Regional Studies in Marine Science 91 (2025) 104591

Contents lists available at ScienceDirect

Regional Studies in Marine Science

journal homepage: www.elsevier.com/locate/rsma

Effects of electromagnetic fields on flatfish

Annemiek Hermans [a,c,*], Allard van Mens [b], Britte Schilt [c], Ruben van der Neut [d], Ralf van Hal [b]

[a] Marine Animal Ecology group, Wageningen University, P.O. Box 338, Wageningen 6700 AH, the Netherlands
[b] Wageningen Marine Research, Wageningen University and Research, P.O. 68, IJmuiden 1970 AB, the Netherlands
[c] Witteveen+Bos, Daalsesingel 51c, Utrecht 3511 SW, the Netherlands
[d] WaterProof Marine Consultancy & Services BV, IJsselmeerdijk 2, Lelystad 8221 RC, the Netherlands

ARTICLE INFO

Keywords:
Plaice
Common dab
Common sole
Offshore wind farms
Subsea power cables
Behavioural effects
Electromagnetic fields

ABSTRACT

The expansion of offshore wind farms has led to increasing concerns about electromagnetic fields generated by subsea power cables and their potential effects on marine life. A species group that might be affected is flatfish, including species such as plaice *(Pleuronectes platessa)*, common dab *(Limanda limanda)*, common sole *(Solea solea)* and flounder (*Platichthys flesus*), which are all commercially and ecologically important in the North Sea. Concerns raised by fisheries organisations and NGO's include altered behaviour, potentially affecting their distribution and migration routes. This study investigated the effects of electromagnetic fields resulting from a 50 Hz 700 MW alternating current cable on flatfish abundance and diversity in the Dutch North Sea. Sampling was conducted in two seasons, under different conditions, in September 2021 (46 locations) and April 2024 (36 locations) using a commercial vessel equipped with beam trawls and a magnetometer. Fish were identified and counted after 5-minute hauls, covering both cable and reference areas. Statistical analyses, permutation tests, assessed differences in abundance between cable and reference areas. There was no significant difference in abundance and diversity of plaice, dab or sole. The findings suggest that, under the measured conditions, electromagnetic fields do not significantly affect flatfish abundance or diversity around the cable. Future studies should focus on electronic tagging or controlled experiments to better understand potential, more subtle, behavioural responses to electromagnetic fields that were not possible to detect using our study design.

1. Introduction

The ocean provides numerous benefits to humankind, including a vital source of protein (Boyd et al., 2022; Walford and Wilber, 1955) and more recently an increasingly essential role in energy production (Melikoglu, 2018; Santhakumar et al., 2024). In the European Union alone, a projected 340 GW of offshore energy is aimed to be generated by 2050, a 20-fold of the currently installed capacity (European Court of Auditors, 2023; Wind Europe, 2023). Generated energy is transported from the turbines to an offshore high voltage station (OHVS) with alternating current (AC) inter-array cables. Energy is then transported towards the shore with AC or direct current (DC) export cables, all referred to as subsea power cables (SPCs) (Öhman et al., 2007).

Transporting power through SPCs generates electromagnetic fields (EMF), which are a combination of magnetic fields and (induced) electric fields protruding into the marine environment (Henkel et al., 2014). The range of these magnetic fields is dependent on several factors, including cable type and power level transported. Modelling has shown that AC-EMFs could be detectable 120 m from the cable and DC even further, to 240 m from the cable (Hermans et al., 2024). As such, SPCs in the coastal marine environment will locally change the magnetic environment used by electro- and magnetosensitive species (Hermans et al., 2024; Hutchison et al., 2020).

Several taxa of marine species have evolved to use magnetic fields for navigational purposes, including sea turtles, marine birds, and fish such as sharks, rays, eels, and sturgeons (Kalmijn, 1978; Klimley, 1993; Molteno and Kennedy, 2009; Quinn et al., 1981; Rommel and McCleave, 1973). Flatfish or *Pleuronectiformes* are believed to be sensitive to magnetic fields (Metcalfe et al., 1993), but evidence base is sparse. A laboratory study found no impact on the mortality of flounder (*Platichthys flesus*) exposed to 3.7 mT field DC for seven weeks (Bochert and Zettler, 2004). Metcalfe et al. (1993) showed that tagged plaice (*Pleuronectes platessa*) were able to maintain a constant course at night, which the authors interpreted as potential evidence of an external magnetic cue.

* Corresponding author at: Marine Animal Ecology group, Wageningen University, P.O. Box 338, Wageningen 6700 AH, the Netherlands.
E-mail address: annemiek.hermans@wur.nl (A. Hermans).

https://doi.org/10.1016/j.rsma.2025.104591
Received 11 July 2025; Received in revised form 24 October 2025; Accepted 26 October 2025
Available online 29 October 2025

This suggests that flatfish may be sensitive to EMFs from subsea power cables. This is supported by a study at the 50 Hz AC SPC of the Danish Nysted offshore wind farm, were electronically tagged flounder crossed the cable more often at a lower versus a higher electromagnetic field (Hvidt et al., 2006). Research on Atlantic halibut (*Hippoglossus hippoglossus*) exposed 72 h to a range of 0.23–1.01 mT DC showed the spatial distribution was altered, where individuals spent less time upstream of the highest EMF (Woodruff et al., 2013).

Given the evidence of magnetic field sensitivity in benthic species and the presence of SPCs directly within their habitats, including both resident areas and migration routes, it is critical to investigate potential effects on flatfish. It is unlikely that EMFs from SPCs form a hard barrier for flatfish, as presence in and around offshore wind farms has been shown (Buyse et al., 2023; Doorenspleet et al., 2024; van Hal et al., 2017; Winter et al., 2010). Possible effects may range from hindrance in migration (Hvidt et al., 2006), to attraction as hypothesised for elasmobranchs (Gill, 2009; Hermans et al., 2024; Hutchison et al., 2020) but also can be non-existent. The perception, biological relevance, and effects of EMFs are likely to vary throughout a species' life stages (Gill et al., 2012). During the larval stage, prolonged or continuous exposure to EMF is unlikely, as sea currents transport individuals over large distances. Juveniles and adults, which spend more time close to the bottom are expected to have a higher rate of encountering the cables. As they exhibit more complex behaviours, and utilise EMF in a different way, they are thus potentially more affected.

Flatfish (Pleuronectiformes) include various families, such as Pleuronectidae (righteye flounders), Bothidae (lefteye flounders), Soleidae (soles), and Scophthalmidae (turbots). They inhabit estuaries and continental shelves (Gibson et al., 2014), areas that are also well-suited for offshore wind development. The role of flatfish in the food web is primarily preying on zoobenthic invertebrates and serving as prey for higher trophic levels, including pelagic fish, thereby facilitating energy transfer through the ecosystem (Gibson et al., 2014; Lee et al., 2010). Historically, the flatfish order has been targeted by commercial fisheries and continues to represent a significant source of both economic revenue and dietary protein (Dierickx et al., 2024; Rice and Andrew Cooper, 2003). Fisheries organizations have expressed concerns regarding the potential effects of anthropogenic EMFs on flatfish species (EMK Foundation, 2020). Anecdotal reports from fishermen suggest a decline in common sole (*Solea solea*) abundance in spawning grounds within the German Bight following the installation of DC interconnector cables (personal communication).

A lack of understanding of EMF effects hinders accurate environmental impact assessments, potentially leading to delays in permitting procedures and complicating decision-making processes to balance offshore wind expansion with environmental and fisheries interests. This study aims to assess whether flatfish abundance and diversity differ in the vicinity of an SPC EMF. To investigate this, the presence and absence of flatfish on and around the SPC were compared to a reference location using beam trawl surveys, while simultaneously measuring magnetic field strength.

2. Materials and methods

2.1. Sampling area

Sampling was conducted along the export cables of two offshore wind farms off the Dutch coast: Borssele and Hollandse Kust Zuid (HK (z)) (Fig. 1). Both sites included four cables, where the HK(z) cables were buried between −2 m and −6 m below the non-mobile seabed at the survey sites, and the Borssele cables −1.5 m to −3.0 m below the non-mobile seabed. Both areas are characterized by predominantly flat sand and mud substrates with water depths between 10 and 20 m. Sampling focused on the northernmost cable at Borssele and the southwestern most cable at HK(z). During the survey on the Borssele cable wind speeds and directions varied between 2 and 4 Beaufort force (Bft) shifting from SE to WSW. During the HK(z) cable sampling the wind speeds and directions varied between 0 and 5 Bft between NE and NW. Sampling activities were stopped when wind speeds dropped below 1 Bft, as at those speeds the turbines do not generate any power and

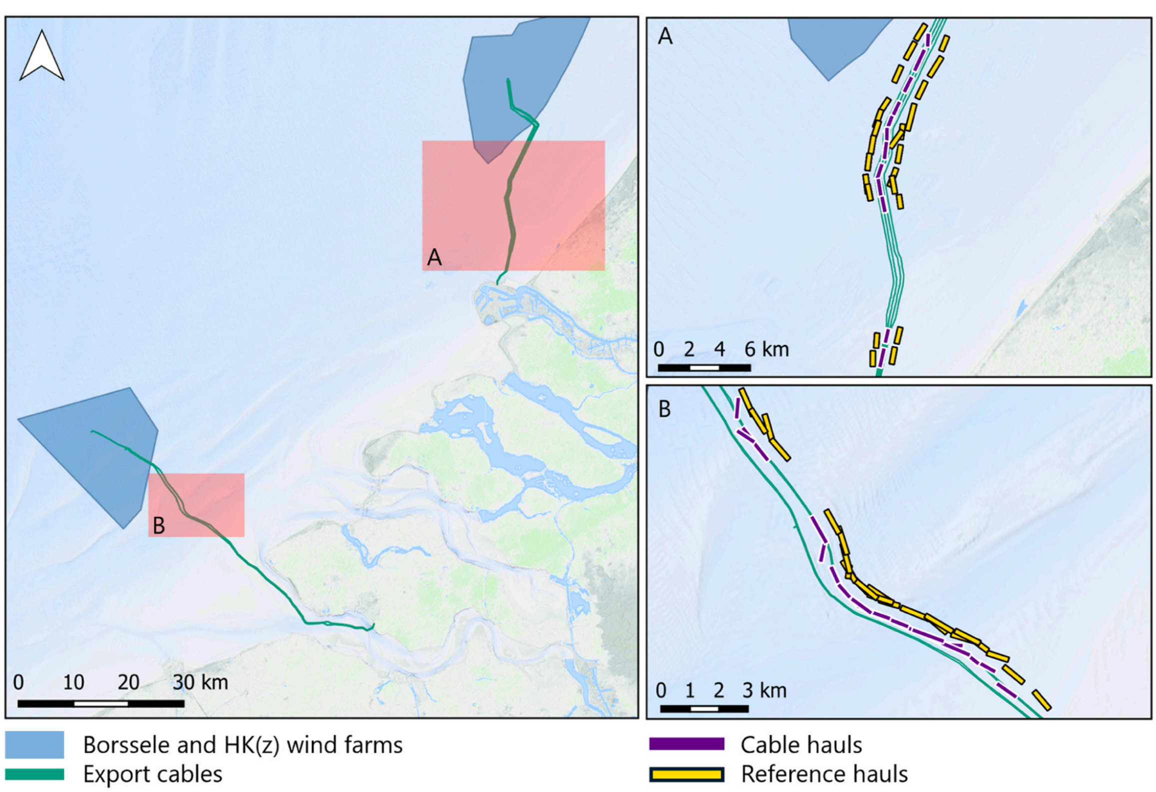

Fig. 1. Map of the study area and sampling locations.

export cable carries little or no current, resulting in lower magnetic field strengths. Conversely, at higher wind speeds more power is generated, and stronger magnetic field strengths are induced around the cable.

2.2. Vessel and equipment

Two surveys were conducted in September 2021 and April 2024 with a commercial Euro cutter OD-3 vessel "Adrianne" (23.8 m and 222 kW engine power) to sample flatfish. The vessel was equipped with two 4.5 m beams fitted with five tickler chains, four net tickler chains and a 14 m ground chain as per standard commercial fishing practice. Codend mesh size was 40 mm, a reduction from the minimal commercial size, to capture a broader size range of the fish population. Tows were limited to 4–5 min at standard fishing speed (4.5 knots), resulting in distances of approximately 620 m. Although commercial and routine monitoring hauls are typically longer, shorter tows minimized deviation from the cable and reference routes and enabled a greater number of hauls within the available time. This was considered preferable to the potential reduction in catchability, particularly of larger, more mobile fish. For each haul, operational data were recorded, including start and end time, GPS coordinates of deployment and retrieval, average depth, wind speed, wave height, vessel speed, and course.

A custom-made tri-axial fluxgate magnetometer was mounted on the trawl beam, approximately 0.5 m above the seafloor. The sensor measured the magnetic field along three orthogonal directions (xyz-plane), and logged continuously at 2071 Hz, allowing frequency analyses up to ~1000 Hz. It was activated at the start and deactivated at the end of each sampling day. Due to the installation setup, live data streaming was not possible, and cable proximity could only be confirmed post-survey based on the recorded data.

Subsequently a similar custom-made land-based tri-axial fluxgate magnetometer was installed approximately 1 m above the Borssele export cable and 2 m above the Hk(z) export cable in the cable landing area to measure stationary magnetic field strengths for 3 months, within which the trawling operations occurred. It is important to note the magnetometer is capable of detecting time-varying and static magnetic fields, it however does not measure electric or induced electromagnetic fields. In addition, mobile magnetic field measurements may be affected by sensor orientation changes (pitch, roll, yaw) due to gear movement during trawling and by low-level noise from residual magnetization and interference from the vessel's hull, gear, and engine operations.

Fish catches from starboard and port tows were processed separately using the same procedure. Target species included plaice (*Pleuronectes platessa*), dab (*Limanda limanda*), sole (*Solea solea*), flounder (*Platichthys flesus*), turbot (*Scophthalmus maximus*), and brill (*Scophthalmus rhombus*). Once on board, catches were sorted to species level. Large individuals were removed prior to sorting. If catches were too large to process fully, they were divided, and a known subsample was sorted. Subsampling was also applied when individual species were overly abundant. Fish were measured to the nearest centimetre and recorded in 1 cm length classes (e.g. 10.0–10.9 cm as 10 cm). All counts, lengths, and subsample factors were recorded for analysis. Catches were returned to sea immediately after processing.

2.3. Survey design

Sampling was conducted during daylight hours along the export cables of the Borssele and Hollandse Kust Zuid (HK(z)) offshore wind farms (Fig. 1). For each cable location, reference sites were selected at least 400 m from any subsea power cable in areas with comparable depth and substrate, and all paired samples were collected within the shortest possible time frame to minimize environmental variability due to tides or weather. The Borssele campaign took place over four days (7–10 September 2021), during which 23 cable locations were sampled, each paired with a single reference location. This resulted in 92 samples in total: 23 cable and 23 reference hauls on both the starboard and port sides (Fig. 1). A magnetometer was mounted on each beam trawl during this campaign. The HK(z) campaign was conducted over two days (22–23 April 2024) and included 12 cable locations. At each location, two reference hauls were taken, one east and one west of the cable, resulting in 12 sets of three paired samples (one cable and two reference hauls). This yielded 72 samples in total: 12 cable and 24 reference hauls on both the starboard and port sides (Fig. 1). For this campaign, a magnetometer was mounted only on the starboard beam, as only one sensor was available; this was considered sufficient to determine whether the hauls were conducted within the EMF generated by the subsea power cable.

2.4. Data work-up

The magnetometers were synchronized to Coordinated Universal Time (UTC) and data were retrieved after each campaign. Upon retrieval, raw magnetic field data were inspected for sensor dropouts and abnormal peak values (exceeding 100 μT), which could indicate sensor malfunction or electromagnetic interference. Time-stamped magnetometer data were then cross-referenced with survey logs to segment the dataset by beam side (port/starboard) and location type (cable vs. reference). Data segments recorded outside of documented survey hauls were excluded from further analysis.

During the HK(z) campaign, a control transect was sailed across the four subsea power cables at the beginning of the survey to verify sensor function and alignment. These data were used as a reference to confirm time synchronization and the presence of the expected EMF peaks at the cable crossings (Fig. 2).

2.5. Analysis

To eliminate low-frequency drift, environmental noise, and earth's magnetic field a digital 4th-order Butterworth high-pass filter with a cutoff frequency of 30 Hz was applied independently to each axis. The filtered signals were segmented in non-overlapping 1-second windows for the haul surveys, and 1-minute windows for the land-based measurement. For each window, the root mean square value was calculated (B). As to determine and characterize the frequencies within the measured signal a fast Fourier Transformation (FFT) was applied. The FFT was applied over the three orthogonal sensor measurements, with a time window set to 0.5 s, and overlap of 0.25 s.

In the analyses the reference areas per offshore wind farm (e.g. Borssele or HK(z)), and cable hauls (starboard and port) were combined. Statistical differences were assessed by survey using a permutation test, a non-parametric method suitable for ecological data with minimal distributional assumptions using statistical package R (4.4.1). For each pair, the difference in mean fish counts between the cable and combined reference hauls, per study area, was compared against a null distribution

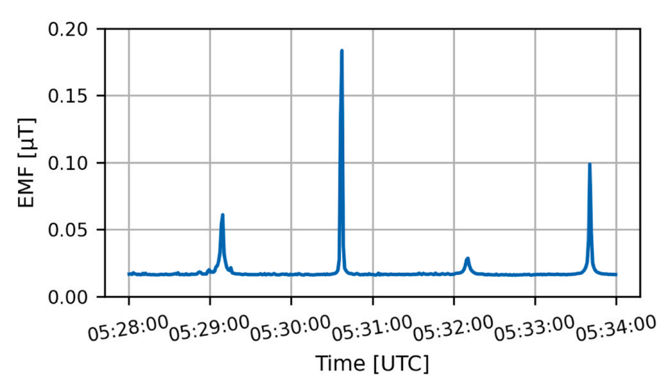

Fig. 2. Sailed control track at the HK(z), magnetic field (RMS) strength in micro-Tesla ~based on fishing speed of 4.5 knot, showing all frequencies above 30 Hz frequency.

generated by randomly reassigning trawls to cable or reference groups 1000 times. The significance was determined based on its rank within the distribution, with thresholds defined for α = 0.05 and 0.1.

3. Results

A total of 46 stations were fished during the Borssele campaign, comprising 23 cable (within the EMF zone) and 23 reference stations, with nets on both the starboard and port sides resulting in 92 catch compositions. For the HK(z) campaign, 36 stations were fished, including 12 on the cables and 24 reference stations resulting in 72 catch compositions. Across both campaigns, 39 species were recorded, including the target flatfish species: 15,777 plaice, 10,517 dab, 1798 sole, and 147 flounder (Table S1).

3.1. *Magnetic fields measurements*

During the Borssele survey, all 23 hauls conducted within the EMF zone exhibited an increased detection of the 50 Hz EMF component along at least one of the three measured axes. In contrast, none of the 23 reference hauls showed a similar distinct increase of 50 Hz EMF component, however the majority of hauls did show noticeable low-frequency EMF components (30–45 Hz). The exact source of these lower frequencies remains unclear but may be introduced by ship-generated or instrumented mounted interference or spectral leakage resulting from real-time FFT analysis.

The land-based magnetometer at Borssele recorded a stable magnetic field of 1.8 μT on the first day (7 September 2021), rising steadily to 3.1 μT by 16:00 UTC. On the second day, similar morning values were observed, with an increase to 2.8 μT around 13:00 UTC. The third day showed more fluctuation, ranging from 1.9 to 2.5 μT in the morning, decreasing to 1.8 μT in the afternoon. The fourth and last day a stable 1.8 μT magnetic field strength was recorded, with in the afternoon a strong increase to 4.9 μT 18:00 UTC (Fig. 3). For reference, magnetic field strengths recorded over the full three-month deployment ranged between 0.6 and 5.3 μT. The wind speeds were 2–4 Bft for the September 2021 survey and 2–5 Bft during the April 2024 survey.

For the HK(Z) cables, magnetic field recordings during the hauls consistently confirmed the presence or absence of the export cable through the detection of 50 Hz components. Land-based magnetometer data from the first survey day (22 April 2024) showed a morning increase from 2.25 μT at 06:30 UTC to 4.25 μT at 08:45 UTC, followed by stable values around 3.5 μT for the rest of the day, with in total 12 hauls surveyed above the cable and 24 hauls as reference. Compared to Borssele only three of the hauls had similar noticeable low-frequency (30–45 Hz) EMF components. On the second day, slightly higher values were observed, with morning levels around 3.75 μT and more variation in the afternoon, ranging from 3.1 μT at 16:00 UTC to 4.8 μT at 17:00 UTC, averaging approximately 4.2 μT (Fig. 3). However, due to the sensor's proximity to the substation and low wind speeds, these elevated values likely reflect interference from a local 50 Hz power sources (e.g., a transformer), rather than residual current through the cable. Consequently, these readings are unlikely to represent actual magnetic field strengths at sea.

3.2. *Catch composition*

The surveys were done in different seasons and areas, which is reflected in the catch composition specifically for non-target species. The benthic organisms, not recorded in detail, affecting the catchability and sorting of the fish catches were in both surveys dominated by *Ophiura ophiura*, *Asterias rubens* and *Psammechinus miliaris*. In Hk(z) several hauls were dominated by *Ecinocardium cordatum*, while in Borssele the common spider crab (*Maja brachydactyla*) occurred in relatively large numbers.

The catch composition was dominated by the target flatfish species plaice, dab, and sole, except for gobies *Gobiidae* in the Borssele survey. The other target species were caught in relative smaller numbers e.g. flounder (Borssele 90, HK(z) 57), turbot (Borssele 8, HK(z) 15), and brill (Borssele 0, HK(z) 2) and were not included in further analysis due to the limited numbers caught (Table S1).

Plaice catches were dominated by small individuals (6–14 cm), representing 0-group fish in September at Borssele and 1-year-olds in April at HK(z), with occasional larger individuals up to 30 cm. Dab in Borssele were mainly 11–16 cm, while HK(z) catches showed two distinct cohorts: 7–13 cm and 13–22 cm. Sole in Borssele were mostly 16–27 cm, with HK(z) also yielding some smaller individuals (12–27 cm). Flounder were primarily 20–35 cm in both areas. Length distributions of all four species were similar between cable and reference hauls.

A clear difference in species abundance was observed between the two surveys: plaice and dab were more abundant in HK(z), while sole was more abundant in Borssele (Fig. 4). The non-parametric results indicated that plaice and dab in Hk(z) and flounder in Borssele showed a nonsignificant trend towards attraction to the cable (α =0.01) (Table 1).

Large differences in catches on a small spatial scale occurred, even the starboard and port catch of the same position resulted in the smallest and largest catch of a pair of three hauls (pair 7 reference area East, Figure S1). In more detail for plaice (Figure S1) reveals that most of the smallest catches of a pair occurred in reference area East, highlighting a distinct difference between reference area East and reference area West. Notably, the catches in reference area West were similar to those in the EMF zone. The catches of dab showed a very similar distribution on the small spatial scale. Overall, both surveys provided no significant

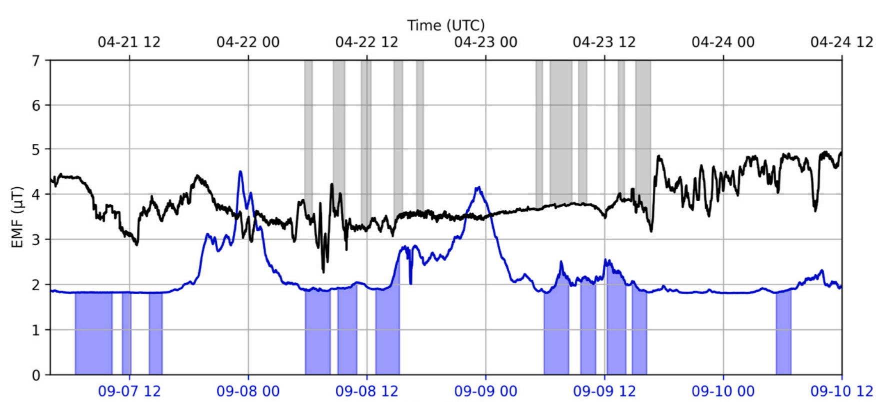

Fig. 3. Measured magnetic field (RMS) strength in micro-Tesla, with blue line and bottom x-axis Borssele and black line and top x-axis HK(z) measurements. Corresponding shaded areas (blue and black) indicate the time intervals where hull surveys where performed.

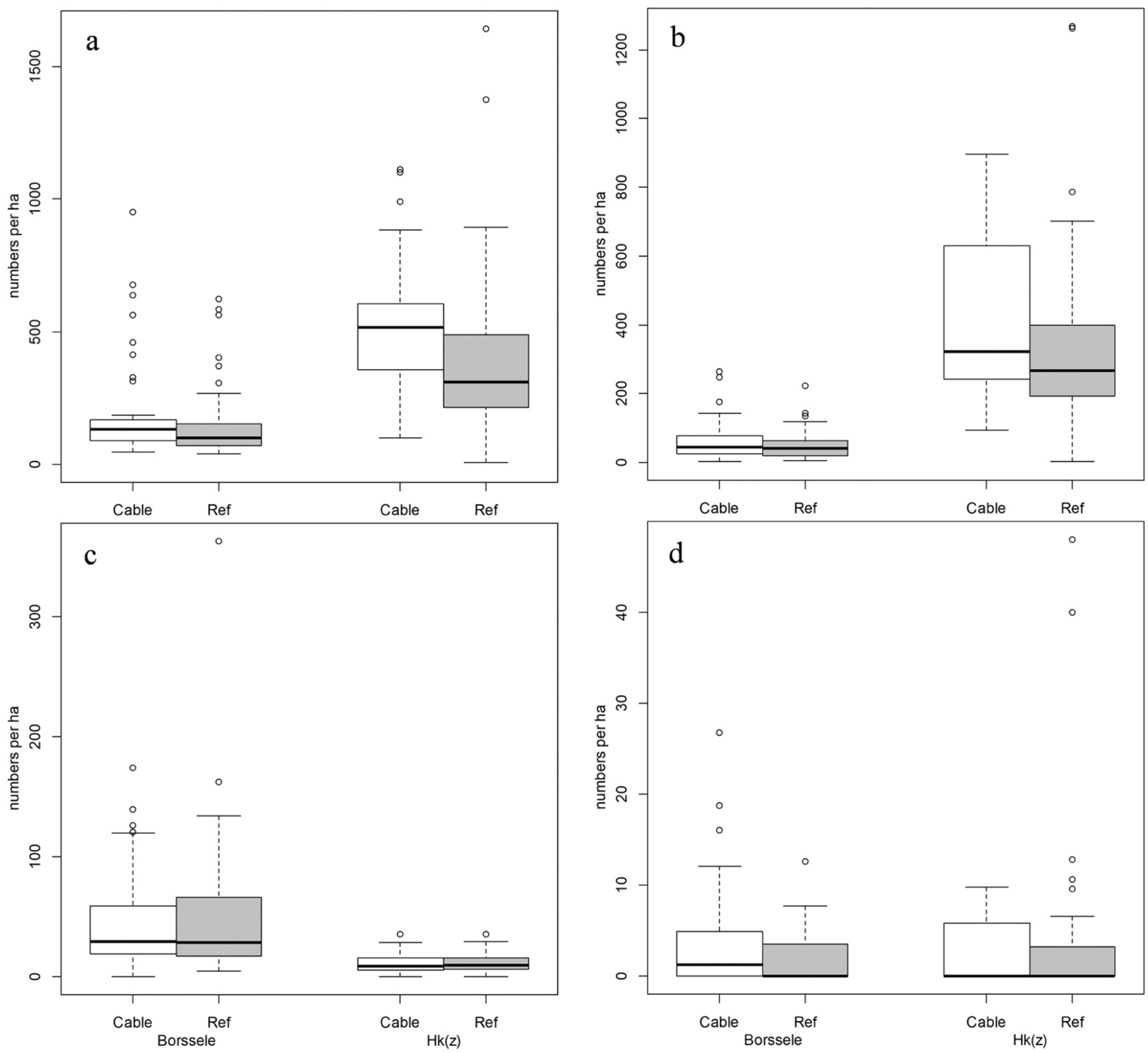

Fig. 4. Catches per haul in numbers per hectare on the cable (white) and reference areas (grey) of (a) plaice, (b) dab, (c) sole, and (d) flounder.

Table 1
The rank number of the observed difference between the EMF and the reference areas, rank close to 1 indicate attraction to the reference areas, while ranks close to 1000 indicate attraction to the EMF. None exceeded the two-side $\alpha = 0.05$ (<26 and >974) and 0.1 (<53 and >948).

	Borssele	HK(z)
Plaice	756	893
Dab	650	847
Sole	441	340
Flounder	899	476

evidence of either avoidance or attraction to the EMF by the target species.

4. Discussion

The biodiversity and abundance of flatfish were studied in an EMF of 50 Hz AC SPCs using 5-minute beam trawl tracks conducted under representative wind conditions for the North Sea (Department of Waterways and Public Works, Netherlands, 2025). No significant difference in flatfish abundance was observed between areas inside and outside the EMF of the SPC during two surveys conducted under different wind conditions, a low-wind autumn survey (September 2021, 2–4 Bft) and a higher-wind spring survey (April 2024 2–5 Bft). Despite variations in wind strength, which were expected to influence EMF intensity, no corresponding effect on flatfish distribution was found, suggesting that EMF intensity may not have played a significant role in influencing their abundance. Sole, plaice and dab did not show significant signs of attraction to or repulsion away from the SPC.

In several fish species (groups) it is known that specific organs or mechanisms are responsible for their electrosensitivity or magnetosensitivity. Magnetosensitivity can occur due to the presence of magnetite (as found in eels, salmon, and tuna), indirectly due to electrosensitivity (possibly elasmobranchs), or via radical pair mechanisms. Electrosensitivity is primarily associated with the Ampullae of Lorenzini, as seen in elasmobranchs. However, although there are strong indications that flatfish are able to sense the Earth's magnetic or associated electric fields (Hvidt et al., 2006; Woodruff et al., 2012), research on flatfish as a species group is lacking. In an extensive literature review to magnetoreception in fish, no research to the sensory abilities of any flatfish species was found (Naisbett-Jones and Lohmann, 2022). It is not known if and how any magnetic or electrical cues are integrated in the sensory system of flatfish or how this sensory information is used. As such, the behavioural effects of EMF found in earlier studies in the lab (Woodruff et al., 2012, DC) and in the field (Hvidt et al., 2006, AC) are not fully understood.

Both the results at the Borssele as well as the HK(z) cable, two different habitats in different conditions, did not show effects on the scale of juvenile flatfish abundance, nor signs that the AC cables form a barrier for the species. Since each location has only been monitored once, it could not be observed whether EMF intensity affected the degree of movement across the cable like in Hvidt et al. (2006). A difference in abundance between the east and the west of the HK(z) cable was observed in 2024, but this is likely caused by other environmental parameters (distance from shore, depth). This is in line with other research to flatfish in OWFs, which have shown that parameters like depth and habitat type are more determining factors for community structure and species abundance than the presence or absence of cables (and with that, EMF) (Bicknell et al., 2025; Buyse, Reubens et al., 2023; Love et al., 2017).

Flatfish are observed within OWFs, as confirmed by electronic tagging and eDNA studies, suggesting that inter-array SPC do not act as a hard barrier or strong deterrent (Buyse et al., 2023; Doorenspleet et al., 2024; Winter et al., 2010). While inter-array SPCs within OWFs transmit lower currents (up to 66 kV), our findings support the presence of these species for export cables with a maximum capacity of 220 kV. It is important to note that our study specifically looks at EMF from 50 Hz AC SPC, and in the future DC cable installations are expected to increase due to their lower transmission losses and higher power transfer capacity (Ryndzionek and Sienkiewicz, 2020). Future studies may therefore need to consider the effects of DC systems and care should be taken when translating our results to different circumstances. Particularity as DC is considered to be more perceptible and similar to the bioelectric field (Bedore and Kajiura, 2013) and is believed to be used for navigation as the geomagnetic field is also DC (Naisbett-Jones and Lohmann, 2022).

Our study design using beam trawl survey is not equipped to explore more subtle behavioural effects as for example effects on foraging, interaction with conspecifics or migration (Hermans et al., 2024). To explore these effects, alternative methods, such as electronic tagging to track migration routes as done with eels and salmon (Abecasis et al., 2018; Klimley et al., 2017; Reubens et al., 2019; Westerberg and Lagenfelt, 2008; Wyman et al., 2023) and fine-scale acoustic tracking studies to explore behavioural changes (Buyse et al., 2023; Winter et al., 2010), are recommended. Additionally, lab-based research using controlled environments (e.g., preference chambers or mesocosms) could isolate and clarify the direct impacts of EMFs on fish behaviour and physiology (Albert et al., 2022; Hutchison et al., 2020). The potential impact of EMF depends on both the sensitivity of the organism, physiologically and behaviourally, and the probability of exposure, which is determined by encounter rate and field strength. Juvenile and adult fish are more likely to experience repeated or prolonged exposure, as they actively control their movements and may remain in EMF-affected areas for extended periods. Their predominantly benthic lifestyle also places them closer to subsea cables, where field strengths are higher. Some studies suggests that EMFs may influence larval development (Cresci et al., 2022; Formicki et al., 2021), the passive dispersal and predominantly pelagic lifestyle of larvae reduce the likelihood of prolonged exposure. This also places them farther from subsea cables, where field strengths are lower, thereby decreasing their overall risk.

The collection of 164 hauls across two distinct surveys yielded a robust and diverse dataset for analysis. Sampling under a range of field conditions, including varying tides and wind patterns, ensured that different environmental conditions (season, wind, tide, current, location) were represented. By closely pairing samples, environmental effects within pairs were minimized; while different environmental conditions between pairs were accommodated. Nonetheless, we do acknowledge that more subtle differences may have remained below the threshold of detection. Wind conditions during HK(z) surveys shifted from moderate (5–6 Bft to calm (1–2 Bft), potentially affecting catchability, fish distribution and magnetic strength via the corresponding reduced power transport. This is relevant as wind-driven mixing and turbulence affect vertical and horizontal movement, particularly in pelagic and semi-demersal species (Nilsson, 2003; Solberg and Kaartvedt, 2017) and might have overshowed EMF induced behavioural effects. No effects of the EMF were observed under the conditions in this survey, but stronger winds and associated EMFs were not tested. Seasonal or migratory variation in fish responses was beyond the study scope but may be relevant for future research. Moreover, while the analysis centred on the presence or absence of the EMF, other environmental factors known to influence species composition, particularly tide and currents, water depth and seabed type (Gibson et al., 2014), were not explicitly accounted for in the sampling design or analysis. However, the variation in these environmental factors was minimized due to the closeness in time and space of the sampling locations. Lastly, haul duration was reduced to 5 min to improve spatial accuracy over cables, which may have biased species composition. Larger, stronger-swimming individuals are more likely to evade capture during short hauls, potentially leading to underrepresentation and affecting interpretation of EMF effects on these species.

This study found no significant effect of EMFs generated by a 50 Hz AC SPC on the diversity and abundance of flatfish. While more subtle behavioural responses may occur, these would be better identified through controlled laboratory experiments or fine-scale electronic tagging studies with juvenile or adult fish. However, under the conditions assessed in this study, SPCs are unlikely to act as a physical barrier or a strong attractant for flatfish. The results from this study reflect on AC cables and care should be taken when translating these to DC cables or other species groups.

CRediT authorship contribution statement

Ruben van der Neut: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation. **Britte Schilt:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Ralf van Hal:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Conceptualization. **Allard van Mens:** Writing – review & editing, Writing – original draft, Methodology, Investigation. **Annemiek Hermans:** Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Author statement

All authors conceptualised the study and designed the experimental set-up. All authors wrote the first version of the manuscript, AM conducted the data collection, and data work-up and processing, RH conducted analysis. All authors reviewed and commented on versions of the manuscript before submission.

Funding

This project was carried out for T.S.O. TenneT as part of the permit requirements for the Offshore grid Nature permit.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Annemiek Hermans (Corresponding author) and Britte Schilt are employed by engineering firm Witteveen+Bos and in that role are seconded to T.S.O. TenneT. All authors declare that they have no known competing financial interests or personal relationships that would influence the work reported in this paper.

Acknowledgements

We would like to thank T.S.O. TenneT for providing the funds to execute this work. We would like to thank the vessel crew of OD3-Adrianna, especially the skipper Jan-Pieter for his excellent navigation skills finding on the cables. Our gratitude extents to Joost Brinkkemper for his support during the data collection and for a final review of the manuscript. We would also like to acknowledge the staff at Wageningen Marine Research, in particular, Sophie Neitzel for coordinating the research at sea on the Borssele wind farm cables, Joey Volwater for assisting with fieldwork during the Borssele sampling campaign, and Yoeri van Es for his support and excellent knowledge during the fieldwork on the HK(z) cable campaign.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.rsma.2025.104591.

Data Availability

Data will be made available on request.

References

Abecasis, David, Steckenreuter, Andre, Reubens, J.A.N., Aarestrup, Kim, Alós, Josep, Badalamenti, Fabio, Bajona, Lenore, et al., 2018. A review of acoustic telemetry in Europe and the need for a regional aquatic telemetry network. Anim. Biotelemetry 6 (1), 12. https://doi.org/10.1186/s40317-018-0156-0.

Albert, Luana, Olivier, Frédéric, Jolivet, Aurélie, Chauvaud, Laurent, Chauvaud, Sylvain, 2022. Insights into the behavioural responses of juvenile thornback ray *Raja clavata* to alternating and direct current magnetic fields. J. Fish. Biol. 100 (3), 645–659. https://doi.org/10.1111/jfb.14978.

Bedore, Christine N., Kajiura, Stephen M., 2013. Bioelectric fields of marine organisms: voltage and frequency contributions to detectability by electroreceptive predators. Physiol. Biochem. Zool. 86 (3), 298–311. https://doi.org/10.1086/669973.

Bicknell, Anthony W.J., Gierhart, Samuel, Witt, Matthew J., 2025. Site and species dependent effects of offshore wind farms on fish populations. Mar. Environ. Res. 205, 106977. https://doi.org/10.1016/j.marenvres.2025.106977.

Bochert, R., Zettler, M.L., 2004. Long-term exposure of several marine benthic animals to static magnetic fields. Bioelectromagnetics 25 (7), 498–502. https://doi.org/10.1002/bem.20019.

Boyd, Claude E., McNevin, Aaron A., Davis, Robert P., 2022. The contribution of fisheries and aquaculture to the global protein supply. Food Secur. 14 (3), 805–827. https://doi.org/10.1007/s12571-021-01246-9.

Buyse, Jolien, Hostens, Kris, Degraer, Steven, De Troch, Marleen, Wittoeck, Jan, De Backer, Annelies, 2023. Increased food availability at offshore wind farms affects trophic ecology of plaice Pleuronectes platessa. Sci. Total Environ. 862, 160730. https://doi.org/10.1016/j.scitotenv.2022.160730.

Buyse, Jolien, Reubens, Jan, Hostens, Kris, Degraer, Steven, Goossens, Jolien, De Backer, Annelies, 2023. European plaice movements show evidence of high residency, site fidelity, and feeding around hard substrates within an offshore wind farm. In: Yates., Katherine (Ed.), ICES Journal of Marine Science. https://doi.org/10.1093/icesjms/fsad179.

Cresci, Alessandro, Perrichon, Prescilla, Durif, Caroline M.F., Sørhus, Elin, Johnsen, Espen, Bjelland, Reidun, Larsen, Torkel, Skiftesvik, Anne Berit, Browman, Howard I., 2022. Magnetic fields generated by the DC cables of offshore wind farms have no effect on spatial distribution or swimming behavior of lesser Sandeel Larvae (Ammodytes marinus). Mar. Environ. Res. 176, 105609. https://doi.org/10.1016/j.marenvres.2022.105609.

Department of Waterways and Public Works, Netherlands. 2025. Rijkswaterstaat Waterinfo. ⟨https://waterinfo.rws.nl/publiek/wind?view=list⟩ (September 26, 2025).

Dierickx, Katrien, Schauer, Peter, Harland, Jennifer, Pipe, Alan, Oueslati, Tarek, Lehouck, Alexander, Ervynck, Anton, et al., 2024. Finding the right plaice at the right time: multi-molecular analysis of flatfish reveals historical catch habitats. Fish Fish 25 (5), 811–822. https://doi.org/10.1111/faf.12847.

Doorenspleet, Karlijn, Lara Jansen, Saskia Oosterbroek, Pauline Kamermans, Oscar Bos, Erik Wurz, Albertinka Murk, and Reindert Nijland. 2024. The Long and the Short of It: Nanopore Based eDNA Metabarcoding of Marine Vertebrates Works; Sensitivity and Specificity Depend on Amplicon Lengths. doi:10.1101/2021.11.26.470087.

EMK Foundation. 2020. Major Concerns Offshore Renewable Energy. ⟨https://visserij.nl/wp-content/uploads/2020/10/Fisheries-protest-letter.pdf⟩ (September 23, 2024).

European Court of Auditors, 2023. Offshore renewable energy: EU auditors highlight green dilemma. Curia Ratio. ⟨https://www.eca.europa.eu/en/news/news-sr-2023-22⟩ (December 30, 2023).

Formicki, Krzysztof, Korzelecka-Orkisz, Agata, Tański, Adam, 2021. The effect of an anthropogenic magnetic field on the early developmental stages of fishes—a review. Int. J. Mol. Sci. 22 (3), 1210. https://doi.org/10.3390/ijms22031210.

Gibson, Robin N., Link, Jason S., Smith, Brian E., Packer, David B., Fogarty, Michael J., Langton, Richard W., 2014. The trophic ecology of flatfishes. In: Nash, Richard D.M., Geffen, Audrey J., Van Der Veer., Henk W. (Eds.), Flatfishes. Wiley, pp. 283–313. https://doi.org/10.1002/9781118501153.ch11.

Gill, A.B., Bartlett, M., Thomsen, F., 2012. Potential Interactions between diadromous fishes of U.K. conservation importance and the electromagnetic fields and subsea noise from marine renewable energy developments. J. Fish. Biol. 81 (2), 664–695. https://doi.org/10.1111/j.1095-8649.2012.03374.x.

Gill, Andrew B., 2009. EMF-sensitive fish response to EM emissions from sub-sea. Electricity Cables of the Type Used by the Offshore Renewable Energy Industry. COWRIE, Newbury.

Henkel, Sarah K., Suryan, Robert M., Lagerquist, Barbara A., 2014. Marine renewable energy and environmental interactions: baseline assessments of seabirds, marine mammals, sea turtles and benthic communities on the oregon shelf. In: Shields, Mark A., Payne, Andrew I.L. (Eds.), Marine Renewable Energy Technology and Environmental Interactions, Humanity and the Sea. Springer Netherlands, Dordrecht, pp. 93–110. https://doi.org/10.1007/978-94-017-8002-5_8.

Hermans, Annemiek, Winter, Hendrik V., Gill, Andrew B., Murk, Albertinka J., 2024. Do Electromagnetic fields from subsea power cables effect benthic elasmobranch behaviour? A risk-based approach for the dutch continental shelf. Environ. Pollut. 346, 123570. https://doi.org/10.1016/j.envpol.2024.123570.

Hutchison, Zoë, Secor, David, Gill, Andrew, 2020. The interaction between resource species and electromagnetic fields associated with electricity production by offshore wind farms. Oceanography 33 (4), 96–107. https://doi.org/10.5670/oceanog.2020.409.

Hutchison, Zoë L., Gill, Andrew B., Sigray, Peter, He, Haibo, King, John W., 2020. Anthropogenic Electromagnetic Fields (EMF) influence the behaviour of bottom-dwelling marine species. Sci. Rep. 10 (1), 4219. https://doi.org/10.1038/s41598-020-60793-x.

Hvidt, C.B., Klaustrup, M., Leonhard, S.B., Pedersen, J., 2006. Fish along the Cable Trace Nysted Offshore Wind Farm Final Report 2004. Orbicon as. Final report.

Kalmijn, Ad.J., 1978. Experimental evidence of geomagnetic orientation in elasmobranch fishes. In: Schmidt-Koenig, Klaus, Keeton., William T. (Eds.), Animal Migration, Navigation, and Homing, Proceedings in Life Sciences. Springer Berlin Heidelberg, Berlin, Heidelberg, pp. 347–353. https://doi.org/10.1007/978-3-662-11147-5_34.

Klimley, A.P., 1993. Highly directional swimming by scalloped hammerhead sharks, *Sphyrna lewini,* and subsurface irradiance, temperature, bathymetry, and geomagnetic field. Mar. Biol. 117 (1), 1–22. https://doi.org/10.1007/BF00346421.

Klimley, A.Peter, Megan T. Wyman, and Robert Kavet. 2017. Chinook Salmon and Green Sturgeon Migrate through San Francisco Estuary despite Large Distortions in the Local Magnetic Field Produced by Bridges ed. Michael L. Fine. *PLOS ONE* 12(6): e0169031. doi:10.1371/journal.pone.0169031.

Lee, Sung I.L., Aydin, Kerim Y., Spencer, Paul D., Wilderbuer, Thomas K., Zhang, Chang I. K., 2010. The role of flatfishes in the organization and structure of the Eastern Bering Sea Ecosystem. Fish. Sci. 76 (3), 411–434. https://doi.org/10.1007/s12562-009-0201-2.

Love, Milton S., Nishimoto, Mary M., Snook, Linda, Schroeder, Donna M., Scarborough Bull, Ann, 2017. A comparison of fishes and invertebrates living in the vicinity of energized and unenergized submarine power cables and natural sea floor off Southern California, USA. J. Renew. Energy 2017, 1–13. https://doi.org/10.1155/2017/8727164.

Melikoglu, Mehmet, 2018. Current status and future of ocean energy sources: a global review. Ocean Eng. 148, 563–573. https://doi.org/10.1016/j.oceaneng.2017.11.045.

Metcalfe, J.D., Holford, B.H., Arnold, G.P., 1993. Orientation of plaice (Pleuronectes platessa) in the open sea: evidence for the use of external directional clues. Mar. Biol. 117 (4), 559–566. https://doi.org/10.1007/BF00349766.

Molteno, T.C.A., Kennedy, W.L., 2009. Navigation by induction-based magnetoreception in elasmobranch fishes. J. Biophys. 2009, 1–6. https://doi.org/10.1155/2009/380976.

Naisbett-Jones, L.C., and K.J. Lohmann. 2022. Magnetoreception and Magnetic Navigation in Fishes: A Half Century of Discovery. 208: 19–40. doi:10.1007/s00359-021-01527-w.

Nilsson, L., 2003. Vertical migration and dispersion of sprat (Sprattus sprattus) and herring (Clupea harengus) Schools at Dusk in the Baltic Sea. Aquat. Living Resour. 16 (3), 317–324. https://doi.org/10.1016/S0990-7440(03)00039-1.

Öhman, Marcus C., Sigray, Peter, Westerberg, Håkan, 2007. Offshore windmills and the effects of electromagnetic fields on fish. AMBIO A J. Hum. Environ. 36 (8), 630–633. https://doi.org/10.1579/0044-7447(2007)36[630:OWATEO]2.0.CO;2.

Quinn, Thomas P., Merrill, Ronald T., Brannon, Ernest L., 1981. Magnetic field detection in sockeye salmon. J. Exp. Zool. 217 (1), 137–142. https://doi.org/10.1002/jez.1402170114.

Reubens, Jan, Verhelst, Pieterjan, Van Der Knaap, Inge, Wydooghe, Benny, Milotic, Tanja, Deneudt, Klaas, Hernandez, Francisco, Pauwels, Ine, 2019. The need for aquatic tracking networks: the permanent belgian acoustic receiver network. Anim. Biotelemetry 7 (1), 2. https://doi.org/10.1186/s40317-019-0164-8.

Rice, Jake, Andrew Cooper, J., 2003. Management of flatfish fisheries—what factors matter? J. Sea Res. 50 (2–3), 229–245. https://doi.org/10.1016/j.seares.2003.07.001.

Rommel Jr., S.A., McCleave, J.D., 1973. Sensitivity of American Eels (*Anguilla rostrata*) and Atlantic Salmon (*Salmo salar*) to weak electric and magnetic fields. J. Fish. Res. Board Can. 30 (5), 657–663. https://doi.org/10.1139/f73-114.

Ryndzionek, Roland, Sienkiewicz, Łukasz, 2020. Evolution of the HVDC link connecting offshore wind farms to onshore power systems. Energies 13 (8), 1914. https://doi.org/10.3390/en13081914.

Santhakumar, Srinivasan, Meerman, Hans, Faaij, André, Martinez Gordon, Rafael, Florentina Gusatu, Laura, 2024. The future role of offshore renewable energy technologies in the north sea energy system. Energy Convers. Manag. 315, 118775. https://doi.org/10.1016/j.enconman.2024.118775.

Solberg, Ingrid, Kaartvedt, Stein, 2017. The diel vertical migration patterns and individual swimming behavior of overwintering sprat Sprattus sprattus. Prog. Oceanogr. 151, 49–61. https://doi.org/10.1016/j.pocean.2016.11.003.

Walford, Lionel A., Wilber, Charles G., 1955. The sea as a potential source of protein food. Advances in Protein Chemistry. Elsevier, pp. 289–316. https://doi.org/10.1016/S0065-3233(08)60107-2.

Westerberg, H., Lagenfelt, I., 2008. Sub-sea power cables and the migration behaviour of the European Eel. Fish. Manag. Ecol. 15 (5–6), 369–375. https://doi.org/10.1111/j.1365-2400.2008.00630.x.

Wind Europe. 2023. Wind Energy Today. ⟨https://windeurope.org/about-wind/wind-energy-today/⟩ (December 30, 2023).

Winter, H.V., Aarts, G., van Keeken, O.A., 2010. Residence Time and Behaviour of Sole and Cod in the Offshore Wind Farm Egmond Aan Zee (OWEZ). IJmuiden. ⟨https://tethys.pnnl.gov/sites/default/files/publications/Winter-et-al-2010.pdf⟩.

Woodruff, D.L., Schultz, I.R., Marshall, K.E., Ward, J.A., Cullinan, V.I., 2012. Effects of Electromagnetic Fields on Fish and Invertebrates. https://doi.org/10.2172/1012305.

Woodruff, D.L., Cullinan, V.I., Copping, A.E., Marshall, K.E., 2013. Effects of Electromagnetic Fields on Fish and Invertebrates, Task 2.1.3: Effects on Aquatic Organisms Fiscal Year 2012 Progress Report. Pacific Northwest National Laboratory. ⟨https://www.pnnl.gov/main/publications/external/technical_reports/pnnl-22154.pdf⟩.

Wyman, Megan T., Kavet, Robert, Battleson, Ryan D., Agosta, Thomas V., Chapman, Eric D., Haverkamp, Paul J., Pagel, Matthew D., Klimley, A.Peter, 2023. Assessment of potential impact of magnetic fields from a subsea high-voltage DC power cable on migrating green sturgeon, Acipenser medirostris. Mar. Biol. 170 (12), 164. https://doi.org/10.1007/s00227-023-04302-4.