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Elisabet Forsgren, Markus Majaneva, Evert Johannes Mul, Frode Thomassen Singsaas

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COVER PICTURE
Offshore wind turbines at Barrow Offshore Wind off Walney Island in the Irish Sea. Photo by Andy Dingley (CC-BY-SA 3.0)

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Abstract

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Ambitious goals of reducing greenhouse gas emissions demand for increased renewable energy. In this context, offshore wind is a promising source of renewable energy production which is developing fast. However, this expansion may come at a cost in terms of impact on the environment. To achieve a sustainable offshore wind sector, it is crucial to assess the ecological risks for marine ecosystems and to minimise negative effects. We conducted a literature search, and we here give an introduction to the field and also take a closer look at the evidence of underwater effects on selected marine organisms, namely plankton, fish, marine mammals, as well as the ecosystem. In short, both negative and positive impacts have been documented, but there still remain large knowledge gaps, especially concerning impacts of floating wind farms.

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Ambisiøse mål for å redusere klimagassutslipp krever økt fornybar energi. I denne sammenhengen er havvind ansett som en lovende kilde til fornybar energiproduksjon og en sektor som utvikler seg raskt. Imidlertid kan denne ekspansjonen ha en kostnad når det gjelder virkninger på miljøet. For å oppnå en bærekraftig havvindsektor er det avgjørende å vurdere de økologiske risikoene for det marine økosystemet og å minimere negative effekter. Vi har gjennomført et litteratursøk, og gir her en kort introduksjon til tematikken og ser nærmere på påviste undervannseffekter for utvalgte marine organismer: plankton, fisk, marine pattedyr, samt økosystemet. Oppsummert er det dokumentert både negative og positive effekter, men det er fortsatt store kunnskapshull spesielt når det gjelder effekter av flytende havvindparker.

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Contents

Foreword

This report is part of the Norwegian Research Centre on Wind Energy NorthWind, with funding from the Norwegian Research Council (Grant number 321954). We thank Roel May, the NINA project leader, for giving us the opportunity to do this literature review. We also thank Johanna Järnegren, Carolyn Rosten and Julia Wiel for taking part in the literature search. The aim of the report is to give a brief introduction to the field and to summarise evidence for underwater effects of offshore wind on selected marine organisms. We are also grateful to Roel May for constructive comments on a previous draft of the report.

Trondheim, May 2025, Elisabet Forsgren

1 Introduction

Ambitious goals of reducing greenhouse gas emissions demand for increased renewable energy sources like hydropower, solar and wind. At the same time, increased opposition to the harnessing of rivers for hydropower, and constructing solar power plants and wind farms on land has led to dramatic increase in planning, development and deployment of large-scale offshore wind farms (Williams & Zhao 2024). Still, the vast majority of wind energy globally comes from land-based wind farms, which in 2018 constituted 96%, 568 GW, versus only 23.1 GW offshore (Hamed & Alshare 2022). Most of the offshore wind farms are in shallow depths, standing in less than 60 m of water by means of bottom-fixed foundations: monopile, jacket or tripod. However, the wind industry has in the last decade shifted focus from these fixed-bottom foundation turbines to floating offshore turbines anchored to the sea floor in deeper waters (Farr et al. 2021, Williams & Zhao 2024) (**Figure 1**). Floating turbines allow for energy generation in vast offshore areas where traditional turbines cannot operate.

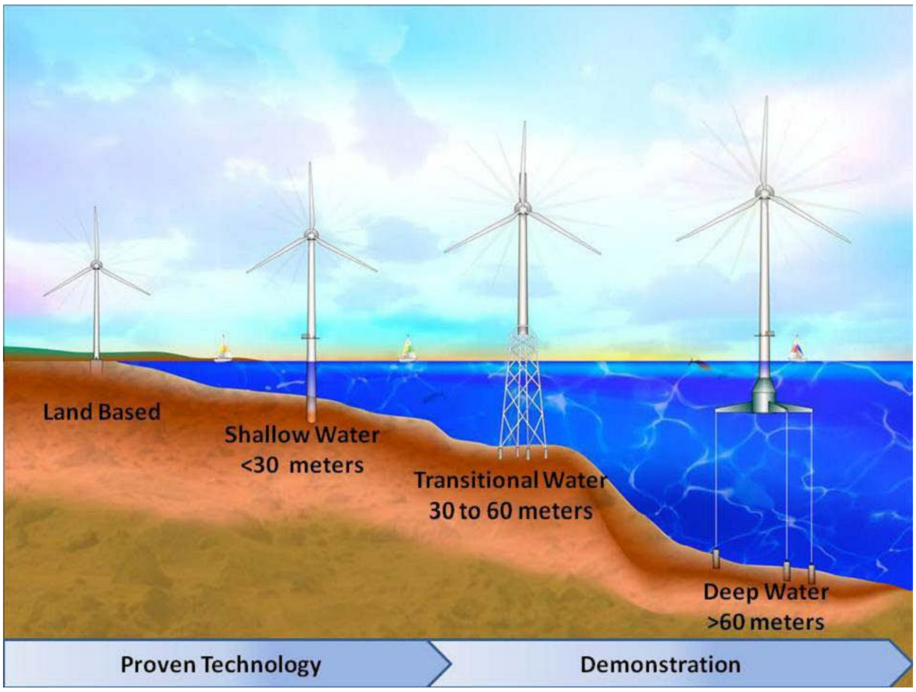

Figure 1. *Progression of expected wind turbine evolution to deeper water (Picture from:* Jplourde umaine *- Own work,* CC BY-SA 4.0*, Wikimedia commons).*

The world's first floating wind turbine was installed in 2007 off the coast of Italy by a now Dutch company, Blue H Technologies, and in 2009 the first full-scale floating pilot turbine *Hywind*, was installed in the North Sea, off Norway (Wikipedia 2024). In 2017 *Hywind Scotland* was the first operating floating wind farm, and from 2022 *Hywind Tampen,* developed by Equinor NW of Bergen in Norway, is the largest floating offshore wind farm producing energy (Equinor 2024, Tollaksen & Rosvold 2024). The Norwegian Water Resources and Energy Directorate (NVE) has identified 20 Norwegian areas for allocation of offshore wind farms to be constructed before 2040 where up to 30 GW of wind energy could be produced (**Figure 2**). Here, floating turbines are considered as a technology that enables deeper areas to be included in future wind power production.

Figure 2. *Identified areas for potential development of offshore wind power in Norway by NVE in 2023 (www.nve.no/energi/energisystem/havvind).*

Even if the goal of reducing CO_2-emmissions by producing renewable offshore wind energy is positive, there are concerns regarding negative impacts on the environment (e.g. Bergström et al. 2014, de Jong et al. 2020, Farr et al. 2021, Rostin et al. 2013). Effects on marine ecosystems can occur during all phases of the wind farm's life cycle, from the construction phase, during operation and to decommissioning (Ouro et al. 2024). Accumulating evidence shows that individual and clusters of wind turbines impact coastal and offshore ecosystems in a number of ways (reviewed in Farr et al. 2021, Galparsoro et al. 2022, Ouro et al. 2024). Obvious negative impacts above water are the (well-studied) disturbance and collision risk with the turbines that birds and bats face. Under water, impacts of concern include sound (noise), which is produced during all phases of a wind farm's life time (Mooney et al. 2020, Stöber & Thomsen 2021), and electromagnetic fields from cables (Hutchison et al. 2020a, Hutchison et al. 2020b). Also, there are hydrological changes in and beyond wind farms (Christiansen et al. 2022). Other underwater effects come from habitat alteration (e.g. seabed degradation and the introduction of new hard substrate). Not all impacts, however, are negative (Inger et al. 2009). Introduction of new hard substrate, for example, promotes fouling, having a positive effect on the occurrence of algae and benthic fauna, and many species are attracted to the facilities, where turbines act as artificial reefs (Degraer et al. 2020). These hard-bottom like habitats can also have a negative impact if being colonised by alien species (Adams et al. 2014). Read more about main types of impact in 3.2. In addition, there are several risks that can potentially occur, such as primary or secondary entanglement of fish, diving seabirds and marine mammals (Farr et al. 2021, Maxwell et al. 2022). Secondary entanglement refers to entanglement in lost fishing gear or debris that is stuck on cables, lines or fundaments. Similarly, increased shipping traffic, related to construction or maintenance of offshore wind turbines, can lead to an increased risk of vessel collisions with marine mammals. Finally, offshore wind parks may form a barrier, preventing organisms from moving between foraging areas, or obstructing migration patterns (Farr et al. 2021, Maxwell et al. 2022).

In a recent review of the scientific knowledge on environmental impacts of offshore wind energy, it was found that about half of the studies were empirical studies, while a bit over a third were modelling approaches (Galparsoro et al. 2022). The majority of studies were conducted in shallow waters of the North Sea close to the coast (Galparsoro et al. 2022). Since offshore floating windfarms are a more recent construction, much less is known about their potential impact as compared to effects of fixed-bottom foundation wind farms (Farr et al. 2021, Maxwell et al. 2022, Mul 2025).

The aim of this literature review was to give a brief introduction to underwater impacts of offshore wind. We conducted a literature search with the objective to find both general papers like reviews and opinion papers, as well as specific studies which could provide evidence (positive or negative) for any underwater effects on marine fauna. We focused on impacts on fish, marine mammals and plankton (both phytoplankton and zooplankton), as well as ecosystem level effects. Furthermore, our main area of interest was the Northern European seas, even if the literature search covered all seas. We also briefly address knowledge gaps and mitigation measures. We hope to here provide a brief and easily accessible summary of the main underwater impacts from offshore wind energy production to inform anyone interested in the area.

2 Methods

We identified relevant search terms, and grouped synonyms and related terms into three different sub-categories:

1) Terms related to offshore wind and constructions
2) Terms related to effects and influences
3) Terms related to the sea, environment, animals and plants

We searched for each term separately. Then the terms within the same category were combined with the boolean operator OR, and eventually the three categories were combined with the boolean operator AND. We ran a few test searches, some of them yielded a large amount of papers. In attempt to limit the numbers, we added qualifying terms to some of the search terms – for example the boolean proximity operator NEAR/* (**Table 1**).

The searches were performed on August 23rd 2022, in Scopus and Web of Science (WoS) Core Collection, the latter including the following four databases:

- Science Citation Index Expanded (1987 – present)
- Social Sciences Citation Index (1987 – present)
- Arts & Humanities Citation Index (1987 – present)
- Emerging Sources Citation Index (2018 – present)

The searches yielded 969 papers in WoS and 2419 papers in Scopus (**Table 1**). All references were imported into EndNote. 389 duplicates were removed automatically, and then 253 more were removed manually. The 2746 remaining papers were imported into the online screening tool Rayyan (https://www.rayyan.ai/).

A broad search like this will always pick up a substantial amount of irrelevant papers in addition to the relevant ones. Therefore, one person conducted a quick screening of all the papers based on title and abstracts, excluding papers which were clearly not relevant. After this first selection phase, 606 papers remained in the library. These papers were divided among four persons who then marked the papers with either *include*, *exclude* or *maybe*. Papers in the include and maybe categories were also tagged with keywords. These papers were then divided among authors and checked more closely for relevant papers. We also excluded all papers on birds and bats given the focus of our literature study on underwater effects. After this, 303 papers remained included. A few of these were not accessible due to lack of access to the paper or because it was written in a foreign language (not English).

Due to time constraints, we were not able to follow up all papers and therefore decided to limit the report to fish, marine mammals, plankton, alien species and ecosystem effects, in addition to general papers relevant for summarising the area. Also, we mainly focus on northern Europe and Scandinavia.

The 25th of November 2024 we did an additional search in Scopus and Web of Science. The same searches as above were conducted, but without the search terms *plant*, seabird* OR "sea bird*", bentho*, seagrass* OR "sea grass*", seaweed* OR "sea wead*"* and *kelp.* The updated searches yielded 351 new papers after duplicate removal. Forty of these were review papers. The new references were quickly scanned mainly to look for highly relevant and recent reviews, and the results from this search was not further scrutinised. At the same time, we also did a search for Norwegian reports ("grey literature") which we will briefly go through in the results section. For the grey literature search we used the Norwegian academic search tool ORIA, to collect reports from relevant Norwegian research institutions.

Table 1. *Results from the literature search done in 2022.*

Terms related to offshore wind and constructions	**WoS**	**Scopus**	**Terms related to effects and influences**	**WoS**	**Scopus**	**Terms related to the sea, environment, animals and plants**	**WoS**	**Scopus**
float* NEAR/3 wind* / float* W/3 wind* (scopus)	1427	3672	pollution* AND (ocean OR sea OR river OR water OR Offshore)	118107	373291	Plant*	1590737	3026982
float* NEAR/3 (offshore OR "off shore") / float* W/3 (offshore OR "off shore") (Scopus)	1298	4595	nois* AND (ocean OR sea OR river OR water OR Offshore)	28463	53876	animal*	1231942	8016958
float* AND (seawind* OR "sea wind*" OR "offshore wind" OR "off shore wind")	1070	2808	light* AND (pollut* OR disturb*)	53198	89238	seabird* OR "sea bird*"	11438	16294
discrete-pontoon	3	4	vibrat* AND (ocean OR sea OR river OR water OR Offshore)	38721	53902	invertebrat*	74006	135462
continuous-pontoon	2	4	barrier* AND (ocean OR sea OR river OR water OR Offshore)	77151	91994	whale*	21347	25335
pontoon-separated	2	3	current* AND (ocean OR sea OR river OR water OR Offshore)	307480	468853	fish*	573932	803855
subsea NEAR/3 wind* / subsea W/3 wind* (Scopus	9	48	collision* AND (ocean OR sea OR river OR water OR Offshore)	21229	26438	seal*	97351	204110
underwater NEAR/3 wind* / underwater W/3 wind* (Scopus	103	232	entangle* AND (ocean OR sea OR river OR water OR Offshore)	3501	4104	mammal*	440545	628194
submerged NEAR/3 wind* / submerged W/3 wind* (Scopus	41	83	alien AND (ocean OR sea OR river OR water OR Offshore)	5385	6151	Bentho*	9066	26832
Suspend* NEAR/3 wind* / suspend* W/3 wind* (Scopus	201	422	non-indig* AND (ocean OR sea OR river OR water OR Offshore)	2051	2288	ecosystem*	355099	571920
Float* NEAR/3 structure* / float* W/3 structure* (Scopus	2274	7826	invasive AND (ocean OR sea OR river OR water OR Offshore)	25221	31097	alga*	174526	251706
wind turbine* AND (sea* OR offshore OR "off shore" OR water)	8567	19664	biofoul* AND (ocean OR sea OR river OR water OR Offshore)	4201	8292	reef*	54874	60518
"wind power" AND (sea* OR offshore OR "off shore" OR water)	4213	18387	reef* AND (ocean OR sea OR river OR water OR Offshore)	31056	35079	seagrass* OR "sea grass*"	12965	14516
"wind farm" AND (sea* OR offshore OR "off shore" OR water)	2790	10048				seaweed* OR "sea wead*"	19444	24481
(cable* OR cord* OR Rope*) AND (bottom OR seabed OR "sea bed" OR seafloor OR "sea floor" OR "ocean floor")	2582	7170				kelp	6116	5999
"marine wind*"	155	247				crustac*	52351	92930
						biofilm	85838	105098
						Pelagi*	31227	36963
All above, combined with OR	**17773**	**49454**	**All above, combined with OR**	**650246**	**1127727**	**All above, combined with OR**	**4227572**	**12286170**
						All three columns, combined with AND	**969**	**2594**

3 Results

3.1 General findings

For the 303 included articles from the literature search performed in 2022, sound was the most commonly tagged theme, while fish and mammals were the most commonly tagged organisms (**Table 2**). It should be noted that the tag ‘review’ was used quite broadly and not in a very strict sense.

Table 2. *The number of times themes were tagged for the included articles from the 2022 literature search. As a given article could be tagged with several themes, the total number exceeds the number of screened articles.*

Soundscape	109
Fish	95
Mammals	84
Benthos	67
Ecosystem	51
Review	48
Context	29
Other infrastructure	27
Physical environment	23
Engineering	16
Crustacea	14
Cables	13
Multi-use	11
Mitigation	10
Magnetic	9
Algae	7
Other animals	6
Alien species	6

We additionally identified 14 relevant publications in our grey literature search in 2023. These were Norwegian reports and one PhD thesis. We found seven reports on offshore wind energy, of which three focused on seabirds (Christensen-Dalsgaard et al. 2012, Layton-Matthews et al. 2023, Nilsson et al. 2023). A review of potential effects from offshore wind energy on the marine ecosystem was found in de Jong et al. (2020), while Utne-Palm et al. (2023a) focuses on offshore wind energy and fisheries. Gudmestad et al. (2021) describes both societal perspectives and environmental consequences, and a recent PhD thesis by Nytte (2024) discusses social acceptance of new floating offshore wind power development in Norway.

In addition, we found seven reports on anthropogenic noise effects in the sea, not specifically related to offshore wind (Forland et al. 2023, Kvadsheim et al. 2020, Sivle et al. 2021, Sivle et al. 2020, Sivle et al. 2022, Sivle et al. 2023, Sivle et al. 2019).

3.2 Main types of impact

Ecological effects from offshore wind farms can occur during all phases during their lifetime. Below is a brief summary of the main proposed underwater impacts from offshore wind farms.

3.2.1 Hydrology

The focal northern seas of this review (North Sea, Norwegian Sea, Baltic Sea) differ in hydrology, mainly due to differences in their bathymetry and freshwater input. The Baltic Sea and North Sea are located on a continental shelf and are much shallower than Norwegian Sea that lies mostly on a continental slope, continental rise and abyssal plain. The North Sea fosters a complex frontal system separating mixed coastal waters from seasonally stratified deeper regions. Coastal fronts exist in the Norwegian Sea, but the deeper areas are seasonally stratified and influenced by major oceanic currents (North Atlantic and Norwegian Current). The Baltic Sea does not have any tides of significance, has very strong freshwater influence, and wind-induced upwelling events parallel to coast. These regional characteristics affect hydrology and also how hydrology is affected by wind farms.

Energy generation using wind turbines withdraws kinetic energy from the atmosphere, which reduces horizontal momentum on the leeward side of the turbines. This causes reduction in the mean wind speed and creates turbulence downwind of the turbines (atmospheric wakes). The wakes behind each turbine merge into a single larger wake when wind turbines are placed in clusters (Akhtar et al. 2021, Christiansen et al. 2022). Atmospheric wakes and reduced wind speed in turn decrease the shear-driven forcing at the sea-surface boundary, and horizontal velocities and turbulent mixing decrease on tens of kilometres around the wind turbine clusters (Christiansen et al. 2022). This does not impact the ocean's overall thermodynamic properties severely, but spatial variability in mean currents increases and large-scale changes in the stratification development and strength may take place.

One of the key hydrological changes due to atmospheric wake and reduced wind speed is formation of upwelling and downwelling dipoles that lead to several meters' deviations of the thermocline depth that may span over several kilometres (Broström 2008, Floeter et al. 2022). Another key change is the enhancement of the stratification strength that has been shown to be particularly influential towards autumn when summer stratification is naturally eroding (Christiansen et al. 2022). Stratification strength and upwelling/downwelling dipoles in turn impact exchange of temperature, salt, and nutrients between upper and lower water masses, which impact pelagic organisms.

However, the effect on hydrology depends on the location of the offshore wind farms. The changes in stratification are relevant only if the wind farm is in an area with seasonally stratified water masses. In such locations, modelling shows that the depth of the seasonal mixed layer is 1–2 m shallower with presence of a wind farm than without a wind farm (Daewel et al. 2022). Carpenter et al. (2016) predicts reduced stratification if large-scale fixed-bottom foundation wind farms are placed in seasonally stratified waters. In frontal areas these processes are obscured by other, naturally occurring processes. Reduction in horizontal flow velocities is relevant in all areas, but its impact has been shown to be larger in deeper locations in the North Sea where reduced bottom-shear stress up to 10 % decreases resuspension of organic matter, and thus, increases accumulation of organic carbon in the sediments (Daewel et al. 2022). This in turn may decrease oxygen concentration in the bottom water (Daewel et al. 2022).

Floating wind farms will have a different impact on hydrology than fixed-bottom foundation wind farms since the piles of fixed-bottom foundation turbines penetrate thermocline and increase artificial mixing of the water masses (Carpenter et al. 2016, Dorrell et al. 2022, Lass et al. 2008). This mixing is generated when tidal currents move past the foundation structures and generate turbulence (Carpenter et al. 2016). Depending on the dimensions of the floating structures, they may or may not penetrate the seasonal thermocline. If they do not penetrate thermocline, stratification may not be disrupted, and wind wakes may stabilize stratification at floating windfarms (Daewel et al. 2022). However, if the structures cross thermocline, windfarms increase artificial mixing in seasonally stratified areas (Dorrell et al. 2022). This anthropogenic mixing will impact biogeochemical cycling and pelagic communities (see 3.3.1 Plankton).

3.2.2 Habitat loss/degradation

Offshore wind farms can lead to loss of seabed habitats, usually soft sediment, and they introduce infrastructure and anthropogenic influence over a large area, degrading marine habitat. This may in turn affect marine organisms like bottom-dwelling fish (Barbut et al. 2020). Wind farms can hence also be in conflict with other interests, like fisheries (Gill et al. 2020, Utne-Palm et al. 2023a).The concerns stem from possible negative impact on the fishery resource as well as conflicts over area use (also see 3.3.2 Fish).

3.2.3 Cables and magnetic fields

Submarine power cables have been used for a long time, but environmental concerns are more recent (Taormina et al. 2018). The impact of such cables may be manyfold, including habitat damage or loss, chemical pollution and electromagnetic fields (Taormina et al. 2018). It has been suggested that overall, ecological impacts associated with submarine power cables can be considered weak to moderate, though uncertainties remain, particularly concerning electromagnetic effects (Taormina et al. 2018). High-voltage subsea DC cables are needed to transport electricity from offshore wind farms. Animals may detect magnetic fields around DC cables (Normandeau et al. 2011), but as the magnetic fields are localized, pelagic actively moving organisms may not be impacted, other than avoiding these electromagnetic fields. However, there is concern because many marine animals have evolved sensory abilities to use electric and magnetic cues to orient or migrate, as well as detecting prey, predators, and mates (Hutchison et al. 2020b). Also, benthic organisms are at high risk of exposure (Hutchison et al. 2020b).

3.2.4 Activity

Other disturbance than noise may also be significant (Galparsoro et al. 2022). During the construction phase construction activities, cable trenching and vessel traffic are present. Some vessel traffic would also be present during the operation phase, causing disturbance. Fisheries activities, on the other hand, will in many cases be prohibited, with the result that wind farms, in that sense, could function as protected refuge areas (Buyse et al. 2022, Gill et al. 2020).

3.2.5 Acoustic effects/noise

All anthropogenic activities at sea produce sound, which can have a range of effects on nearby wildlife. While airborne sound is known to influence the behaviour of some species, such as seabirds and seals (Acevedo-Gutiérrez & Cendejas-Zarelli 2011), the impacts of underwater sound are far more influential. Underwater sound travels much faster, and over much greater distances, compared to air, due to the high density of water (Atema et al. 1988). Since water is such a good conductor for sound, many species have evolved a dependency on sound for a variety of behaviour types, including communication, orientation, prey detection, etc. (Kuşku et al. 2018). The increasing amount of background noise from anthropogenic activities is therefore affecting a wide variety of species, including fish, marine mammals, and plankton (Dolman et al. 2015, Culloch et al. 2016, McCauley et al. 2017, Popper & Hawkins 2019). Marine organisms are affected by sound in several ways, and consequences of exposure to sound range from relatively minor behavioural changes to physical injury or death. For example, abrupt and intense noise may cause damage to either the hearing, or the swim bladders of fish, causing physical injury or death (Hawkins & Popper 2017). Such sound sources can also cause hearing damage in marine mammals, which can obstruct their foraging abilities and may ultimately lead to death (Thompson et al. 2020). Toothed whales (such as dolphins, sperm whales and porpoises) are particularly vulnerable to this type of injury, as they rely on their hearing to locate their prey (echolocation). Other consequences of increased sound levels include stress-related reduction of the oxygen consumption rate in fish (Debusschere et al. 2016), and changes in surfacing behaviour in porpoises and seals (Koschinski et al. 2003). Physical and behavioural responses have also been documented in other species groups, such as zooplankton (Tremblay et al.

2024), crustaceans, such as lobsters (Edmonds et al. 2016) and cephalopods, such as squids (André et al. 2011). In some cases, behavioural responses to sound can influence important ecological processes. For example, the particle transporting behaviour of benthic invertebrates, which is crucial for ecological nutrient cycling, can be influenced by broadband sound, as produced by construction activities (Solan et al. 2016).

Consequences of anthropogenic sounds depend on the characteristics of sound, such as the frequency, the intensity, the duration and the continuity. While the risk of physical damage is highest in close proximity to the sound source, behavioural changes in response to sounds can occur at distances of up to 50 km (Bailey et al. 2010).

Offshore wind facilities contribute to anthropogenic sounds in several ways. The construction phase often involves pile-driving activities which produces high-intensity, low-frequency impulse sounds (Stöber & Thomsen 2019), while rotating turbines produce relatively low-intensity continuous sounds (Stöber & Thomsen 2021). Indirect contributions to elevated sound levels may include seismic surveys during the site selection phase, or vessel noise related to maintenance and decommission phases (Mooney et al. 2020, Yoon et al. 2023). Factors that can help reduce the contribution to anthropogenic sound by offshore wind farms include the use of bubble-net curtains to reduce the impact of pile-driving sounds, and the use of acoustic deterrent devices to scare away certain species, prior to a pile-driving event. Technological developments influencing the size of the turbines, or the level of sound transmission through the foundations of the turbines are also likely to reduce the level of sound from offshore wind farms (Tougaard et al. 2020).

3.2.6 Artificial reef effect

Marine energy infrastructures provide new hard substrate for colonisation and can increase heterogeneity in the area. Offshore wind turbines introduce hard substrate to the water column and to the soft bottom, and they are normally surrounded by scour protection, which often consists of gravel and rock/boulder, to prevent erosion of sediment around turbine foundations (Glarou et al. 2020, Langhamer 2012). Wind turbines and their scour protection therefore resemble marine rocky reefs, providing substrate for colonising algae and invertebrates, which further adds to the complexity and provides food for fish, birds and marine mammals. As an effect, wind farms act as artificial reefs and attract a wide variety of organisms (Degraer et al. 2020, Glarou et al. 2020, Langhamer 2012). Whether this has only local effects or an effect on the larger scale, however, is uncertain.

3.2.7 Alien species

Because wind turbines introduce hard substrate and function as artificial reefs (see 3.2.6), they provide habitat not only for native species but also for alien (non-indigenous) species. This could facilitate the spreading and settlement of alien species into new areas (Firth et al. 2016). Hence, marine renewable energy installations can act as “stepping-stones” for alien species (Adams et al. 2014).

In our literature search we did not find many studies concerning alien species in connection to wind farms. In a study of the macrobenthic fouling community on wind turbines in the Belgian part of the North Sea, in total ten alien species were found (De Mesel et al. 2015). Most of these (8 species) were in the intertidal zone; three species of barnacles, an amphipod, midge, crab, oyster and limpet. In the deep sub-tidal zone only two alien species were found, a limpet and a tunicate. Their conclusion was that alien species used the foundations to expand their range and strengthen their position in the area. Another study of artificial hard substrates in the southern North Sea investigated occurrence of native and non-native *Caprella* shrimps, showing little habitat overlap between species (Coolen et al. 2016). Only at wind farm foundations in near-shore locations with an intertidal zone, the introduced and invasive Japanese skeleton shrimp *Caprella mutica* was found to co-exist with the native *Caprella linearis* shrimp. In the southwestern parts of UK, epibenthic assemblages on cables and associated rock armouring of marine renewable energy installations was investigated in a 5-year study (Sheehan et al. 2020). Only three records of two non-native species (sea squirts) were found.

3.3 How are different organisms affected?

Below we summarise the main findings from the literature review with a special focus on northern Europe and Scandinavia.

3.3.1 Plankton

Stratification and availability of nutrients are key drivers of phytoplankton production in marine waters, and thus, changes in hydrology (see chapter 3.2.1) affect phytoplankton directly. Artificial mixing may increase nutrient availability through resuspension of organic and inorganic substances in shallow areas (Wang et al. 2019). In deeper areas, deterioration of stratification may trigger phytoplankton growth (Carpenter et al. 2016, Floeter et al. 2017). Further, the turbulent wakes and surface gravity waves underneath and leeward side of the turbines may impact aggregations of plankton. However, nutrient cycling and primary production were negatively affected in the wind farm construction phase due to increased suspended particulate matter in the water according to a North Sea modelling study (Burkhard et al. 2011). This effect may not be relevant for floating wind farms as they will be in deeper waters and the foundation structures are much lighter than in fixed-bottom foundation wind farms. Further, modelling suggests that the negative impact on primary production and nutrient cycling is not as significant in the operational phase as it is in the construction phase (Burkhard et al. 2011).

A more recent North Sea modelling exercise (Daewel et al. 2022) supported the observations of Floeter et al. (2017) and showed that large-scale offshore wind farms provoke changes in annual primary production, but this change of up to ± 10 % is local and primary production remains unchanged regionally. This modelling suggests that greatest increase in primary production will occur in shallow near-coastal areas while decreasing primary production coincides with productive frontal zones. Also, the deeper seasonally stratified areas showed an increase in production and an upward shift of the depth of production maximum in presence of offshore wind farms (Daewel et al. 2022). These changes in primary production translate into changes in phytoplankton biomass, and further to zooplankton biomass. However, the model of Daewel et al. (2022) does not consider trophic levels over zooplankton, and therefore, there is uncertainty in confidence of the model beyond phytoplankton.

While changes in stratification affect phytoplankton through nutrient and light availability, zooplankton may be affected by changes in temperature and food availability. Increased mixing in seasonally stratified areas may decrease surface water temperature and, in principle, lead to trophic mismatches (Edwards & Richardson 2004). Wang et al. (2018) observed a shift from larger to smaller zooplankton species after establishment of a windfarm. Their analysis indicated that the area was experiencing eutrophication after construction. However, the study area was near-coast wind farm founded at very shallow depth, and therefore, it is difficult to generalize their findings to hold for offshore floating wind farms located in deeper waters since the hydrological conditions differ extensively. Floeter et al. (2017) in turn observed an increase of echinoderm larvae in waters around an offshore wind farm, but this increase might also be due to natural accumulation of the larvae in a frontal zone in the North Sea.

Additional complexity of the effects arises from filter-feeding epifauna attached to the wind farm structures. Slavik et al. (2019) estimated that up to 8 % decrease in primary production can be attributed to *Mytilus edulis* settlements in the southern North Sea wind farms. This in turn can negatively affect zooplankton via increased competition of food sources, as well as increase predation of zooplankton. The wind turbines have also the potential to increase the abundance of medusae, whose polyps rely on hard surfaces – such an effect has been modelled based on field observations of polyp settlement plates in the offshore Baltic Sea (Janssen et al. 2013).

Overall, the effects of wind farms on plankton have been poorly studied, and only a handful studies exist that concentrate on the northern European seas (**Table 3**).

Table 3. *Offshore windfarm effects on phytoplankton and zooplankton in Northern Europe.*

Type of impact	Effect	Group of organisms	Location	Area	Type of study	Type of structure	Reference
Hydrology	Increased production	Phytoplankton	North Sea	Offshore, shallow	Field observations when turbines not operating	Tripod and tripile foundations	(Floeter et al. 2017)
Hydrology	Increased/decreased production	Phytoplankton	North Sea	Coastal & offshore, shallow	Modelling	Fixed foundation	(Daewel et al. 2022)
Reef effect	Decreased production	Phytoplankton	North Sea	Coastal & offshore, shallow	Modelling	Fixed foundation	(Slavik et al. 2019)
Hydrology	Decreased production	Phytoplankton	North Sea	Offshore, shallow	Modelling	Fixed foundation	(Burkhard et al. 2011)
Reef effect/Hydrology	Increased abundance	Larvae of Echinodermata	North Sea	Offshore, shallow	Field observations when turbines not operating	Tripod and tripile foundations	(Floeter et al. 2017)
Reef effect	Increased abundance	Medusae	Baltic Sea	Offshore, shallow	Field observations, modelling	Theoretical fixed foundations	(Janssen et al. 2013)

3.3.2 Fish

How fish could be affected by marine wind farms is a question that has attracted considerable attention (e.g. Gill et al. 2020, Glarou et al. 2020, Langhamer 2012, Methratta 2020, Staudinger et al. 2020). There are many studies that have investigated such effects in northern Europe (**Table 4**).

Artificial reef effect

A major impact of offshore wind farms on fish is the artificial reef effect (see 3.2.6). The turbines and the scour protection can function as artificial rocky reefs providing shelter, nursery habitat, or habitat for reproduction and feeding opportunities for fish (Glarou et al. 2020, Langhamer 2012). Also, introduced infrastructure can act as a fish aggregation device (FAD) (e.g. Inger et al. 2009). Many studies have shown evidence of a positive reef effect on fish (**Table 4**). This is corroborated in a meta-analysis of studies from northern Europe showing that finfish were more abundant inside wind farms compared to reference sites (Methratta & Dardick 2019). Likewise, another review found a change in species assemblages at artificial structures in comparison to naturally occurring habitats, with an increase in hard substrata associated species and reef associated fish (Ashley et al. 2014). Several fish feeding ecology studies have shown that wind farms are suitable foraging grounds providing good feeding opportunities (De Troch et al. 2013, Mavraki et al. 2021, Reubens et al. 2014b). The attraction of high abundances of fish to good feeding grounds may lead to increased local production inside wind farms. There is an ongoing production versus attraction debate, i.e., whether there is enhanced fish production inside wind farms, and not only attraction (Brickhill et al. 2005, Pickering & Whitmarsh 1997, Reubens et al. 2014b, Reubens et al. 2013c).

Refuge

In many wind farms fisheries activities are not allowed, and the area is therefore like a sanctuary for fish and other trawled organisms. This can lead to fish seeking refuge in the wind farm area, with positive effects on commercial fish species (Buyse et al. 2022, Lindeboom et al. 2011, Stenberg et al. 2015). However, exclusive area use by wind farms can cause conflicts with other maritime uses, such as fisheries, and local stakeholders may therefore be interested in multi-use of wind farms where fisheries are allowed (Schupp et al. 2021). Since fish aggregations are particularly vulnerable to fishing pressure, this could lead to local overfishing, and hence to the recommendation that fisheries activities should be avoided (Reubens et al. 2014b)

Area use

Area use by wind farms lead to degradation and loss of soft-bottom habitat and may lead to negative impact on fish populations. Several flatfish species are likely to be negatively affected because existing and planned wind farms overlap spatially with flatfish spawning grounds (Barbut et al. 2020).

Hydrodynamics

Local or regional hydrodynamic *effects* of offshore wind farms on fish are possible through changes in wind fields or oceanographic parameters (reviewed in van Berkel et al. 2020). However, it is not so easy to disentangle hydrodynamic effects from natural variability or other effects, and more studies are needed (van Berkel et al. 2020). Individual-based models of animal behaviour can be especially useful in this context to give insights into animal movements in water (Willis 2011).

Noise

Noise during the construction, operation and decommission phase of wind farms are stressors which can have negative impacts on fish (Popper & Hawkins 2019). For example, pile-driving, which causes extreme noise, is known to be of great concern. To reduce adverse effects, it is important to plan hazardous construction events outside biologically sensitive periods. It was shown that avoiding pile-driving and cable trenching during the reproduction/recruitment period of Atlantic cod *Gadus morhua* significantly reduced the ecological risk (Hammar et al. 2014).

Electromagnetic fields
There is concern that fish could be negatively influenced by the electromagnetic fields generated by submarine DC cables. Orientation of magneto-sensitive fish may be affected, and there may also be physiological effects in less mobile fish (reviewed in Öhman et al. 2007). In an *in-situ* enclosure experiment, electromagnetic field emissions increased the swimming activity of little skate *Leucoraja erinacea* (Hutchison et al. 2020a). However, in sand eel *Ammodytes marinus* larvae spatial distribution and swimming behaviour was not affected in a laboratory setting (Cresci et al. 2022). At present, there is limited evidence that fish are influenced by electromagnetic fields of underwater cables from wind turbines (Öhman et al. 2007).

Table 4. *Offshore windfarm (OWF) effects on fish in Northern Europe. Review and opinion papers are not included.*

Type of impact[1]	Effect	Species	Location	Area	Type of study	Type structure[2]	Reference
Reef effect	Positive (higher abundance)	Two-spotted goby *Gobiusculus flavenscens* Goldsinny wrasse *Ctenolabrus rupestris*	Sweden, Skagerrak	Coastal <10m depth	Field experiment, pillars vs. surrounding soft bottom (and rock wall n.s.), visual census	Vertical steel and concrete pillars	(Andersson et al. 2009)
Reef effect	Positive (higher abundance)	Two-spotted goby *G. flavenscens*	Sweden, Baltic Sea	Kalmar strait 7-9 m depth	Field observations, 7 yrs after construction, visual census, control sites	OWF turbine foundations	(Andersson & Öhman 2010)
Area use	Negative (recruitment)	Flatfish (several species)	North Sea		Modelling, overlap with spawning areas	Planned OWF	(Barbut et al. 2020)
Several (cables, noise, reef effect)	No large scale effect / Positive local scale (density)	Benthic and semipelagic species	Sweden, Öresund	4-10 depth	Field observations, before-after and reference areas	OWF	(Bergström et al. 2013)
Pile driving noise	No effect on mortality	Common sole *Solea solea* larvae	Netherlands	---	Laboratory experiment	---	(Bolle et al. 2012)
Reef effect, absence of fisheries (refuge)	Positive (higher abundance)	Plaice *Pleuronectes platessa*	Belgia, North Sea	14-37 m depth	Field observations, diving transects, trawl catches, reference areas	OWF, turbines, scour protection	(Buyse et al. 2022)
Cables (MF)	No effect (behaviour)	Sand eel (larvae) *Ammodytes marinus*	Norway	---	Laboratory experiment	---	(Cresci et al. 2022)
Pile driving noise	No effect on mortality	European seabass juveniles	Belgium, North Sea	Lodewijckbank 30-33 m depth	Field experiment, 45 m from monopile	OWF	(Debusschere et al. 2014)
Pile driving noise	Strong stress reaction	European seabass juveniles	Belgium, North Sea	Lodewijckbank 30-33 m depth	Field experiment, 45 m from monopile	OWF	(Debusschere et al. 2016)
(Reef effect, foraging)	Suitable feeding ground	Codfish	Belgia, North Sea	sandbank	Field sampling, energy profiling	OWF	(De Troch et al. 2013)
Cables (MF, EMF)	Negligable?	Rainbow trout, *Oncorhynchus mykiss* (embryos, larvae)	Poland	---	Laboratory experiment	---	(Fey et al. 2020, Fey et al. 2019b)
Cables (MF)	Negligable	Pike *Esox lucius* (embryos, larvae)	Poland	---	Laboratory experiment	---	(Fey et al. 2019a)
Reef effect	Hard bottom species abundant close to turbines	e.g. small-spotted catshark (*Scyliothinus canicula*)	Irish Sea	Off Walney Island	Field observations, baited video system, distance to turbine	OWF	(Griffin et al. 2016)
Several (e.g. disturbance cable trenching, noise)	Negative / High ecological risk	Atlantic cod *Gadus morhua*	Sweden, Kattegat	20-31 m depth (cod spawning ground)	Ecological risk assessment	Planned OWF	(Hammar et al. 2014)
Reef effect	Habitat for mobile demersal hard bottom species	e.g. gobies, wrasses, pouting *Trisopterus luscus*, horse mackerel	Germany, North Sea	German Bight 20-29 m depth soft bottom	Field observations of different foundations and future projection	OWF turbines and hypothetical (future)	(Krone et al. 2013)

Several, incl. reef effect	No effect (several measures)	eelpout *Zoarces viviparous*	Sweden, Öresund	4-9 m depth	Field, fish capture, reference.areas	OWF	(Langhamer et al. 2018)
Reef effect, absence of fisheries	Minor effects on fish assemblages. Possible refuge function for some fish.	+ sole, whiting, mullet - weever. Atlantic cod	Netherlands, Egmond aan Zee	17-21 m depth	Field, trawl, acoustic surveys, video, reference areas	OWF	(Lindeboom et al. 2011)
(Reef effect, foraging)	Feeding grounds for some species	benthopelagic and benthic species	North Sea	Thornton Bank	Field catches, stomach content, stable isotopes. No control sites	OWF	(Mavraki et al. 2021)
Pile-driving	Negative (reduced abundance)	Clupeids	UK	Scroby Sands, Ca 2-20 m depth	Field trawl and net catches, tern foraging, before-after, reference sites, modelling	OWF	(Perrow et al. 2011)
Reef effect (+) vs. perturbation (-)	Could lead to increased abundance	Benthos feeding fish	France, Normandy	Bay of Seine, English Channel 22-31 m depth	Modelling	Planned OWF	(Raoux et al. 2018)
Reef effect	Could lead to increased abundance	E.g. piscivorous fish species	France, Normandy	Bay of Seine, English Channel Ca 20 m depth	Field abundance data, Modelling	Planned OWF	(Raoux et al. 2017)
Reef effect, foraging	Higher population density/size, good quality food. No effect on fitness measures (cod), indication of higher fitness (pouting)	Atlantic cod, pouting	Belgium, North Sea	Thorntonbank 18-24 m depth	Field, catches (condition, stomach fullness/content, length), scuba observations, reference area	OWF	(Reubens et al. 2013a, Reubens et al. 2011, 2014b, Reubens et al. 2013c)
Reef effect, foraging, shelter?	Behaviour, habitat use	Atlantic cod	Belgium, North Sea	Thorntonbank	Field, acoustic telemetry, stomach content, no control sites	OWF	(Reubens et al. 2014a, Reubens et al. 2013b)
Reef effect, refuge from fisheries?	Higher fish abundance and biodiversity close to turbines	Especially rocky bottom species attracted. No adverse effects on sand-dwelling species. Most common species: whiting, dab, sandeels	Denmark, North Sea	Sand bank, 6-14 m depth	Field, Catches, before-after and reference area	OWF	(Stenberg et al. 2015)
Reef effect	Higher fish abundance close to turbines	Especially gobies attracted	Sweden, Baltic Sea	Kalmar strait, 6-8 m depth	Field, Visual SCUBA census, distance from turbines, and control sites	OWF	(Wilhelmsson et al. 2006)
Unclear (Reef effect, refuge, or other?)	Seasonal increase in abundance in areas with artificial structures	Atlantic cod, plaice, thornback ray	North Sea	Many areas	Field, Fisheries surveys, electronic tags	Man-made structures (oil, gas, cables, wrecks, wind turbines)	(Wright et al. 2020b)

[1]MF = magnetic field, EMF = electric magnetic field; [2]All OWF consisted of turbines with foundations into the sea floor, i.e., no studies on floating wind were found.

3.3.3 Marine mammals

Offshore wind farms affect marine mammals primarily through the production of sound (Lucke et al. 2006, Madsen et al. 2006, Verfuss et al. 2016, **Table 5**), although vessel collision and (secondary) entanglement may also have an effect (Farr et al. 2021, Maxwell et al. 2022). One of the main concerns for marine mammals is the noise produced during the construction phase, particularly from pile-driving. The effects of pile-driving sounds on marine mammals has received a great deal of attention, as reflected by Table 5. Most studies have been focussed on harbour porpoises (*Phocoena phocoena*), harbour seals (*Phoca vitulina*) and grey seals (*Halichoerus grypus*), since they are common species throughout northern Europe, and relatively easy to study (compared to many other marine mammal species). Studies include both captivity experiments (e.g. Kastelein et al. 2013) and field studies using acoustic monitoring, visual observations or biotelemetry studies (Dahne et al. 2017, Russell et al. 2016, Thompson et al. 2010).

Pile-driving sounds are audible up to hundreds of kilometres for seals (Kastelein et al. 2013) and up to tens of kilometres for harbour porpoises (Kastelein et al. 2013). At close range, these noises can cause temporary or even permanent hearing loss, but this is highly unlikely to occur at distances > 100 meters from the sound source (Bailey et al. 2010). Behavioural responses are more likely to occur, however. Harbour porpoises have been observed leaving an area up to 20 km from the sound source (Brandt et al. 2011). In seals, area avoidance behaviour has been observed within a 25 km radius from the sound source (Russell et al. 2016), and possibly even further away (Brasseur et al. 2012). Other behavioural responses from harbour porpoises to pile-driving sounds include a reduction in fish-catching efficiency (Kastelein et al. 2018a), changes in vocalization behaviour (Tougaard et al. 2009a) and increased swimming speeds (Kastelein et al. 2018b). Harbour seals and grey seals have been observed to reduce their haul-out behaviour near construction sites (Skeate et al. 2012). Similar responses to pile-driving sounds can be expected from other marine mammals species, such as minke whales and bottlenose dolphins (Bailey et al. 2010, Fernandez-Betelu et al. 2021).

Several measures have been proposed and implemented to mitigate the effects of pile-driving noise on marine mammals and other marine organisms. First, vibration piling has been proposed as an alternative method to conventional impact piling. One study compared the effect of both methods on harbour porpoises and bottlenose dolphins but found no significant difference (Graham et al. 2017). The authors highlighted the need for further research before vibration piling can be recommended as a mitigation measure. In addition, various mitigation measures aim to deter marine mammals within close proximity to the pile-driving site, allowing them to leave the area. For example, adjusting the impact or strike rate of the first few hammer blows (respectively “soft-start” and “slow-start”) can help to “warn” marine mammals in the area (Stephenson et al. 2023). However, the authors warn that implementing a slow-start and soft-start might be insufficient in the case of larger piles and higher energy hammers. In that case, implementing a slow-start and soft-start in combination with an Animal Deterrent Device (ADD) is recommended (Dahne et al. 2017, Stephenson et al. 2023). An ADD is a device to keep marine mammals away from aquaculture facilities, fishery activities or construction activities, by playing sounds that scare nearby marine mammals, typically sound pulses of varying length and frequency (Götz & Janik 2013, Koschinski et al. 2003). One potential downside of ADDs is that the negative effects of the device can outweigh the potential negative effects of the pile-driving itself, as animals can have a strong behavioural reaction to these devices (Dahne et al. 2017). Finally, the negative effects of wind farm construction on marine mammals can be mitigated by attenuating the noise of pile-driving. Bubble curtains can disrupt the transmission of sound through water and absorb sound (Würsig et al. 2000). Bubble curtains have been used successfully to mitigate adverse effects of pile-driving during the construction of offshore wind farms (Dahne et al. 2017).

Sounds that are produced during the operational phase of offshore wind farms are less intense, and more constant. As a result, it is unlikely that sounds from wind farms during the operational phase have a strong negative impact on marine mammals (Lindeboom et al. 2011, Tougaard et al. 2009b, Tougaard et al. 2020). However, one long-term study found less frequent vocalization behaviour of harbour porpoises near a wind farm, compared to a reference location (Teilmann & Carstensen 2012). It was unclear if this was caused by the operational phase of the wind farm, or a very slow recovery after the construction phase. In contrast, some studies found a positive relationship between the operational phase of an offshore wind farm and the presence of harbour porpoises (Scheidat et al. 2011) and seals (Russell et al. 2014). An increase of marine mammals could be attributed to increased food availability within an offshore wind farm (Lindeboom et al. 2011).

***Table 5**. Offshore windfarm effects on marine mammals in Northern Europe.*

Type of impact	Effect	Group of organisms	Location	Area	Type of study	Type of structure	Reference
Construction noise (pile-driving)	Displacement (area avoidance behaviour)	Harbour porpoises and possibly dolphins	Scotland (same site as Bailey et al. (2010))	Offshore ~40m deep	Acoustic monitoring & Visual observations	OWF	(Thompson et al. 2010)
Construction noise (pile driving)	Theoretical effect (potential injury < 100m radius, potential displacement behaviour 50km radius)	Bottlenose dolphins, harbour porpoises, minke whales, common seals, grey seals	Scoltand (same site as Thompson et al. (2010))	Offshore ~40m deep	Detailed noise recordings, compared to exposure criteria for marine mammals	OWF	(Bailey et al. 2010)
Pile-driving noise	Displacement (area avoidance behaviour), but only during pile-driving	Harbour seals	North Sea / UK (multiple sites)	4 wind farms, coastal	Biotelemetry study (Satellite tracking)	OWF	(Russell et al. 2016)
Pile-driving noise	Behavioural responses, mainly to high frequency sound	Harbour porpoise	Captive study	-	Playback of pile-driving sound recordings to a captive porpoise	-	(Kastelein et al. 2013)
Pile-driving noise & effect of bubble net curtain	Displacement (area avoidance behaviour). Bubble net reduced the reaction range.	Harbour porpoises	North Sea	German Bight (offshore)	Acoustic monitoring of porpoise presence/behaviour during pile-driving, with and without bubble net curtain.	Steel monopiles (6m diameter)	(Dahne et al. 2017)
Pile-driving noise	Displacement	Harbour porpoises	North Sea	German Bight (offshore)	Acoustic monitoring of porpoise presence/behaviour during pile-driving.	OWF (monopile foundations)	(Brandt et al. 2018)

Pile-driving noise	Reduced fish-catching efficiency	Harbour porpoises	Captive study	-	Playback of pile-driving sound recordings to two captive porpoises	-	(Kastelein et al. 2019)
Pile-driving noise	Temporarily affected hearing frequency and hearing threshold shift	Harbour seals	Captive study	-	Playback of pile-driving sound recordings to two captive seals	-	(Kastelein et al. 2018a)
Construction noise (pile driving)	Theoretical effect on hearing threshold	Harbour porpoise	North Sea	Germany	Simulation study, based on observed noise levels	OWF	(Schaffeld et al. 2020)
Pile-driving noise	Displacement (area avoidance behaviour).	Harbour porpoises	North Sea	Borkum Reef Ground (offshore Germany)	Acoustic monitoring of porpoise presence/behaviour during pile-driving, with and without bubble net curtain.	OWF	(Dahne et al. 2013)
Pile-driving noise	Changes in vocalization behaviour	Bottlenose dolphins	North Sea	Moray Firth (offshore ~45m depth)	Acoustic monitoring	OWF	(Fernandez-Betelu et al. 2021)
Sounds during operation	Increased presence during operation	Harbour porpoise	North Sea	Egmond aan Zee	Acoustic monitoring	OWF	(Scheidat et al. 2011)
Pile-driving noise	Detection range (how far can porpoise detect pile-driving sounds)	Harbour porpoises	Captive study	-	Playback of pile-driving sound recordings to a captive porpoise	-	(Kastelein et al. 2013)
General construction activity	Reduced haul-out behaviour in seals	Grey seals and harbour seals	North Sea	Scroby Sands offshore wind farm	Visual observations of haul-out behaviour from a plane	OWF	(Skeate et al. 2012)
Long term effect of operation	Decline in echolocation activity after 10 years	Harbour porpoise	North Sea	Denmark	Acoustic monitoring	OWF	(Teilmann & Carstensen 2012)
Pile-driving noise	Changes in vocalization behaviour, at distances of 20 km or more	Harbour porpoise	North Sea	Horns Reef	Acoustic monitoring	Monopile foundations (4m diameter)	(Tougaard et al. 2009a)

Operational effects	Increased foraging behaviour within the wind farm	Seals	North Sea	Norfolk	Satellite tracking	OWF	(Russell et al. 2014)
Pile-driving (vibration piling and impact piling)	Reduced presence	Bottlenose dolphins and harbour porpoises	North Sea	Moray Firth (offshore ~45m depth)	Acoustic monitoring	OWF	(Graham et al. 2017)
Pile-driving	Reduced presence up to 17.8 km	Harbour porpoise	North Sea	Horns Rev II	Acoustic monitoring	OWF	(Brandt et al. 2011)
Pile-driving	Increase swimming speed	Harbour porpoise	Captive study	-	Playback of pile-driving sound recordings to a captive porpoise	-	(Kastelein et al. 2018b)

3.3.4 Ecosystem effects

Marine pelagic and benthic ecosystems are tightly coupled, and changes in the pelagial will affect benthos and vice versa. Wind turbines extend from the surface to the bottom; this also applies to floating wind turbines that must be anchored to the bottom. Consequently, individual and clusters of wind turbines will cause interrelated changes in pelagic and benthic ecosystems as exemplified above. These changes can be considered as 'positive' or 'negative', but this is an anthropocentric view. From nature's point of view, these are changes and should be considered artificial as such. Further, an important aspect is whether these changes are restricted to the vicinity of the wind farm, or do they reach far beyond, as well as what is the concerted ecosystem effect of many clusters of wind farms (Carpenter et al. 2016, van der Molen et al. 2014).

Impacts on ecosystems can also be considered on changes in processes rather than focusing on single species or groups of species. Significant processes include cycling and transformation of energy and matter. Energy capture and loss (respiration) are incorporated in the energy budget while nutrient and carbon cycling and transport are incorporated in the matter budget.

Considering impacts on the matter budget, changes in the rate of resuspension and accumulation of organic matter depends on local stratification strength and flow velocities (see also chapters above on hydrology and plankton). On one hand, increased accumulation of organic matter may increase benthic production (Wang et al. 2019). On the other hand, it can decrease oxygen concentration below harmful level and cause drastic decline in benthic production if the area is prone to oxygen depletion, like the Baltic Sea (Janssen et al. 2015). The same two-directional impact holds for increased resuspension of sediments. In one hand, it can increase nutrient availability in the euphotic zone and increase primary production and food availability to zooplankton (Wang et al. 2019), but on the other hand, it may decrease light availability and with that decrease primary productivity (Burkhard et al. 2011, van der Molen et al. 2014). Turbidity can also impact fish (Bergström et al. 2014). But it is estimated that the effect of resuspension may reach less than a kilometre from the farm in the construction phase (Bergström et al. 2014).

Observational evidence indicates that biodiversity increases in wind farms, mainly due to the artificial reef effect of the piles (Lindeboom et al. 2011), but also exclusion of fisheries may induce increase in biodiversity (Nogues et al. 2022). However, modelling evidence is not always indicating an increased biodiversity – this is also a question of scale (Nogues et al. 2022, van der Molen et al. 2014). For example, in the case of fish, wind farms may attract fish from outside the wind farms and therefore decrease outside abundance and diversity of fish (Nogues et al. 2022). Models of Burkhard et al. (2011) indicated a significant reduction in ecosystem respiration, but very small increase in nutrient cycling, organization, and abiotic heterogeneity, perhaps indicating emergence of a more complex ecosystem, or a regime shift, due to new hard bottoms (Burkhard & Gee 2012). This was more pronounced if the North Sea would be extensively utilised for wind power production (Burkhard & Gee 2012). Here, floating or semi-submerged wind turbines could mitigate this effect as hypothesised by Carpenter et al. (2016) who modelled significant reductions in stratification if windfarms fill large portions of the German Bight.

Some examples of ecosystem scale effects of wind farms in the Northern Europe are given in the Table 6.

Table 6. *Offshore windfarm effects on ecosystem level in Northern Europe.*

Type of impact	Effect	Location	Area	Type of study	Type of structure	Reference
Reef effect	Regime shift	North Sea	Coastal & off-shore, shallow	Modelling	Fixed-bottom foundation & theoretical	(Burkhard & Gee 2012)
Hydrology	Loss of stratification if extensively built	North Sea	Coastal & off-shore, shallow	Modelling & in situ measurements	Fixed-bottom foundation & theoretical	(Carpenter et al. 2016)
Energy budget	Local anoxia	Baltic Sea	Offshore, shal-low	Modelling & in situ measurements	Fixed-bottom foundation & theoretical	(Janssen et al. 2015)
Reef effect	Increase in biodiver-sity	North Sea	Offshore, shal-low	In situ measure-ments	Fixed-bottom foundation	(Lindeboom et al. 2011)
Reef/reserve effect	Structure of the ecosystem	English Channel	Offshore, shal-low	Modelling	Fixed-bottom foundation & theoretical	(Nogues et al. 2022)
Reef/reserve effect	Increased heteroge-neity	North Sea	Offshore, shal-low	Modelling	Fixed foundation & theoret-ical	(van der Molen et al. 2014)
Overall	Very minor changes	North Sea	Coastal & off-shore, shallow	Modelling	Fixed-bottom foundation & theoretical	(Burkhard et al. 2011)
Matter budget	Increased sedimen-tation	Inner Seas off the West Coast of Scotland	Coastal, shal-low	In situ measure-ments	Experimental structures	(Wilding 2014)

4 Knowledge gaps

It has been suggested that the magnitude of potential underwater environmental effects of deep-water, floating offshore wind farms are minimal (Farr et al. 2021). However, since the number of floating offshore wind farms currently are few, and only recently in operation, we found no monitoring data on this type of wind farm. Thus, there are obvious knowledge gaps regarding effects of offshore floating wind farms in general (Farr et al. 2021). An exception is the Hywind Tampen area, where cruise reports from the early operational phase are available (de Jong et al. 2023, Hestetun et al. 2024, Tenningen et al. 2024, Utne-Palm et al. 2023b). However, these reports did not show up in our literature search, but we were aware of them since NINA is involved in the research that is currently ongoing there.

In some of the earlier reviews (Buenau et al. 2022, Dannheim et al. 2020, de Jong et al. 2020, Farr et al. 2021, Taormina et al. 2018), authors have identified gaps in knowledge that include basic observational knowledge about habitat use of whales and seals, effects on primary production, effect of fouling communities on larvae recruitment, effects of foundations and noise on pelagic fish and their populations. Generally, there is a lack of knowledge on long-term and large-scale effects of offshore wind farms (de Jong et al. 2020). Further, Farr et al. (2021) stress that deep-water floating wind farms may have cascading effects on large-scale atmospheric and oceanic processes, that need to be studied to reveal the underlying uncertainties of this impact.

In a modelling perspective, there exists significant room for improvement. Buenau et al. (2022) conclude that physical models need realistic spatial complexity and validation with operating devices while the biological models, especially those including behavioural responses, require further development and adaptation. Most modelling studies focus on single stressor-receptor interactions, but a holistic approach could streamline monitoring requirements, and feedback between monitoring and modelling is crucial for improving environmental assessments. Many studies model abstract systems, but quantitative validation with observational data is rare and challenging according to Buenau et al. (2022). Thus, strengthening the relationship between modelling and monitoring is essential, and addressing information gaps with multi-stressor approaches may advance wind farm development.

Overall, it is evident that a more holistic view of the impacts of offshore wind farms is missing. Some future directions for research include more hypothesis-driven questions, through targeted field studies or experiments (Dannheim et al. 2020), collecting data on sensitivity thresholds or tolerance for electromagnetic fields for a larger number of taxa (Taormina et al. 2018), modelling throughout the levels of the food web to quantify the effects on species distribution and diversity (Daewel et al. 2022). This holds especially for phytoplankton and zooplankton that are understudied, and running atmospheric and oceanic models together on a high resolution for several years to reveal robustness of the estimated changes (Daewel et al. 2022).

Moreover, the fate of offshore wind farms and future decommissioning is currently debated. What should the requirements be and could some of the installations be left in the environment after decommissioning (Fowler et al. 2018)? To inform decommissioning decisions, more knowledge of the biological communities on offshore wind structures are needed (Fowler et al. 2020).

5 Discussion and conclusion

Replacing fossil energy production to limit climate change is urgent and there is a growing need for renewable energy, which is generally considered environmentally friendly (e.g. Wright et al. 2020a). However, just like offshore wind, all types of marine renewable energy production, like wave, ocean currents and tidal energy, have impacts on the environment (Boehlert & Gill 2010, Buenau et al. 2022, Copping et al. 2015, Ouro et al. 2024, Wright et al. 2020a). Similar types of impacts and conflicts are expected as for offshore wind, and some of these are due to the mere presence of physical infrastructures in the ocean (Inger et al. 2009). When it comes to offshore wind, we have seen that there can be a range of impacts on the environment during all phases, from construction, through operation to decommissioning (Ouro et al. 2024). During the construction phase, particularly acoustic effects from pile-driving on marine mammals and fish are of concern (Bergström et al. 2014). During the operational phase, both negative and positive effects can be expected. Negative effects can be caused by acoustic disturbance and electromagnetic fields around cables (Bergström et al. 2014). However, ecological impacts associated with submarine power cables can be considered weak to moderate, though many uncertainties regarding effects remain (Taormina et al. 2018). Positive effects are caused by the addition of new hard substrate (artificial reef effect) and to fisheries exclusion from the wind farm areas (Bergström et al. 2014, Gill et al. 2020, Inger et al. 2009). Towards the end of a wind farm's life, negative effects from decommissioning are expected (Ouro et al. 2024). There may be benefits of letting the infrastructure remain in the sea (Fowler et al. 2018), although other recommendations are to remove the infrastructure after the operation period (de Jong et al. 2020).

Careful spatial considerations are crucial when selecting areas for offshore wind development to minimize overlap with spawning grounds and other important areas such as Marine Protected Areas and ecotones with higher biodiversity, as well as avoiding spatial conflicts with fisheries interests. Siting decisions should balance profitability of energy production, societal impacts and negative consequences for biodiversity (Virtanen et al. 2022). Different siting scenarios of wind farm development should assess the cumulative exposure of wildlife (Goodale & Milman 2019).

It is important to carry out as many mitigation measures as possible to reduce negative impacts. Many negative effects could be mitigated to lower the risk for the marine environment if developers adopt appropriate mitigation strategies and best-practice protocols (Farr et al. 2021, Maxwell et al. 2022). Spatial planning is crucial, and offshore wind development should be avoided in particularly vulnerable, important or valuable areas, like spawning areas, along migration routes or coral reef areas (de Jong et al. 2020). Ecological risks can be significantly reduced by planning hazardous construction events outside biologically sensitive periods, such as avoiding extreme noise from pile-driving and disturbance by cable trenching in the reproduction/recruitment period (Hammar et al. 2014).

Knowledge on how offshore wind farms impact the marine environment has accumulated over the last decades and is by currently quite considerable. However, there are still many knowledge gaps and areas for future research. Standardised protocols for data collection should be developed for wind farm facilities, including thorough investigations of the area before development (pre-construction monitoring), as well as monitoring of both physical and biological changes during operation and after decommissioning (de Jong et al. 2020). It is both timely and needed to increase our knowledge on how offshore wind farms affect the environment in order to ensure the environmentally friendliness of offshore wind energy production.

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