

## Review

## Towards understanding environmental and cumulative impacts of floating wind farms: Lessons learned from the fixed-bottom offshore wind farms

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## ABSTRACT

Renewable energy sectors have been rapidly growing over the last three decades due to the environmental concerns regarding fossil fuels and increasing demand of energy by human. Among those, offshore wind farms are one of the most attractive and promising technologies for clean energy production due to the strong and steady offshore winds, less turbine fatigue, less visual and space limitations compared to onshore wind farms. Rapid development of offshore wind farms, which is expected to reach 70% by 2030, can effect on marine ecosystems and organisms. Hitherto, different studies have comprehensively discussed the potential impacts of offshore wind farms on marine habitats; however, they are just potential and rarely validated through observations. This review focuses on the proved environmental impacts of offshore wind farms gained from post-construction environmental monitoring programs. Particularly, this study provides significant insights on: 1) the area and time span over which biological effects may occur, 2) responses to disturbance by different target organisms; 3) quantification of short/long-term effects; 4) recovery from impacts in the long term. The monitoring studies showed little or only local impacts of offshore wind farms on the marine environment, either during their construction or the operational phases. However, further research is needed to answer whether synergies of little and local impacts may determine consequences at the population level. As the number and size of offshore wind farms increase it is necessary to consider consequences at the population level as well as cumulative impacts of these activities on marine ecosystems.

## 1. Introduction

The interest on wind energy sector stems from the long history of wind usage for energy production by humans (i.e., usage of vertical axis windmills for energy production in Persian-Afghan borders around 200 BC and the horizontal-axis windmills of the Netherlands and the Mediterranean in 1300–1875 AD), mature knowledge in corresponding technology, no fuel-price volatility and abundant wind energy sources globally (Díaz and Guedes Soares, 2020; Guo et al., 2022; Kaldellis and Zafirakis, 2011; Kaldellis et al., 2016). Generally, there are two main types of wind energy technologies for electricity production including (1) onshore wind farms which are an array of wind turbines in the land

(Guo et al., 2022; Wilson et al., 2010) and (2) offshore wind farms (OWF)<sup>1</sup> which are an array of installed wind turbines and substations for electricity transport at the sea (Guo et al., 2022; Willstead et al., 2018a). Offshore wind does, however, have several advantages over onshore wind. In general, inland winds are weaker and less consistent than offshore winds (Leung and Yang, 2012a, 2012b; Msigwa et al., 2022). Offshore wind is also advantageous for reducing wind-induced turbine fatigue since it has lower turbulence intensity and a more steady prevailing direction (Arvesen and Hertwich, 2012; Lindeboom et al., 2015). Moreover, an offshore wind turbine (OWT)<sup>2</sup> is less constrained by noise limits, visual obstruction, space limitations and objections from nearby neighbors comparing to onshore wind turbines (Arvesen and Hertwich,

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2012; Lindeboom et al., 2015; Chen and Kim, 2022). It is expected that OWFs will significantly grow over the next few years due to the growing global demand for clean eLeung and Yang, 2012a, 2012bnergies, the expansion of the renewable energy industry, and the possibility of higher wind speed of the offshore over the onshore winds (Díaz and Guedes Soares, 2020; Bergström et al., 2014). In 2021, total global wind power capacity was up to 837 GW (GLOBAL WIND REPORT 2022, 2022), of which 236 GW in Europe. However, of this amount, 93% were onshore systems (present in 115 countries around the world), with the remaining 7% OWFs (GLOBAL WIND REPORT 2022, 2022) in just 19 countries. Statistics show that while onshore wind capacity additions declined by 31% in 2021, new offshore capacity increased more than three times (IRENA, 2020). The two largest markets for wind energy are China and the United States, where an increasing number of offshore installations is emerging (Fitch Ratings, 2021). Major increases were also recorded in Europe, where 5795 grid-connected offshore wind turbines were installed, with a cumulative capacity of 28.4 GW in 2022 (Wind Europe, 2022). Currently United Kingdom, Germany, Denmark, and the Netherlands are the pioneering countries in respect to the total number of grid-connected wind turbines in the European marine areas (Díaz and Guedes Soares, 2020; Kirchgeorg et al., 2018). However, in the first half of 2022, 13 European countries had at least one grid-connected OWF with the last installation provided by the first OWF in Italy and the Mediterranean Sea at Taranto harbour (30 MW, 10 turbines). Fig. 1 shows a comparison of onshore and offshore wind energy production at different sea depths, as well as the energy demand in Europe. This figure clearly reveals the capacity of growing offshore wind energy at higher sea depths (Esteban et al., 2011). In Fig. 2 European and Global targets for wind energy development are provided.

The most popular and widely used OWTs are monopiles which are installed at relatively shallow water depths (<40 m) (Chen and Kim, 2022; Díaz et al., 2022). Almost 81% of all operating OWTs in Europe had monopile foundations by the end of 2016 (Chen and Kim, 2022). However, with the technology progress other types of OWTs have been developed (e.g., tripods, jackets, gravity based) which made it possible to install OWTs at sea depths up to 50 m and longer distances from the shore (Díaz et al., 2022). All these OWTs are installed with fixed-bottom foundations and each structure design has its own merits and advantages. But the main technical disadvantage of all Fixed-Bottom OWTs (FB-OWT)<sup>3</sup> is that they are only technically and economically feasible in shallow waters (Díaz et al., 2022). In fact, the deepest fixed base OWF is Seagreen, located about 27 km off the coast of Angus 59 m below the sea level, East to Scotland. (Sea green wind energy, 2023). However, the growing technology and market made it possible to extract offshore wind energy at higher water depths (up to 700 m) and soft sea beds by the invention of Floating Offshore Wind Turbines (F-OWT)<sup>4</sup> (Wilson

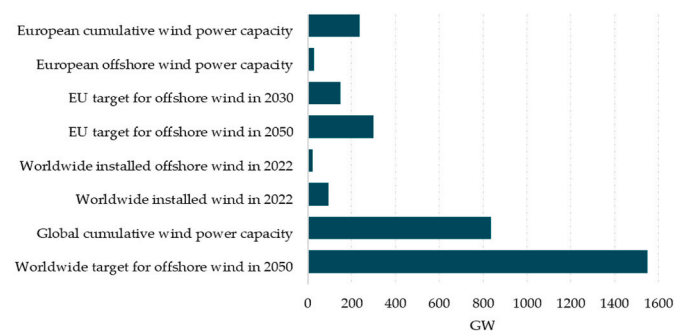


Fig. 2. EU and worldwide targets for OWF installation by 2050 (IRENA, 2020; WilliamsFeng Zhao, 2022; Lee. and Zhao, 2021).

et al., 2010; Díaz et al., 2022). F-OWTs are less constrained by laws regarding size, noise and landscape since they are installed far from the shore. The first floating offshore wind farm (Hywind wind farm) was launched with the capacity of 30 MW at water depth of 110 m and 25 km of shore in Scotland in 2017 (Díaz et al., 2022). Afterwards, Portugal, USA, Japan, and South Korea started to install F-OWTs commercially (Díaz et al., 2022; Díaz and Guedes Soares, 2022). Fig. 3 shows a schematic of different types of FB-OWTs and F-OWTs.

Although OWFs has the advantages of the availability of ample resources around the world as well as the potential to generate high amount of clean electricity (e.g., Walney OWF, the largest one in the world, produces electricity for more than 500 thousands household) (Díaz and Guedes Soares, 2020) several non-technical barriers still need to be considered carefully for further development of them especially in mega scales. The most significant of these non-technical issues is the necessity to comply with the EU Environmental Impact Assessment (EIA)<sup>5</sup> Directive and associated national legislations. Accordingly, regulatory authorities are able to make an informed decision on the proposed project and its potential environmental impacts at an early stage.

Generally, OWF installations lead to a succession of ecological and socio-economic changes. Besides, they might strongly effect on the capacity of ecosystems in the context of ecosystem services (Negro et al., 2020; Galparsoro et al., 2022a, 2022b; Baulaz et al., 2023). Therefore, EIA of offshore wind structures is inevitable. Hitherto, different studies have been published on the effect of OWFs on marine ecosystems (Kaldellis and Zafirakis, 2011; Kaldellis et al., 2016; Leung and Yang, 2012a; Arvesen and Hertwich, 2012; Kirchgeorg et al., 2018; Hall et al., 2022; Willsted et al., 2018b; Abramic et al., 2022; Hernandez C et al., 2021; Amponsah et al., 2014; Cook et al., 2018a; Medina-Lopez et al., 2021; Hooper et al., 2017; Ren et al., 2021). However, most of the discussed impacts by previous studies are focused on the potential environmental impacts of OWFs, as required by EIA, and not the validated impacts through observations. On the other hand, the commercial implementation of F-OWTs for electricity generation is new and their impacts on marine ecosystems are still not thoroughly known. Therefore, in this review the authors aim to specifically focus on the proved environmental impacts of FB-OWTs to ultimately search for the possible answers to the question “how can the environmental impacts of FB-OWTs be expanded to F-OWTs?”. For this purpose, the data were gathered from short/long-term post-construction environmental monitoring programs conducted at FB-OWTs. Special attention is given to the experience gained from the North Sea with 72% of the installed FB-OWTs in the European marine regions (Cook et al., 2018a; Janßen et al., 2015). The marine ecosystem-FB-OWT’s interactions as well as the observed environmental impacts of FB-OWTs are comprehensively discussed in consecutive sections including; Artificial reef effect of OWFs, noise and electromagnetic disturbance effects on marine habitats, fish,

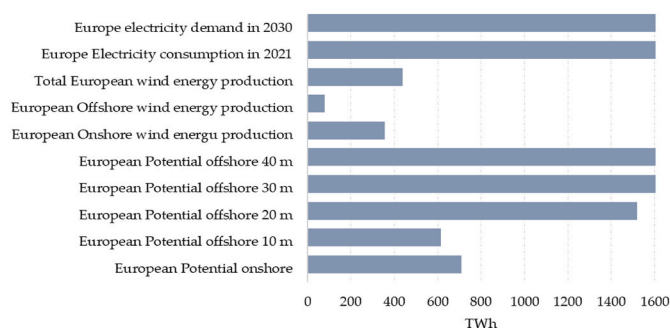
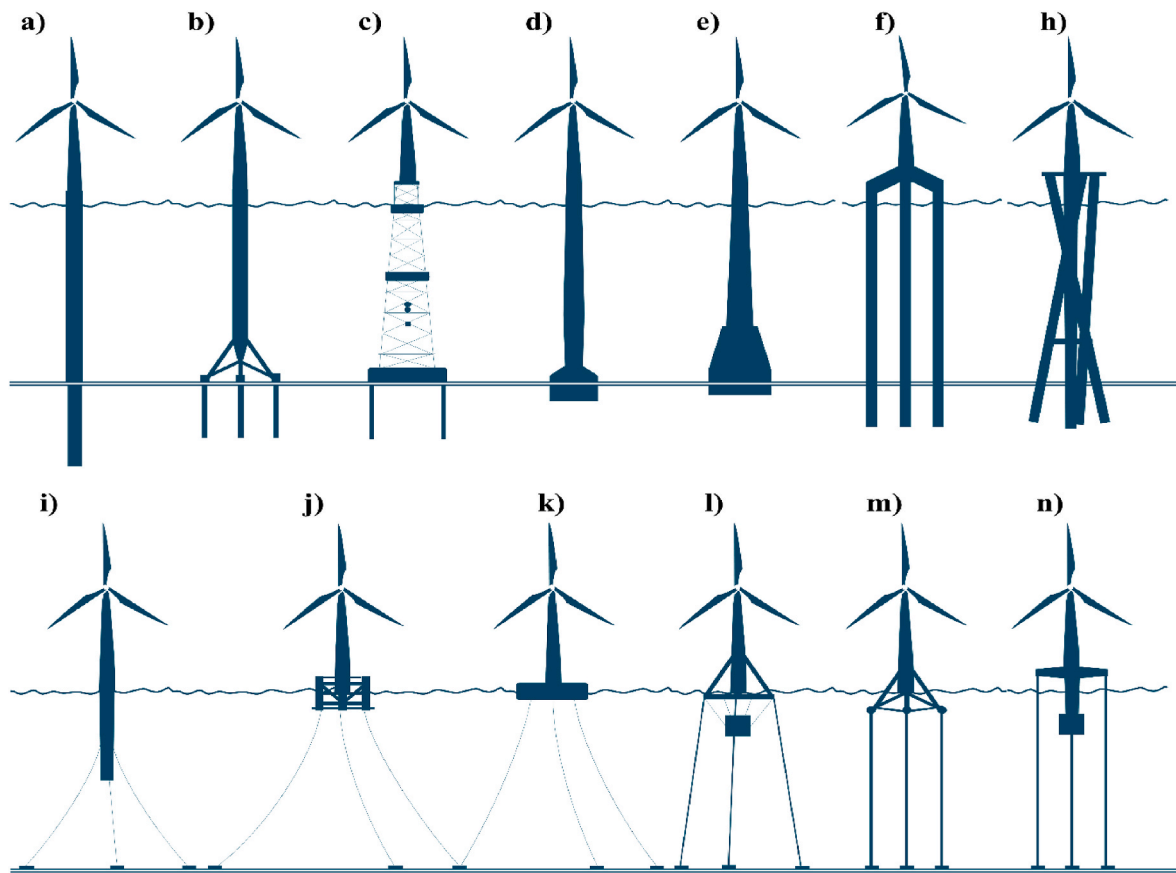


Fig. 1. Comparison between the potential of inland and offshore wind energy at different depths, and the energy demand in Europe (Esteban et al., 2011).

<sup>3</sup> Fixed-Bottom OWTs (FB-OWT).

<sup>4</sup> Floating Offshore Wind Turbines (F-OWT).

<sup>5</sup> Environmental Impact Assessment (EIA).



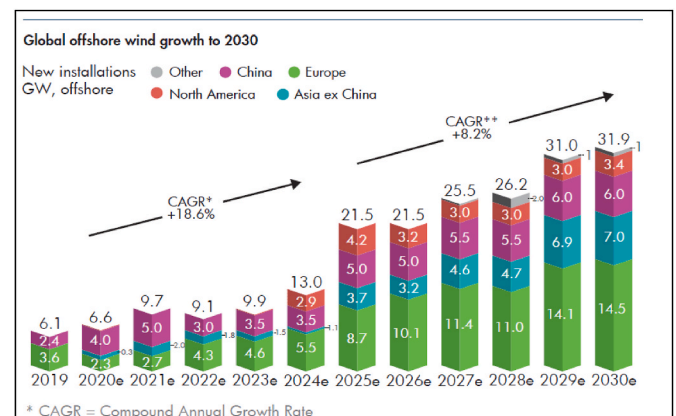
**Fig. 3.** A schematic of different types of OWTs. Fixed-bottom offshore wind turbines including; (a) Monopile (b) Tripod (c) Jacket (d) Suction caisson (e) Gravity base (f) tripile (g) Twisted jacket. Floating offshore wind turbines including; (i) Spar buoy (j) Semisubmersible (k) Barge (l) Pendulum floater (m) Tension leg platform (n) Advanced spar.

large marine vertebrates (e.g., sea birds, marine mammals and large fish), chemical releases from metal corrosion, eutrophication, hydrology and water turbidity. In the final section, cumulative environmental impacts of FB-OWFs and the limitations and boundaries of the study are discussed. At the end, conclusions and recommendations are mentioned. Considering rapid development of F-OWFs in the near future, this review could provide a practical guideline for future research on environmental impacts of F-OWFs. It is noteworthy that this study is based on the implicit assumption that the water depth for forthcoming F-OWFs does not differ much from the deepest ever designed. The last is represented by Hywind Tampen farm, located around 140 km off the coast of Norway, in depths ranging from 260 to 300 m (Snorre Unit and Gullfaks Unit, 2019).

## 2. A literature review on the environmental impacts of offshore wind farms

The first FB-OWT at sea were installed in Sweden in 1990 (Esteban et al., 2011). The first real offshore North Sea wind farm came into operation in Denmark in 2002, followed by The Netherlands in 2007, UK and Belgium in 2008 and Germany in 2010 (Lindeboom et al., 2015). Afterwards, the development of FB-OWFs has significantly increased over the last decade and is expected to grow more than 70% by 2030 (Díaz and Guedes Soares, 2020). Fig. 4 shows the forecasting growth rate of global OWFs till 2030.

Along with the global expansion of OWFs, environmental monitoring programs have been constantly considered for investigation of the impacts of these structures on the surrounding marine ecosystems (Wilson et al., 2010; Elliott, 2002; Lindeboom et al., 2011; Degraer et al., 2018; Ecological Research at the Offshore, 2014). Environmental data



**Fig. 4.** Forecasting growth rate of global OWFs till 2030 (Global offshore wind report, 2020).

collection on FB-OWFs started first in Denmark around 2000 (Petersen and Malm, 2006; Leonhard et al., 2011). These early studies indicated possible effects concerning the introduction of hard substratum fauna into a sand dominated environment, and some other potential effects on the seabirds and marine mammals (Lindeboom et al., 2015). Since then, the research effort at the European/global level has increased significantly aimed at covering a wide range of potential impacts and all ecosystem components (Bergström et al., 2014; Lindeboom et al., 2011). Table 1 summarizes a list of review studies that have been done on the potential environmental impacts of FB-OWFs on marine ecosystems. All

**Table 1**

A list of review studies on the environmental impacts of FB-OWF on marine ecosystems.

#	Review study	Year	Ref.
1	Mitigation approaches for decrease of birds collision with OWTs	2023	Martin and Banks (2023)
2	Potential impacts of floating wind turbines on seabirds, benthic, fish and marine mammals	2022	Maxwell et al. (2022)
3	Assessment and mitigation framework for the impacts of OWFs on marine birds	2022	Croll et al. (2022)
4	Potential environmental impacts, mitigation measures, and alternative actions for the decommissioning of offshore wind farms	2022	Hall et al. (2022)
5	Potential ecological impacts of offshore wind farms	2022	Galparsoro et al. (2022a)
6	Environmental effects of OWFs on the Good Environmental Status (GES) and a novel suggested EIA-GES checklist	2022	Abramic et al. (2022)
7	Impacts of wind turbines (offshore and onshore) on avian life, noise pollution, visual impacts, microclimate and vegetation	2022	Msigwa et al. (2022)
8	Activity–stressor–receptor–impact framework for measuring environmental impacts of offshore wind installation, operation, maintenance, and decommissioning activities (case study of Brazil)	2021	Hernandez C et al. (2021)
9	OWT maintenance, strategy selection, schedule optimization, on-site operations, repair, assessment criteria, recycling, and environmental concerns	2021	Ren et al. (2021)
10	Satellite data for the offshore renewable energy sector and their implementation in EIA	2021	Medina-Lopez et al. (2021)
11	Impact of underwater sound from OWTs on marine life	2021	Stöber and Thomsen (2021)
12	Effects of OWFs on hydrodynamics and fishes	2020	van Berkel et al. (2020)
13	Artificial reef effects of OWFs on marine ecosystem structure and functioning	2020	Degraer et al. (2020)
14	Reef effect of OWFs	2020	Glarou et al. (2020)
15	Effect of OWFs on benthic organisms	2020	Dannheim et al. (2020)
16	Risk to animals from electromagnetic fields emitted by electric cables and marine renewable energy devices	2020	Gill et al. (2020)
17	Life cycle environmental impacts of offshore and onshore wind farms	2019	Mendecka and Lombardi (2019)
18	Potential impacts of submarine power cables of OWFs on the marine environment	2018	Taormina et al. (2018)
19	Potential impacts of corrosion protection systems' emissions on marine environment	2018	Kirchgeorg et al. (2018)
20	Evaluation of offshore wind farm cumulative impacts	2018	Willstedt et al. (2018b)
21	Collision risk and avoidance behaviour of seabirds towards offshore wind turbines	2018	Cook et al. (2018b)
22	Impacts of offshore wind development on ecosystem services by mapping ecological and cultural parameters	2017	Hooper et al. (2017)
23	Comparison of environmental and social footprints between offshore and onshore wind farms	2016	Kaldellis et al. (2016)
24	Decommissioning options for OWFs and their potential reef effect	2015	Smyth et al. (2015)
25	Life cycle greenhouse gas emissions from renewable energy sources	2014	Amponsah et al. (2014)
26	The potential of co-location of OWFs and marine protected areas	2014	Ashley et al. (2014)
27	World wind energy scenarios, the status of wind turbine development, development trends of OWFs, the environmental and climatic impact of wind farms, the wake effect of wind turbines	2012	Leung and Yang (2012b)
28	Life cycle environmental impacts of offshore and onshore wind powers	2012	Arvesen and Hertwich (2012)
29	Global market facts, technology issues, economics, environmental performance, wind	2011	Kaldellis and Zafirakis (2011)

**Table 1 (continued)**

#	Review study	Year	Ref.
	energy prospects and research & development in offshore wind farms		
30	Potential impacts of offshore wind farm construction and the implementation of conceptual models to quantify and address their impacts	2010	Wilson et al. (2010)

these studies, over the last years, have contributed to a significant increase in understanding potential environmental effects of FB-OWFs. The scientific knowledge has been enhanced in some topic areas, particularly at the species level for some benthic animals, fish, birds and marine mammals and a good knowledge has been acquired on many of the general short-term effects on the marine systems. Some knowledge has been also acquired about long-term changes that could be correlated with the interactions between FB-OWFs and the environment.

The main lesson that can be acquired from these monitoring activities is that FB-OWFs change the local environment and these changes concern all ecosystem components. However, if some of these changes can be regarded as potentially negative (e.g. potential avoidance responses, habitat loss and collisions of birds, changes to benthic and pelagic habitats, noise and electromagnetic disturbance), some other can be considered as potentially positive (e.g. increased local fish populations and biodiversity (Bergström et al., 2014; Leonhard et al., 2011; Wilhelmsson et al., 2010)). Regarding the biodiversity enhancement, however, it would be better to define it as of “uncertain impact”: it remains unknown, in fact, if some displaced individuals recolonised or if any recovery is caused by colonization of further animals which would imply disruption of original social structure (Glarou et al., 2020; Langhamer, 2012). The major impacts of FB-OWFs are focused on the most obvious changes within the local environment such as the very high sound levels produced during the construction phase (Collaborative Offshore Wind Research Into The Environment Huddleston, 2010; Norro et al., 2013), the introduction of hard substratum (Degraer et al., 2018; Petersen and Malm, 2006; Langhamer, 2012; De Mesel et al., 2015), the rotating blades (Drewitt and Langston, 2006; Mendel et al., 2014) and the exclusion of fisheries, such as trawling (Lindeboom et al., 2011; Degraer et al., 2018; Dannheim et al., 2014). Knowledge has been gained on the short-term effects on benthos, fish, birds and marine mammals, including attraction to and avoidance of the FB-OWFs (for references: see (Lindeboom et al., 2011)). Whereas, on the effects and consequent changes over the long-term there is still need to investigate (e.g., the effect of trawling cessation on the benthos (Lindeboom et al., 2011), the displacement effects on seabirds (Vanermen et al., 2015a; Mendel et al., 2019a)). Some studies have outlined how the basic monitoring by itself (e.g., following the Before-After-Control-Impact design of FB-OWFs versus reference area (Pezy et al., 2017)) may not be sufficient to understand specific cause–effect relationships especially in systems with a high natural variability (Lindeboom et al., 2011; Gray and Elliot, 2009). However, it cannot be denied that targeted monitoring activities, such as the near turbine effect studies on benthos (Degraer et al., 2018; Coates et al., 2014), the feeding behaviour of demersal fish in the wind farm (Reubens et al., 2013a, 2014a; Derwe-duwen et al., 2016) or the escape behaviour of harbour porpoises during piling (Haelters et al., 2015), have provided significant new and important knowledge on cause–effect relationships (Degraer et al., 2018). In many monitoring programs there has been an attempt to differentiate between ‘positive’ and ‘negative’ responses to FB-OWFs. Ecologically ‘negative’ impacts may include; altered sediment characteristics, increased erosion of the natural sandy sediments around wind turbine foundations (Eynde et al., 2013), increase in the non-indigenous species on the hard substrata (Kerckhof et al., 2011), obvious disturbance of seabirds because of avoidance and collision (Vanermen et al., 2015a; Busch et al., 2013; Mendel et al., 2019b), increased turbidity in



construction/demolishing stages (Amponsah et al., 2014; Hooper et al., 2017), chemical release due to corrosion of the installation (Kirchgeorg et al., 2018; Mao et al., 2011) and the increased sound pressure on the marine environment and its impact on marine mammals (Vanermen et al., 2015a; Dähne et al., 2013) and fish (Ecological Research at the Offshore, 2014; Gill et al., 2012). The 'positive' impacts include; colonization of the soft and hard substratum from invertebrates and fish (e.g. (Degraer et al., 2018; De Mesel et al., 2015; Coates et al., 2014)) as well as the reef effect (e.g. (Coates et al., 2016; Krone et al., 2017; van Hal et al., 2017)).

### 3. Cause-effects relationships

Understanding the environmental impacts of human activities is a fundamental step to improve existing regulations on the protection of natural ecosystems (ICES, 2013). In this regard, gained experiences from FB-OWFs could help not only to mitigate the impacts of current installations but also to predict the environmental impacts of the new F-OWFs. In the following sections the cause-effect relationships between OWF and marine environments are discussed.

#### 3.1. Wind farm reef effect

The foundations of wind turbines can provide artificial habitats for marine organisms (Amponsah et al., 2014). Different studies showed that some fish and seabird species were attracted to the wind turbines due to improved feeding conditions as a consequence of habitat alterations (Agency, 2013; Reubens et al., 2014b). In a study on benthos communities at 50 m depth of the coastal strip of Canary Islands results showed that OWF could increase benthos biodiversity. However, the authors suggested that the reef effect of OWF at depths over 50 m relies mainly on the predicting models and still not well known (Consortium, 2020). Similarly, it has been reported that the density of European plaice, *Pleuronectes platessa*, increased after construction of OWFs due to the increased food availability and/or fisheries exclusion effect (De Backer and Hostens, 2017). Although overall fish assemblages did not change, feeding behavior of some fish species changed from preying sandy bottom species to the species typically associated with hard substrates (Derweduwen et al., 2016). Stomach analysis of cod, *Gadus morhua* and pouting, *Trisopterus luscus*, demonstrated that these species were primarily preying on the hard substratum epifauna generated by the OWF installations (Reubens et al., 2011, 2014a). Reubens et al. (2013) studied the spatio-temporal variability of Atlantic cod (*Gadus morhua*) and pouting (*Trisopterus luscus*) in wind farms, shipwreck and sandy bottoms in the Belgian Sea from 2009 to 2011. Their results showed that population densities of both species increased at the hard substrates (i.e., wind farm, shipwreck) during the feeding and spawning periods (i.e., summer and autumn) whereas no changes were observed at sandy bottoms (Reubens et al., 2013b). In another study the echolocation activity inside the wind farm (Nysted Offshore Wind Farm) gradually increased up to 29% of the baseline level since its construction. The authors proposed that it could possibly relate to the habituation of the porpoises to the wind farm, generation of artificial reefs, and reduced fishing (Teilmann and Carstensen, 2012). Stenberg et al. (2015) reported that fish abundance and species variety (*Merlangius merlangus*, dab *Limanda limanda*, and sandeels *Ammodytidae* spp.) increased marginally in the OWF area while decreased in the control area of 6 km distant (Leonhard et al., 2011). However, the results reported by Scheidat et al. (2008) is in contrast to the previous studies (Scheidat et al., 2008). It can be concluded that findings from one OWF may not necessarily be applicable to or valid for another OWF in a different location (Scheidat et al., 2008). On the other hand, some fish species (e.g., *Gobiusculus flavescens* and *Ctenolabrus rupestris*) were shown attraction behaviour to the OWF reef while the bottom-dwelling gobies, *Pomatoschistus* spp, did not show such attraction. Therefore the reef effect can vary by species too (Raoux et al., 2017; Andersson et al., 2009).

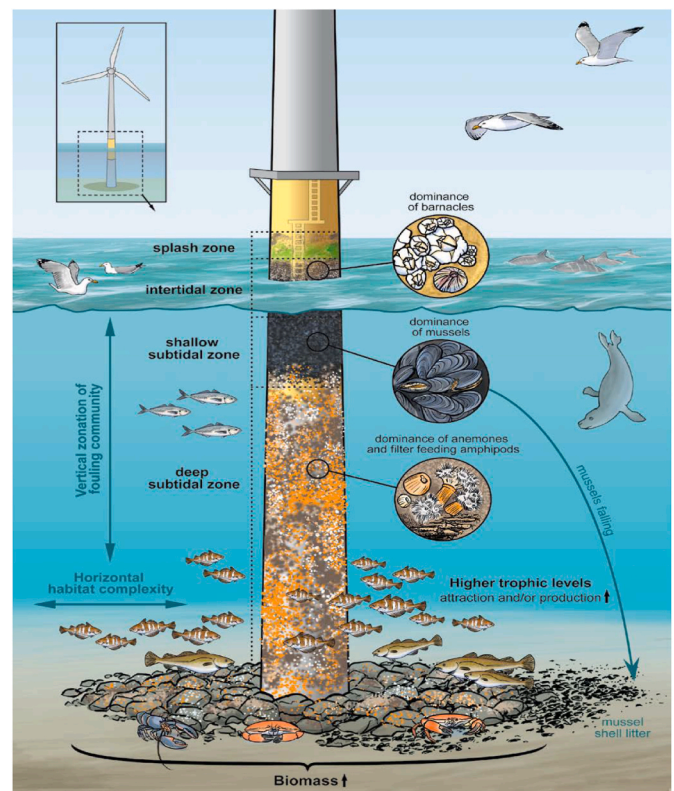


Fig. 5. Reef effect of FB-OWF on marine invertebrates and vertebrates (Bednarek et al., 2020).

Fig. 5 shows the reef effect and habitat changing along the depth gradients provided by OWFs.

Although the attraction-production hypothesis in artificial reefs has been investigated in detail for several fish (Reubens et al., 2014b) there are much less studies on invertebrates (e.g. edible crab, *Cancer pagurus* and European lobster, *Homarus gammarus*) (Krone et al., 2017), and fish species common to OWFs which prey on the hard substratum epifaunal community (Krone et al., 2017). Study on biomass estimates of these prey species may be useful to quantify food availability created by the whole OWF artificial reef (Joschko et al., 2008; Krone et al., 2013). Trawling cessation in the OWF area might also lead to changes in energy flow and trophic structure of soft-sediment macrobenthos which subsequently could alter trophic connectivity in the vicinity of wind turbines (Dannheim et al., 2014; Degraer, 2013). The artificial reef effect may also explain the attraction of some bird species (e.g. common tern, *Sterna hirundo* or great cormorant, *Phalacrocorax carbo*) to the wind farms as a result of an increased availability of pelagic fish (Vanermen et al., 2015a). Other bird species such as lesser black-backed gulls, *Larus fuscus*, seems to use the turbines along the edge of the wind farm to roost, especially those situated closer to the colonies and also largely avoided the inner part of the OWF (Vanermen et al., 2018a).

Almost all the above-mentioned studies concluded that OWF reefs positively draw fish species with rocky habitat preference and the sandy bottom habitat species. However, it is important to consider that they only included short term studies of OWF reef effects. The only long term (10 years) study by Degraer et al. (2020) showed that OWF reef effects can be identified in three succession stages; (1) primary stage (0–2 years) with early colonizers species followed by (2) an intermediate stage (3–5 years) with divers suspension-feeding invertebrates and a (3) climax stage with large number of mussels and anemones species (Bednarek et al., 2020). The actual artificial reef impact, however, could vary depending on the type of foundation. In European seas, steel monopile, tripod, and jacket foundations—the latter typically lacking an

erosion prevention layer—are the most typical (The European offshore wind Energy Association, 2013). The concrete gravity-based foundations with an extended erosion protection layer (e.g. (Reubens et al., 2014b; Reubens et al., 2014c)) or jacket foundations have been the subject of extensive reef effect monitoring, particularly with regard to fish and megafauna attraction (e.g. (Degraer et al., 2018; Krone et al., 2017; Krone et al., 2013)).

### 3.2. Effect of electromagnetic field

Some marine species detect electromagnetic fields (EMF)<sup>6</sup> that helps them in orientation, migration and prey finding (Hutchison et al., 2018). EMF generated as a result of human activities can interfere with naturally existing EMF and cause changes in behavioural patterns of these organisms. Generally, the EMF of wind farm cables is in the range of 1–100  $\mu\text{V}/\text{cm}$  (Gill, 2020) which is similar to the bioelectric fields released by prey. Therefore, the OWF electromagnetic field can attract electrosensitive ocean predators (Kaldellis et al., 2016; Wilber et al., 2018). However, larger OWFs could generate greater magnetic fields which hinders migratory movements of predator species due to a perceived barrier effect (Westerberg and Lagenfelt, 2008). It should be remarked that up to now, only a few number of organizations (e.g., Oregon State University, Swedish Defence Research Agency) have developed an apparatus to detect E-fields at low intensity levels around the OWFs, and measuring EMF emitted by OWF cables is still technically limited and most of the results comes from mathematical modelling and laboratory experiments (Gill, 2020). It has been reported that the swimming speed of migrating silver eels between the Oland island and the Swedish mainland across the OWF AC-cables was significantly lower in the interval with the cables (Öhman et al., 2007).

The most comprehensive assessment on the effect of electromagnetic fields on fish was conducted at Nysted in Danish OWF between 1999 and 2006 (Agency, 2013). For this purpose, a specifically designed setup and a fishing gear were applied to the area along the cable route connecting the wind farm to the shore in order to detect the migration direction of the fish and to estimate the number of fishes crossing the cable. Their results on migration direction showed significant impacts on some species (e.g. baltic herring, *Clupea harengus*, common eel, Atlantic cod and flounder, *Platichthys flesus*), suggesting that the migration of some species across the cable route might be impaired. Concerning the effect on fish behaviour, significant results were only obtained for common eels that reacted to EMF by leaving the area along the cable route, also for Atlantic cod that exhibited some accumulation close to the cable route. However, the intensity of the electromagnetic field around the cable was not measured at Nysted OWF and only its proportionality was assumed with the power production at the wind farm. Correlations between the above mentioned effects and the power production were examined but a significant correlation was only found for flounders which apparently crossed the cable when the intensity of the electromagnetic fields was estimated to be low, during calm periods. However, the authors clarified that it is not clear whether fish might also be reacting to the physical conditions along the cable route or not (Agency, 2013). In another study by Wyman et al. (2018) the construction of a 200 kV HVDC subsea cable showed little to no impact on the Chinook salmon's (*Oncorhynchus tshawytscha*) migration success rate in San Francisco Bay, California, although fish were found on one side of their typical migration path (Wyman et al., 2018). Similarly, behavioural change in Crustacea was reported when exposed to the electromagnetic fields (Coates et al., 2016; Hutchison et al., 2018). Fig. 6 shows the effect of electromagnetic fields emitted by OWF cables on the movement of fishes. It is important to consider that among all EMFs emitted by subsea

cables, magnetic field (B-field)<sup>7</sup> and induced electric fields (IE-field)<sup>8</sup> can interfere with natural background magnetic fields and should be considered as the primary focus for study of the effect of EMF on marine organisms (Gill, 2020).

### 3.3. Effect of noise exposure

Offshore wind turbines can generate noise pollution either in construction/decommission phases or operation phase. Literature is strongly directed to assess the impacts of noise exposure on underwater species while for the birds it is considered as a protective factor against collisions. In fact, the birds' acoustic perception is mainly hampered by background noise from waves and wind (Nehls et al., 2016). Hitherto, several studies have been conducted on marine mammals as one of the most critically affected species (Dannheim et al., 2020; Scheidat et al., 2008; Molen et al., 2014).

A monitoring program was carried out on the seals of the Scroby Sands-OWF in the UK (Hastie et al., 2018). The results of the study revealed a significant post-construction decline in harbour seal's number, whereas the grey seal population significantly increased (Hastie et al., 2018). The authors suggested that extreme noise generated by piling operations is the main reason for seals displacement with effects extended to the mid-term. Similarly, tagged harbour seals showed 11–41% decrease in area usage around 500 m from the turbine (Hastie et al., 2018). Grippo et al. (2020) found a significant decline in fish numbers as the distance to the turbine decreased to less than 140 m as well as a horizontal displacement rather than vertical displacement in response to the generated noise by OWTs (Grippo et al., 2020). Similar conclusions on harbour porpoises were reported by Brandt et al. (2011) for various case studies in Germany. Comparing the disturbance effects during construction of OWFs with and without active noise abatement systems revealed the effect of piling noise on harbour porpoises. During traditional piling, porpoise detection declined 50% at 10–15 km distance whereas using noise countermeasures only 17% decrease was observed (Brandt et al., 2011). A different phenomenon was observed in the Egmond aan Zee OWF, Netherlands. Stationary acoustic monitorings were carried out using Timing porpoise Detector (T-POD)<sup>9</sup> in the OWF as well as two reference areas during a period prior to construction (June 2003–June 2004) and a similar period in normal operation of the OWF two years after the construction (April 2007–April 2009) (Scheidat et al., 2008). Results showed that the acoustic activity was significantly higher inside the wind farm than in the reference areas, indicating that the occurrence of porpoises in OWF increased. Authors suggested two possible reasons for this preferences by porpoises: (1) an increased food availability inside the wind farm (i.e., reef effect) and/or (2) the absence of vessels in a heavily trafficked part of the North Sea (known as “sheltering effect”) (Scheidat et al., 2008).

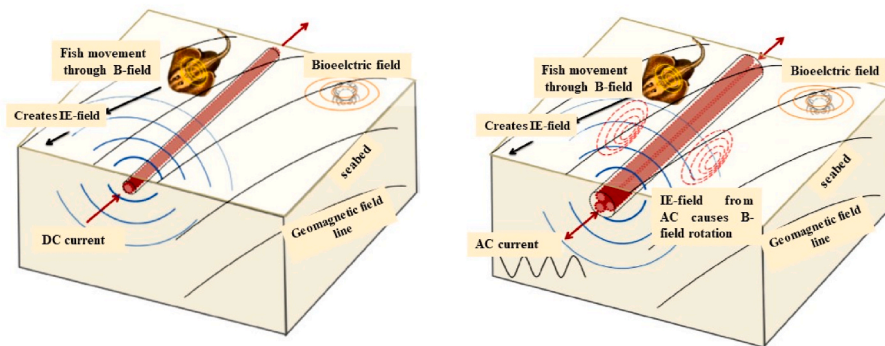
A long-term monitoring study (2007–2012) showed the noise effects on the seals and porpoises (*Phocoena phocoena*) during construction and operation of Horn Rev and Nysted OWFs, Denmark (Agency, 2013; Issue DOWKE, 2006). Initial results showed smaller effects on seals than on porpoises, and smaller effects at Horns Rev than at Nysted OWF. The authors reported no negative effect on seal's population during the operation of the two OWFs. Whereas, a strong short-term effect on porpoises was reported during the construction phase only at Nysted OWF where the porpoises left the wind farm area almost completely. After two years of operation the porpoise activity in the reference area reverted to the baseline level. However, the activity in the Nysted Wind Farm was still lower than expected. The authors suggested that although a comparatively low number of animals was affected, the population of porpoises in the western part of the Baltic Sea is also smaller. Therefore,

<sup>6</sup> Electromagnetic Fields (EMF).

<sup>7</sup> Magnetic Field (B-field).

<sup>8</sup> Induced Electric Fields (IE-field).

<sup>9</sup> Timing porpoise Detector (T-POD).



**Fig. 6.** Effect of OWF magnetic field (B-field), electric field (E-field) and induced electric fields (IE-field) on fish movement and bioelectric field (—) of the organisms across the seabed (Gill, 2020).

the relative impact on the population was higher at Nysted OWF, both because of the stronger response to the wind farm and the longer duration of the disturbance at Horns Rev (Agency, 2013; Issue DOWKE, 2006). Another monitoring study in Nysted OWF showed that strong negative effects on porpoises gradually diminished possibly due to habituation of the porpoises to the wind farm, less fishing, and artificial reef effects (Petersen and Malm, 2006; Teilmann and Carstensen, 2012). The authors concluded that habitat preference may effect on harbour porpoise's response to a disturbance (Teilmann and Carstensen, 2012; Gray et al., 2006). Thus, the porpoises at Horns Rev might be more tolerant to disturbance if the area is of great importance to their survival whereas the porpoises around Nysted may not be particularly interested in the area. Another hypothesis is that the Nysted area is relatively sheltered whereas Horns Rev is exposed to higher background noise, therefore the OWT noises at Nysted could be higher above the background noise than at Horns Rev so the porpoises were able to hear the turbines at greater distances at Nysted (Teilmann and Carstensen, 2012).

Another study reported lower harbour porpoise's population during the construction of Alpha Ventus OWF in the North Sea in 2009 (Krägefsky et al., 2014). The spatial distribution pattern seen on two aerial surveys three weeks prior to and precisely during pile-driving suggested a strong avoidance response within 20 km of the noise source (Dähne et al., 2013). Brandt et al. (2011) reported that the presence of Hector's dolphin (*Cephalorhynchus hectori*) decreased at the detector closest to the piling of OWF but increased at the mid-harbour detectors (Brandt et al., 2011). Leunissen and Rayment (2019) reported similar results and confirmed that dolphin detection rates near the piling operation took up to 83 h to return to pre-piling levels (Leunissen et al., 2019). Longfin squid (*Doryteuthis pealeii*) showed altered body patterns and feeding changes (e.g., decreased capture rates and increased inking and jetting) in response to pile-driving noise from OWF construction (Jones et al., 2021). It has been reported that bottlenose dolphins would suffer auditory damage within 100 m of the pile-driving, whereas porpoises might be affected up to 2 km away (Brandt et al., 2011; Bailey et al., 2010). Nehls et al. (2016) proposed that appropriate mitigation procedures (i.e., big bubble curtain (Nehls et al., 2016) or seal scarer (Issue DOWKE, 2006)) could decrease hearing damages in porpoises in the vicinity of the construction sites (Issue DOWKE, 2006). However, since sound source levels can vary depending on the type of foundations and geomorphology of the locations, the ranges that porpoises might be at the risk of temporal or permanent hearing damages should be considered specifically for each OWFs project.

In contrast to the previous studies, European plaice (*Pleuronectes platessa*), Sheepshead (*Archosargus probatocephalus*) and flatfish showed no significant changes in daytime residency or displacement when exposed to the pile-driving noise during OWF construction (Wilber et al., 2018; Bruintjes et al., 2016; lafrate et al., 2016). Therefore, it can be concluded that the intensity and duration of hearing damages caused by OWF construction/operation could be species-specific. Some studies

revealed that goldfish, cod, and Atlantic salmon are able to recognize OWTs at wind speeds of 8–13 m/s and at distances of 0.4–25 km (Tougaard et al., 2009). The detection range is affected by the size and quantity of wind turbines, the fish's auditory system, the depth of the water, and the bottom substrate.

Some studies reported that pelagic fish were scared away by construction sound, as well a decrease in food gathering of mackerel in the OWF area was reported (Dähne et al., 2013). Since the mackerel can act as potential food resources for higher trophic levels, more monitoring programs are needed to understand whether this might affect pelagic fish occurrences in the long-term or not. Some literature discussed that positive artificial reef effect of OWFs may be partially neutralised by both the generated noise during construction/operation phases and the produced electromagnetic fields (Krägefsky et al., 2014; Gill et al., 2014). However, to understand and calculate the response distances to the OWF's noise, different parameters should be considered (i.e., the environmental situation, the sounds' source level, factors affecting sound propagation, and background noise levels) (Siddagangaiah et al., 2022).

### 3.4. Observed effects on seabirds

Millions of birds migrate over the sea each year. In this sense, studying the impacts of OWFs on birds and other avian species seems indispensable. In general, studies show that average annual bird deaths from turbine accidents range between 0 and 50 (Martin and Banks, 2023; Cook et al., 2018b; Thaxter et al., 2015). However, most of these studies refer to inland wind farms. Birds collisions were investigated around OWFs in Denmark by means of specifically designed thermal animal detection systems (Hall et al., 2022). From the empirical evidences of the study, it was revealed that sea bird collisions are very rare events. Interestingly, bird tracking by radar as well as visual observations showed that many bird species tend to avoid the wind farm by changing flight direction some kilometres away of an OWF (Hall et al., 2022; Petersen and Fox, 2007). As well, those birds flying through the wind farm show tendency to alter their altitude to avoid the risk of collision. Under adverse weather conditions, which were thought to likely increase collision risk, results showed instead that birds tend to avoid flying (Agency, 2013) and/or to largely avoid the inner part of the OWFs (Vanermen et al., 2018b). The strong avoidance behaviour leads very low estimates of collision risk, suggesting instead an increase in habitat loss and travel costs. The bird studies demonstrated also strong differences between bird species in response to the OWFs. Some species of conservation concern such as divers and scoters showed particularly high aversion to these structures (Agency, 2013) and a displacement effect up to 10–15 km away from the wind farms (Degraer, 2013). Mendel et al. (2019) observed displacement effect and bird reduction density to 16 km and 60% (within 10 km radius of the turbines) in a newly build OWF, respectively (Mendel et al., 2019a). Similar results



were reported by Vanermen et al. (2020) in lesser black-backed gulls (*Larus fuscus*) that showed a significant decrease in flying close to the centre of the wind farm to a distance of at least 2 km (Vanermen et al., 2020). The displacement and avoidance behaviour could increase to 75% when the turbines are in operation and rotating (Peschko et al., 2020). Thaxter et al. (2015) used GPS-telemetry to study lesser black-backed gulls' interactions with OWTs in the UK for two years. Their results showed that the use of OWTs during chick-rearing was substantially higher in males than in females. As well, during the incubation period the use of OWF decreased in comparison to the chick-rearing period. The authors suggested that seabird's interaction with OWF can differ greatly across individuals and sexes, as well as between seasons and years. Therefore, it is crucial to focus on acquiring sufficient data on spatio-temporal variability of seabird migration patterns as well as assessments of the necessary sample sizes (Thaxter et al., 2015).

In observing geese and ducks with radar, Desholm and Kahlert (2005) found that the percentage of flocks entering the wind farm area decreased significantly (by a factor of 4.5) from pre-construction to initial operation. Overall, less than 1% of the ducks and geese migrated in a distance to the turbines to be at any risk of collision. For such breeding species which are able to detect and avoid large OWFs, turbines ultimately act as barriers for movement (Desholm and Kahlert, 2005). On the contrary, the response of gulls towards OWFs appear to be subject to both temporal and (within-OWF) spatial variation, which in turn can be of high value in modifying collision risk modellings (Vanermen et al., 2018a). Fig. 7 shows a summary of seabird collision rates with OWFs in five species (Lesser black-backed gull, Herring gull, Small gull spp., Large gull spp., Gull spp.). The figure clearly shows that the collision rates are less than 1% in the studied species. Cook et al. (2018) suggested that the degree of avoidance behavior in seabirds is probably correlated with the ecological significance of a site to a species at a particular time, as well as how it is being used (Hall et al., 2022). Different levels of collision risk and avoidance behavior may be linked to active usage of OWF by seabirds during foraging or chick-rearing seasons. Martin and Banks (2023) reported that the birds usually fly in low light, especially at night and in poor visibility on their migratory routes that makes them more vulnerable to barriers such as OWTs. The authors proposed that the rate of birds collision can be reduced by adding an achromatic surface pattern to wind turbines (Fig. 8) (Martin and Banks, 2023). A pattern element larger than 8.7 m (OWT's normal length is  $\geq 60$  m) could be observable at a viewing distance of 1000 m for the vulnerable birds with acuity of 30 min of arc at low light levels and poor visibility situations. This means that the interval time between detection and a potential collision with a patterned turbine increase to 30 s for the birds with 13–20 m/s flying speed (Martin and Banks, 2023).

In conclusion, it seems that the OWFs cause lower risk of collision for the birds comparing to traditional inland/onshore wind farms because of two main reasons: (1) Being in the ocean; it is possible to modify the

site of the wind farm according to the well-known migration trajectories, (2) Probably a bird is more likely to avoid an array of wind turbines compared to a single row of turbines which might be species-specific (Fox and Petersen, 2019).

### 3.5. Effect of corrosion

Offshore facilities frequently come into contact with seawater and have a variety of possible emissions as a result of corrosion, such as considerable metal emissions from galvanic anodes. As well, organic coatings may emit organic compounds to the seawater and sediments through weathering and/or leaching process (Kirchgeorg et al., 2018). All the OWT's parts that are not submerged in water are concerned with atmospheric corrosion. Generally corrosion emission is typically higher from the zones that are in contact with water (i.e., submerged zone, Tidal water zone (TWZ)<sup>10</sup> and splash water zone (SWZ)<sup>11</sup>) (Mao et al., 2011; Mottin et al., 2012). TWZ is effected by waves, sunlight, and floating items such as sea ice in the Baltic Sea while the SWZ is mainly corroded through the contact with seawater salt and waves (Kong et al., 2022). The steel corrosion rates in TWZ and SWZ are estimated to range from 0.07 to 0.21 mm per year and from 0.08 to 0.14 mm per year below sea level that can be intensified by high chloride concentrations and pH fluctuations of the seawater (DIN 81249-2 standard, 2013) (Mombere and Marquardt, 2018). Al anodes usually contain other trace metals (e. g., Zn (2.5–5.75%), Mn, Fe, In (0.015–0.04%), Cd, Si, Pb, Cu) (DNVGL-RP-B401 standard, 2017) which their release to the sediments and water within the piles may be considered as a potential threat to the marine environment in the long-term (Kirchgeorg et al., 2018; Smith and Goolsby, 1996).

Kirchgeorg et al. (2018) estimated that an OWF can emit  $45 \cdot 10^3$  and  $2 \cdot 10^3$  kg of aluminum and zinc per year, respectively (if assume that it consists of 80 OWT monopiles and one offshore survival system). Currently, Al concentrations in saltwater are not subject to any national, international, or environmental quality assessment standards (Kirchgeorg et al., 2018). Golding et al. (2015) proposed that Al toxicity thresholds can vary depending on the investigated species for instance; the oyster (*Saccostrea echinata*) showed 10% inhibition in embryo development at the concentration of 410  $\mu\text{g Al/L}$  whereas 18  $\mu\text{g Al/L}$  was determined as a growth rate inhibitor to a diatom (*Nitzschia Closterium*) (Golding et al., 2015). Gillmore et al. (2016) in the study of the effect of dissolved and precipitated Al species on diatoms reported that either dissolved or precipitated Al can be toxic depending on the type of diatom (Gillmore et al., 2016). Caplat et al. (2010) reported that Al (III) and Zn (II) released from galvanic anodes had less severe effects on developmental or fertilization rates of a sea urchin (*Paracentrotus lividus*) compared to their sulfate salts (Caplat et al., 2010). Gabelle et al. (2012) found that the concentration of aluminum significantly increased in the sediments near the galvanic anodes in a harbor basin in Le Havre, France, In contrast low concentrations of Al was detected in the water because of the dilution effects (Gabelle et al., 2012). Similar results reported by Deborde et al. (2015) on the study of Al dispersion in experimental tanks filled with seawater. The authors proposed that bonded Al with suspended particulate matters and the non-soluble forms of Al can deposit in the sediments around the OWF (Gabelle et al., 2012; Deborde et al., 2015). Mao et al. (2011) investigated Al effect on mussels (*Mytilus edulis*) using experimental tanks filled with natural seawater and seawater contaminated with Al (810  $\mu\text{g/L}$ ). The authors showed that digestive glands could act as potential temporary storage sites for Al accumulation in mussels (Mao et al., 2011). It is not yet known, however, the long-term impact of these emissions on sea sediment concentrations and on benthic organisms. Since clay minerals are the main source of Al in marine sediments it might be challenging to distinguish

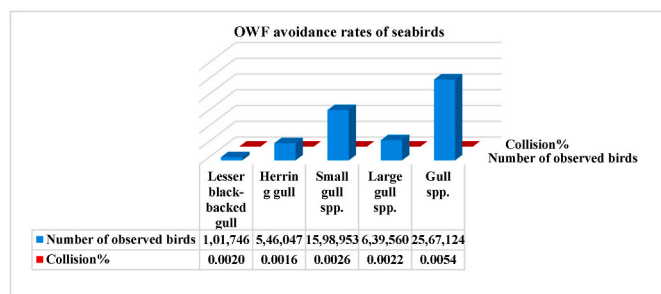


Fig. 7. Number of observed birds and collision percentage in five species (Lesser black-backed gull, Herring gull, Small gull spp., Large gull spp., Gull spp.) within the wind farms. Reproduced by permission from Ref. (Hall et al., 2022).

<sup>10</sup> Tidal Water Zone (TWZ).

<sup>11</sup> Splash Water Zone (SWZ).





**Fig. 8.** Demonstration of a patterned wind turbine to decrease birds collision risks. The black and white parts increase visibility by birds and the yellow parts increase the detectability of marine wind turbines for shipping (Martin and Banks, 2023).

between natural background Al levels in the sediments and the accumulated Al released from galvanic anodes.

In addition to Al, galvanic anodes are a source of release and dispersion of zinc in marine environments (Mottin et al., 2012; Rousseau et al., 2009). The physicochemical characteristics of the environment (e.g., pH, salinity, organic matters in seawater, ...) have a significant impact on the Zn species and its distribution in the seawater and sediments. The eco-toxicological assessment criteria for Zn is equal to 0.5–5 µg/L in water and 50–500 mg/kg dw in sediments according to OSPAR (Wilding, 2014). Mottin et al. (2012) studied the toxicity effects of zinc on the Pacific oyster (*Crassostrea gigas*) emitted by sacrificial anodes. The authors reported 82% mortality rate in the oysters exposed to 10 mg Zn/L (one week experimental period), whereas no mortality was reported for the oysters exposed to 0.5 mg Zn/L (ten week experimental period). They suggested that zinc pollution can interfere in the immune system activities of oyster *C. gigas* (Mottin et al., 2012). Gomiero et al. (2015) in the study of metal accumulation in mussels (*Mytilus galloprovincialis*) from an offshore gas platform found the galvanic anodes as a source for Zn, Cd and Ni emission and accumulation in the mussels in Adriatic Sea (Gomiero et al., 2015). Experimental tank studies using Zn anodes showed a rise in  $Zn^{2+}$ , zinc hydroxide or Zn-suspended particle complexes in the water (Rousseau et al., 2009). The metal (Al, Zn, Fe) emissions from Al anodes were examined by Deborde et al. (2015) in a seawater tank. From the results of their study, dissolved Zn initially increased and then gradually decreased through sorption by particulate matters and water dilution process. An amorphous white coating with high Al and Zn concentrations were observed on the surface of galvanic anodes (Deborde et al., 2015). Although studies have shown that Zn from galvanic anodes has a relatively low toxicity and that Zn emissions from offshore wind farms are significantly lower than those from onshore wind farms (roughly 2 tons/year) compared to Al, further research is still required to evaluate long-term effects of Zn emissions from OWF on marine environments (Deborde et al., 2015).

Along with environmental concerns about Al and Zn emissions from OWF facilities, they could be a substantial new supply of Indium emission in the seawater and sediments (0.01–0.04% of galvanic anodes' substance is Indium) (Kirchgeorg et al., 2018). Therefore, further research on eco-toxicological effects of Indium emissions from OWF on marine ecosystems is crucial in the future. Furthermore, Leaching, weathering, or material losses can all result in the release of organic compounds, solvents, binding agents, pigments and fillers from organic coatings of an OWT parts that come into contact with seawater (Kirchgeorg et al., 2018; Mao et al., 2011; Deborde et al., 2015). Some suggestions have been proposed by researchers about the application of Epoxy resins (EP), polyurethane (PUR)-based coatings and impressed

current cathodic protection as substitutes of traditional coatings that are more lasting and efficient for protecting steel from corrosion in marine environments especially in submerged zones (Lyon et al., 2017; Price and Figueira, 2017). However, their environmental impacts have not been thoroughly examined. It is also important to analyze Al-species in marine sediments to understand the fate of released Al from galvanic anodes in marine environments. Hitherto, different national and international standards have been developed on coatings application for OWF and to reduce metal emissions (DIN EN ISO 12944-1 standard (2017)), (VGB-S-021-03-2018-04-EN standard, 2018), (NORSOK M-501 standard (2012)), (ISO 12944-9 standard (2018)). It is suggested to reconsider those standards considering long-term environmental impacts of organic matter and metal releases from OWF (Kirchgeorg et al., 2018; Lyon et al., 2017; Price and Figueira, 2017).

### 3.6. Eutrophication and oxygen budget

It has been reported that OWF structures can contribute in nutrient concentration and primary production through a localized vertical mixing (van Berkel et al., 2020; Molen et al., 2014; Broström, 2008; Floeter et al., 2017; Cazenave et al., 2016). Janßen et al. (2015) in the study on regional impacts of OWF on oxygen conditions in southwest Baltic sea observed that the OWF structures could change mixing dilutions and current velocities and facilitate buildup of biomass (e.g., biofouling organisms like blue mussels) (Janßen et al., 2015). The expansion of the benthic biomass would be accelerated in the presence of a secondary hard substrate like wind farms or other fixed installations. The authors also speculated that development of large OWFs may favor local anoxia, especially in waters already rich in nutrients and semi-enclosed water bodies. Moreover, as biomass increases, the consumption of oxygen and degradation of organic matters will also rise, potentially intensifying eutrophication (Janßen et al., 2015). These authors suggested that a well-chosen site for an offshore wind farm could mitigate eutrophication problems by accurately predicting and ensuring sufficient water renewal (Janßen et al., 2015). Nunneri et al. (2008) on the study of ecological risk assessment of the construction of OWF in the North Sea reported that OWF's construction could decrease primary production in the short term. However, the authors proposed that the synergistic effects of eutrophication and offshore wind farm construction require a more thorough examination (Nunneri et al., 2008). Daewel et al. (2022) proposed that annual primary production rate could change  $\pm 10\%$  as the result of stratification and generated wind wakes by OWFs in the North Sea (Daewel et al., 2022). From numerical modelling, sediment carbon amount showed an increase in deeper areas of southern North Sea. Additionally, the installation of OWFs in the

southern North Sea has shown significant impacts on oyster grounds due to decreased dissolved oxygen concentration, reduced horizontal currents, and lower bottom shear stress. The authors suggested that OWFs in seasonally stratified waters experience an upward shift of the vertical production during summer which typically takes place at the mixed layer depth. The expected changes in the spatial distribution of primary production may have an impact on the nursery habitats and survival of fish in their early life stages through differences in the match-mismatch dynamics with their food or as a result of low oxygen conditions (Daewel et al., 2022).

Stamford and Azapagic (2014) estimated that the eutrophication potential of an offshore wind farm with turbine capacity of 2–5 MW (capacity factor of 30–50%) is equal to 60 mg  $\text{PO}_4^{3-}$ -eq./kWh which is still less than shale gas (138 mg) and solar photovoltaics (280 mg) (Stamford and Azapagic, 2014). Mendecka and Lombardi (2019) calculated that an offshore wind turbine with the capacity in the range of 1000–5000 kW (wind speed and turbulence class of IIIA, IIA, IA) has a eutrophication potential <0.008 g  $\text{PO}_4^{3-}$  eq./kWh (Mendecka and Lombardi, 2019).

Qvarfordt et al. (2006) on the study of fouling communities on bridge piling in the western Baltic Sea observed the development of six algal taxa on the piles. They reported that macroalgae was the dominant taxon at 1.5 m deep (34% of the total biomass). The authors proposed that macroalgae can have a mutual effect on the water oxygen budget. During photosynthesis they can produce oxygen and increase the surface layer's oxygen budget while they can act as an oxygen consumer at night or when they break off from the substrate and sink to the sediment (Qvarfordt et al., 2006). Janßen et al. (2015) suggested that site-specific values like ventilation and current velocity may be used in licensing processes for establishment of OWF as well as marine spatial planning (Janßen et al., 2015).

Although effect of OWFs on eutrophication might be disregarded in light of the natural variability, wind farms may not be suitable for placement in places particularly with high biomass values and limited oxygen supplies or there might be need for additional biofouling management methods. It is also advised regular monitoring and in-situ analyses of the levels of dissolved oxygen, biochemical and chemical oxygen demand, total nitrogen, total phosphorus and chlorophyll-A concentrations in OWFs to predict eutrophication problems (Janßen et al., 2015; Qvarfordt et al., 2006).

### 3.7. Hydrographic changes and turbidity

Studies have demonstrated that OWF can enhance turbulent vertical mixing effects; however, detecting and observing these effects necessitate extensive data sets. Combining experimental studies, remote sensing and modelling data, researchers have shown that each turbine can generate an upwelling effect reaching up to 1 km (Cazenave et al., 2016; Vanhellemont and Ruddick, 2014; Rennau et al., 2012; Lass et al., 2008). Christensen et al. (2014) showed that OWF structures may produce hydrographic changes in two ways; (1) through slowing wind speed on the lee side of the turbines (2) by wave energy loss due to surface friction and vortex shedding. As a consequence, these effects could lead to a 5% reduction in wave height extending over three times the length of the monopiles (Christensen et al., 2014). Bärffuss et al. (2021) reported that waves with increased energy and shorter wavelengths were observed at 55 km of downstream area of Amrumbank West, Nordsee Ost, and Meerwind Süd/Ost OWFs, Germany (Bärffuss et al., 2021). The consequences of changing hydrographic conditions on marine ecosystems can be significant and diverse; among these, the potential effects of increased turbidity are controversial (Shields et al., 2011). Although the effects of elevated turbidity are thought to be low to moderate on sandy benthic organisms (Bergström et al., 2014), it may impair sensitive creatures such as young fish (Partridge and Michael, 2010; Auld and Schubel, 1978; Lowe et al., 2015). Previous studies

showed that water turbidity significantly impairs pursuit-diving birds' vision and harbor seals' vision (Weiffen et al., 2006; Strod et al., 2004). However, it may also have a positive effect for fish communities by reducing the impact of predation (Utne-Palm, 2004). Baeye and Fettweis (2015) implemented Doppler current profiler and aerial imagery to study suspended particulate matters (SPM)<sup>12</sup> changes in an OWF in Belgium (Baeye and Fettweis, 2015). Their results showed that monopile foundations caused to increase turbidity levels up to  $\pm 15$  mg SPM/L in the direct vicinity of wind turbines which could contribute to generation of turbid plums up to 150 km length and 30 km width. The mentioned authors proposed that the epifaunal organisms which inhabit on the monopile's surface or on the base's protective granite collar were the primary sources of the suspended debris in the turbid plumes. The organisms remove fine SPM from the water column and trap it, which causes a dominant accumulation of SPM, including debris and (pseudo-) feces, at the base of the piles (Baeye and Fettweis, 2015). However, higher tidal current's velocity can resuspend the near-bed fluff layer's fine particles and carry them to the downstream in the wake of the piles (Floeter et al., 2017; Baeye and Fettweis, 2015).

Floeter et al. (2017) analyzed high resolution CTD data along with oxygen and chlorophyll-a measurements to understand the pelagic effects of OWF in the German EEZ (BARD and GTI sites) in summer (Floeter et al., 2017). Their results showed that only one of the four investigated transects exhibited 20% light reduction in 1% photosynthetically active radiation depth while the other three transects showed no variations in light availability inside and outside the OWFs. The authors also reported that LANDSAT pictures did not exhibit any turbid wakes in the study area (Floeter et al., 2017). In contrast, Vanhellemont and Ruddick (2014) reported that from Landsat-8 images, turbid wakes of individual turbines were observed with 30–150 m width and several km length aligned with tidal currents in Thames estuary (Floeter et al., 2017). These different results might be due to that BARD and GTI OWF sites are significantly deeper and more stratified than the area examined by Vanhellemont and Ruddick (2014). Devlin et al. (2008) emphasized that although increased turbidity in a region may be detected in moderate resolution satellite data, it would be challenging to identify because it will be (much) smaller than the short-term changes in SPM in the area. These studies reveal that interpreting changes in surface SPM and turbidity can depend critically on the spatial data resolution (Devlin et al., 2008). In addition to offshore wind turbines, cable construction operations for transferring OWF's energy to the port can also alter topography of the seabed, movement of sediments, and the quality of the water (Wilding, 2014). Generally, type of sediment, installation method, hydrodynamic conditions and cable laying size can affect the extent and characteristics of the generated plumes (Taormina et al., 2018). Currently, trenching, burying, and dumping rocks are the three methods of laying cables. During a trenching operation, sea floor is cleaned and scarped for burying the cables in an approximately a meter beneath the surface (Vanhellemont and Ruddick, 2014). Fig. 9 shows a schematic of OWF's cable trenching and its effect on the sea. Hernandez et al. (2021) in their study of environmental impacts of OWF in Brazil, reported that trenching operation could increase water turbidity (Hooper et al., 2017). Another study on cable installation on sand substrates in Nysted offshore wind farm, Denmark, showed that trenching with a backhoe dredger generated mean particle concentrations up to 75 mg/L at a distance of 200m from the operation site, and up to 18 mg/L during jetting (Taormina et al., 2018). From their study, excavating 17,000 m<sup>3</sup> of sediment ( $\sim 10$  km  $\times$  1 m  $\times$  1 m) for cable trenching took one month. The authors proposed that although turbidity can last during the whole cable construction operations it still constitutes localized and short-term effects (Taormina et al., 2018).

<sup>12</sup> Suspended Particulate Matters (SPM).

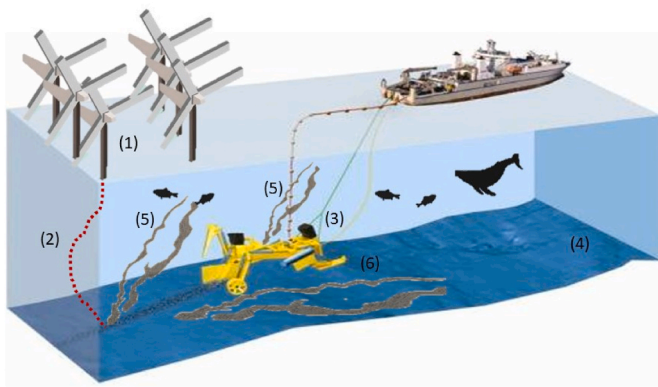


Fig. 9. Schematic of OWF's cable trenching. (1) OWF. (2) transmission cable. (3) trenching vehicle. (4) seabed. (5) turbidity plume. (6) sediment transport.

#### 4. Challenges and limitations of EIA studies on FB-OWFs

##### 4.1. Short-term or long-term effects

Monitoring associated with the Environmental Impact Assessment is a requirement of environmental legislation across many countries. The most common type of monitoring in environmental impact studies is basic monitoring, which focuses on the outcome of human activities such as the construction and operation of OWFs. It allows keeping track of major and even unforeseen impacts and is therefore a suitable research strategy for a better understanding of the environmental impact of anthropogenic developments. It may also trigger adjusting or even halting activities if unacceptable impacts occur. However, limitations and knowledge gaps of this method have been outlined by past studies. So far, all the studied ecosystem components have shown some degree of response to FB-OWFs. However, most of the evidences have been interpreted while the altered ecosystem was still developing and the observed patterns were considered as short-term effects that probably reflect the initial stages of an ecological change and succession (Lindeboom et al., 2011). Therefore, it can be concluded that some impacts may not have been detected yet, because they are still not developed to a detectable extent. For instance, no short-term effects were observed on the benthos communities in the sandy area between the FB-OWF generators in Egmond aan Zee (OWEZ, Netherlands) two years after operation (Lindeboom et al., 2011). In another study, no effect of fisheries exclusion was observed in soft sediment epibenthos and fish between the wind turbines of the Thornton and Bligh Bank FB-OWFs in the Belgian part of the North Sea six years after their construction (De Backer and Hostens, 2017). In addition, no changes in macrobenthos related to fisheries exclusion was observed in the investigated wind farms (Reubens et al., 2016). Monitoring time period after construction is probably still too short, and the whole wind farm concession area is not yet large enough to detect the effects of fisheries exclusion beyond the immediate vicinity of the turbine. In contrast, in the same OWFs temporary phenomenon was observed such as the density and biomass peak of epibenthos that lasted only two years after construction and gradually decreased to the comparable reference levels three years after construction (Degraer et al., 2018; De Backer and Hostens, 2017). Accordingly, the previous observed FB-OWF's effects was probably only a temporary phenomenon. A similar positive short-term effect was observed at Horns Rev FB-OWF, Denmark, where an initial increase in the abundance of juvenile sand eels (fish species associated to the sediment) was observed one year after the construction (Agency, 2013).

Another temporary local impact of OWFs was observed on temperature and humidity in the Amrumbank West, Meerwind Süd and Nordsee Ost OWFs at the North Sea from September 2016 to October 2017 (Siedersleben et al., 2018). The aircraft observations along with

numerical simulations showed an increase in temperature by 0.5 K and a decrease in humidity up to 0.5 g/kg at the hub height of 90 m. However, the authors suggested that these micrometeorological phenomena can only occur in the presence of inversion below or at the rotor area which could facilitate mixing of warmer air downward by the rotors. On the other hand, this process can cause either a cooling or warming effect depending on the height of inversion. The authors concluded that these redistribution of heat and moisture, however, has insignificant impact on the local climate (Siedersleben et al., 2018). In another study a visible fog layer was observed at the Horns Rev 2 FB-OWF, Denmark, in 2016 (Middleton and Bethany, 2022). The authors proposed that the wake effect probably caused by the synergy between different factors (e.g., the presence of cloud or fog layer, prevailing winds, and atmospheric instability). However, this phenomenon is considered as a short-term rare event in OWFs that is extremely unlikely to happen in the absence of even one of the fundamental involving factors (Middleton and Bethany, 2022). While these studies demonstrate that localized microclimate changes can occur within OWFs, it is reported that the local climate can only be permanently influenced by changes in air-sea interactions and not by the mere existence of OWFs (Siedersleben et al., 2018; Middleton and Bethany, 2022; Fiedler and Bukovsky, 2011; Vautard et al., 2014).

Nevertheless, the long-term continuation of the basic monitoring of all ecosystem components is generally recommended to understand the impacts over the time. However, it is still unclear what is the discrimination between short-term and long-term effects, since it varies from component to component.

##### 4.2. The issue of research efforts

It is well known that the likelihood of an impact detection strongly depends on research effort, impact size and data variability. Research effort is significantly influenced by the objectives of a study and the quantity of observations or collected samples. Data variability is the inherent or sampling-induced variability in the data, and impact size is the magnitude of the deviation from a specified reference condition (e.g. (Gray et al., 2006; Collie et al., 2000)). As an example, the low likelihood of impact detection has been pointed out as the main obstacle of detecting the impacts of Belgian FB-OWF on seabirds (Vanermen et al., 2015b). Also, the challenges encountered in demonstrating consistent effects of FB-OWTs on fish and soft-sediment epibenthos in the same study was probably related to a combination of natural and sampling-induced variability (e.g., the time scale of sampling, variation in physio-chemical and biological responses, ...) (Lindeboom et al., 2015).

It can be concluded that, when developing basic monitoring programs the research effort issue would undoubtedly require more attention. Statistical power should also be taken into account to determine how likely it is to detect an impact of a given extent. Additionally, methods for reducing data variability should be further investigated. Some authors have concluded that natural variability can be reduced by limiting data collection to one season and so avoiding seasonality (Rogers et al., 2008) however this strategy may be effective only when dealing with short-term impacts. Sampling-induced variability can be lowered by increasing the sample size alongside an appropriate balance in the number of samples per group. In this matter, studies suggested that a higher number of passive acoustic monitoring devices inside and outside wind farms could facilitate investigating the possible repulsion or attraction of harbour porpoise, *Phocoena phocoena*, to FB-OWFs (Teilmann and Carstensen, 2012; Brandt et al., 2011; Thompson et al., 2010; Scheidat, 2011).

##### 4.3. Impacts and cumulative impacts

Although studies on environmental concerns regarding the offshore wind industry are growing, cumulative impacts have remained less



studied (Maxwell et al., 2022). Cumulative impact are the incremental, combined, and interactive impacts that may result from repeated human activities over the time and space. Single impacts, as discussed in the previous sections, could be insignificant when considered individually. However, if the look falls on the environment -in the vicinity of an OWF- as a whole, substantial and sometimes irreversible changes could be recognised, as observed for other human activities in the sea (i.e., the Oil and Gas sector). Many Directives such as Marine Strategy Framework Directive (MSFD)<sup>13</sup> and the European Habitats-Bird Directives (Nature, 2000) defined the good environmental status as the critical criterion for the sustainability of the human activities at sea (Croll et al., 2022). A recent European Parliament resolution (2022/C 99/10) regarding the effects of OWFs and other renewable energy systems on the fishing sector emphasizes on assessing cumulative impacts of OWFs. In this regard, Busch et al. (2013) analyzed the cumulative habitat loss caused by the construction of OWFs in the exclusive economic zones of Germany, Netherlands, Belgium and United Kingdom in the context of EU MSFD. The study demonstrates challenges of putting into practice the MSFD requirements to assess the cumulative impacts of OWFs at the regional sea scale. It also highlights different experiences and legislations between neighbouring/riparian states of a common regional sea which may generate opposing priorities, goals, measurements and consequently assessments (Joschko et al., 2008). The research also emphasizes an urgent need for conservation strategy harmonisation and collaboration across riparian states in transnational "management units" in order to successfully execute the MSFD (Joschko et al., 2008).

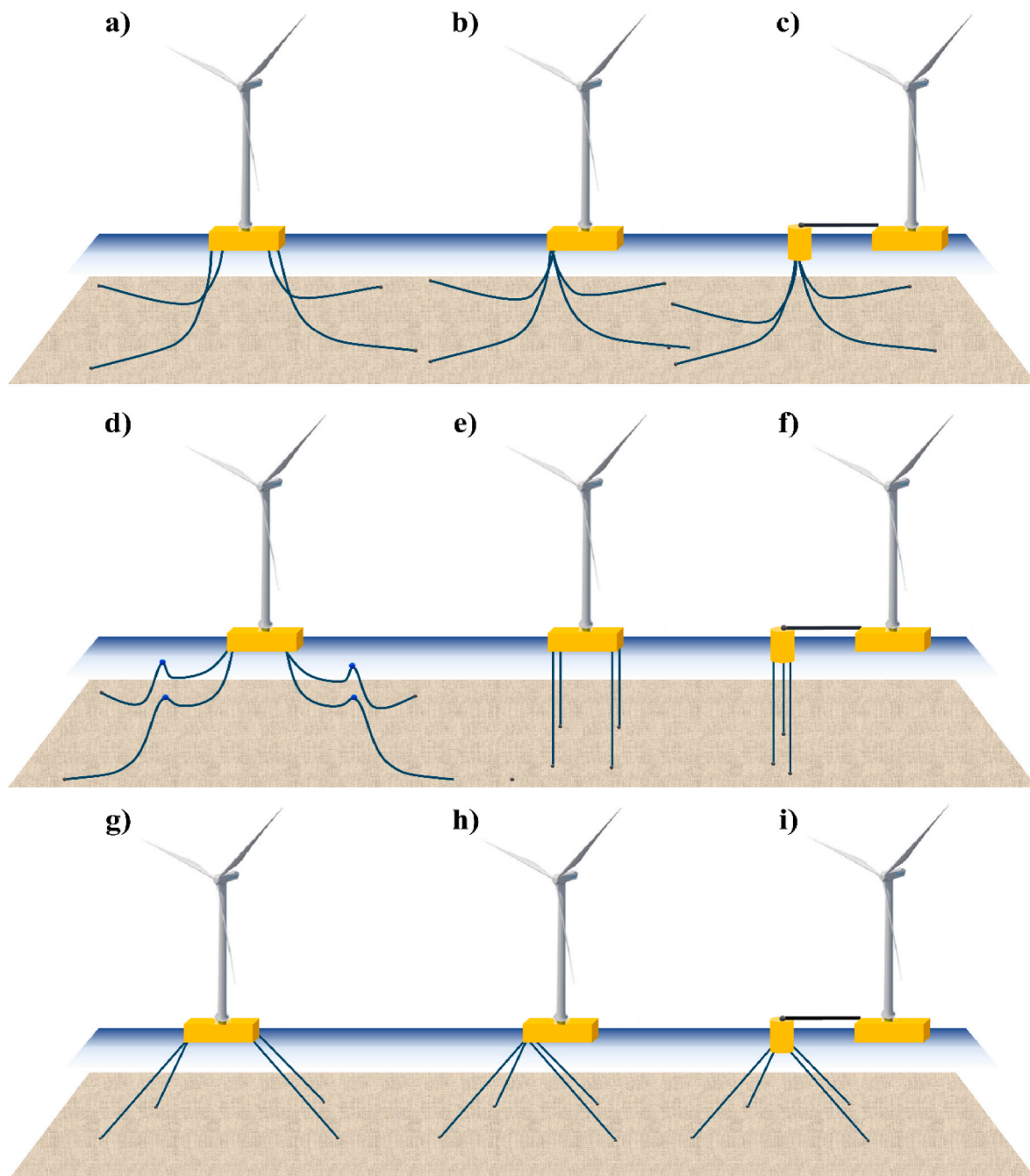
Basically, a major challenge of all OWF environmental monitoring programs is to assess cumulative impacts and to upscale locally observed impacts to a larger scale at which different ecological processes take place. Although the majority of monitoring efforts that have been done so far are concentrated on the environmental effects of a single wind farm and certain receptors (Lindeboom et al., 2011; Degraer et al., 2018; Beiersdorf, 2014), currently the goal of monitoring studies is to look into the overall impacts of OWFs and other anthropogenic activities on certain receptors (such as marine birds). For instance, using a Before-After-Control-Impact study approach and a long-term data collection, it has recently been explored how the installation of OWFs and the corresponding increases in ship traffic might affect Loon distributions in the German North Sea at a broad regional scale (Mendel et al., 2019c). The spatial distribution patterns of Loons changed profoundly between the before and after periods. Greatest decline in density was at distances within 10 km from the wind farms. The cumulative effect of OWFs and ships led to a further reduction of Loon densities that might indicate an additional negative impact of ships on bird densities at the OWF site (Mendel et al., 2019c). Long-term effect due to habitat loss can be evaluate by considering if habituation to OWFs will occur or if the effect will be prolonged. Hereof, no signs of habituation were found three years after construction of an OWF in Germany (Mendel et al., 2019c), whereas common scoters have been spotted in equal numbers both inside and outside of an OWF in Denmark (Agency, 2013; Petersen and Fox, 2007). The more observed common scoters in the OWF indicates their presence in great densities between recently built wind turbines at the sea. However, this result may not be applicable to the OWTs with a longer installation age (Agency, 2013; Petersen and Fox, 2007). The authors concluded that rather than a change in the behavior of the birds themselves the observed variations may reflect variation in the food availability at the OWF site (Agency, 2013; Petersen and Fox, 2007).

Ecologists advise expanding the scope of the impact investigation to take into account both the population level of the impacted species and the species which span over wider territories. For example, sea birds attracted to the wind farms having an increased risk of collision with the wind turbine blades. The number of collisions may actually put the

sustainability of certain bird populations at risk. However, it can only be reliably assessed by considering the multitude of wind farms throughout the range of the bird's spatial distribution (Lindeboom et al., 2015; Krone et al., 2013). According to van Berkel et al. (2020) wind farms can result in wind distortion over a radius of 5–20 km. Moreover, some studies suggested that OWFs can have an impact on primary production decline and fish behaviour up to 10 and 15 km, respectively, while farm development can have an impact on bird and mammal behaviour up to 16 and 50 km, respectively (Haelters et al., 2015; Mendel et al., 2019b). Recently, modelling exercises (i.e., agent-based models) have been suggested to evaluate the cumulative effects of numerous wind farms on the red-throated diver population in the Baltic under various scenarios. According to the assumptions, red-throated diver populations were anticipated to decline by only 0.1% as a result of current and future wind farms. The model predicted that red-throated diver numbers would only decrease by 1.7% in the worst-case scenario with the maximum expected future growth of offshore wind farms in Danish waters and throughout the Baltic (Agency, 2013). Likewise, findings from three alternative wind farm growth scenarios revealed that the Baltic Sea and Danish waters will only see extremely little effects. Nevertheless, this type of modelling approach relies on numerous assumptions and simplifications that may be very challenging to validate. Therefore, the authors of the study concluded that these findings must be considered and used with great caution (Agency, 2013). Similarly, results from an individual-based simulation model that sought to forecast the cumulative effects of ships, wind farms and bycatch on the population dynamics of harbour porpoises in the Inner Danish Waters suggested that bycatch in commercial fisheries has a greater impact on the size of the porpoise population than noise from ships and wind farms (Agency, 2013; Petersen and Fox, 2007). The results of this model should be interpreted cautiously, as with other population models that have been presented.

It is suggested that before final conclusions on the attraction-production hypothesis, even the effects that are expected to be positive from a local perspective (e.g., the improved feeding conditions for demersal fish attracted to the wind turbines) should to be evaluated at the population level (Reubens et al., 2014a). However, in order to do that, research should be conducted at both the spatial scales pertinent to the population of each specific species and the scale of the local food web. As well, threshold values for acceptable overall mortality or habitat loss should be determined based on those findings. It should be also considered that OWFs are just one of numerous human activities that have an impact on the structure and operation of the marine ecosystems (Vanermen et al., 2018a; The European offshore wind Energy Association, 2013). A holistic approach would be necessary to evaluate the cumulative impact of all those activities and frame the observed effects of wind farms in a larger context, both of which are seen to be crucial for the management of the marine ecosystems. However, the absence of study designs and the potential scarcity of knowledge make it difficult to effectively address the problem. In fact, monitoring basin-wide cumulative impacts is a tremendously ambitious task that cannot be successfully completed by a single nation or research team. To gather and thoroughly analyze all the necessary data would call for strong cooperation between scientists and administrators, ideally across national boundaries. Stock (2016) suggested that software like Eco-Impact-Mapper would be useful to study and prepare ecosystem sensitivity map, cumulative pressure map, and cumulative effect assessment (Stock, 2016). It is also worthwhile to remark that in F-OWF foundations different mooring line profiles should be considered, as shown in Fig. 10. For such technologies, possible components of the ground tackle system include; dead weight (deadman) anchors, drag embedded anchors, suction caisson/pile anchors with padeye offset and inverted catenary, pile/micropiles with padeye on top, subsurface plates, dynamically installed anchors. The main difference between FB-OWF and F-OWF from an environmental point of view is the spatial extension, the seabed intervention for foundations (habitat loss for benthonic), changes to sedimentary processes and corrosion-related

<sup>13</sup> Marine Strategy Framework Directive (MSFD).



**Fig. 10.** A schematic of different types of mooring profiles for F-OwTs: a) multi-catenary; b) multi-catenary turret; c) catenary anchor leg mooring; d) intermediate buoy; e) tension leg; f) single anchor leg mooring; g) taut spread; h) taut turret; i) taut anchor leg mooring.

risks. Additional impacts could be connected with the noise/vibration problems (Wilson et al., 2010; Díaz et al., 2022). From the perspective of cumulative impact assessment, some local positive impacts may not be positive at a larger scale. For instance, the artificial habitat reef effect for fish leads to the attraction of more predators in the area (e.g., sharks, dolphins, ...) as a result of an increase in the fish biomass that may subsequently cause a localised change in marine communities.

Finally, concerns over decommissioning of OWTs increases along with their installation. Existing wind turbines have a lifespan of approximately 20 years while little consideration has been given to the decommissioning practices (Chen and Kim, 2022; Díaz et al., 2022). Limited experience makes it difficult to predict environmental impacts of OWT's decommissioning. The potential environmental impacts could probably depend on the location of the wind farms as well as the type of

end-of-life scenario (i.e., full or partial removal). Some studies proposed that the decommissioning process could increase the amount of suspended solids, mobilizes pollutants in the sediments and affects filter-feeding organisms. Noise associated with decommissioning activities could have a potential impact on sensitive species comparable to the one observed during construction phase. In addition, removal or alteration of the generated habitats and organism on the structure (i.e., hard substrate introduced in sand dominated environment) may have indirect impacts on various trophic levels (Fowler et al., 2018; Hall et al., 2020). However, the assessment of the environmental effects of the end-of-life activities and the decommissioning industry as a whole, still needs a lot of effort. Hence, future monitoring programs should involve international collaboration to establish the necessary techniques for a long-term impact assessment of OWFs from construction to the

decommissioning phase (Joschko et al., 2008).

## 5. Conclusions and recommendations

The monitoring studies show little or local environmental impacts of FB-OWFs either during their construction or operational phases. However, it is still not clear whether several little and local impacts may cause significant biological consequences at the population level in the long term. The key lessons which are learned from EIA studies on FB-OWFs can provide an insight for future environmental monitoring programs on the emerging floating technologies. These lessons are summarized as following.

- I) EIA programs are generally designed to understand whether habitat changes occur as a result of the presence of OWFs or marine organisms change their behavioural patterns and/or avoid naturally the surrounding area affected by the construction/operation of the wind farms. Such studies are not able to detect which of the specific factors (e.g., noise, turbine presence, boat traffic or change in the prey availability) are responsible for the observed effects.
- II) Construction activities (e.g., pile driving operations) were found to produce the highest level of disturbance including underwater noise, re-suspension of the particulate matters of the seabed, magnetic field generation.
- III) Although the possible OWF impacts at the population level is still unclear, offshore wind farms have shown very little impacts on the environment.
- IV) The experiences gained at the Nysted and Horns Rev sites, Denmark, are important because of their long-term evaluations of the impacts.
- V) The tools developed for studying behavioural responses of marine mammals (e.g., the T-POD system for recording porpoise sound's production underwater) and birds (e.g., the thermal animal detection systems to measure collisions of birds) can be useful for future research on new offshore installations.
- VI) Collision risk for the sea birds could be a minor concern comparing to either the potential habitat loss or an increase in energy consumption for travelling, which might subsequently affect the survivorship.
- VII) The studies on marine mammal's responses to underwater noise demonstrate that the habitat preferences of a species could affect their response to a disturbance. Ecological importance of a site for a species and the percentage of affected population should be considered in evaluation of the impacts.
- VIII) Short-term effects do not necessarily reflect long-term effects. Long-term monitoring programs are essential to assess possible recovery from short-term impacts.
- IX) Statistical biases and natural variability in data should be carefully considered in investigation and interpretation of EIA studies on OWFs.

It is recommended to investigate cumulative impacts of OWFs at the population level in both short-term and long-term in future studies, since their neglect may cause a bias in the EIA results. As well, it is suggested that future monitoring studies involve regional or international cooperation for an effective data and experience sharing.

## Author contributions

AA- Conceptualization, methodology, investigation, original draft preparation, writing, reviewing and editing. FR- Investigation, writing, original draft preparation, draft reviewing and editing. PC- Supervision, writing, reviewing and editing. DV- Supervision, writing, reviewing and editing. All authors have approved the final article.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Pasquale Contestabile, Diego Vicinanza reports financial support was provided by Ministry of the Environment and Energy Safety (MASE), Italy.

## Data availability

Data will be made available on request.

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