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Ecological impacts of floating offshore wind on marine mammals and associated trophic interactions: current evidence and knowledge gaps

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ABSTRACT

Floating offshore wind is expected to expand globally into further offshore, deeper and highly productive shelf seas to utilise increased and more consistent wind energy. Marine mammals represent mobile species that connect across regions and can indicate wider ecosystem changes. To date, only a handful of ecological impact studies have been conducted at floating offshore wind farms, due to the infancy of the technology and small numbers of operational sites. Understanding how floating offshore wind could alter ecosystem functions and impact species at individual and population levels will be essential to mitigate potential negative ecological impacts as the sector expands. Currently, numerous floating offshore wind sites are planned or already in development. Therefore, evaluating current knowledge and remaining knowledge gaps will benefit future projects in assessing ecological impacts and determining where additional research should be conducted. This review summarises the positive and negative ecological impacts that have been previously highlighted as potential impacts from floating offshore wind, focusing on marine mammals, whilst also considering prey and broader trophic interactions. Current studies at operational floating offshore wind sites are summarised and discussed in context of observed and/or anticipated impacts. Finally, key outstanding research areas are suggested in relation to each impact.

1. Introduction

Renewable energy, with offshore wind as a major contributor, is essential for reducing carbon emissions and achieving net-zero goals (GWEC, 2024). Offshore wind is projected to grow rapidly, from 75.2 GW of global capacity at the end of 2023 to an estimated 370 GW by 2030 (GWEC, 2024). Achieving this expansion will require development in deeper waters, as 80 % of the global offshore wind potential is located at depths >60 m (GWEC, 2023). Currently, most offshore wind turbines are fixed-bottom structures, suitable for shallow waters. However, floating offshore wind (FLOW) technology enables development in deeper waters (> 60 m), facilitating continued growth of offshore wind energy.

The world's first operational floating wind farm, Hywind Scotland, was built in 2017 in the Scottish North Sea. By the end of 2023, FLOW contributed 236 MW to global offshore wind capacity, which accounted for around 0.3 % of the total installed offshore wind energy capacity (GWEC, 2024). The UK accounted for 78 MW (from Hywind Scotland and Kincardine), with the remaining capacity provided by Norway (101 MW), Portugal (25 MW), China (23 MW), and smaller contributions from Japan, France, and Spain (<10 MW total). By 2030, FLOW is expected to deliver 8.5 GW globally, marking rapid growth over the coming years (GWEC, 2024).

However, as FLOW technology is relatively new, its development faces challenges due to a lack of scientific studies on environmental and ecological impacts, during both construction and operational phases. Understanding these impacts will be critical to ensuring the sustainable and successful expansion of this technology.

The anticipated expansion of FLOW, combined with cumulative impacts and additional stressors such as climate change, highlights the urgency of understanding its potential effects (e.g., Isaksson et al. (2023)). Mobile species such as marine mammals play a critical role in connecting habitats and ecosystems across continental shelf regions. Their distributions are closely tied to prey distributions (Williamson et al., 2022) and hence primary production (Engelhard et al., 2013). Studying predator and prey dynamics at FLOW sites could therefore

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serve as an indicator of broader ecosystem changes, offering valuable insights into impacts across trophic levels.

At fixed offshore wind and oil and gas platforms, research on impacts to marine mammals has focused on several key areas, including underwater noise from construction (Graham et al., 2019) and operation (Thomsen et al., 2006), hydrodynamic changes (Floeter et al., 2017), and alterations to prey availability and reef effects (Clausen et al., 2021; Love et al., 2019). While some of these impacts may also occur at FLOW sites, FLOW systems differ significantly from fixed offshore wind farms and oil and gas platforms in several critical ways, such as the location of developments, the physical space they occupy, the use of dynamic substructures, and the nature of construction and maintenance activities. As a result, impacts observed at fixed wind farms and oil and gas platforms cannot simply be extrapolated to FLOW systems. Understanding the ecological effects of FLOW, particularly on key indicator species like marine mammals, will be essential to guiding future developments while ensuring the protection of ecosystems and marine species.

This review examines the potential impacts of FLOW on marine mammals, building on previous reviews such as Farr et al. (2021) and Maxwell et al. (2022). It extends this work by incorporating recent ecological studies from FLOW sites and evaluating whether they provide evidence supporting the potential impacts previously identified. Furthermore, this review highlights where significant knowledge gaps remain, with the aim of guiding future research and reducing existing uncertainties. Whilst the impacts discussed are focused on marine mammals, all current ecological evidence from FLOW sites is incorporated - including physical processes, primary production, biofouling and prey species - to ensure that trophic interactions with the potential to impact top predators are considered.

2. Floating offshore wind

2.1. Infrastructure

Floating offshore wind differs structurally from fixed offshore wind in several important ways. FLOW platforms extend partially into the water column and are anchored to the seabed using mooring lines (Fig. 1). These dynamic structures occupy a larger, more variable footprint compared to fixed structures. Platform designs are categorised by their stabilisation methods (Edwards et al., 2023) and vary in motion range, physical footprint and hence ecological impacts. For detailed reviews on FLOW infrastructure and technological components see Edwards et al. (2023, 2024) and Zhou et al. (2023a).

Platform designs influence stability, costs, and site suitability (Edwards et al., 2024). Additionally, designs may have differing ecological impacts due to factors such as surface availability for colonisation by epibenthic communities (e.g., Karlsson et al. (2022)), structural complexity (affecting fish attraction; Love et al., 2019), infrastructure movement (influencing noise production and potential barrier effects; e.g., James and Costa Ros, 2015), and site-specific factors like size and location. For example, spar-buoy platforms likely provide greater surface area for colonisation, while semi-submersible designs offer higher structural complexity, both of which could enhance artificial reef effects (Love et al., 2019). However, all platform types may present similar risks for the introduction of invasive non-native species.

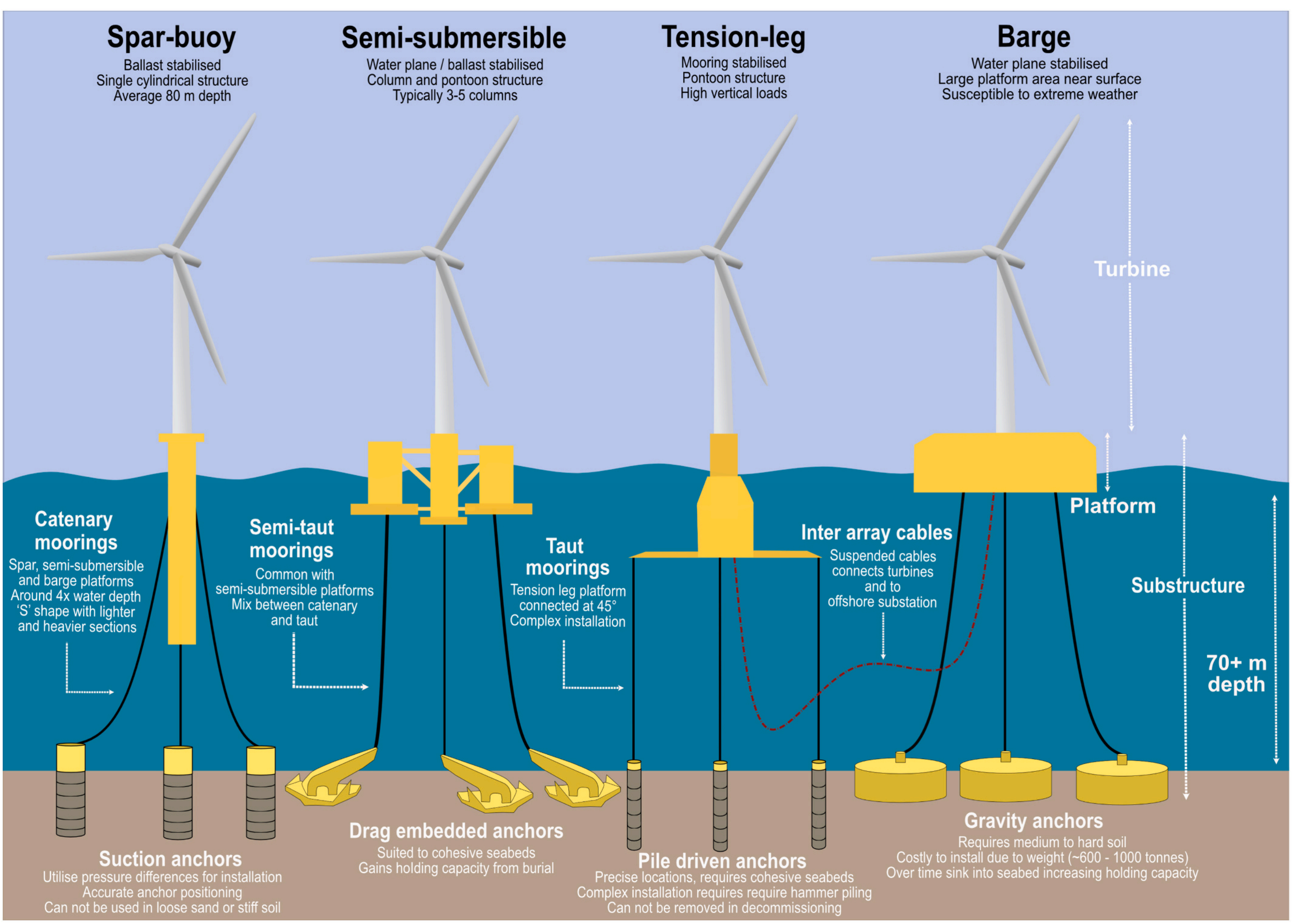

Fig. 1. Overview of the main floating offshore wind platform, mooring and anchor designs.

Typically, FLOW platforms are anchored to the seabed with at least three mooring lines (Fig. 1). However, as FLOW developments expand in size and extend into deeper waters, it is likely that adjacent platforms will share moorings and anchors to reduce costs (Connolly and Hall, 2019). Mooring choice constrains platform motion and affects the ecological footprint. For example, catenary moorings, often four times the water column depth, allow significant movement. Key ecological impacts of moorings arise from seabed disturbance, movement within the water column (contributing to noise; Edwards et al. (2023), Risch et al. (2023)), and colonisation potential, which depends on chain material and diameter. FLOW systems also include inter-array cables that link turbines within a site and convey electricity to substations. Inter-array cables are a vital component of FLOW infrastructure but contribute to the site's physical footprint and potential ecological impacts, including electromagnetic field effects and disturbance to the water column.

Anchors secure mooring lines to the seabed (Fig. 1), with the choice of anchor type depending on site conditions, platform design, and the required holding capacity (Arias et al., 2016). Multi-line anchors, which can connect multiple mooring lines to a single anchor point, help reduce costs but must withstand forces from various directions (Fontana et al., 2018). Compared to other components, anchors generally have lower long-term ecological impacts, with disturbances mostly occurring during installation and decommissioning. These disturbances vary depending on the anchor type. For instance, pile-driven anchors produce significant noise during installation while suction pile anchors generate less noise by using a vacuum for installation (Arias et al., 2016). Environmental impacts from anchors depend on factors such as installation methods, decommissioning processes, and physical size, with larger turbines requiring correspondingly larger anchors.

2.2. *Interactions with shelf seas and physical oceanography*

Floating offshore wind is being developed for use in highly productive shelf seas, where these structures will interact with marine organisms and ecological processes. Shelf seas cover approximately 9 % of the global ocean area but account for around 16 % of global ocean primary production and support 90 % of the world's fish catches (Simpson and Sharples, 2012). These regions are vital for higher trophic-level species, including marine mammals, whose behaviour and distribution are closely linked to oceanographic features that influence the availability of prey (Cox et al., 2018; Scales et al., 2014). Therefore, despite their relatively limited extent, shelf seas are ecologically significant, supporting high biodiversity and playing a crucial role in both ecosystem health and human livelihoods.

Within temperate shelf seas, shallow coastal areas of mixed water are distinct from the deeper, seasonally stratified waters further offshore (Simpson and Sharples, 2012). Stratification plays a key role in driving primary production, influencing prey availability, and maintaining overall ecosystem function (Lozier et al., 2011; Zhao et al., 2019). Tidal-mixing fronts, which occur between seasonally stratified mid-shelf waters and mixed coastal waters, along with other features like wind-driven upwelling fronts, create ephemeral but predictable and reliable seasonal sources of primary production that support higher trophic levels (Cox et al., 2018). These factors play a crucial role in driving spring phytoplankton blooms within stratified waters, which in turn significantly influence ecosystem functioning across entire shelf sea regions (Simpson and Sharples, 2012; Wyles et al., 2022). As FLOW expands into deeper, highly productive, and seasonally stratified mid-shelf waters, it is essential to understand how these developments will impact local and regional ecosystems and broader environmental processes.

Floating offshore wind farms introduce dynamic structures into the shelf sea marine environment, potentially impacting local hydrodynamic processes with ecosystem-wide consequences that are not yet fully understood. FLOW turbines, which are likely to span the thermocline in seasonally stratified waters, will interact with distinct layers of the water column at varying depths. For example, Hywind Scotland's spar-buoy platforms extend to roughly 80 m depth (Ramasco, 2022), while Kincardine's semi-submersible turbines extend approximately 50 m (Atkins, 2016). Within this region, the summer pycnocline has been found at approximately 20 m (Ramasco, 2022).

As tidal currents pass these structures, turbulence will be generated downstream, leading to artificial mixing and diffusion of the thermocline (Dorrell et al., 2022). This can reduce seasonal stratification, delay its onset, and shorten its duration (Luneva et al., 2019), ultimately altering productivity in the surrounding area (Floeter et al., 2022). The level of impact will depend on location, season and on the platform design, size, and number of turbines in the development, which may contribute to cumulative impacts over time. On a smaller scale, such impacts might be localised, with waters re-stratifying outside the immediate area. However, larger-scale impacts could shift the location, timing, and intensity of tidal fronts and spring blooms (Luneva et al., 2019; Simpson and Sharples, 2012), which could significantly affect ecosystem functioning.

Offshore wind turbines also create wind wake effects, which reduce wind speed and increase both atmospheric and sub-surface turbulence downstream (Wise and Bachynski, 2020). The effects of interaction between tidal and wind wake effects in the sea remain unclear. As FLOW developments expand, the cumulative impact of multiple sites may affect mixing, seasonal stratification and primary production at local and regional scales (Carpenter et al., 2016; Dorrell et al., 2022).

2.3. *Current ecological studies at FLOW*

To date, only a few ecological studies have been conducted at floating offshore wind sites (Table 1). These studies cover various topics, including sound characterisation, biofouling and colonisation of structures, pelagic and benthic fish communities, primary production, fishing trials, and potential reef effects (Table 1). Only two studies have reported marine mammal detections (Risch et al., 2023; Welch et al., 2025), and this represented a small component rather than the main focus of the research.

The sites where these studies have been conducted are relatively small, as large-scale FLOW sites have not yet been established. The studies have been conducted at Hywind Scotland (Equinor, 2025a) and Kincardine (PrinciplePower, 2025) wind farms in Scotland, involving five turbines each, and at Hywind Tampen (Equinor, 2025b) in Norway, containing eleven turbines. Consequently, any observed impacts are likely to be localised and limited in scale due to the modest size of these developments.

As FLOW expands in size, capacity, and deployment in deeper waters, it is essential that research continues to monitor and evaluate their ecological effects. Sections 3 and 4 review the evidence from these studies on the potential positive and negative ecological impacts of FLOW that have been previously highlighted on marine mammals, considering broader ecological processes, and highlight where knowledge gaps still exist.

3. Positive impacts

Previous reviews (Farr et al., 2021; Maxwell et al., 2022) have identified both potential positive and negative impacts of FLOW on marine mammals. These impacts can stem from direct sources, such as the physical substructures or noise emissions, as well as indirect sources, like reduced fishing pressure or changes in prey distribution. This section summarises the key potential positive impacts (Fig. 2), whether current ecological studies at FLOW developments provide evidence for these impacts and highlights the remaining knowledge gaps in each area.

Table 1
Summary of existing ecological studies at operating floating offshore wind farms.

Reference	Site	Species/study area	Data	Main findings
Burns et al. (2022)	Hywind Scotland[1]	Sound characterisation	A four-hydrophone tetrahedral array was moored within the wind farm, and a single omni-directional hydrophone was moored outside the wind farm.	• Turbines generate continuous tonal sounds during operation, primarily below 500 Hz, originating from rotors and generators. • Moorings produce transient noises, caused by strain and friction near the platform. • Noise levels vary between individual turbines, with differences in both loudness and signal characteristics.
Hestetun et al. (2023)	Hywind Scotland[2]	Pelagic and demersal fish, plankton	Environmental DNA was sampled at 10 m and 50 m depths within the windfarm and a nearby reference area.	• Metabarcoding identified 26 species of pelagic and benthic fish. • No significant differences were found between wind farm and reference site sample locations, with no evidence of either positive or negative effects on fish or plankton in relation to distance from the wind farm. • The findings highlight that the site is relatively small, with only five turbines. Results may change over time or if more turbines are added.
Hestetun et al. (2024)	Hywind Tampen[3]	Pelagic and demersal fish, plankton	Environmental DNA was sampled at depths of 20 m and at the seabed, both within the wind farm, upstream and downstream of it, as well as at three reference locations.	• Variations in community structures were observed with depth, reflecting natural patterns. • No clear effect of the wind farm on fish or plankton communities was observed; however, not all turbines had been installed at the time of the study. • Additional CTD measurements revealed no differences in oceanographic conditions between sample stations.
Karlsson et al. (2022)	Hywind Scotland[1]	Biofouling species, fish	High-definition video footage was collected via a work class remotely operated vehicle (ROV) with LED flood- and spotlights.	• All substructure components were colonised, with clear zonation patterns observed. • Coverage and growth increased between 2018 and 2020; however, the thickness varied between years, displaying no consistent overall pattern. • Fish species, including Atlantic cod (*Gadus morhua*), sand eel (*Ammodytes* spp.), ling (*Molva molva*), and whiting (*Merlangius merlangus*), were observed in close proximity to the structures.
Priou et al. (2024)	Hywind Tampen[3]	Pelagic fish, zooplankton	Two Sailbuoy gliders equipped with echosounders conducted transects within the windfarm and downstream of it, and in an upstream reference area.	• There was no evidence of the wind farm affecting biomass or vertical distribution of fish or zooplankton either upstream or downstream of the site. • Scattering features included persistent weak surface zooplankton layers, strong diel-migrating zooplankton and fish layers and distinct fish schools. No relationship was observed between the movement of these layers and windfarm proximity.
Ramasco (2022)	Hywind Scotland[1]	Fish, phytoplankton, zooplankton, reef effect	An echosounder mounted on the autonomous Sailbuoy glider collected data along gradients ranging from 150 m to 35 km from the wind farm.	• Primary production within the wind farm is likely enhanced by the presence of structures, potentially influencing fish aggregation in the area. • Fish densities were not consistently higher within the wind farm. Aggregations were associated with localised increases in zooplankton. • Single fish targets showed reduced densities within the wind farm area.
Ray et al. (2022)	Hywind Scotland[1]	Pelagic fish	Environmental DNA samples were collected within the wind farm and at a reference area at 10 m and 50 m depth.	• Metabarcoding revealed that the most common species were pelagic schooling fish of commercial interest, such as mackerel (*Scomber scombrus*), sprat (*Sprattus sprattus*), and herring (*Clupea harengus*). • Sprat and herring were more abundant within the wind farm area compared to reference sites. However, as samples were taken on a single day, additional sampling across longer time periods and varying times of day and tide would be beneficial. Multiple sampling points would be required to confirm any significant differences between control and wind farm locations.
Risch et al. (2023)	Hywind Scotland[1] and Kincardine[2]	Sound characterisation, harbour porpoise	Three passive acoustic moorings were deployed at each site, positioned at varying distances from the turbines: 200 m, 600 m, and 1500 m at Kincardine, and 300 m, 600 m, and 2400 m at Hywind.	• Moorings create transient impulsive noises which increased at both sites during higher wind speeds. • Noise levels from the Kincardine turbines were approximately 3 dB higher than those from Hywind Scotland at wind speeds of 15 m/s. • Predicted unweighted sound pressure levels for the five-turbine arrays exceeded ambient levels at

(*continued on next page*)

Table 1 (*continued*)

Reference	Site	Species/study area	Data	Main findings
				distances of 2.5–4 km for Kincardine and 3–3.7 km for Hywind Scotland. • Harbour porpoises were present at both sites, but detections were reduced within 1 km of the turbines.
Tenningen et al. (2024)	Hywind Tampen[3]	Fish survey	Fish were captured using gillnets at specific locations, while multibeam sonar transects extended 18 nautical miles southwest (SW) and 10 nautical miles northwest (NW) of the wind farm.	• No significant relationship was found between species richness and distance from the wind farm site. • No fish schools were detected in the acoustic data. • Weak scattering layers were observed in most of the transects in the acoustic data. These layers were absent in the 2022 pre-construction survey, suggesting potential changes in organism distribution since the establishment of the wind farm. Additional sampling would be necessary to statistically confirm any change.
Welch et al. (2025)	Hywind Tampen[3]	Sound characterisation	Two single omnidirectional hydrophones were deployed 4 km from the wind farm, along with two four-hydrophone arrays positioned at 2 km and 10 km from the wind farm.	• Sound emitted from the turbines is below 200 Hz, with tones at 25 and 75 Hz. • Very few transient mooring noises were recorded, far less than those at Hywind Scotland, which is suggested to be due to differences between the substructures and mooring systems. • Sperm whales and killer whales were both detected, sperm whale clicks were detected at the same time as low-level amounts of mooring noises, suggesting little effect on the species.
Wright et al. (2023)	Hywind Scotland[1]	Fish, fishing	Static commercial fishing gear including fish traps, crab & prawn creels and electronic jiggers.	• Fishing at the site can be conducted safely under specific sea and weather conditions, using the tested gear and at designated distances from the structures. • The fishing methods tested were feasible, with no safety issues or gear loss, provided they were used under the specified parameters. The commercial viability of these methods in this location was not assessed. • Few juveniles or small fish were caught, indicating that they were likely not present in large numbers at the site.

[1] Hywind Scotland: 5 turbines; 6 MW spar-buoy turbines; total capacity 30 MW; operational 2017; water depth 95–120 m; Hywind Scotland - the world's first floating wind farm – Equinor.

[2] Kincardine: 5 turbines; 9.5 MW semi-submersible turbines; total capacity 47.5 MW; operational 2021; water depth 60–80 m; Projects: Kincardine Offshore Wind Farm - Principle Power, Inc.

[3] Hywind Tampen: 11 turbines; 8.6 MW spar-buoy turbines; total capacity 88 MW; operational since 2022; water depth 260–300 m; Hywind Tampen – Equinor.

3.1. *Habitat creation and reef effects*

The introduction of physical structures into the marine environment can create new habitats by providing surfaces for colonisation and egg deposition in areas previously lacking suitable substrate. These structures can generate habitats across regional spatial scales and throughout the water column, benefiting a range of species from pelagic to benthic. This habitat creation can ultimately lead to colonisation (Langhamer, 2012), increased foraging opportunities (Mavraki et al., 2021), reef effects (Clausen et al., 2021) shelter (Reubens et al., 2014a), refuge (Orr et al., 2017) and social interactions (Soria et al., 2009).

Floating structures are known to attract various fish species and often function as fish aggregating devices (FADs) (Castro et al., 2002). Theories explaining this attraction include predation avoidance, resource availability, spawning areas, nursery grounds, and resting areas (Castro et al., 2002; Leonhard et al., 2013; Soria et al., 2009). Sheltering benefits for fish (Reubens et al., 2014a) arise from protection against predators or anthropogenic activities, often due to access restrictions or camouflage provided by the structures (Rountree, 1989). However, the complexity and materials of these structures can affect both settlement and species diversity (Komyakova et al., 2022), as more complex structures support more diverse fish communities (Love et al., 2019). Furthermore, nature-inclusive designs can further enhance habitat suitability by incorporating features like additional rock layers or 'fish hotels' (Hermans et al., 2020; Pardo et al., 2023). Artificial structures have also been described as nursery grounds and foraging areas for fish species (Leonhard et al., 2013; Love et al., 2019). However, marine mammals' attraction to these structures can sometimes lead to a decrease in fish presence after their visits (Brehmer et al., 2012).

Colonisation of these structures can create artificial reefs, and subsequent fish attraction can turn areas into feeding hotspots, a process often referred to as "artificial reef effects" (Langhamer, 2012; Reubens et al., 2014b; Wilson et al., 2001). Fish are drawn to these structures to feed on biofouling organisms (Mavraki et al., 2021; Reubens et al., 2014b) or local pelagic species (Mavraki et al., 2021). Evidence also suggests that marine mammals, including cetaceans and pinnipeds, utilise these structures for foraging, likely due to the increased predictability of prey near the structures (Clausen et al., 2021; Fernandez-Betelu et al., 2022; Russell et al., 2014). Such reef effects have been estimated to extend up to 800 m from oil and gas platforms (Clausen et al., 2021). Platform substructures, mooring lines and anchors at FLOW sites could all provide substrate for settlement and artificial reefs.

Therefore, if FLOW substructures create suitable habitats for biofouling communities and fish, this could result in enhanced fish presence in the region. Furthermore, due to the structure's presence, additional anthropogenic activities will be reduced within the sites, such as fishing and commercial vessel activity (expanded in Section 3.3). Therefore, some marine mammals may be attracted to structures, for prey, refuge or shelter from certain anthropogenic disturbances (Scheidat et al., 2011), though responses are likely to vary between species and individuals.

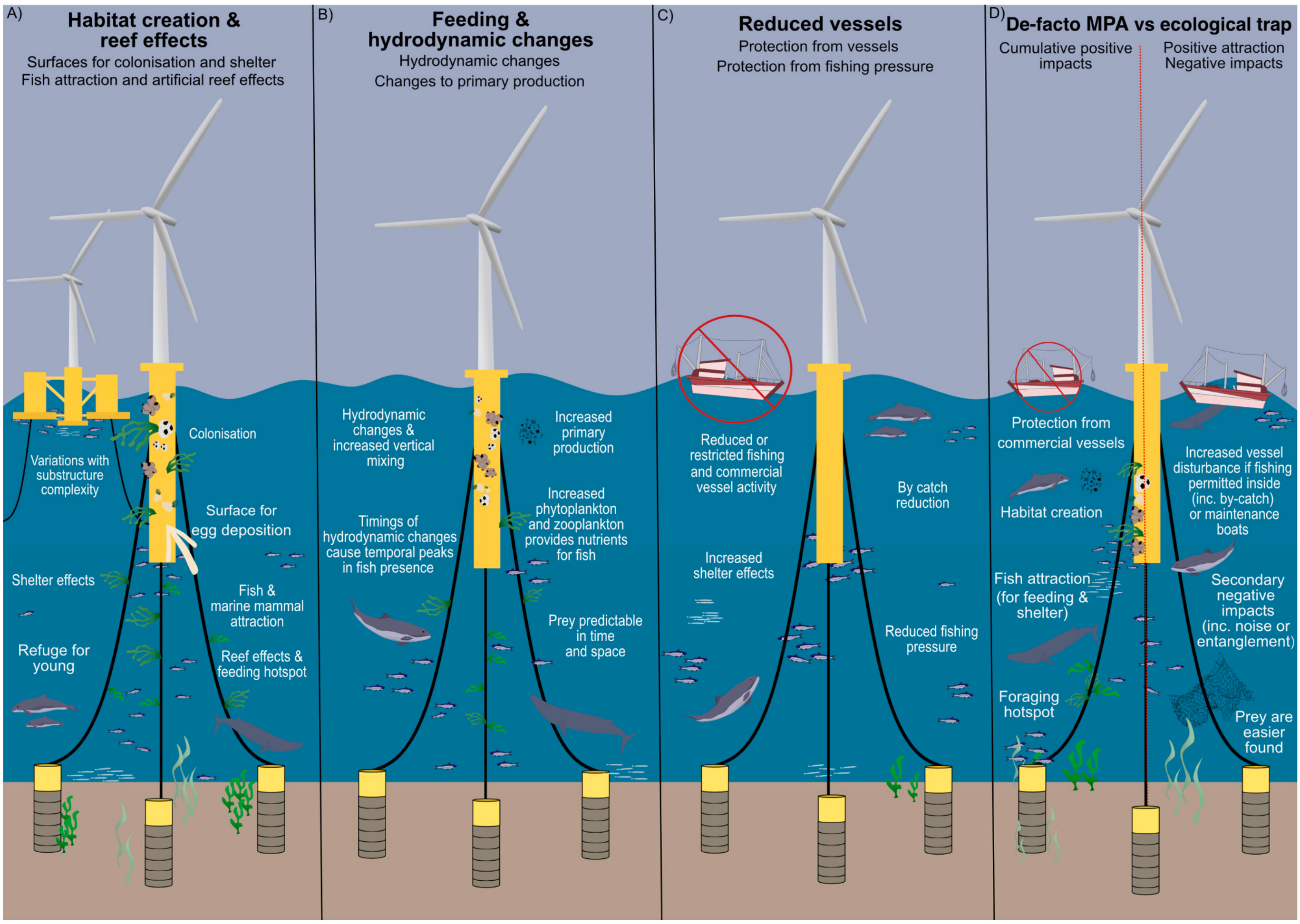

Fig. 2. Potential positive impacts from floating offshore wind turbines on marine mammals, associated prey and trophic interactions including A) habitat creation from substructures and reef effects B) increased feeding opportunities due to hydrodynamic changes C) reduced vessel disturbance and associated impacts D) potential opportunities for de-facto Marine Protected Areas (MPAs) versus risks of ecological traps.

3.2. *Increased foraging opportunities from physical changes to water column*

Increased foraging opportunities at FLOW sites can result from habitat creation by the substructures as discussed, or from changes to physical hydrodynamic processes (Section 2.2) that enhance primary production. Offshore structures crossing the thermocline increase vertical mixing, reducing stratification (Carpenter et al., 2016) and increasing phytoplankton growth (Floeter et al., 2017). Increased phytoplankton and zooplankton production provides nutrients for filter feeders and pelagic fish species (Wang et al., 2019), which in turn could attract marine mammals. The extent of mixing and stratification will depend on local conditions such as water depth, the depth of the mixed layer, the existing level of stratification, and factors like turbine size, number, and the amount of wind energy extracted (Hogan et al., 2023). Foraging opportunities at a given site may vary between marine mammal species and depend on factors like age, health, presence of dependent young, and condition.

Given the observed attraction of fish and predators to existing offshore structures (Clausen et al., 2021; Mavraki et al., 2021), and the widespread use of floating objects as fish aggregating devices (FADs) worldwide (Castro et al., 2002), hydrodynamic changes and enhanced primary productivity at FLOW sites (Carpenter et al., 2016; Floeter et al., 2017), are also likely to increase foraging opportunities and promote any reef effects. However, more data specific to FLOW are needed to confirm this. Additionally, the timings of hydrodynamic changes and associated productivity at FLOW sites may lead to temporal peaks in fish and marine mammal presence, rather than consistent increases. This is particularly likely if such changes are significant, regular and predictable in both space and time, potentially influencing ecosystem-level functioning.

Whether FLOW sites will serve as beneficial feeding resources for marine mammals depends on several factors, including the dynamic nature of the turbines, the ecological and physical footprint of substructures (e.g., space available for colonisation or interaction across thermoclines), and the potential effects of altered oceanographic processes on local and regional primary production and prey predictability.

3.3. *Reduced vessel activity*

Vessel traffic, including commercial and fishing vessels, is often restricted within offshore wind farms (OWFs). Marine mammals are known to avoid areas with high vessel activity (Pigeault et al., 2024), including offshore construction vessels (Culloch et al., 2016). Vessel disturbance can lead to various impacts, such as reduced communication ranges (Putland et al., 2018), acoustic and behavioural responses, increased stress, and mortality/injury through collisions (Erbe et al., 2019). During the operation phase of FLOW, these vessel restrictions can help reduce anthropogenic pressures, including fishing, bycatch, and noise, potentially enabling FLOW sites to act as refuges from these disturbances. However, this potential benefit must be weighed against the increased presence of maintenance and OWF-specific vessels, which may continue to introduce noise and collision risks, potentially altering the overall disturbance landscape.

There is an ongoing debate regarding the viability of co-location of OWFs and certain fisheries, which if implemented, could reduce – to different extents depending on type of fishing and scale of implementation – any potential sheltering benefits from noise, collisions and fishing pressures (Stelzenmüller et al., 2021; Van Hoey et al., 2021). Conflicts between fisheries and offshore renewables have often centred on spatial constraints and increased uncertainties in fish stock assessments (Haggett et al., 2020). However, even if fishing were permitted within wind farms, commercial fisheries using mobile gear such as trawls would likely avoid these areas due to the high risk of gear damage, making safe operation within FLOW sites impractical (Fayram and de Risi, 2007).

If all fishing is restricted, FLOW could provide refuge for fish, potentially leading to stock increases within the protected area. This could result in a "spillover effect" where fish populations expand beyond the boundaries of the sites, offering indirect benefit to fisheries (Gill et al., 2020). Spillover effects may also encourage "fishing the line", where fisheries target the perimeter of FLOW sites to exploit increased stocks (Kellner et al., 2007). While this could benefit fishers (Halouani et al., 2020), a concentration of fishing effort immediately outside FLOW sites may also lead to challenges such as increased bycatch of marine mammals attracted to the same increased biomass of fish (Reeves et al., 2013).

3.4. De-facto marine protected area vs ecological traps

If species benefit from the impacts discussed in this section, FLOW sites could function as "de-facto Marine Protected Areas (MPAs)" (Wilhelmsson and Langhamer, 2014). De-facto MPAs have the potential to reduce overall disturbance in the marine environment by offering refuges from anthropogenic activities like fishing and vessel traffic, as well as associated threats such as bycatch. Understanding this is critical for assessing wider implications, such as shifts in species distributions across multiple developments and changes in predator-prey dynamics. However, co-locating MPAs and OWFs can be challenging, as the increased abundance of species within these sites may not meet the conservation objectives required for official MPA designation (Stephenson, 2023). Additionally, such sites can still pose threats to species and habitats (Stephenson, 2023).

Ecological traps occur when species are drawn to the sites for positive reasons such as feeding, shelter, or breeding, based on cues that would normally enhance their fitness, yet experience negative consequences that decouple these cues from their expected benefits (Swearer et al., 2021). For instance, larger predators may be attracted to substructure components due to the aggregation of fish (Brehmer et al., 2012; Castro et al., 2002). However, this attraction might expose them to heightened risks, such as entanglement or noise pollution (e.g., Clausen et al. (2021)). Such behaviour could become more pronounced under the influence of stressors like climate change, which may change species' abundance and distribution (Gallagher et al., 2022).

Additionally, if FLOW sites benefit predators by enabling easier prey location — due to hydrodynamic changes, altered prey behaviour, or enhanced acoustic signals — FLOW sites might become ecological traps for prey species. While offshore wind farms have not been found to negatively impact the fitness or body condition of Atlantic cod in the North Sea (Reubens et al., 2013), increased fish mortality due to predation has been observed at artificial reefs in the Southern Hemisphere (Komyakova et al., 2021). Therefore, increased predation could also cause ecological traps along with direct stressors from the sites such as noise and electro-magnetic field effects.

Depending on the degree of positive and negative impacts associated with the attraction to FLOW, an ecological trap scenario could potentially have population-level impacts, especially if negative impacts result in serious injury or death. Section 4 looks further at the potential negative impacts that could occur at FLOW sites; the chance of both positive and negative impacts should be considered together.

3.5. Current evidence of positive impacts

Evidence from FLOW (Table 1) was reviewed to determine whether the positive impacts discussed have been observed at operational sites to date.

Since Hywind Scotland became operational in 2017, all components of the substructure have been colonised by macrofauna, macroalgae, and filamentous algae (Karlsson et al., 2022). While the platform substructure hosted fewer taxa compared to the unpainted mooring lines, species exhibited clear zonation across the entire substructure, with growth coverage increasing over the two years of the study (Karlsson et al., 2022). This demonstrates that FLOW provides habitat for colonisation throughout the entire water column, with diversity and extent likely to evolve over time and vary depending on platform and mooring designs. Notably, no invasive species have been recorded on the substructures to date (Karlsson et al., 2022).

A diverse range of pelagic and demersal fish species has also been recorded at Hywind Scotland using visual surveys (Karlsson et al., 2022), eDNA analysis (Hestetun et al., 2023) and fishing techniques (Wright et al., 2023). Species such as Atlantic cod, ling, sand eel, and whiting were observed within 1 m of the structures (Karlsson et al., 2022). Additionally, eDNA surveys identified 26 fish species, with Atlantic mackerel being the most abundant, followed by sprat and herring (Hestetun et al., 2023). These observations confirm the presence of fish (including pelagic species) near FLOW substructures, raising the question of whether these sites exhibit a reef effect. If so, this could attract higher trophic-level predators, such as marine mammals, to these locations. Evidence indicates that some seabird species utilise fixed structures for foraging (Dierschke et al., 2016; Johnston et al., 2022) and detections of seabirds at the floating wind farm Hywind Tampen (Spoor, 2023), further suggest that FLOW may offer foraging opportunities for some species.

The extent to which FLOW enhances primary production appears to play a key role in determining whether fish biomass consistently increases, which may in turn, influence the presence of top predators. Ramasco (2022) found that the floating turbine structures at Hywind Scotland likely enhanced local primary production of phytoplankton and zooplankton, with fish biomass showing a correlation with zooplankton peaks. However, the study did not detect a consistent increase in fish biomass within or around the site. This indicates that while fish presence may be associated with enhanced food resources, the evidence for sustained reef effects at Hywind Scotland remains inconclusive. However, the scale of the study needs to be considered. Ramasco (2022) could not collect data on fish aggregations closer than 100 m from a turbine, and so potential reef effects on a smaller scale could not be ruled out. Furthermore, Priou et al. (2024) found no increase in pelagic fish school biomass or density within or around Hywind Tampen wind farm, nor any significant impact on primary production. It is important to note that, at the time of the study, the Hywind Tampen turbines had been in the water for a maximum of two years, with some still being installed. In contrast, the turbines at Hywind Scotland had been operational for five years during the Ramasco (2022) study. The relatively limited extent of biofouling on the newer Hywind Tampen turbines may have influenced the degree of attraction or aggregation of fish at the site. Therefore, if a reef effect is currently present at these sites it appears to only potentially operate on a small scale (< 100 m), which could increase over time and as sites expand in size.

Marine mammals have also been observed near FLOW structures. While not the primary focus of their study, Risch et al. (2023) acoustically detected echolocating harbour porpoises (*Phocoena phocoena*) at both Hywind Scotland and Kincardine (with monitoring equipment located at distances of 300 m and 2400 m, and of 600 m and 1500 m from the nearest turbine, respectively). These detections confirm the presence of these top predators at these sites; however, detection rates were reduced closer to the turbines (300 m and 600 m, respectively), and feeding behaviour was not investigated at the time.

However, as Ramasco (2022) suggested that reef effects might only operate on a scale of <100 m from the turbine, whether top predators such as harbour porpoises approach this range likely depends on the balance between perceived benefits and perceived threats. For example, the potential benefits to individuals, such as enhanced feeding opportunities, depend on the attractiveness of available prey – shaped by factors like prey abundance and spatiotemporal consistency – which are central to discussions of predator-prey dynamics and optimal foraging theory (Charnov, 1976; Friedlaender et al., 2016; Iorio-Merlo et al., 2022). However, perceived threats could include movement of dynamic turbine components, noise or increased vessel activity during operations and maintenance. Although the information on porpoise presence from Risch et al. (2023) is limited, the findings suggests that porpoises maybe be exhibiting avoidance behaviour rather than an attraction to the turbines at both Kincardine and Hywind Scotland, which would not support the presence of a significant reef effect at these sites at this time.

Hywind Scotland, covering an area of approximately 4 km^2, is situated in a region heavily utilised by fishing and other vessel traffic. However, Ramasco (2022) found no significant difference in fish biomass between the low-traffic area within the Hywind Scotland floating wind farm and the surrounding high-traffic areas. Similarly, Wright et al. (2023) recorded only small catches of juvenile fish at the site, providing no current evidence of fish production at Hywind Scotland. As a result, there is currently no indication of a spillover effect or that fish are using the wind farm as a refuge from fishing or vessel activity. However, sampling design is likely to influence the species composition and size classes detected, and further targeted studies – particularly focusing on key prey species for top predators – are needed to fully assess ecological function. Although commercial and fishing vessels may be restricted within the site, maintenance vessels still operate in the area. The impacts of these maintenance vessels could differ based on factors such as the nature of their work, engine capacity, noise emissions (whether engines are idling or off), and the frequency and number of visits required (Culloch et al., 2016; Oakley et al., 2017). Understanding how these operational differences in vessel traffic influence species behaviour and distribution is essential to evaluating whether FLOW sites can serve as effective ecological refuges.

Whether FLOW could function as de-facto MPAs or become ecological traps depends on various decisions influencing their management and use. For sites to potentially become MPAs, vessel traffic, particularly fishing vessels and activities, would need to be restricted or suspended within wind farm boundaries. However, interest in co-locating fisheries and wind farms is growing. Wright et al. (2023) conducted the first study examining safety of utilising static fishing gear – such as fish traps, crab and prawn creels and electronic jiggers – within designated areas of a floating wind farm (200 m from turbines and dynamic substructure components and 50 m from remaining static components) at Hywind Scotland. They found no safety concerns or damage to equipment under these controlled conditions and at specific sea states. The economic viability of such fishing methods for fisheries using these methods and at these distances from shore was not assessed, yet the success of fishing within FLOW would also depend on the scale of implementation at increasing distance from shore as FLOW expands. Nevertheless, permitting fishing activities within these areas would diminish the potential for FLOW to act as de-facto MPAs. Currently, there is insufficient evidence to determine whether species are attracted to and benefiting from FLOW sites, and so the potential for de-facto MPAs remains inconclusive. Section 4 explores potential negative impacts at these sites which could result in ecological trap scenarios.

3.6. Remaining knowledge gaps

Floating offshore wind farms may positively impact marine mammals through various mechanisms, including enhanced primary production, increased foraging opportunities, and a reduction in additional pressures, such as commercial vessel activity and fishing. Although early studies indicate some promising benefits, including habitat creation and potential foraging opportunities, harbour porpoise presence was reduced closer to the turbines, hence, these findings require further investigation across developments and over longer timescales. Additionally, significant knowledge gaps persist and must be addressed to fully understand these impacts.

The knowledge gaps identified through this review, specific to the potential impact areas, are summarised in Table 2. Organisations such as the Scottish Government, through its Scottish Marine Energy Research (ScotMER) programme (ScotMER, 2025), have comprehensively outlined knowledge gaps across the marine renewable sector for different receptor groups. Relevant ScotMER knowledge gaps are integrated into the key areas highlighted in this review to supply wider context and applicability for studies in these regions (Supplementary Tables S1 and S2).

There are broader research areas beyond those highlighted here that are equally essential for advancing understanding of the impacts of FLOW. These include a deeper knowledge of population trends, dynamics, and demographic rates to better understand the changes taking place; estimates of how many individuals may interact with or be affected by FLOW sites; and data to support the development of population models.

Furthermore, cumulative impacts – whether arising solely from FLOW developments or in combination with other stressors such as climate change and anthropogenic pressures – remain a significant area of uncertainty. However, addressing the outlined research areas should contribute to understanding and mitigating these broader impacts.

4. Negative impacts

In addition to the potential positive impacts of FLOW, there are various potential negative effects that could influence the behaviour and distribution of marine mammals and associated ecosystem dynamics (Farr et al., 2021; Maxwell et al., 2022). These negative impacts can manifest physiologically, through injury or death, or behaviourally, including avoidance, displacement, deeper diving, or changes in distribution. If such impacts are identified, it is essential to employ mitigation measures and to consider development locations in relation to migration routes, as well as critical feeding and breeding areas. This section delves into some of the key potential negative impacts at FLOW sites (Fig. 3), examines existing evidence, and highlights remaining knowledge gaps.

4.1. Noise

Underwater noise is generated during all stages of offshore wind farm lifecycles from construction, operation, maintenance, and decommissioning. Noise input to the marine environment impacts a wide range of species and can cause behavioural responses such as displacement, increased stress or reduced communication area (Fernandez-Betelu et al., 2021; Fernandez-Betelu et al., 2024; Wartzok et al., 2003), as well as physiological including hearing loss, injury or in severe cases, death (Thomsen et al., 2006).

Mitigation measures for noise emissions at fixed offshore wind have concentrated around construction activities (Gartman et al., 2016) as operational noise levels are low frequency (Tougaard et al., 2020), and there is a lack of evidence of mortality or any long term effects to marine species from operational exposure (Svendsen et al., 2022). Fish have displayed behavioural changes due to the sound pressure and particle motion of the construction phase (pile driving) of fixed wind (Svendsen et al., 2022), yet responses may diminish over time (Mueller-Blenkle et al., 2010). Similarly, marine mammals often avoid fixed offshore wind sites during construction (Brandt et al., 2011; Dähne et al., 2013), yet presence can increase again during operational phases (Scheidat et al.,

Table 2
Key knowledge gaps and research areas related to potential positive impacts of floating offshore wind on marine mammals and related trophic links.

Potential impact	Research areas
Habitat creation	**Colonisation of substructures** (1) Do different platform and mooring designs experience varying levels of colonisation? (2) How does colonisation on these structures change or increase over time? (3) Are substructures utilised for egg deposition, and if so, by which species? (4) Does the colonisation of substructures lead to the development of complex ecosystems? (5) If complex ecosystems are formed, are they occurring in areas that previously lacked such ecosystems? (6) What are the impacts of these ecosystems on higher trophic levels? (7) Does the colonisation of substructures occur at a similar rate and with the same species as other offshore structures? **Social and survival impacts** (1) Do substructures function as fish aggregation devices (FADs)? (2) Are fish attracted to or associated with substructures, and if so, at what distances? (3) Do different components of substructures attract or support fish differently? (4) Is there evidence of fish forming shoals around substructures? (5) Are substructures used by fish as shelters, either to avoid natural predators or to mitigate anthropogenic stressors? If so, how can the underlying reasons be determined?
Increasing foraging opportunities	**Increased primary production** (1) What is the spatial extent of wind and tidal wave effects, and how do these hydrodynamic changes affect mixing, primary production and trophic interactions? (2) Is primary production increased within the wind farm area? If so, is this increase consistent over time? (3) Are fish attracted to wind farm sites for foraging, and is this linked to increased primary production or biofouling? (4) Is seasonal stratification affected, and if so, to what extent spatially and temporally? (5) How do any observed changes scale with the increasing size of wind farms? (6) How do variations in foundation type, size, and depth affect water column stratification and mixing? **Artificial reef effects** (1) Is food accumulation occurring as a result of increased primary production or nutrients from colonisation? (2) Are fish attracted to wind farm sites, and is their presence predictable in space and time? (3) Is fish density consistently higher within wind farms, and if so, at what distances from the turbines? Alternatively, does prey availability fluctuate in response to patterns in primary production? (4) Does the scale of the artificial reef effect differ depending on the platform and mooring design? (5) Are top predators attracted to these sites, and are they actively foraging there? (6) Is prey availability increased within wind farms, and do marine mammals experience higher foraging success in these areas?
Reduced vessel activity	**Sheltering benefits** (1) Is there a significant reduction in vessel activity within wind farm boundaries compared to the surrounding region? (2) Can a reduction in vessel strikes be observed, particularly if vessels within wind farms operate at slower speeds? (3) Is a reduction in bycatch evident within wind farm regions? (4) Do fish stocks increase in areas where fishing is restricted within wind farms? (5) Is there evidence of production within the wind farm site, and, if so, are there any spill-over effects on surrounding areas? (6) Does the change in vessel activity within wind farm boundaries lead to lower sonar levels compared to the surrounding area? (7) How does this compare to the overall soundscape when accounting for wind farm operations and vessel traffic outside the wind farm?
De-facto MPA vs ecological trap	**De-facto MPAs** (1) Is there a consistently higher density of fish or marine mammals within the wind farm area? (2) What is the demographic composition of the individuals present? (3) Are the sites being utilised as breeding or nursery grounds? (4) How might these developments impact populations across multiple wind farms? Could population increases be observed? (5) In what ways are the sites being used by marine life? Ecological traps (1) Are fish more heavily predated upon if predators are attracted to the area to feed? How does this impact food webs and ecosystem functioning? (2) What are the cumulative effects of combining other stressors, such as fishing and climate change? (3) Would noise, entanglement, or electromagnetic fields (EMF) have greater impacts if individuals spend more time at sites due to benefits such as foraging or shelter? (4) Is there increased mortality or bycatch when fisheries target the perimeter of wind farms?

2011; Vallejo et al., 2017). Hearing ranges and sensitivities vary widely among marine species (e.g., Engell-Sorensen (2002) for fish hearing sensitivity, and Southall et al. (2019) for marine mammals), leading to differences in how underwater sounds are perceived. Frequencies that are detectable or sensitive for one species may be inaudible or irrelevant to another, making this variation a critical factor to consider when conducting underwater noise assessments.

Noise levels from floating offshore wind farms are likely to differ from those of fixed structures during both construction and operation, meaning the impacts on marine species could vary compared to existing installations. Furthermore, noise levels are likely to change with increasing turbine sizes.

4.2. Electromagnetic fields

Electromagnetic fields (EMF) are generated when electrical currents produced by turbines are transmitted through the cables to shore (Grear et al., 2022). EMFs contain both electric (E-fields) and magnetic (B-fields) components (Hutchison et al., 2018), which affect marine species differently based on their electro- and magneto- sensitivity (Normandeau et al., 2011). Many marine species rely on the Earth's natural geomagnetic field for navigation and prey detection, EMFs emitted from turbines could potentially disrupt these signals (Normandeau et al., 2011; Peters et al., 2007). While there is evidence of electro sensitivity in many elasmobranch and fish species (Normandeau

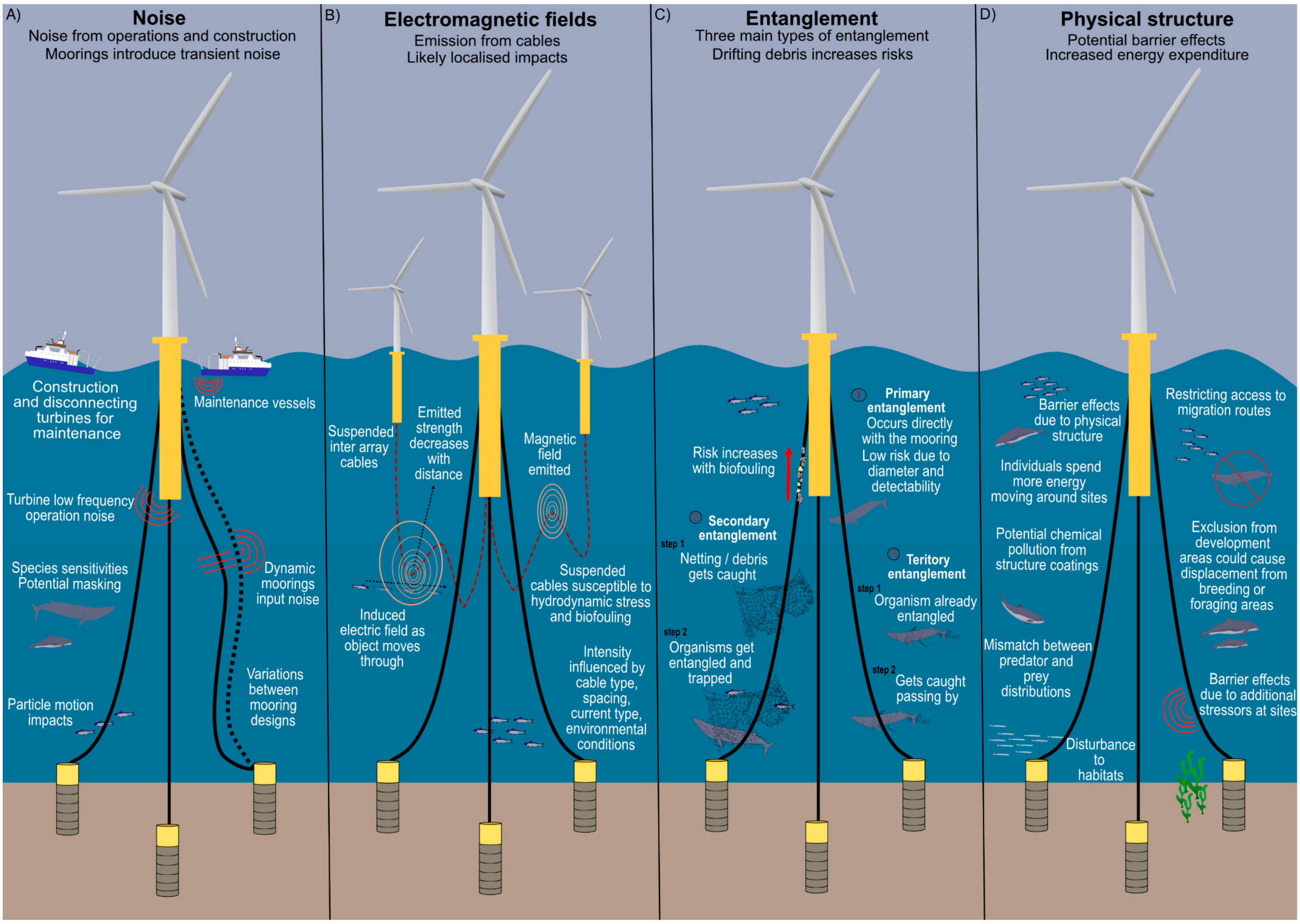

Fig. 3. Potential negative impacts from floating offshore wind turbines on marine mammals, associated prey and trophic interactions including A) noise emissions B) electromagnetic fields C) entanglement and D) physical obstruction from the structures.

et al., 2011), there is limited evidence of this for marine mammals (Czech-Damal et al., 2012; Hüttner et al., 2022). However, marine mammals might have higher magnetic sensitivity (OSC, 2022), and geomagnetic changes have been hypothesised as the cause for several cetacean stranding events (Kirschvink et al., 1986). Therefore, interference may occur if the sensory threshold of certain organisms overlap with the EMF levels emitted by the turbines (Normandeau et al., 2011).

In fixed offshore wind farms, cables are typically buried within the seabed, and because EMF intensity decreases with distance (Hutchison et al., 2018), this minimises exposure for species within the water column. In contrast, FLOW cables are suspended in the water column, increasing potential interactions with marine organisms. Therefore, pelagic species are more readily able to approach cables and may experience prolonged contact with higher EMF intensities, increasing exposure and potential impacts (Farr et al., 2021; Lloret et al., 2022; Maxwell et al., 2022). However, the impact of EMFs on marine mammals is believed to be minimal, as the expected level of influence is low, and individuals are unlikely to stay within the affected areas long enough for significant disruption to their orientation (Normandeau et al., 2011). The intensity of emitted EMFs is influenced by factors such as the type of cable, spacing between cables, the current type (direct current [DC] or alternating current [AC]), and local environmental conditions (Copping and Hemery, 2020; Hutchison et al., 2018). As such, understanding and mitigating these impacts will require careful consideration of cable design, placement, and site-specific characteristics.

4.3. Entanglement

Entanglement in fishing gears, ropes and other marine debris, poses a global threat to both fish and marine mammals, often leading to severe injury or death (Johnson et al., 2005; Northridge et al., 2010; Wells et al., 2008). There are three main types of entanglement to consider at FLOW sites:

- primary entanglement occurs when an organism becomes directly entangled with a structure;
- secondary entanglement refers to a situation where debris such as ghost fishing gear becomes caught on a structure and subsequently catches or traps an organism;
- tertiary entanglement refers to a situation where an organism already entangled in debris then becomes caught on the structure (Farr et al., 2021).

FLOW mooring lines are typically constructed from chain or synthetic rope with diameters of approximately 120–200 mm (Harnois et al., 2015; Zhou et al., 2023b). As a result, the risk of primary entanglement in such structures is generally considered low (Maxwell et al., 2022). However, secondary or tertiary entanglement risks are potentially higher due to the dynamic movement of moorings and suspended inter-array cabled at FLOW sites. Key factors influencing secondary/tertiary entanglement risk include the amount of gear or debris, detectability of moorings and debris, the behaviour of animals in proximity to the turbines, the range of movement of the mooring lines, the total number and length of moorings within a site, mooring design and material, array layout and the level of biofouling on the substructures (Benjamins et al., 2014).

4.4. Physical structure

Turbine substructures might act as physical barriers within the environment, causing organisms to avoid them and potentially excluding them from previously accessible areas. This exclusion could lead to restricted access to migration routes, breeding grounds or feeding areas. Behavioural changes resulting from such barriers are likely to increase energy expenditure as animals navigate around wind farms, with additional time spent searching for prey or alternative habitats (Maxwell et al., 2022). Physical structures also have the potential to disturb key habitats, including benthic communities. However, directed anchoring and reducing chain length can help minimise impacts on the seabed (James and Costa Ros, 2015).

Studies on fixed offshore wind farms (Russell et al., 2014; Scheidat et al., 2011; Vallejo et al., 2017) and oil and gas platforms (Clausen et al., 2021; Todd et al., 2022) have reported marine mammal presence and foraging within these sites at baseline or even elevated levels, suggesting that avoidance or barrier effects may not be significant at such locations, at least for certain individuals of some species. The likelihood of FLOW generating significant barrier effects for marine mammals is presently considered low (OSC, 2022), although evidence to support this will be crucial. Species sensitive to rapidly changing environments may show more pronounced avoidance behaviours, potentially being replaced by more resilient and adaptable species (Williamson et al., 2021). Such shifts could alter the local ecological functioning of a region, highlighting the need for further studies to understand these dynamics.

4.5. Current evidence of negative impacts

Initial studies of FLOW sites in the North Sea (Hywind Scotland, Kincardine and Hywind Tampen) have characterised operational noise outputs. The overall sound frequency range was classified as low frequency (< 200 Hz), comparable to fixed offshore wind farms (Risch et al., 2023). However, floating wind differs due to mooring-related noises which can produce distinct 'snap' sounds occurring individually or in rapid succession, also described as 'rattling' or 'creaking' noises (Burns et al., 2022; Risch et al., 2023). These sounds are present across a broad frequency range (10–48 kHz), and likely originate from strain and friction of the platform moorings in response to variable wave and current action (Burns et al., 2022, Risch et al., 2023).

Risch et al. (2023) observed a higher occurrence of these mooring-related sounds at the Kincardine site, which employs a semi-submersible platform and gear box design, compared to Hywind Scotland, which uses a spar-buoy platform and direct drive design. These variations could be due to differences between platform type, mooring design, power output systems, prevailing wind speeds, seasonal variability, and the turbines' drive system (gearbox vs. direct drive) (Risch et al., 2023). Additionally, variations in acoustic signatures among individual turbines within the same site as reported by Burns et al. (2022) highlight considerable variability within the FLOW soundscape. In contrast, Welch et al. (2025) reported negligible mooring-related transients at Hywind Tampen. This difference is attributed to structural differences from the other sites, including variations in buoyancy and mooring systems. At Hywind Tampen, the substructures are made of hollow concrete and have a honeycomb style connection linking the turbines and to shared anchors, whereas Hywind Scotland and Kincardine use steel substructure platforms with individual anchor systems. These findings suggest that the operational soundscape of floating offshore wind farms may not only differ significantly from that of fixed offshore wind but also vary considerably between different floating substructure and mooring configurations. This highlights the importance of understanding these design differences and their potential impacts on marine megafauna.

Anthropogenic noise exposure levels can be evaluated based on exposure required to elicit behavioural or physiological damage, the latter of which can be described as either recoverable (temporary threshold shift – TTS) or permanent injury or hearing loss (permanent threshold shift – PTS) (Southall et al., 2008; Southall et al., 2019). Burns et al. (2022) and Risch et al. (2023) both found that the daily sound levels emitted during FLOW operations were below the thresholds for either temporary or permanent hearing threshold shifts under non-impulsive categorisation. For example, it was calculated that a harbour porpoise would need to remain within 50 m of a turbine for 24 h, with winds speeds of 15 kn, before reaching TTS levels (Burns et al., 2022), which is consistent with studies modelled in the Mediterranean Sea (Baldachini et al., 2025). However, limited evidence exists regarding how transient mooring related noises may impact marine species, as a more audible and unpredictable sound field is expected. Potential behavioural effects, such as avoidance or reduced vocalisation rates, remain a concern (Baldachini et al., 2025). Although Risch et al. (2023) recorded fewer harbour porpoise detections closer to the turbines at Hywind Scotland and Kincardine, this was not investigated further in relation to operational noise levels, including mooring related sounds. To date, no studies have directly investigated the impact of FLOW turbine noise emissions on either fish or marine mammals.

Data on the intensities of EMFs emitted by FLOW systems is currently lacking, leaving uncertainty regarding any potential ecological impacts. However, if species are attracted to FLOW for foraging or other benefits, their increased residency near these structures may result in prolonged exposure to EMFs compared to transient individuals (Hutchison et al., 2018). Dynamic, suspended inter-array cabling could further elevate EMF exposure, particularly for pelagic and migratory species (Hutchison et al., 2018). However, the strength of EMF reduces with increasing distance from the cable, with B-field emissions back to ambient levels within 20 m of a cable (CMASS, 2003); impacts are therefore expected to be localised rather than impact at population levels (OSC, 2022).

No cases of entanglement at existing offshore structures have been reported in the literature to date, likely due to the irregular and infrequent nature of such events, which makes dedicated studies challenging. However, models have been developed to assess the likelihood of entanglement, survival outcomes, and associated risks. Benjamins et al. (2014) found that the likelihood of an individual breaking free from entanglement involving FLOW moorings – whether primary, secondary or tertiary – is low due to the high strength of the mooring lines. The risk levels may vary depending on the mooring design. Harnois et al. (2015) found that taut moorings pose a lower relative risk of entanglement compared to catenary moorings. Despite mooring choices, risks are likely to increase over time due to biofouling on substructure components, which can elevate the chances of debris snagging. This process, which would increase the risk of secondary and tertiary entanglement, is further facilitated by the proximity of sites to active fishing grounds and the presence of circulating debris or ghost fishing gear (Maxwell et al., 2022). Hence, the potential of entanglement may become a more significant concern if fishing is permitted within FLOW sites. Although static fishing gear was successfully trialled at Hywind Scotland with all gear subsequently removed, Wright et al. (2023) noted that sea conditions contribute significantly to the safety of the activity. For instance, strong winds or tides could cause entanglement between fishing gear (specifically jigging lines or static gears left in the water for periods exceeding 24 h) and substructure components (Wright et al., 2023). Therefore, fishing within FLOW sites continues to pose entanglement risks, potentially compromising both operational safety for developers and gear security for fishers. Due to the practical difficulties of conducting entanglement studies, it is suggested that subsea infrastructure inspections conducted by developers, using remotely operated vehicles (ROVs) or similar platforms, could be leveraged to monitor for signs of entanglement or potential entanglement hazards (Benjamins et al.,

Table 3
Key knowledge gaps and research areas related to potential negative impacts of floating offshore wind on marine mammals and related trophic links.

Potential impact	Research areas
Noise	**Soundscapes** (1) Continuation of soundscape characterisation at FLOW. How do operational soundscapes from FLOW developments vary across sites and between different platform and mooring designs? (2) Are mooring noises predictable based on temporal factors, such as time or tide? (3) How do environmental conditions influence mooring noise? (4) Which components of the mooring system contribute most significantly to the soundscape and potential impacts? (5) Do mooring noise signatures and intensities vary significantly between individual turbines and across different sites? (6) What are the primary causes of differences in operational noise from FLOW developments (e.g., gearbox mechanics, platform design)? (7) How do maintenance vessel operations influence the local soundscape within FLOW sites? **Impacts** (1) How do marine mammals and fish respond to the operational noise of FLOW turbines? (2) Do individuals exhibit avoidance behaviour around turbines under specific conditions, such as varying sea states and noise levels? (3) Is acoustic masking caused by FLOW noise, and if so, which species are affected and under what conditions? (4) Do individuals return to FLOW sites after being displaced during noisy periods, such as construction or maintenance activities? (5) Are fish affected by particle motion caused by different stages of the FLOW lifecycle, including mooring movements? (6) Do marine mammals avoid FLOW sites due to operational noise, and at what distances is this avoidance behaviour observed? (7) How do fish and marine mammal distributions change when FLOW turbines are operational? (8) Is foraging behaviour disrupted during periods of mooring noise? (9) What are the cumulative impacts of future scenarios involving increased FLOW developments and turbine arrays? To what extent could these impacts be observed across multiple arrays?
Electromagnetic field effects	**Emissions** (1) What are the levels of EMF emissions generated by FLOW? (2) What is the intensity of EMF emitted from suspended cables at FLOW? (3) How do environmental conditions (e.g., salinity, temperature, tidal flow) influence the intensity, propagation and distribution of EMFs, and how might any variability impact sensitive species around cables? **Impacts** (1) What are the sensitivity levels of different species to EMF, and how might their responses vary across different life stages? (2) How long would an individual need to be exposed to in-situ EMF emissions for adverse effects to occur? (3) How do individuals and populations respond behaviourally to in-situ EMF? Could these responses impact migration patterns?
Entanglement	**Causes and mechanisms** (1) Do local fisheries operate gear that poses a higher risk of causing entanglement within offshore developments? (2) What is the rate of ghost fishing gear or other debris accumulating within development areas? (3) Is there evidence of fishing gear caught on moorings, and does the risk increase over time due to biofouling? (4) Does the proximity of fishing activity to offshore developments increase the risk of entanglement? (5) What are the potential encounter rates for an individual species across multiple offshore developments? **Injury or fatality risks** (1) How likely is it that an individual can free itself from secondary or tertiary entanglement on FLOW moorings? (2) What is the most severe type of entanglement predicted (e.g., secondary or tertiary)? (3) Could the rate of injuries or fatalities from entanglement lead to population-level consequences? (4) How do different species behave around moorings and cables, and could this behaviour increase the risk of entanglement? (5) What are the detection capabilities of different species for avoiding entanglement?
Physical obstruction	**Barrier effects** (1) Are marine mammals, including migratory species, being displaced or altering their routes to navigate around FLOW areas? (2) Does proximity of approach to substructures within wind farm areas vary with the size of the individual? (3) How many FLOW developments intersect key migration routes, what potential barrier effects could arise from this, and what would population consequences be? (4) How do effects change with increasing turbine sizes, larger arrays, more compact layouts, and developments spanning wider areas? (5) Are local populations from Special areas of Conservation (SACs) or protected species avoiding FLOW sites? (6) How are fish and marine mammals using FLOW sites, and is their behaviour similar to or different from that observed at fixed OWFs? (7) Does the introduction of habitat through artificial structures compensate for habitat loss caused by seabed disturbance, or does the structure increase barrier effects on species movement and habitat connectivity?

2014).

Within operational FLOW sites in the North Sea (Hywind Scotland, Kincardine and Hywind Tampen), both fish and marine mammals have been detected using a variety of monitoring techniques (Karlsson et al., 2022; Ramasco, 2022; Ray et al., 2022; Risch et al., 2023; Wright et al., 2023). Multiple species of fish have been observed near platform foundations (Karlsson et al., 2022), and harbour porpoises have been acoustically detected as close as 300 m from turbines, albeit at significantly lower levels compared to detections farther away (>1.5 km) (Risch et al., 2023). These findings suggest that if barrier effects are present, this might only be for larger species, such as marine mammals, but are likely limited to close proximity (<1 km) to infrastructure.

However, the study by Risch et al. (2023) was conducted over just one month, and porpoises were not the focus of the study, making it difficult to draw definitive conclusions about avoidance behaviour. Longer-term data collection would be necessary to validate these initial observations. Additionally, further behavioural studies are needed to confirm the presence and extent of barrier or reef effects. Acoustic tracking studies, such as those outlined by Gillespie et al. (2022), could provide valuable insights into these dynamics. Such studies could help determine whether observed avoidance behaviours are driven by physical barrier effects or other stressors, such as noise, thereby providing a clearer understanding of the overall impact of FLOW on marine species. Substructure design and the compactness of turbine arrays may also influence the degree of exclusion between sites (OSC, 2022).

4.6. Remaining knowledge gaps

It remains unclear whether FLOW has long-term negative impacts on marine mammals or their prey. While initial studies suggest minimal impacts on prey and a potential localised reduction in porpoise activity within a close range (<1 km), these sites are still relatively new. Long-term studies are needed to determine whether these initial findings change over time. Additionally, this review focuses on the operational phase of FLOW, but it is important to note that construction, maintenance, and decommissioning phases, could have different impacts, which are not covered here.

The remaining knowledge gaps regarding potential negative impacts are summarised (Table 3). Given that many of these research areas – particularly EMF effects and entanglement – currently lack empirical evidence from FLOW sites, substantial uncertainty remains. The knowledge gaps identified here aim to help direct future research efforts to address these limitations. Additional broad-scale research priorities include the need for cumulative impact assessments and understanding whether the impacts of FLOW can be distinguished from those of other stressors, such as climate change. Moreover, broader issues related to FLOW include the construction of ports and harbours to support these developments. These activities may have associated impacts, such as noise pollution, dredging, blasting, and increased vessel traffic, all of which carry their own ecological consequences.

5. Conclusions

There are still very few operational FLOW farms globally, as such there is limited information regarding ecological impacts of sites. However, several studies at FLOW sites have been published in the last few years which can provide insight into ecological impacts and identify remaining major knowledge gaps regarding ecological impacts on key mobile predator and prey species. Results that have emerged so far indicate that structures have been colonised by epibenthic communities, and that structures might impact local increases in primary production, both of which may result in increased biomass levels for certain fish species. However, evidence of consistently increased fish biomass across FLOW sites remains elusive, and obvious reef effects have not been observed in relation to fish communities. If reef effects are present, they may only occur close to (within ~100 m) of the turbines. While the noise characterisation of FLOW sites has proven to be different from fixed offshore wind – due to transient mooring noises and variability between FLOW sites – the impact on species is still relatively unknown, although physiological injuries are currently deemed unlikely.

These initial studies provide critical information regarding the initial impacts of FLOW on the marine environment. However, sites are still relatively young and only contain small numbers of turbines (two sites with 5 and one with 11 turbines), therefore, continued hypothesis-driven monitoring over time and across sites is critical. Many knowledge gaps remain regarding potential ecological impacts, addressing these gaps will aid with wider questions regarding cumulative impacts and climate change concerns. As FLOW is set to expand globally at a rapid rate, this review highlights what is currently known at FLOW in the context of impacts to marine mammals and associated trophic links. Furthermore, key knowledge gaps are summarised that could assist with future research to support the sustainable expansion of floating offshore wind in the coming decade.

CRediT authorship contribution statement

Caitlin B. Harris: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Steven Benjamins:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Beth Scott:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Benjamin J. Williamson:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2025.118059.

Data availability

No data was used for the research described in the article.

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