in a year. Such randomness could thus impact the results. Figure 13. compares the catch sizes in 2017-2020 in SN II (green bars) to the total catches for the southern and central North Sea in 1983-2021 (blue line, please note the differences in scale). The figure could indicate that 2020 is a local peak, but the correlation in the other years is not obvious. The figure further shows that one should be careful interpreting the catches in 2017-2020 as an increasing trend. The fluctuations in catch values could be due to biological processes for the relevant fish species and climate change (Henriksen et al. 2021). ICES summarise the fluctuations as 'interannual variability of recruitment and biomass as well as early maturation, both of which are typical for a short-lived species' (2022: 2). In addition, the few observations in the SN II area make the randomness of the catches an important factor as well.

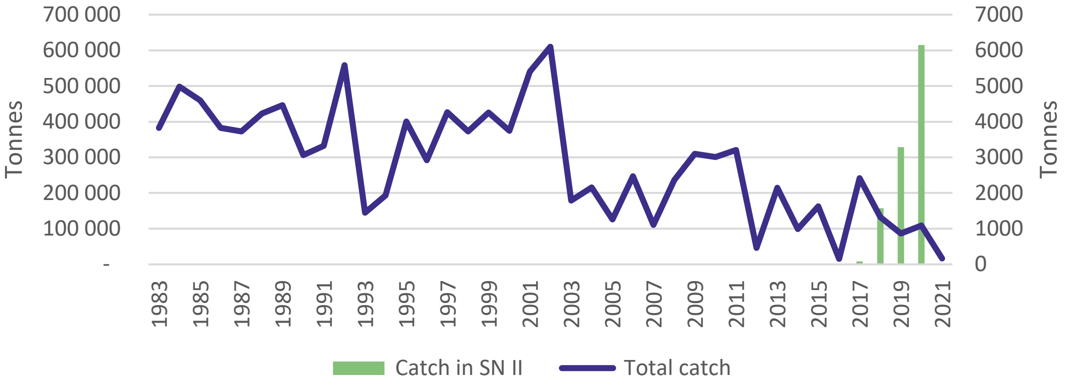

Figure 13. Total catch of sandeel in southern and central North Sea (divisions 4.b-c, Sandeel Area 1r) in blue (measured on the left y-axis) and estimated catch of sandeel in SN II in green (measured on the right y-axis). ***Source: ICES (2022) and our estimations.***

Figure 14. quantifies the importance of sandeel in catches in SN II. Throughout 2017-2020, an estimated 94 per cent of the catch value was from sandeel. Other species (and their per cent of catch value) include cod (4%), haddock (1%), whiting (0,2%), saithe (0,2%) and herring (0,2%). The figure also shows that bottom trawling is the main fishing gear used in the area: An estimated 95

per cent of the catch value in the area from 2017-2020. The estimated catch size of sandeel is about 82-6000 tonnes, depending on the year.

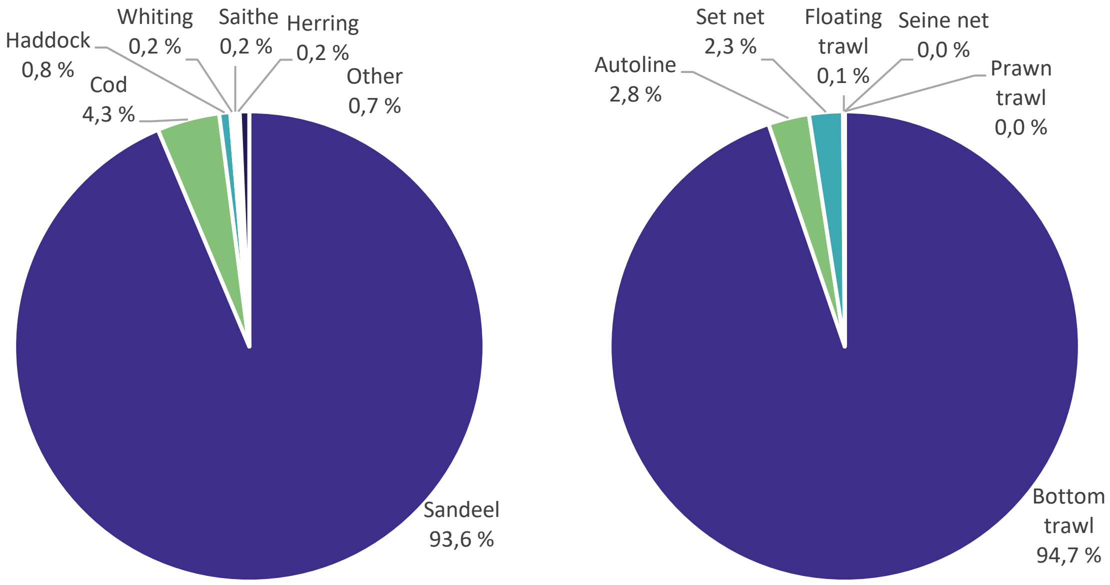

Figure 14. Total catch value in SNII for the time-period 2019-2022, by species (left) and fishing gear (right). ***Source: The Norwegian Directorate of Fisheries (landing message data).***

In response to suggested adjustments to the SN II area by Ministry of Petroleum and Energy, *Fiskebåt*[11] summarize the fishing industry's experience of fishing in the area the latter years.[12] The letter emphasise that part of the area (Inner Shoal) is recently developing into an attractive area for sandeel fishing, and is an area that has first priority by the fishery. A part of the sandeel fishing fleet has since 2019/2020 also switched to fishing gear which enables them to fish in new areas. These are arguments for the observed catches and catch sizes in 2020 being more representative for possible future catches and catch sizes in the area.

In the area near SN II,[13] both Norwegian and foreign fishers report catch and catch values in Norway (as landed in Norway and registered by The Norwegian Directorate of Fisheries). The foreign fishers in the area surrounding SN II are Swedish and Dutch, but the estimated catch is mainly from Norwegian fishers. Regarding ship size, there are reported catches from vessels smaller than 28 meters in the areas near SN II, and, to some extent, vessels smaller than 15 meters. In the SN II area, however, we found no catch and no catch values from ships smaller than 28 meters. One possible reason could be the long distance to the coast (see Figure 8 in the appendix).

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[11] An interest and employer organization for the Norwegian sea-going fishing fleet.

[12] www.regjeringen.no/contentassets/b6e593d0f2c04398a2b0d12a54ea622f/fiskebat.pdf?uid=Fiskeba%CC%8At [16.06.22].

[13] ICES-areas 41-54, 41-64, 41-65 and 41-75.

4. Findings from the existing literature

4.1. The effects of offshore wind on fisheries

A significant body of literature exists on the effects of offshore wind on fisheries and marine life, consisting of both scholarly articles and industry reports. This knowledge covers topics such as the effect of offshore wind installations on various marine life and other offshore industries, disturbances on the marine life during the construction and operational phases of bottom fixed wind turbines, and the following expected changes in the commercial catch rates of various fish such as sandeel and herring. Knowledge gaps occur for possible population wide impact on fish from noise induced low intensity stress or masking causing changes in behaviour. It is also relevant to study regional effects from changes in primary production due to changed ocean mixing, increased growth on foundations and reduced bottom trawling activity. While not from the SN II area specifically, the reviewed studies represent relevant findings as nearly all research to date is based on OWFs in similar environments in the North Sea and associated water bodies.

Several studies, such as Bat, Sezgin and Şahin (2013) and de Jong et al. (2020), review a range of potential impact in the exploration/planning, construction, and operational phases of OWFs, including noise from seismic shooting, drilling and operation, seafloor disturbance from the construction of OWF structural elements, changes in water currents, and obstruction of fishery activities. The existing knowledge presents both positive and negative impacts of OWFs on fisheries. The following subchapters will present a thematic overview of different types of possible effects that OWFs could have on fisheries, though it must be emphasised that measured impact for individual OWF projects often remain minor. The applicability of the findings on SN II specifically, including identified knowledge gaps in our current understanding of OWF impact, will be highlighted throughout this section, as well as general mitigation measures described in the reviewed literature.

4.1.1. Noise

Sound travels faster and farther in water than in air, with speeds up to 1500 m/s depending on the water density. Anthropogenic noise introduced to the ocean range from very low levels in the order of natural background noise either biogenic of generated by e.g., rain, wind or breaking waves, to higher levels including those with potentially destructive force. Very high energy “noise” from e.g., explosions or close-range pile driving can cause physical damage to fish such as ruptured swim bladder or stunning of the fish. Lower level or distant anthropogenic noise can on the other hand be masked by naturally generated noise. While different fish species vary in their sensitivity to sound and spectral range of hearing (Dalen et al. 2008), anthropogenic noise from both low-frequency continuous noise from ship engines and construction activities, and low- and high-frequency noise from seismic and echosounders, constitute potential sources of disturbance for fish species. Wind turbine foundations in offshore wind farms emit low-intensity underwater noise, most of which are in the frequency spectrum that can be detected by fish (Wahlberg and Westerberg 2005: 303-304; Andersson, Sigray and Persson 2011: 9). Fish species without swim bladder, such as many flat fish species and sandeel are considered less sensitive to sound since a bladder is required to detect the pressure oscillations of the acoustic field in addition to what the fish ear can detect (Wahlberg and Westerberg 2005: 297). Low-intensity noise has been shown to impair hearing in snappers (Caiger, Montgomery and Radford 2012: 228) and cause attention shift in sticklebacks (Purser and Radford 2011: 5). Further potential impact includes masking of natural noise e.g., the ability to detect prey and predators, and possibly communication during mating (Wahlberg and Westerberg 2005: 305-306). However, given the range in life strategies, behaviour, and ability to remove themselves from noise sources, as well as variation in anthropogenic noise frequency, intensity, and duration for each specific OWF, predicting noise impact is difficult (Slabbekoorn et al. 2010: 424). Thus, investigating long term population level noise impact needs to be connected to field studies relevant to the specific habitat and species of concern.

Disturbance from underwater noise from seismic shooting that takes place during the pre-construction phase has been reported to reduce fish quantities in affected areas (Dalen et al. 2008: 42). This effect has, to a larger degree, been noted on larger fish compared to smaller fish. The intensive seismic activity can change the roaming movements of certain fish, such as the Greenland halibut, which can impact specific fisheries during the time the shooting is being done. On Norwegian fishing grounds, Løkkeborg, Ona, Vold, and Salthaug found that the use of seismic air guns caused a 50-80 per cent reduction in catches of Atlantic cod and haddock from longlines and trawls but increased gillnet catches of redfish (86 per cent) and Greenland halibut (132 per cent) (2012: 1287). Whereas a lower commercial catch rate is a reported effect of the exploration phase of OWFs, the effect appears to be short-term and pronounced displacements have not been observed. However, various species react differently to seismic shooting based on behaviour, habitat preference, morphology, and hearing ability (Løkkeborg et al. 2012: 1290). Thus, seismic shooting should be done with caution, ideally avoiding the spawning season of important species in the area, and short-term negative effects on the catch rate should be expected.

Construction activities, in particular pile driving but also the preparation of the seabed for gravity foundations and placement of cables, may result in short-term impacts on marine life in the surrounding area. These activities will emit noise and may cause resuspension of sediment increasing turbidity in the water column. Some fish and marine mammals may leave the area but are expected to return once the construction ends (Bat Sezgin and Şahin 2013: 249). Several options for mitigation of these issues have been used and proven successful. To reduce the effect of noise from pile driving, various kinds of techniques to lessen emissions to the surrounding water are in use. This includes bubble curtains and cofferdams (Koschinski & Lüdemann 2013: 11, 35; Dähne et al. 2017: 222). Another way to reduce the impact of pile driving is by applying a 'ramp-up' piling strategy where the force of the hammer is low to begin with, slowly increasing to full power over a period of 5-10 minutes, allowing fish and mammals to distance themselves from the immediate surroundings (Bailey, Brookes and Thompson 2014: 8; Mooney, Andersson and Stanley 2020: 89). A third strategy is to set time windows for when piling and dredging would be permitted, avoiding times of the year when specific species are sensitive to noise disturbance, such as calving harbour porpoises or spawning cod (Brandt et al. 2018: 230; Hammar Wikström and Molander 2014: 414). A combination of all the measures mentioned above is often required by regulators and should be considered for 'best-practice' guidelines for developers (Dolman & Simmons 2010: 1023; Juretzek, Schmidt and Boethling 2021: 14-15).

Noise will be generated during the construction and, to a lesser extent, operational phases of an OWF. Noise from the placement of cables and during piling can cause nearby species to avoid the area during the construction work (Nedwell, Langworthy and Howell 2003: 37). Thomsen et al. noted that both Atlantic herring and Atlantic cod may detect noise from piling up to 80 kilometres from the source, but once the OWF has been commissioned, the species are believed to return (2006: 50). Mitigation strategies exist for reducing noise during the construction phase, including bubble curtains, cofferdams, 'ramp-up piling' and similar reviewed in e.g. de Jong et al. (2020).

Mitigation activities also include monitoring of cetaceans during piling with the possibility to stop piling if cetaceans are observed within a specified distance from the piling.

Production noise from a limited number of wind farms has been described in detail and is generally considered to give a higher background noise at frequencies under 1 kHz and have peaks, depending on the type and load of the turbine and the foundation type, between 0,1 and 1 kHz (Andersson, Sigray and Persson 2011: 9; Degraer, Brabant and Rumes 2011: 2). The 48 turbines of 2.3 MW each at the OWF at Lillgrund, Sweden, for instance, had a noise peak at 127 Hz for which the level was 23 dB above the background noise 100 m from the turbine (Andersson, Sigray and Persson 2011: 9). Slabbekoorn et al. argue that although sonar, piling and seismic typically attract the most attention, less intense longer-duration sounds may represent a greater impact over time (2010: 424). In a recent literature review, de Jong et al. concluded that the long-term effects of noise generated during the OWF production phase on fish and invertebrates cannot be ruled out without studies based on data collected from wind farms (2020: 40). They highlight that there may be a negative impact on fish species from low-level noise inducing stress or masking behaviour which could, if confirmed, reduce the positive effect the wind farm provides in terms of shelter and habitat. To date, there are no records of such negative effects from long term research projects on offshore wind farms (van Deurs et al. 2012; Stenberg et al. 2015). It is a challenge to detect long term impact from low level stressors without direct controlled experiments in the field. One way to assess such impact is to study a sensitive species that may act as an indicator species for low level stressors. A study designed to assess the long-term impact of low-intensity stress on fish, using the viviparous eelpout as such an indicator, was not able to detect any negative impact on the fish from a wind farm relative to the fish in a nearby reference area (Langhamer, Dahlgren and Rosenqvist 2018: 5). The study was conducted in a well-established OWF (Lillgrund, Sweden) during two years of data collection. The study showed that the variation in the parameters investigated was larger between years than between the impact site and the reference site (Langhamer, Dahlgren and Rosenqvist 2018: 5).

It will be important to continue environmental impact monitoring during the production phase in a similar way as is done for other marine industries such as aquaculture and oil and gas extraction (Dannheim et al. 2020: 1104). De Jong et al. note that several studies have shown how the design of OWFs, including the choice of transmission and generator, influence resulting noise levels, and recommend that noise mitigation is considered for the turbine, fundament, and mooring construction to minimise vibration during the operational phase (2020: 40).

Although data from field studies are scarce (Tougaard, Henriksen and Miller 2009; Andersson, Sigray and Persson 2011), they indicate that larger turbines do not necessarily emit more noise than smaller ones suggesting that a wind farm with fewer large turbines generates less noise impacting a smaller area than one with a higher number of smaller turbines. The spacing between turbines is greater in OWFs with larger turbines, resulting in a smaller fraction of the area being exposed to the noise. OWFs planned today are with turbines in the range of 10-20 MW while the abovementioned literature (e.g., Lillgrund's OWF) is based on early OWFs with turbines in the range of 0,5-3 MW.

Figure 15. Offshore wind turbine being constructed, Norfolk, UK. ***Credit: iStock (user: DJMattaar).***

4.1.2. Magnetic fields

Underwater power cables, while effectively shielded against direct electric field emissions, will still emit magnetic fields resulting in induced electric fields. Various cable designs and transmission systems will emit electromagnetic fields of different strengths. As an example, the magnetic fields emitted by a certain type of cable is dependent on the distance between the conductors (cable core) where a short distance like in a two-core cable, will result in a low magnetic flux (Öhman, Sigray and Westerberg 2007: 631). While insignificant from a human perspective, magnetic fields may alter behaviour in fish and crabs, but data from field studies are not conclusive (Hutchison, Secor and Gill 2020: 100). OWFs are associated with a network of high-voltage direct current (HVDC) cables. Current knowledge of any effects in operational OWFs is limited (Bat, Sezgin and Şahin 2013: 245). A change in the behaviour of some species has been suggested in laboratory studies (Hutchison, Secor and Gill 2020: 101), but the impact on the ecosystem from field studies has not been recorded. The behaviour of migrating European eel (*Anguilla anguilla*) was studied at the Lillgrund OWF before construction and during operation some years later (Lagenfelt, Andersson and Westerberg 2012). No change in their migration behaviour in the area was detected. The study extended over several years and involved tracking devises placed in transects and recorded eel movements (Lagenfelt, Andersson and Westerberg 2012). A recent study of sandeel (*Ammodytes marinus*) larvae exposed to a magnetic field gradient (150-50 µT), found no change in distribution or behaviour (Cresci et al. 2022: 3). The authors conclude that magnetic fields from DC cables do not affect the behaviour of lesser sandeel larvae. While they cannot exclude effects on later life stages (Cresci et al. 2022: 4), OWF sandeel field studies, such as Lindeboom et al. (2011) or van Deurs et al. (2012), have not reported any related impact.

4.1.3. Sediment, water, and air dynamics

Offshore wind farms may alter the physical conditions in the pelagic ecosystem at OWF sites in several ways.

1. The structures of the foundations cause increased turbulence in the water flowing through the area. This is documented by satellites in shallow, silty water where the turbulence causes a resuspension of sediment, making it easy to observe (Vanhellemont and Ruddick 2014: 107). However, corresponding turbulence also increases water mixing in the upper ocean layers (van Berkel et al. 2020: 115).
2. The wind wake effect, downwind, from an OWF creates a divergence in wind driven surface currents (the Ekman transport), causing downwelling and upwelling in the upper ocean layers (Broström 2008: 586). The effect increases with the size of the OWF.
3. The foundations are structures that will increase the growth of filter-feeding epifauna such as blue mussels and amphipods (Slavik et al. 2019: 36; Ivanov et al. 2021: 13). The enhanced growth will lead to increased assimilation of organic carbon in the OWF and thus the removal of carbon from the water mass. A model-based study from Belgium indicated increased assimilation within an OWF of 50 000 tonnes (Mavraki et al. 2020: 2690).

These effects will be different in seas with different stratification (i.e., depth and strength of stratification) and there is a need to further study the implications on the pelagic ecosystem and the benthic pelagic coupling for the North Sea given future expansions of OWFs, preferably using long term monitoring of the production and deposition parameters (van Berkel et al. 2020: 116). While knowledge gaps still exist related to physical effects of OWF structures, the scale of impact is closely related to the effect of large numbers of turbines spread over large areas, and OWF-induced changes for individual farms are expected to be within the scope of natural fluctuations (Clark et al. 2014: 6-8; de Jong et al. 2022: 15, 25).

Sediment dynamics could also be affected by scouring around the foundations causing changing near-seafloor hydrodynamics and resulting resuspension (Baeye and Fettweis 2015: 247). While increasing water column turbidity, it may also cause the release of toxic compounds buried in the sediment with potentially harmful effects to the ecosystem (Roberts 2012: 239-240). The phenomenon has been observed in the shallow silty area in the Thames estuary associated with strong tidal currents (Vanhellemont and Ruddick 2014: 106) and will likely not be an issue at the much deeper SN II site.

4.1.4. Habitat changes, artificial reef, and FAD effects

A concept that has been given much attention with regards to OWF and other manmade developments in marine areas is the so-called artificial reef effect. Manmade structures such as wrecks, oil rigs, and OWF pilings and moorings add hard substrate to soft-bottom dominated areas. These structures are quickly colonised by various hard-substrate benthic species and create a more complex and facetted habitat. This leads to higher total biodiversity and biomass for benthic organisms, especially suspension feeders, which in turn increases local food availability and can positively influence species at higher trophic levels, including fish (Degraer et al. 2020: 51). OWFs are likely to produce an artificial reef effect, which can attract various species to the area (Wilhelmsson et al. 2006: 775, 780). Such artificial reefs also act as intermediate steppingstones in dispersal pathways for hard-substrate organisms. This may also cause negative unintended consequences such as the spread of non-native species and climate migrants (Adams et al. 2014: 335). The issue of invasive species stepping-stones is related to invasive species in the newly introduced 'subtidal' habitat of a turbine foundation and cannot be attributed to species at reefs on the seafloor where hard structures exist, albeit less abundant (Wilhelmsson and Malm 2008: 464).

The issue may also be important to consider during decommissioning of an OWF when structures with attached epifauna are moved (Kerkvliet and Polatidis 2016: 72).

The tendency for manmade structures in the ocean to attract fish species, acting as a so-called fish-aggregating device (FAD), is documented as being used by fishers in many countries around the world (Freon and Dagorn 2000: 184). OWFs have been shown to cause an increased abundance of fish, likely due to a combination of the artificial reef and FAD effects, and due to the decline in fishing mortality and disturbance from trawling (Bergström, Sundqvist and Bergström 2013: 208; Vandendriessche, Derweduwen and Hostens 2015: 33; Methratta and Dardick 2019: 252). Several studies have shown that artificial reefs in general hold greater fish densities and biomass compared to surrounding areas. Fish attraction to OWF structures has been reported for gobiid and gadoid species associated with predation of small crustaceans associated with OWF structures by cod and pouting, which agrees with similar reports of fish foraging on the fauna associated with an artificial substrate in the wider non-OWF literature (Stenberg et al. 2015: 257). Other species with reported increased abundances include goldsinny wrasse, black sea bass and plaice (Degraer et al. 2020: 53).

In addition to providing increased feeding opportunities for demersal foragers due to the elevated biodiversity from an artificial hard substrate, structures can provide sheltered spawning areas, act as a refuge for juvenile fish and crayfish, and therefore improve both the quantity, quality, and sustainability of fish and crayfish catches (Langhamer and Wilhelmsson 2009: 151; Krone et al. 2017: 54; Sala and Giakoumi 2018: 1167; Jefferson, Palomares and Lundquist 2022: 9-10). Such habitat services also attract and benefit pelagic fish species such as mackerel (Wilhelmsson, Malm and Öhman 2006: 782).

It is important to note that changes in fish communities and biodiversity can be caused by a combination of factors, including refugium effects from lack of fishery activities, fish-specific FAD effects, and trophic interactions with hard-substrate organisms due to artificial reef effects. Observed changes may derive from a lack of fishery activity rather than any large-scale changes in the ecosystem, given that the magnitude of the introduced habitat (<1% of the area in a typical OWF) is relatively modest (Stenberg et al. 2015: 263). Furthermore, whereas these effects can cause fish and other species to relocate to the areas surrounding the OWF (spillover effect), it is likely to take several years for this to have a measurable impact on the populations (Bat, Sezgin and Şahin 2013: 245). Still, artificial reefs have the potential to become significant management tools for fisheries (Parkinson 2001: 22, Methratta and Dardick 2019: 254).

Even in cases where total biodiversity increases, it is possible to imagine a situation where the abundances of certain soft-bottom species could potentially decrease due to a combination of altered currents, sediment transport and introduction of new species dynamics, such as predator-prey relationships or competition. The complexity of species interactions makes it challenging to accurately predict OWF effects on specific species, which further emphasises the importance of field studies and regular monitoring of OWF sites (Bat, Sezgin and Şahin 2013: 246).

However, while long-term studies of OWFs are sparse, a few studies have investigated the effects on sandeels, which represented 96% of the SN II area's catch value from 2019-2022 (Figure 14.). The effect on sandeel populations, one of the most commercially important fish species in the North Sea, has been central in the debate on the coexistence between fisheries and OWFs. In 2012, van Deurs et al. published a study on the 'short-term and long-term effects of an OWF situated in the North Sea off western Denmark'. This study tested whether the change in habitat quality before and after the construction of the Horns Rev I OWF (80 turbines of 2 MW each) would impact the density and quality of the sandeel community. In the short run, the study found a positive impact on the density of both juvenile and adult sandeel in the impact area. In the long run, the great sandeel (*Hyperoplus lanceolatus*) had a moderate, yet stable decline in the study's control area, whereas it had a steeper decline after the short-term increase in the impact area. No effect was observed for the lesser sandeel (*Ammodytes marinus*) that is the dominating sandeel species in the North Sea. Overall, the density of sandeel did not vary significantly between the impact area and control area, meaning that the OWF neither represented a clear threat nor benefit to sandeel abundance. With regards to the quality of their habitat, there was, in general, little variation between the impact and control areas (van Deurs et al. 2012: 174-175). In the short term, the sandeel density increased due to improved habitat quality through the 'reduction in the silt and clay weight fraction in the sediment' (van Deurs et al. 2012: 176). The extent of fishing in the study area before the construction of the OWF is not mentioned in the paper but was likely not significant due to the shallow waters and the proximity to land (van Deurs et al. 2012). A similar study was conducted by Lindeboom et al. in 2011. They studied the Dutch coastal zone and the short-term impact that the construction of OWFs had on sandeel. The findings of Lindeboom et al. are in line with the findings of van Deurs et al., who noted that sandeel did not avoid the constructions in OWFs, but rather migrated daily in and around them (Lindeboom et al. 2011: 6). Similarly, Stenberg et al. found that OWF development at Horns Rev I did not appear to affect sandeel or dab (2015: 260). Thus, the best available science does not support that the construction and operational phases of OWFs are a significant threat to local sandeel communities. At Horns Rev 1 OFW the distance between each turbine is 560 m while the distance between turbines in OWFs planned today is around 1 km, reducing the footprint significantly and most likely also the risk that SN II will have a negative impact on sandeel populations.

4.1.5. Fishery exclusion zones and MPA effects

The main source of effects of introducing OWFs is restrictions on other marine activities in the same area, such as fishing. If the restrictions are on activities that negatively affect the environment, OWFs could create *de facto* marine protected areas (MPAs) if the benefits of restricting access exceed the negative effects of establishing the OWF (Thurstan, Yates and O'Leary 2018: 214). Dupont, Herpers and Le Visage have reviewed the scientific literature and found that the negative effects of OWFs (see also previous sections in this report) are inconclusive and rather showed increases in fish stocks in the studied areas due to artificial reef and FAD effects and a reduction of local fishing pressure (2020: 14). Positive ecosystem effects from discontinued bottom trawling are clear (e.g., Hiddink et al. 2011: 1448; Sala et al. 2021: 3).

In areas where bottom trawling for sandeel occurs, the closure of such activities due to e.g., OWF development will function as a refuge and be beneficial for the population similar to the establishment of an MPA (Christensen, Mosegaard and Jensen 2009: 62). Increasing fish stocks in an MPA may lead to an increased number of fish in surroundings areas, i.e., a net export of fish or invertebrates from the area to the surroundings (*spillover effects*). Coolen et al. found increased catches of brown crabs in the southern North Sea at the regional level by such facilitation of fish stock increases (2019: 17). A meta-study of 27 no-take MPAs support that MPAs help conserve and restore fish populations and marine invertebrates (Ohayon, Granot and Belmaker 2021: 1307). They also found *edge effects* in that the edges of MPAs do not experience the same fish stock increases as in the interior of the MPAs. This is because the edges are more disturbed by activities near and at the borders of the MPA. The results point to edge effects reaching up to 1-1.5 km into the MPAs and that fish stocks here are 60 per cent smaller compared to the MPA interior. This edge effect thus implies that smaller MPAs experience a smaller effect of increased fish stocks than larger MPAs. The size of SN II is 2591 km^2. Ohayon, Granot and Belmaker suggest that fishing activities concentrate around MPAs, indicating that fishing activities move to these areas (2021: 1307-1308). The results indicate that the edge effect reduces the spillover effect, but the authors emphasise that spillovers are not necessarily eliminated by the edge effects.

The effects of MPAs on fishing opportunities are currently not well researched for OWFs (Jefferson, Palomares and Lundquist 2022: 2). In the end, 'the impact of turbines on fishing depends on the importance of the area as a fishing ground' (Bat, Sezgin and Şahin 2013: 247). Should the area be largely used for fishing, then the development of OWFs will create a physical obstruction for the fisheries. The fishing activity could be displaced to another site, or specific types of fishing (such as trawling) could be excluded from the OWF.

In sum, OWFs, given they are big enough and placed in a suitable location, might function as an MPA. For sandeel, the closure of areas for bottom trawl fisheries and the creation of safety zones can provide undisturbed habitats for larger local spawning aggregations. In the long run, this may increase the population past the local area as larvae drift further away. The undisturbed spawning in safety zones due to the construction of OWFs can, therefore, create beneficial conditions for the fishing industry in the long run.

For the SN II area, the data study indicates limited fishing activity, suggesting that the upcoming OWFs may not create a large physical obstruction for the fishing industry. The limited fishing activity also means that the MPA effect from the closure of the area will be relatively modest, with no clear positive effects on increased fish populations with spillover effects. Mitigating measures, such as burying cables, as well as the fact that fewer large turbines with increased inter-turbine distance may allow certain activities in the area, may be considered relevant if there is a preference to preserve possible fishing activity in the area, though bottom trawling might be the type of fishing gear that would need the most accommodation.

4.1.6. Evaluating OWF impact

Most of the questions that remain on how OWFs may impact fish stocks (and a healthy marine ecosystem that provide the basis for a sustainable long-term fishery) relate to the long term and cumulative impact from subtle effects that are likely not to show up in a normal short term or single OWF research study. Such impacts can be the result of low-intensity stress imposed by a sound emitted from the turbine foundations, EMR from cables or low levels of toxins leaking from the installations. The organic polymer could, as an example, become toxic due to the grouting mixtures used during the construction phase. The effects this has on the marine community have not yet been properly monitored and studied (Parkinson 2001: 34). Since these stressors probably are small, it's likely that confounding effects from other artificial activities such as shipping, oil and gas exploitation, fishing and ocean acidification cannot be ruled out. One way to understand the impact of general low-intensity stressors is to use model species that are sensitive to stress and thus act as 'canaries in a coal mine'. One such study using the viviparous fish species *Zoarces viviparous* (eelpout) was not able to detect any impact from a large OWF relative to nearby reference areas (Langhamer, Dahlgren and Rosenqvist 2018: 5).

Another way to address these possible 'hard to measure' issues is to use ecological risk assessment (Suter 1993: 3-20). In a study to assess the possible long-term impact on a cod population in Kattegat with spawning grounds overlapping with a planned OWF, it was found that while the construction phase could be a threat to the cod, the operational phase was not (Hammar, Wikström and Molander 2014: 419). The possible impact of the installation activities could be mitigated primarily by restricting the work to a period with minimal impact on the spawning cod (Hammar, Wikström and Molander 2014: 419).

Other recent attempts to address long-term and cumulative impacts also include modelling studies. These studies have focused on the more general impacts of OWFs on the marine ecosystem. This includes the accumulation of large numbers of filter feeders (e.g., *Mytilus* spp.) on the foundations (Slavik et al. 2019: 35) and shifts in ocean primary production through changes in upper ocean mixing caused by turbulence and new wind patterns (Broström 2008: 586; Floeter et al. 2017: 170; van Berkel et al. 2020: 115-116). Also, the spill-over effect from the closure of the fishery in an OWF has been studied using modelling of the spatial food web (Halouani et al. 2020). This study showed that the increased catches outside of the OWF significantly compensated for the loss of catch in areas previously available to fishers but limited in space to the vicinity of the OWF. Further analyses would be required to fully understand the effects on larger regions and a higher rate of the area used for OWFs. As a result of the larger rate of primary production, the development of OWFs could also have an impact on climate change (other than the replacement of fossil fuels in power generation). The accumulated biomass on the foundations is significantly larger than the loss of biomass in the footprint area of a foundation (Mavraki et al. 2020: 2690; Ivanov et al. 2021: 13). In cases where the installation of OWFs replaces bottom trawling, this may further help mitigate climate change as bottom trawling has been shown to release carbon from natural carbon sinks at shelves (Sala et al. 2021: 3).

All three approaches, model organisms, ecological risk assessments and model analyses, are here considered as necessary and needed to further understand the long term and cumulative impact. In conjunction with the scale of OWF development planned for the larger North Sea region, within a 20-year time frame, such studies are necessary to inform management of optimal conditions to facilitate a sustainable fishery while preserving biodiversity and natural carbon sinks.

Figure 16. Offshore wind farm, Kattegat, Denmark. ***Credit: iStock (user: BPHOTO).***

4.2. Coexistence

To only focus on the financial costs and opportunities do not provide a complete understanding of the effects of offshore wind on fisheries. Fishers attribute significance to their 'identification as members of occupational and place-based communities on land and at sea' (Haggett et al. 2020: 42). For many local coastal communities, fisheries are rooted in their local economy, and there are concerns that 'trade-offs' will cause a loss of heritage, skills, and way of life (Reilly et al. 2015: 88).

The ocean is a complex entity, and its users have a multi-dimensional relationship with its depth and distance. The notion of 'communities at sea', in which the users of the ocean, such as fishers, are not only defined by the communities in which they live but also their offshore workspace, is important to understand the possible effects OWFs may have on fisheries (St. Martin and Olson 2017: 123). This highlights the importance of examining potential measures for coexistence between these two industries in the planning, construction, and operational phases of an OWF.

4.2.1. The planning phase

In 2020, the European Commission did a background study on interactions between OWFs and fisheries. They found that OWFs and other users of the sea already do coexist in the North Sea, which is Europe's most busy sea basin (Dupont, Herpers and Le Visage 2020: 19). OWFs are well developed in this area, without having experienced major conflicts with other industries, such as fisheries. In fact, the effect OWFs have on fisheries depends on the significance of the selected area as a fishing ground. The users of the specific ocean space should therefore be identified prior to the construction phase to help determine the importance of the area for such users. This could be done through a fishery intensity study conducted together with local authorities (Bat Sezgin and Sahin 2013: 247). Should the study find the area to be heavily used for fishing, further measures can be relevant. For trawling, this may mean that the fishermen must bring their nets back onboard when passing turbines and recast them once they've passed, which will demand more manpower and reduced fishing effort. For drift nets, the routes that have been used might need alteration to ensure the nets do not entangle with the turbines. As fish populations rarely are restricted to only one exact location (that is too close to the turbines) the use of an alternative route is not likely to be an issue (Parkinson 2001: 24). Either way, early dialogue between all the stakeholders is necessary to ensure a low level of conflict. The multi-use of the area, within the framework of ensuring safety for all activities in the OWF, is to be prioritised.

The perhaps most central aspect to a successful coexistence between offshore wind and fisheries is continued dialogue. All those who are affected by the development are to be recognised and offered participation in the decision-making process. In a study by Menon Economics and SINTEF Ocean, particularly three industries were noted as having a larger potential for conflict with other industries at sea. These were oil and gas, fisheries, and offshore wind (2020: 81). Conflict was noted in the relations between offshore wind and fisheries, however, other offshore industries also experienced conflicts with fisheries. This may, among other things, be related to the fact that fisheries to a large extent have had access to most of the ocean space first, and thus always will be displaced when new industries are added (Menon Economics and SINTEF Ocean 2020: 81).

The coexistence between offshore wind and fisheries, therefore, requires continued interaction between fishers and developers throughout the process of integrating the offshore wind industry into what is an already crowded offshore space (Hooper, Ashley and Austen 2015: 17). Clear communication and protocols are helpful when compromises are necessary, and port visits by developers can help create relationships with the local fishing industry. In the context of Marine Spatial Planning (MSP), where all stakeholders are involved and fully engaged, both the communication and trust between the various parties can advance. When the various parties feel that they can affect the outcome of various situations, by considering and addressing various impacts and benefits, their outlooks and perceptions of fairness towards the project are likely to be improved (Haggett et al. 2020: 43). In Gray et al's study from 2010, they found that many fishers did not find there to be any meaningful discussion between the two industries and that the conversations between them were merely performative, done to tick off a box on a to-do list (132) giving the fishers a feeling of powerlessness. Mackinson et al. found that the mistrust among the fishers partly resulted from earlier negative experiences with the government, developers, and other authorities, in which the fishers' opinions were overlooked and they were left feeling alienated (2006: 6). Action, therefore, matters and two-way communication should be used to establish effective engagements. That being said, facilitating such a process demands extensive time and dedication. The fishing industry is broad and entails an excessive amount of gear, activity, and concerns. Fishers can also be hard to reach and finding times for meetings that suit all the stakeholders can be challenging for some developers.

To help keep an open and fair dialogue, a fisheries liaison can be hired. A liaison is 'someone hired by a developer to provide information to fishers, convey their concerns and issues to the developer, and convene meetings as appropriate' (Haggett et al. 2020: 43). The liaison is someone hired and paid by a developer, not the government, and tends to be someone well known within the fishing community that would take advantage of opportunities that will drive a more collaborative process. The liaison can be relevant to use in both the development phase, as well as the commissioning and operational phases.

4.2.2. The construction phase

The construction phase of an OWF should be planned so that any impact from e.g., noise and resuspension of sediment on local spawning aggregations is minimized (see 4.1.1. above). The construction phase for a one GW wind farm is estimated to be three years from the start of the onshore works (BVG Associates 2019: 79), however, this depends on several factors, such as the number and size of the turbines to be installed, the ocean floor in the specific area, the distance from land, as well as the weather conditions. In addition to the timing to reduce impact as mentioned above, the weather can cause delays and thus increase costs as BVG Associates (2019: 79) estimates that one-third of the time is often lost whilst waiting for appropriate weather conditions. The construction phase, therefore, appears as a long waiting period with several smaller periods of activity when, for instance, the foundations and turbines are installed. Similarly, the importance of an open dialogue between the industries, mentioned during the planning phase, remains a significant measure for coexistence throughout the life cycle of an OWF.

Figure 17. Offshore wind farm. ***Credit: Agder Energi.***

4.2.3. The operational phase

Once the OWF is operational, the risk of collisions in the area increases (Bat, Sezgin and Sahin 2013: 250). As presented in the data study, SN II is currently used for navigation, and turbines will create an obstacle for these vessels. This could cause collisions that would release pollutants or cause the loss of human lives. The location of all turbines must be known by the users of the area. The turbines should be marked on all fishing and Admiralty charts, and to increase their visibility, they should be lit and marked, as well as having fog signalling devices and radar reflectors (Parkinson 2001: 26).

Compensation and participation are two key aspects of a just energy transition (Hagget et al. 2020: 42). In cases where OWFs cause disruptions to both fish stocks and fisheries in general, there has been a call for compensation to those who fish commercially (ten Brink and Dalton 2018: 2). To tackle such deficits, Vineyard Wind in the U.S. set up a trust fund that would assist with any increased insurance cost, as well as the supply of various safety and navigational gear. They, furthermore, established an innovation fund (Bureau of Ocean Energy Management 2020: 80) and collaborative research projects and programs were launched.

Laurence David Mee finds that a major step to maximising the value of a state's ocean is to have the users of the ocean coexist with as many economic activities as possible (2006: 4). Mee indicates that mitigation of conflict between OWFs and fisheries can be reached through aquaculture (2006: 4). By using OWFs for aquaculture production, new sites for farming various species have the potential to be opened. As aquaculture is a static activity it will not interfere with the operational phase of OWFs. Furthermore, aquaculture has the potential to reduce the level of conflicts with fisheries, as the industry can offer various types of employment for the fishers.

Passive extractive aquaculture can be practised in association with OWFs, which may increase the growth of blue mussels within the area (Buck et al. 2008: 269; Buck, Ebeling and Michler-Cieluch 2010: 276). The feasibility of growth of blue mussels in an OWF was recently studied based on models strongly suggesting a positive rate of return (van den Burg et al. 2017: 6). The increased primary productivity in the OWF further supports the sustainable co-location of mussel farms and OWF (Di Tullio et al. 2018: 40). The research project EDULIS, a collaboration between the University of Ghent and the offshore wind industry in Belgium, is a pilot project that aims to further assess this opportunity for industrial co-location[14]. If properly planned, aquaculture can assist in maximising the use of- and production from the leasing area. However, aquaculture is a relatively new concept that needs to undergo trials before full-scale production can start. The seabed owner must also allow for such activities to take place in the leased OWF area (Bat, Sezgin and Şahin 2013: 244).

A restriction of some fisheries can be considered during the lifetime of the OWF. This includes both a restriction in the space of the actual footprint of the OWF as well as possible restricted areas surrounding it. Various fishing management measures have been suggested, but the fishing method hitherto proven to be incompatible with an OWF is bottom trawling (Stelzenmüller et al. 2022: 5). The reasons for bottom trawling prohibition in current OWFs are the risk of the moving bottom contact gear damaging cables and the long turning radius of trawlers increasing the risk of collision. While currently the most common fishing method used globally as well as in the North Sea, providing for one-third of global landings (Amoroso et al. 2018: 10275), evidence is mounting that the practice is not ecologically sustainable (Thurstan, Brockington and Roberts 2010: 5) and may therefore face limitations of being phased out in forthcoming management advice to the advantage of less harmful fishing methods (Letschert et al. 2021: 3639).

Restrictions to bottom trawling open-up possibilities for the use of passive gear such as creels for *Nephrops* and bottom set gillnets for demersal fish species (Stelzenmüller et al. 2016, European Commission 2020) – methods that cannot be used in trawled areas. This passive gear fishery is normally practised by coastal and smaller vessels and a shift from the larger trawlers operating from more distant ports may have a positive effect on local communities. Hammarlund et al. showed that passive gear fishery for *Nephrops* using creels instead of bottom trawling increased both net income (measured as net present value) and the environmental performance of this fishery in Sweden (2021: 94).

As mentioned, co-location between OWFs and passive gear fisheries is an option. Passive gear such as gillnets can be used by both commercial and artisanal fishermen and vary in terms of type, soaking time, and net size (Stelzenmüller et al. 2016: 797). Løkkeborg et al.' study on gillnet catches in the vicinity of North Sea oil platforms provided empirical evidence of an increased number of fish nearby the oil installations (2002: 296). In two of the experiments from that study, the catch rate was three to four times higher within 110-165 metres of the platform, compared to catches from greater distances (Løkkeborg et al. 2002: 296). The presence of hard substrates, and the potential occurrence of artificial reefs, therefore, seem to be able to provide benefits for fisheries (Hooper and Austen 2013: 295).

The foundations and scour protection of turbines in an OWF have, as earlier mentioned, the potential to act as artificial reefs and thus add habitats available to species such as crabs and lobsters

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[14] EDULIS web page http://bluegent.ugent.be/edulis

(Langhamer & Wilhelmsson 2009: 151; Skerritt et al. 2012: 4). In combination with removing the trawl fishery in the area the OWF has the potential to provide an additional fishing opportunity for fishermen using passive gear to catch these species, in particular the highly valued European lobster *Homarus 28gammarus* (Hooper & Austen 2014, Hooper et al. 2015). It has been shown that a temporary closure of the fishery during the construction phase of an OWF increased the abundance and size of lobster in an area benefitting the fishery after that the closure was lifted (Roach et al. 2018: 1424). In a recent study at Westermost Rough offshore wind farm in England, and a nearby control site, there was a small increase in lobster catches shortly after the construction subsequently changing to similar size catches after some time (Roach, Reville and Johnson 2022: 7).

Co-location through recreational fisheries is also possible. Andrew H. Fayrama and Arturo de Risi claim that 'creating a limited entry recreational fishery and excluding commercial fishing from the area surrounding offshore wind turbines may aid in controlling total harvest and may benefit several important stakeholder groups' (2007: 597). This will aid both commercial and recreational fishermen as it may cause both a higher recreational catch rate, as well as a generally greater return. It will be easier to have precise control of the total harvest from the recreational fisheries when they are more closely controlled in a recreational setting, which increases the possibility of a sustainably managed fishery (Fayrama and Risi 2007: 601). The extent of fisheries allowed in the area surrounding the OWF would depend on the stock. Should the stocks of certain species be overfished, the cessation of both recreational and commercial fisheries could recover the stock. Once the stock has increased, the exclusion can end. The recovery of the stock would benefit fisheries in the long run. In the area of SN II, however, it is not likely for recreational fisheries to take place. The area is too far from land and is not particularly relevant for recreational fishermen.

Coexistence between OWFs and fisheries appears possible in all three phases, where caution must be taken at all steps to ensure safety for all those navigating the area. Where aquaculture, passive gear fisheries, and the use of the OWFs as artificial reefs are possible measures for coexistence, recreational fisheries in the SN II area appear less relevant. A continued dialogue throughout the life cycle of an OWF is necessary for successful coexistence between the industries.

Table 2. Mitigating measures

Issue	**Mitigating measure**
Clash of interests between fisheries and the offshore wind industry within a specific area.	Conduct a fishery intensity study to determine the importance of the specific area as a fishing ground. Marine spatial planning. Fisheries liaison. Bury cables. Increase the inter-turbine distance.

Collision risks with vessels.	The turbines should be marked on all fishing and Admiralty charts, be lit and marked, and have fog signalling devices and radar reflectors.
Leakages of harmful liquids (e.g., gear oil) from the installations.	Good engineering practices during construction. Prevent the loss of contaminants from vessels.
Noise from turbines.	Vibration-dampening construction, fewer large turbines rather than many small turbines
Pile driving.	Bubble curtains, cofferdams, and ‘ramp-up piling’. Have set time windows for when piling is permitted. Monitoring of cetaceans during piling.
Restrictions on bottom-trawling.	Usage of passive gear that cannot be used in trawled areas (e.g. creels for Nephrops).
Restrictions on fisheries.	Artificial reefs. Aquaculture. Good communication to ensure fishers know where they can work once the turbines are operational.
Seismic shooting.	Avoid seismic shooting during the spawning seasons of important species in the area.

4.3. Synergies

Synergies may be here understood as benefits between offshore wind and other activities that create additional values, relative to the activities being conducted separately. As described and discussed in sections **Fel! Hittar inte referenskälla.**-4.1.5, constraining fishing activities in an OWF area in combination with the FAD and reef effects could lead to increased fish population in the area that may increase catch sizes for fishing around the OWF. Increasing a fish population may also be a positive effect in itself, to the extent people value the protection of fish species. Brouwer et al. show that Dutch beach visitors to the North Sea are willing to pay (WTP) for protecting marine areas, and their WTP is motivated mainly by non-use values[15] of protecting fish species (2006: 39). Restricting fishing activities could thus be similar to using marine protected areas as a management practice for fisheries (Sala and Giakoumi 2018: 1167) and thus create a synergy, where fisheries and people who value fish protection are benefitting.

Other synergies could arise due to economies of scale by other activities making use of infrastructure, manpower and others that are necessary for the OWF. Distributing investments and operating costs on more activities, creates synergies by reducing costs. Such potential synergies could be in offshore fish farming, where aquaculture installations may make use of existing foundations to attach infrastructure and there may be economies of scale in coordinating transport and workers for maintenance activities. Several research projects are exploring such multi-use of areas, but there are very few pilots (Schultz-Zehden et al. 2018: 3). Currently, there are no plans for locating offshore fish farms near the SN II area, but the Norwegian aquaculture industry (Stiim Aqua Cluster and The Federation of Norwegian Industries) has suggested that the potential for aquaculture should be explored in an area that partially overlaps with SN II, see Figure 19.

Other potential synergies could concern tourism activities, such as diving, recreational fishing, and renewable energy production other than wind, such as exploiting wave and tidal energy (Schultz-Zehden et al. 2018: 18). The OWF has the potential to create favourable conditions for diving or be a potential tourism destination (Schultz-Zehden et al. 2018: 9), but the distance from land for SNII limit the possibility for such synergies. Production of other renewable energy could make use of existing infrastructure, such as cables. The produced electricity from the OWF could be used to produce other energy carriers on-site, such as ammonia, liquid hydrogen, and synthetic fuels.[16] If there are benefits to producing these here, such as reduced costs for underwater cable to land or economies of scale, there could be synergies here as well. Lastly, connecting OWFs to oil and gas rigs could help lower emissions from the oil and gas activities by reducing the need for gas turbines.[17] The latter effect requires that there are nearby rigs that are more effective to connect to rather than to land. Wind power is also an unreliable source of energy, meaning that alternatives must be available in times with less wind.

In sum, a wide range of synergies between OWF and other economic activities have been suggested. We have, however, not found clear results showing such synergies materialising. There must be a willingness among the relevant partners to invest and cooperate in creating the synergies. With the benefits being uncertain and potential coordination costs, there is a high level of uncertainty relating to the possible synergies discussed above. This also applies to SN II. The location of the area, 140 km from the coast, could also limit the attractiveness of synergy activities.

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[15] Non-use values are the values people attach to goods that they have not used them themselves, or plan to use. For instance, people may attach a value to protect species they will never see, eat or in other ways directly interact, but in order to know the species exist and that their existence can be passed on to future generations (i.e., existence and bequest value)

[16] www.offshorewind.biz/2021/11/04/aker-presents-massive-offshore-wind-to-hydrogen-project-in-scotland-at-cop26/ [May 2, 2022].

[17] https://blog.sintef.com/sintefenergy/wind-energy-for-offshore-installations-opportunities-and-challenges/ [May 4, 2022].

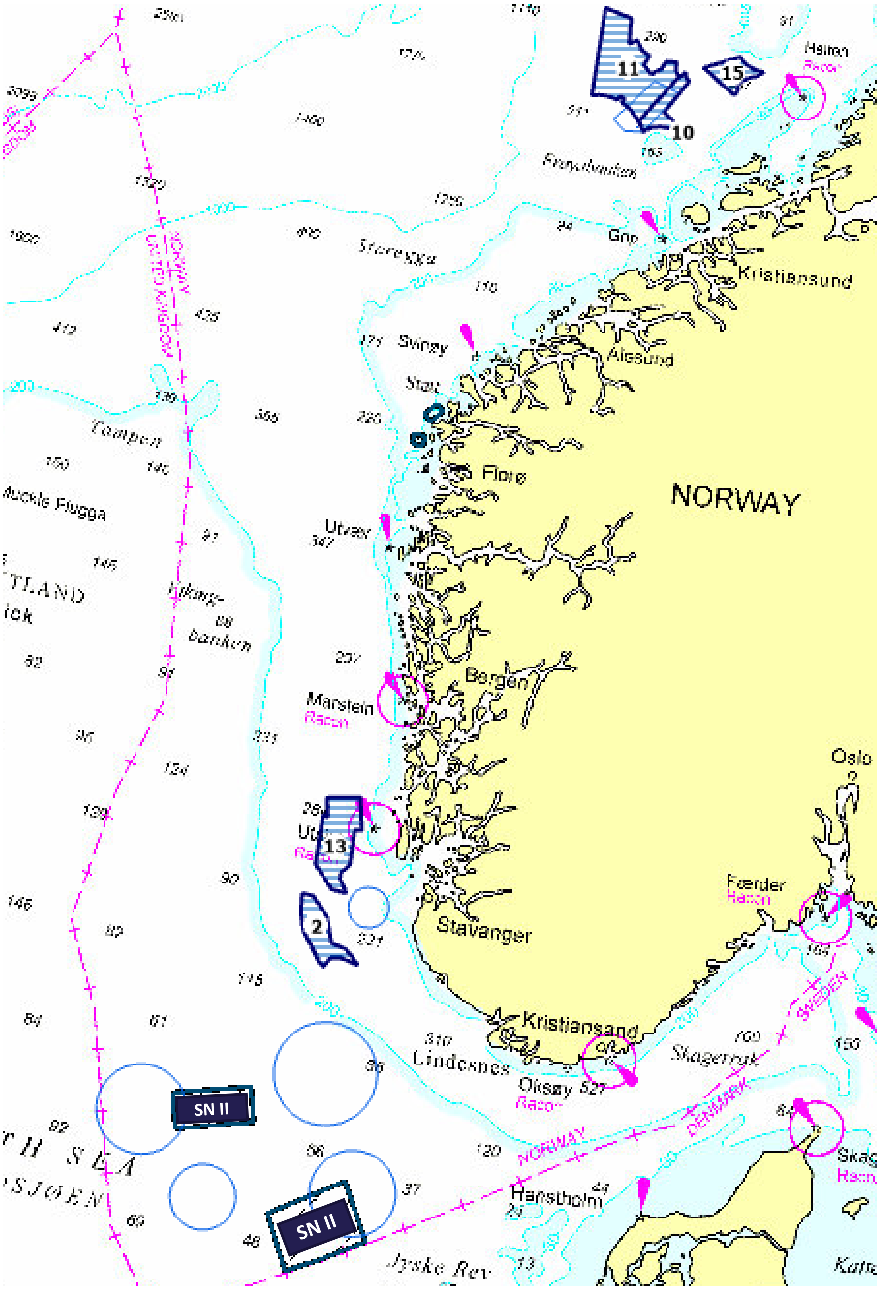

Figure 19. Suggested areas by the industry for potential offshore fish farming shown as circles and areas decided by the Norwegian Directorate of Fisheries to be assessed for an offshore wind farm in shaded squares. SN I and SN II are marked with names. ***Source: The Norwegian Directorate of Fisheries (Yggdrasil).***

5. Conclusions

The effects of offshore wind farms on fisheries, with a focus on Southern North Sea II (SN II), have been collated in this report. For the fisheries, the development of OWFs can cause losses in fishing areas. For the SN II area, the data study has shown some marine activities, mainly by non-Norwegian ships. There are fishing activities in the area, nearly exclusively bottom trawling of sandeel, with catch sizes varying strongly between years. The estimated annual value of fish caught in SN II vary from NOK 120 000 to 22 million per year over the period 2017-2020. The annual variation is possible due to a combination of fluctuations in sandeel biomass in the southern North Sea, random variations in fishing activities in the area and possible increase in fishing interests in the area since 2019/2020. A relatively low level of fishing activity within SN II means that fishing decisions and catches for single trips influence the aggregate statistics. Restricting fishing in the SN II area will likely lead to increased fishing in other areas, meaning that the economic loss will be smaller than the estimated catch values.

Offshore wind farms (OWFs) may cause several types of impact, which need to be mapped and assessed for potential severity both in a general sense, and for OWF development in the SN II area. Noise is generated from the construction phase of the OWF, including seismics, construction and operation. Seismic noise and pile driving lead to temporary displacement of many fish species but can be mitigated through avoiding activity in e.g., spawning times and other sensitive periods, and by using measures such as bubble curtains during construction. In the operational phase, fewer large turbines produce less noise than a larger number of smaller turbines. As long as mitigating measures are taken where appropriate, noise levels have not been found to create long-lasting effects on fish abundance. While magnetic fields may affect certain fish species, studies have not been able to show any impact on sandeel.

Man-made structures may influence the type and distribution of marine life in SN II due to artificial reef and fish-aggregating device (FAD) effects. This will likely lead to an increased local fish abundance. The effect could be relatively modest given the small total area of OWF structures. A more significant effect on the ecosystem is anticipated if the area is closed to bottom trawling, creating a *de facto* marine protected area (MPA). Such MPA effects can be used in fisheries management of the larger area.

While studies have not shown clear long-term effects of individual stressors, knowledge gaps still exist in assessing cumulative impact of minor stressors over time. In particular, scientific studies using indicator species, ecological risk assessments, and modelling, have not been able to find adverse impact due to OWF operation. Long-term studies at Horns Rev I show no significant adverse effects on the marine ecosystem including sandeel populations due to OWF development. Subtle effects should not be discounted on marine life but have not been shown to produce adverse effects at OWF developments at the scale of the SN II area. Still, mitigating measures should be applied as preventative measures when identified, and long-term monitoring of relevant fish species, marine mammals and benthic fauna would provide further knowledge on the effects of the OWF development useful for the management of Norwegian marine resources.

To ensure a sustainable energy transition with a minimum of impact on overlapping interests, it will be important to hold early and continued dialogue between the users of the area. Aquaculture, and the use of passive gear fisheries are potential measures for coexistence between the offshore wind industry and the fishing industry. In a wider perspective management will benefit from a science based marine spatial planning of anthropogenic activities in Norwegian waters. When compromises are necessary, clear communication and protocols are helpful. To facilitate an open and fair dialogue, a fisheries liaison can be hired by the developer.

With regards to synergies, the removal of some fishing activities within the area of an OWF can cause an increase in the abundance of fish in the area. In the long run, this could increase catches in the region. There could also be synergies with other new economic activities, such as offshore fish farming, other renewable energy production, production of energy carriers on-site such as hydrogen, or tourism. Although discussed and investigated, such synergies have been assessed and observed to a lesser extent in the implemented projects. There are thus substantial uncertainties about whether such synergies materialise for SN II.

Coexistence between the two industries capture fisheries and offshore wind energy conversion appears viable. The findings from this report have shown that OWFs and other users of the sea (including the fisheries) already do coexist, to some extent, in other countries surrounding the North Sea, and that several mitigating measures for coexistence are available. Based on the findings from the data study and the literature study in this report, the coexistence between offshore wind and fisheries in the general area of the SN II can be facilitated, with continued dialogue as a central component.

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7. Appendix

The following gives more details on the methods and the results of the data study.

Table 1 Ship types used and how they relate to less aggregate categorisation

Aggregate ship types used in the report	Ship types from Clarksons
Cargo ship	General Cargo Ship
	Bulk Carrier, Self-discharging
	Ro-Ro Cargo Ship
	Refrigerated Cargo Ship
	Bulk Carrier
	Container Ship (Fully Cellular)
	Palletised Cargo Ship
	Open Hatch Cargo Ship
	Livestock Carrier
	Vehicles Carrier
	Waste Disposal Vessel
Fishing vessel	Fishing Vessel
Offshore support vessels and special vessels	Research Survey Vessel
	Standby Safety Vessel
	Platform Supply Ship
	Anchor Handling Tug Supply
	Tug
	Platform
	Offshore Tug/Supply Ship
	Utility Vessel
	Pipe Burying Vessel
	Buoy Tender
	Offshore Support Vessel
	Pilot Vessel
	Training Ship

Passenger ship	Crew Boat
	Passenger/Cruise
	Crew/Supply Vessel
	Yacht
Tanker	Chemical Tanker
	Crude Oil Tanker
	Crude/Oil Products Tanker
	Molasses Tanker
	Chemical/Products Tanker
	LPG Tanker
	LNG Tanker
	CO2 Tanker
	Products Tanker

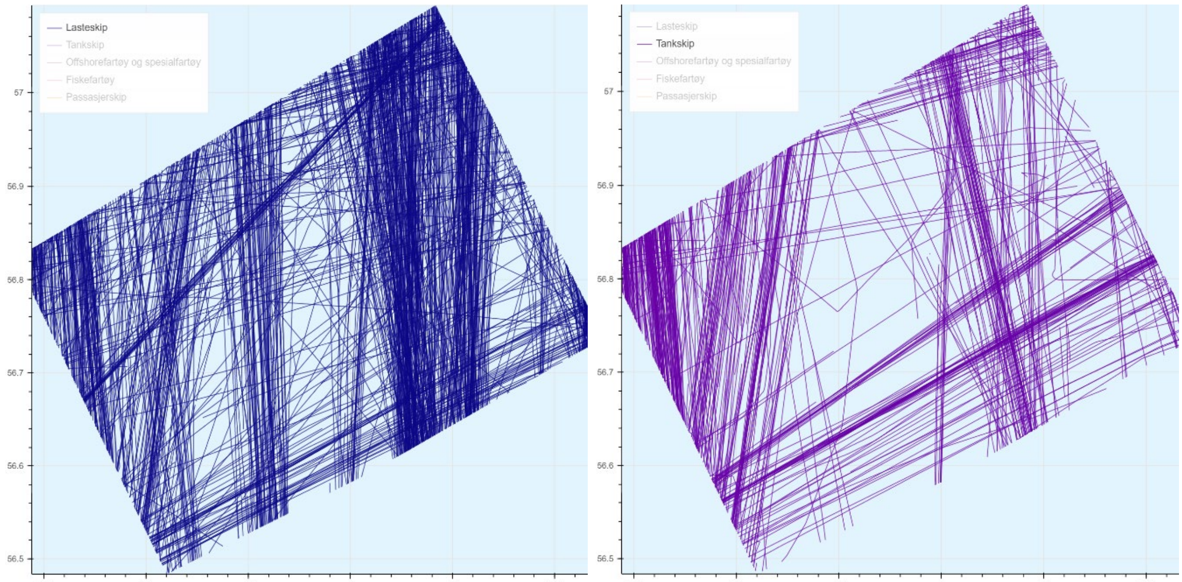

Figure 3 Movement of cargo ships (left) and tankers (right) in SN II in 2021.

Source: Norwegian Coastal Administration (Kystdatahuset) and Clarksons World Fleet Register

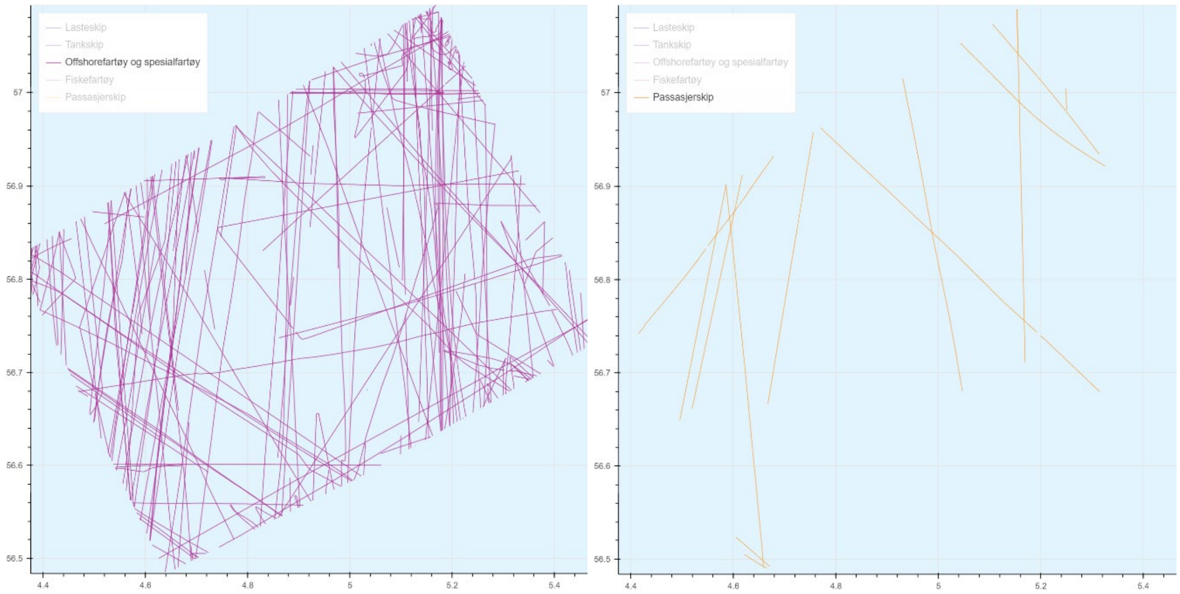

Figure 4 Movement of offshore support vessels and special vessels (left) and passenger ships (right) in SN II in 2021.

Source: Norwegian Coastal Administration (Kystdatahuset) and Clarksons World Fleet Register.

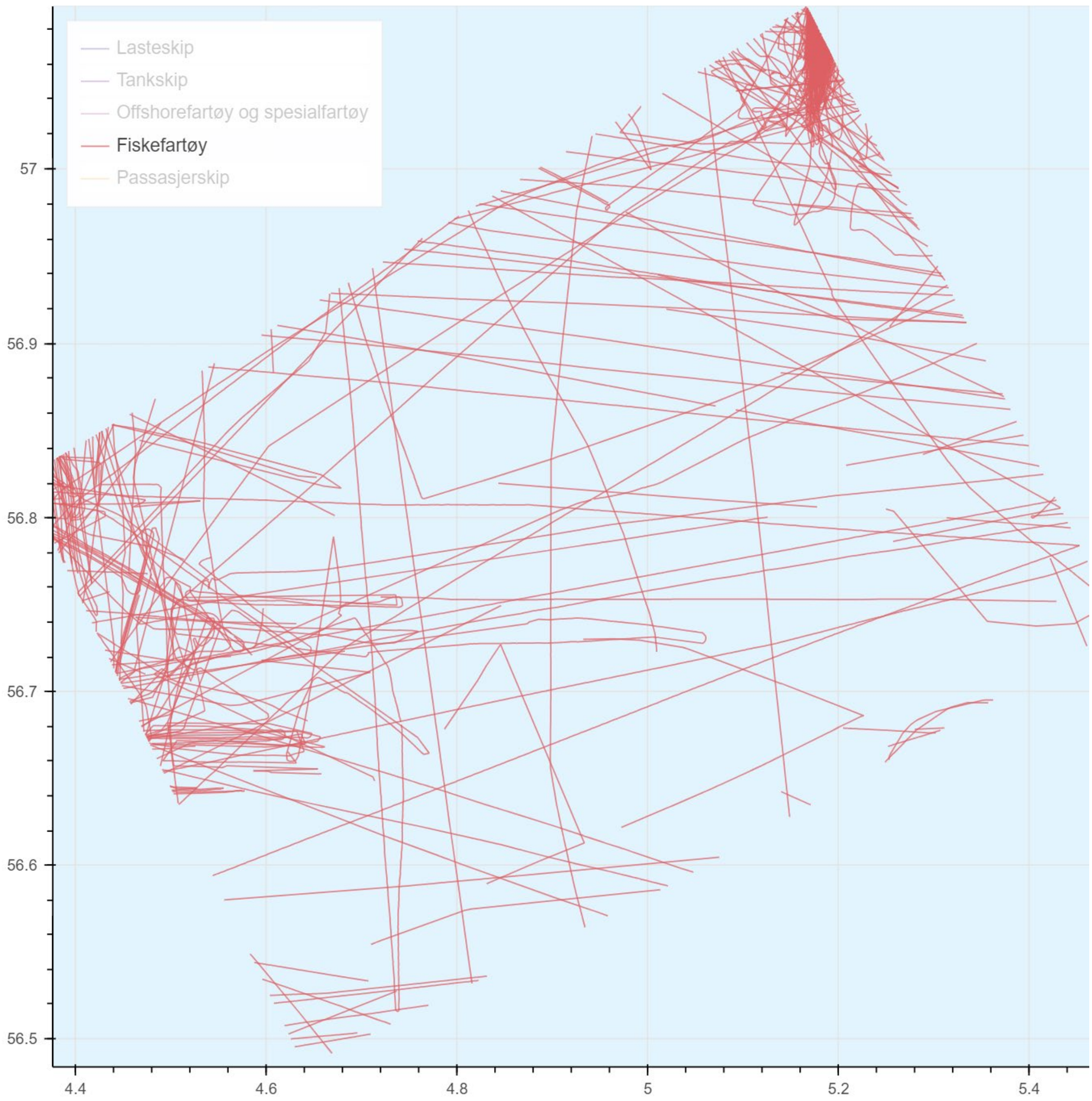

Figure 5 Movement of fishing vessels in SN II in 2021.

Source: Norwegian Coastal Administration (Kystdatahuset) and Clarksons World Fleet Register.

Estimating catch sizes and catch values in the SN II area are based on reported catches and catch values from the landing messages fishers' make to the Norwegian Directorate of Fisheries ('landings- og sluttseddel-registeret'). These are reported on statistical areas that are not perfectly overlapping with the SN II area (see Figure 6). To estimate the share of the reported values in the statistical areas that are due to catches in the SN II area, we have used AIS data on ship movements. The share of the sailing time of given ships in the SN II are of the total sailing time in the statistical areas is determining the estimated share of the catch in the statistical areas. For instance, if ship *x* spends two hours in the statistical area, where 30 minutes of this time in the SN II area, and report 1 tonne of catch, the estimated catch in SN II is 0,25 tonnes. We use sailing time, as it takes into account that the vessels spend more time per covered nautical mile when fishing than when in transit.

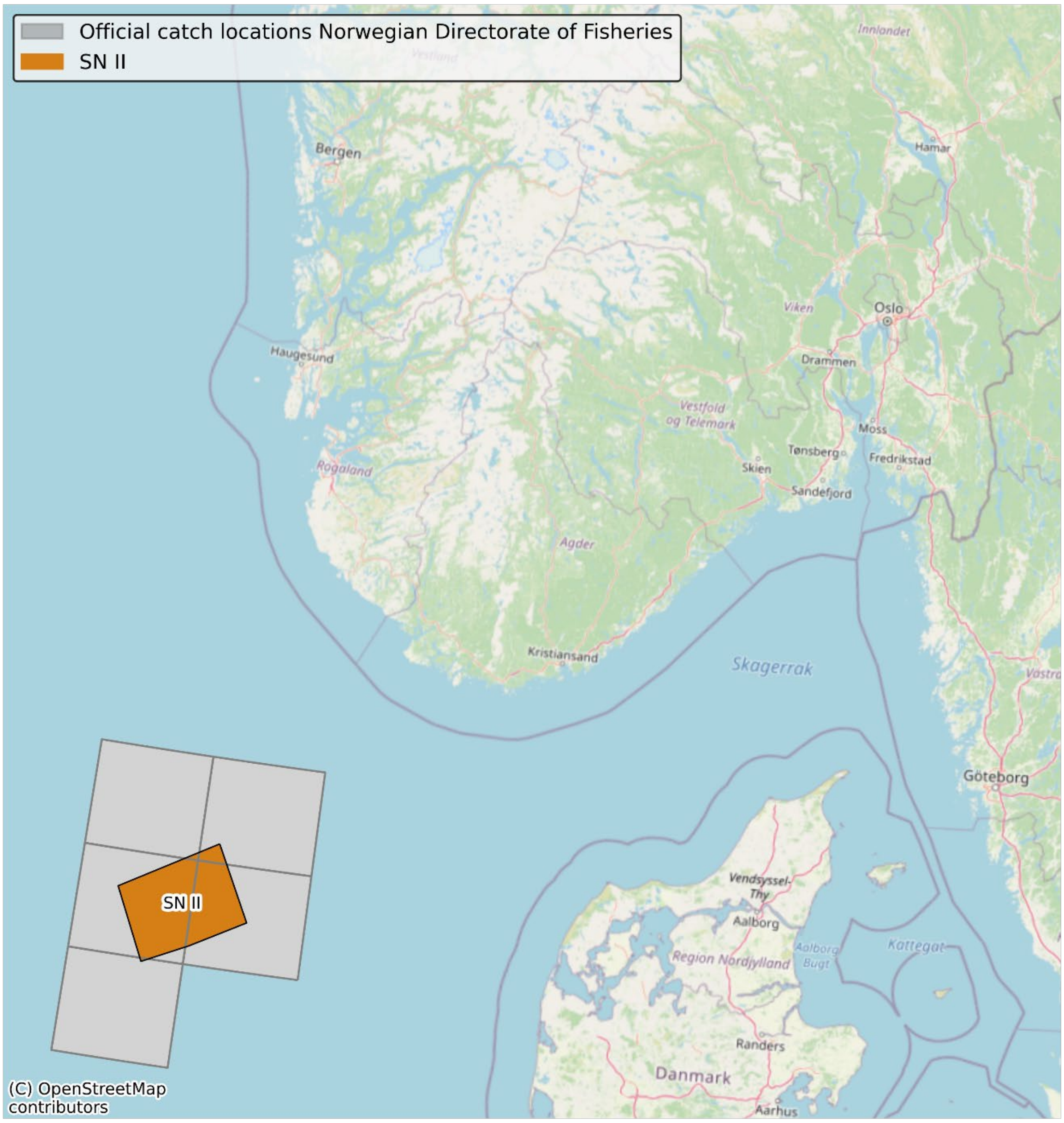

Figure 6 SN II and the statistical areas for reported catches and catch values.

Source: The Norwegian Directorate of Fisheries (landing message data).

Figure 7 indicates the movements of the fishing vessels that have reported catches to the Norwegian Directorate of Fisheries.

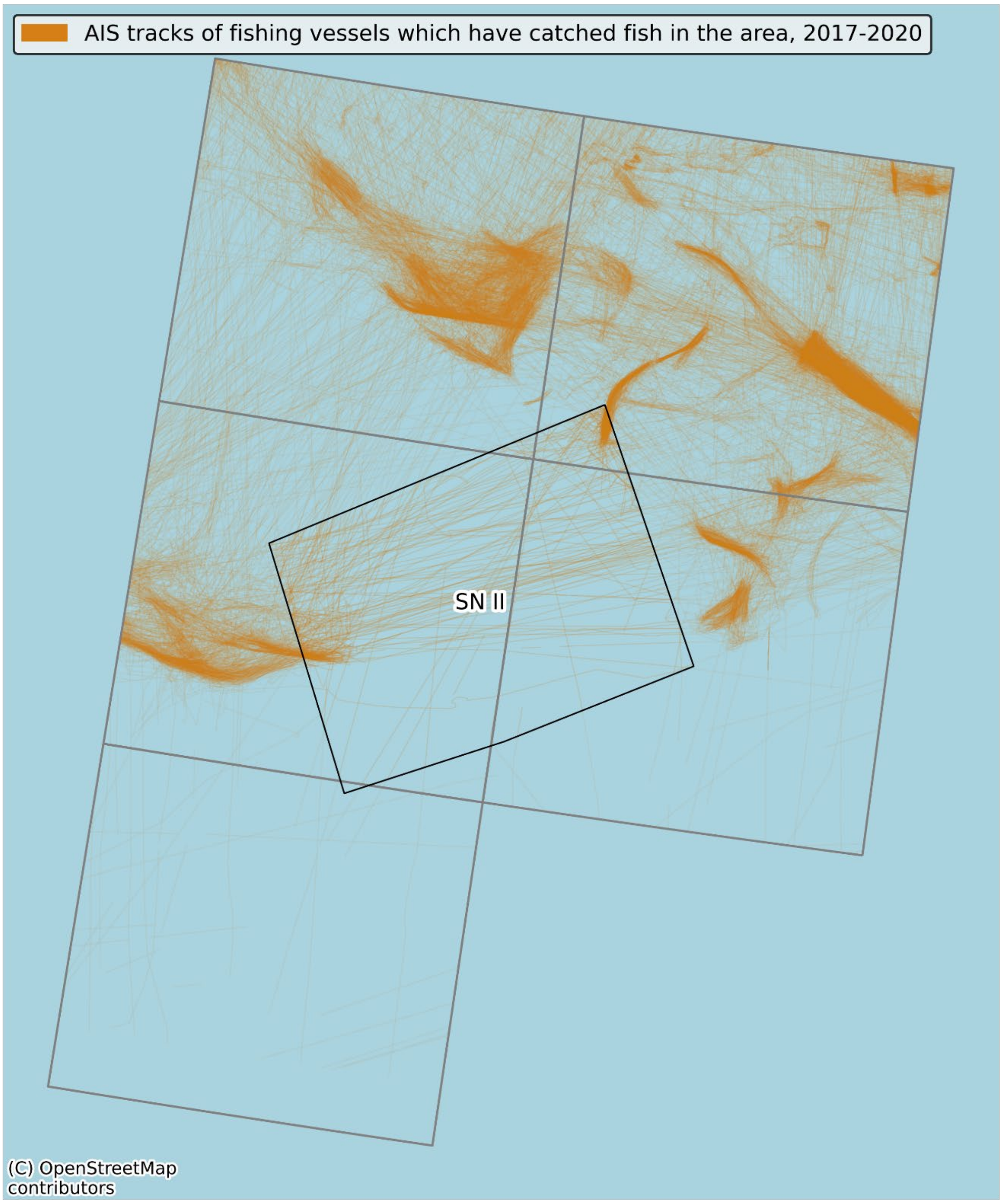

Figure 7 Movement of fishing vessels that have reported catches in and around SN II in 2017-2020.

Source: The Norwegian Directorate of Fisheries (landing message data), Norwegian Coastal Administration (Kystdatahuset) and Clarksons World Fleet Register.

Figure 8 shows that the movement of smaller vessels (less than 28 meters long) is nearer the coast than SN II and indicate that the fishing activities are dominated by the larger vessels.

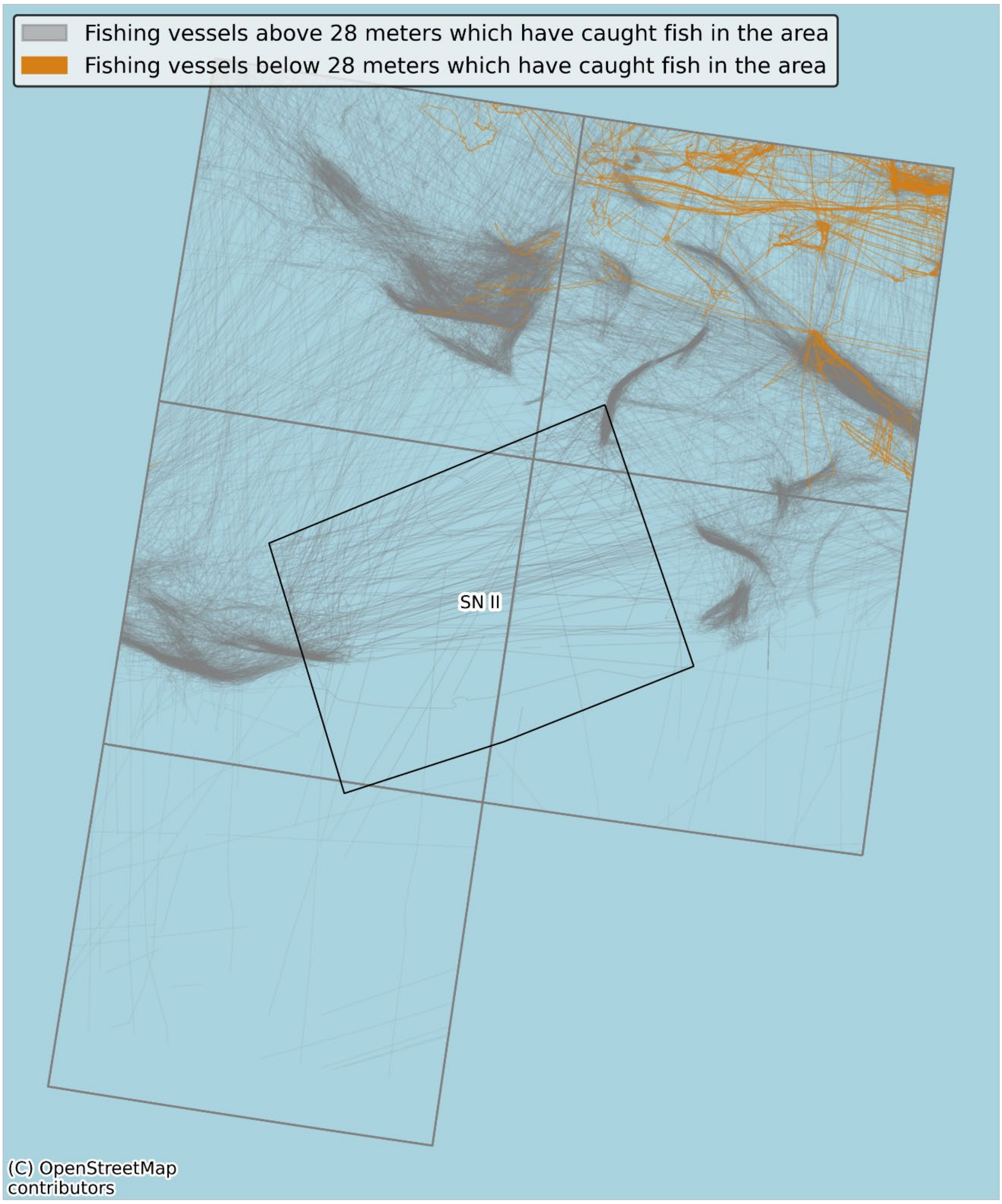

Figure 8 Movement of fishing vessels – larger and smaller than 28 meters – that have reported catches in and around SN II in 2017-2020.