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Ecosystem Benefits of Floating Offshore Wind

MaREI – Science Foundation
Ireland Centre for Energy,
Climate and Marine

University College Cork

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Executive Summary

The offshore renewable energy (ORE) sector is at a crucial moment with multiple governments enacting policies and legislation that will decisively accelerate the expansion of offshore renewable energy globally. Floating offshore wind energy will become increasingly important over the next decade and this report seeks to elucidate the potential ecosystem benefits of floating offshore wind energy developments. The known ecosystem impacts of ORE fall under 7 broad categories:

- Changes to the atmosphere and ocean/energy removal
- Sound pollution
- Electromagnetic Fields (EMF)
- Habitat modification - artificial reef effect
- Barrier effects
- Water quality – chemical pollution
- Fisheries exclusion and displacement

There is general acceptance that habitat modification and the fisheries exclusion have the potential to confer substantial ecosystem benefits, while changes to the atmosphere and ocean are tentatively identified as potentially having some ecosystem benefits. Floating offshore wind (FOW) developments are likely to result in partial or complete restrictions on fishing activities within the boundaries of a development, essentially creating non-statutory marine protected areas, also called Other Effective Area-based Conservations Measures (OECMs). This is important because over-exploitation and damage from bottom trawling results in a substantial decrease in biodiversity, abundance, and biomass, particularly on benthic biogenic reef habitats, with negative implications for fundamentally important ecosystem functions and services. The exclusion of damaging activity such as trawling allows benthic habitats to recover, developing diverse and complex infaunal and epifaunal communities, attracting more mobile species, and enhancing benthic-pelagic coupling which is vital for ecosystem functioning. The evidence from existing marine protected areas highlights the ecosystem benefits of area closures, positively impacting biodiversity, abundance, organism size, and abundance compared with surrounding unprotected areas. Five key features which increase MPA efficacy are 1. no take, 2. Enforcement, 3. More than 10 years old, 4. More than 100 km^2, and 5. Isolated by deep water or sand.

FOW infrastructure can act as artificial reefs and fish aggregating devices (FADs) which increase habitat complexity and positively influence biodiversity by providing refugia, nursery grounds, and enhanced larval settlement. The degree to which FOW devices will act as FADs and artificial reefs is not well understood, however, recent surveys on the Hywind Scotland spar turbines recorded 121 epifaunal and mobile species. Evidence suggests that similar oil and gas (O&G) platforms are among the most productive marine fish habitats, comparable with designed reef habitats, benefiting pelagic and demersal fish species, and hosting diverse invertebrate communities. O&G platforms also attract a diverse range of large migratory species, including fish, sharks, reptile, marine mammals, and turtles, although, the nature of their interaction with structures remains poorly understood.

FOW farms are likely to create oceanographic change, or a wake effect, via two main mechanisms: 1) Current flows flowing around infrastructure will create a wake effect, and 2) wind flow over and around an array of turbines will create a wind shear that can generate vertical rotation in the water column, i.e., upwelling and downwelling. These wakes increase turbulence and vertical mixing which can enhance primary productivity, with positive bottom-up effects for mid and high trophic level taxa. The increased turbulence also creates valuable foraging and resting opportunities for larger mobile species.

The most likely ecosystem benefits of FOW will accrue because of area protection in combination with the artificial reef (and FAD) effect. There are possible positives and negatives associated with any oceanographic wake effect and the scale and magnitude of these is uncertain at present. The ecosystem impacts of multiple FOW developments across large continental shelf regions remain highly uncertain and research priorities need to address cumulative spatial and temporal impacts at the population level of potentially impacted species. Achieving these goals will require greater collaboration at regional and international levels, working towards shared standards of data collection and analysis, and adapting the current regulatory approach to ensure ecosystem benefits can be detected in a cost-effective manner.

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1 Introduction

The offshore renewable energy (ORE) sector is at a crucial moment with multiple governments enacting policies and legislation that will decisively accelerate the expansion of offshore renewable energy globally. To date, Europe has led the way, beginning in the early 90s with the first fixed bottom wind turbines, increasing from 0.8 GW in 2006 to 3.3 GW in 2021 (Breton and Moe, 2009; Causon and Gill, 2018; Wieczorek et al., 2013). In 2021, an additional 21.1 GW of offshore wind capacity was commissioned, and growth is expected to continue, adding a further 90 GW from 2022 - 2026 (Global Wind Energy Council, 2022). A large proportion of recently commissioned offshore energy developments are in China, although the US, Brazil, Australia, India, and other countries are progressing their own plans (Global Wind Energy Council, 2022).

This expansion in ORE is clearly driven by the need to reduce greenhouse gas (GHG) emissions as human society strives to stay within a 1.5 °C average global temperature increase. Failure to achieve this has enormous negative implications for individual and societal health and wellbeing. Likewise, every incremental increase in warming up to and beyond 1.5 °C will result in increasingly severe environmental change, damage, and the loss of terrestrial and marine ecosystems globally. In terrestrial ecosystems, warming of 1.5 – 5 °C means 14 – 48% of species face a very high risk of extinction (Bednar-Friedl et al., 2022). Marine biodiversity is difficult to assess because we do not fully understand the number of extant species (Appeltans et al., 2012; Foggo et al., 2003; McQuatters-Gollop et al., 2022), however, warming of 1.5 °C means moderate to very high risks of biodiversity loss. Endemic species in biodiversity hotspots will be particularly vulnerable and increased warming, from 1.5 – 3 °C may result in a 10-fold increase in losses (Bednar-Friedl et al., 2022). In this context, the single greatest ecosystem benefit accruing from a sustainable transition to renewable energy will be a global benefit – the conservation of countless species and ecosystems (Snyder and Kaiser, 2009). While it is important to always keep this in mind, the expansion of ORE will include the construction, operation and decommissioning of infrastructure which will have ecosystem impacts at a local and regional scales, and these impacts are the focus of this report. Specifically, this report seeks to elucidate the potential ecosystem benefits of floating offshore wind energy developments.

2 Environmental Impacts of Offshore Energy Development

Environmental assessments and research efforts to date have largely been concerned with understanding the potential risks and negative ecosystem impacts of ORE developments (Bailey et al., 2014; Copping et al., 2020; Gill, 2005). This is understandable, as identifying and quantifying adverse impacts (stressors) is clearly important and might be considered a ‘need to know,’ whereas potential ecosystem benefits were likely considered a less important ‘nice to know’ (Wilson et al., 2010). This has resulted in large knowledge gaps that must be addressed, as developing a more complete understanding of all ecosystems effects is vital for planning where future sites will be situated as part of a fully integrated ecosystem-based MSP framework. Another reason for the slower realization or recognition of ecosystem benefits is simply because, until developments were constructed and operational for several years, this knowledge did not exist. Now that there have been large scale developments in operation for >10 years, it is becoming clear that there are ecosystem benefits associated with fixed bottom wind farms, and some of the potential risks are perhaps not as severe as predicted (Inger et al., 2009; Wilson et al., 2010; Wilson and Elliott, 2009). Recent reviews/reports do an excellent job of collating all the relevant research, capturing ecosystem impacts under 7 broad categories, and showing that the specific effects of different technologies will depend on the habitat type and the species communities within (Boehlert and Gill, 2010; Copping et al., 2016; Farr et al., 2021; Gill, 2005; Gill et al., 2020; Hammar et al., 2016; Inger et al., 2009). In no order of importance, the 7 categories are.

- Changes to the atmosphere and ocean/energy removal
- Sound pollution
- Electromagnetic Fields (EMF)
- Habitat modification - artificial reef effect
- Barrier effects
- Water quality – chemical pollution
- Fisheries exclusion and displacement

2.1 Changes To the Atmosphere and Ocean Dynamics Due to Energy Removal

Studies on fixed bottom wind farms demonstrate changes in wave height, current velocity, and turbulence within and downstream of farms have the potential to effect turbidity, light penetration, and primary productivity, with both positive and negative implications for pelagic and benthic ecosystems (Carpenter et al., 2016; Cazenave et al., 2016; Inger et al., 2009; van der Molen et al., 2014). In general, models indicate that wind farms will have relatively small ecosystem effects, particularly in shallower tidally mixed areas (Carpenter et al., 2016; van der Molen et al., 2014), however, larger scale wind farms may begin to impact seasonal stratification and thus vertical mixing with more significant ecosystems effects (Carpenter et al., 2016). Investigations using remote sensing (LIDAR and satellites) indicate that wind farms also create an atmospheric wake, with reduced wind velocity and increased turbulence extending approximately 5-20 km downstream, although there is no horizontal dispersion of the wake (Porté-Agel et al., 2020). The atmospheric wake from FOW is unlikely to differ and although turbines will be substantially larger than current fixed bottom turbines, it is unclear if this will affect wake dispersion. Although FOW turbines will use mooring systems rather than a monopile or jacket that descends to the seafloor (section 3), hydrodynamic models suggest that wind shear around the turbines will create a substantial wake effect, with upwelling and downwelling downstream of the farm (Ludewig, 2015). The potential ecosystem impacts are likely to be the same as those outlined for fixed bottom, although due to the greater depth there may be less impact on the benthic ecosystem. The wake effect may benefit some mobile predators, providing an enhanced area of foraging (Lieber et al., 2019) and potentially enhance primary productivity, benefiting higher trophic levels, however, the overall ecosystem impact remains uncertain.

2.2 Sound Pollution (noise)

Sound (noise) will be generated by all human activities associated with every phase of ORE development. Installation, particularly if it involves piling, and decommissioning will be periods of increased sound pollution, although these tend to be short in duration. Operational sound will be less intense and may not be continuous, but it remains a concern to regulators (Copping et al., 2016). Although not fixed to the sea floor, some FOW mooring systems may still require piling, for example, tension leg platforms (TLP), but the intensity and duration will not be great by comparison with fixed bottom turbines. Operational noise from gearboxes, tower vibration and generators are low frequency, at low decibel levels, and is considered unlikely to negatively affect most species (Farr et al., 2021). The highest measured sound pressure level from an operational fixed bottom turbine is 137 dB re 1 μPa at a distance of 40 m and emitted sound is attenuated rapidly with distance (Tougaard et al., 2020). Operational turbines sounds are 10 – 30 dB lower than ship sound in the same frequencies (Tougaard et al., 2020). It is expected that FOW, with its reduced submerged structures which are built into the sea floor, will reduce sound transmission to the environment. At present, there are no measured sounds levels for FOW, however, the FORTUNE project is Scotland is currently investigating this and results are expected in 2022. There is no evidence indicating that sound pollution will be beneficial to the receiving environment.

2.3 Electromagnetic Fields (EMF)

Electromagnetic fields are generated by devices and cables that carry an electrical current and many species are sensitive to EMF, using it to navigate (e.g., salmon), forage (e.g., elasmobranchs), and possibly communicate (Copping et al., 2016; Gill and Desender, 2020; Zoe L. Hutchison et al., 2020). At present EMF is considered unlikely to significantly alter survival and fitness of sensitive species (Farr et al., 2021; Gill and Desender, 2020; Taormina et al., 2020), however, studies outside the laboratory are few and a limited number of species have been investigated. Studies on fish and invertebrate species have demonstrated that EMFs produced by cables and other structures do not present a barrier, although behaviour can be affected. Exposure to the EMF from a buried high voltage direct current (HVDC) cable instigated increased foraging behaviour in a demersal skate species (Zoe L. Hutchison et al., 2020) and magnetic fields in lab experiments were found to affect the behaviour of brown crab and induce stress at levels likely to be emitted from buried cables (Scott et al., 2021, 2018). Many of these studies used small numbers of animals with a single cable or structure and uncertainty remains over the effect of a scaled-up development with extensive interconnecting cables, which may be buried, unburied and dynamic. In addition, in situ measurements on both HVDC and HVAC, carrying variable current magnitudes and emitting variable EMFs are lacking. The ecosystem impacts of EMF remain uncertain, particularly with respect to scale and cumulative effects.

2.4 Habitat Modification

Habitat modification includes the introduction of novel structures that will inevitably provide new habitat, which is often called the 'reef effect.' The reef effect can be perceived as either positive or negative, with some concerns including the effect of biofouling on device operation and colonization by non-indigenous species. In Belgian waters, fixed bottom turbines are colonized by non-indigenous species, predominantly intertidal species, however, all these species were already established on artificial and natural substrates (Kerckhof et al., 2016). Kerckhof et al. (2016) concluded that existing subtidal turbine habitats will make a marginal contribution to the spread of non-indigenous species which would suggest that FOW with no intertidal area will likewise present a minimal risk. Nonetheless, the scale of future ORE developments and climate change mean that the monitoring of non-indigenous species must be maintained.

A growing body of literature suggest that the positives outweigh the negatives and artificial reefs can enhance biodiversity, increase invertebrate and fish biomass, especially when developments are placed on homogenous benthic habitats (Farr et al., 2021; Hammar et al., 2016; Inger et al., 2009; Langhamer, 2012). Fixed bottom turbines and the scour protection around them create substantial areas of reef habitat and while FOW will not have foundations, some anchoring systems and seabed cables will need some form of scour protection and/or rock armoring. Floating foundations will vary in size and depth depending on the design used and will (Gavin & Doherty Geosolutions, 2022; Zountouridou et al., 2015), with the possible exception of spar type turbines, present a greater 3-dimensional area for biofouling and reef formation in comparison with fixed bottom. Moreover, large floating structures are known to attract a wide variety of large mobile fauna and their ability to create a living reef with permanent, semi-permanent and transient fauna suggests they can be a net ecosystem benefit (Claisse et al., 2014). FOW will create artificial reefs in the benthic and pelagic habitats leading to some demonstratable ecosystem benefits (Farr et al., 2021; Hammar et al., 2016).

2.5 Barrier Effects

Barrier effects include both collision risk for seabirds and marine mammals, and the imposition of large potentially inaccessible areas that will force migrating or foraging animals to increase travel distances to avoid ORE developments. Collision risk for seabirds remains a prominent concern for regulators, although studies suggest that for many species, flying around developments is not energetically expensive, and they fly between turbines or beneath blades with low collision risk (Farr et al., 2021). Collision risk is multifactorial, depending on species, flight behaviour, location, distance from land, turbine spacing, visibility, lighting, blade colour, blade height and blade velocity (Adams et al., 2016; Ainley et al., 2015; Garthe and Hüppop, 2004; May et al., 2020). In terms of FOW, the increased distance from land will likely reduce the number of species at risk, and the larger turbine spacing will likely reduce the risk of collision. Collisions or entanglements between marine mammals and dynamic cables is discussed in the literature, although there is little anecdotal or quantitative evidence to indicate that this has ever been a problem for the large number of existing floating structures with the catenary or semi-taut mooring, which is most likely what FOW will use (Copping et al., 2020; Farr et al., 2021). Secondary entanglement with lines and nets caught on mooring lines and cables may be a moderate risk for large baleen whales (Benjamins et al., 2014). There is no evidence that the barrier effect has any beneficial effect on the receiving environment.

2.6 Water Quality – Chemical Pollution

Chemicals will leach into the water from antifouling and anti-corrosion paints or coatings applied to structures. In addition, sacrificial anodes will mean a substantial quantity of aluminium (maybe other metals) per structure will enter the ecosystem. There are a range of negative effects associated with biocidal antifouling coatings and with the long-term presence of ORE structures there is a risk of bioaccumulation in the immediate sediment around structures (Copping et al., 2016). Spills of mineral oils, lubricants, hydraulic fluids, and other petroleum-based compounds is a risk, although it is deemed low (Karlsson et al., 2022). There is no evidence that any of these chemical pollutants will have a beneficial effect on the receiving environment.

2.7 Fisheries Exclusion

Commercial fishing and particularly benthic trawling does significant damage to the marine ecosystems by removing large mature fish and destroying benthic habitat (Jennings and Kaiser, 1998; Kaiser et al., 2006, 2000). Regulations within ORE sites will likely vary from country to country, for example, Belgium prohibits all fishing inside ORE sites but Germany and the UK allow some types (Gill et al., 2020). Given the depth, distance from shore and exposure of most

FOW sites, they will be largely inaccessible to small coastal vessels. Moreover, it is likely that exclusion zones will be enforced around FOW sites, effectively closing these areas to all commercial or recreational fishing. This means that FOW sites may operate at a high level of protection – higher than many statutory partial MPAs created for the express purpose of nature conservation. The success of a site in terms of conservation and/or a return to a natural state is largely dependent on the size of the area, the duration of protection, and the level of protection (Costello and Ballantine, 2015). Area restrictions and closures may displace fishing effort, which is difficult to predict and quantify. Substantial displacement of effort into previously less intensively fished areas may well undermine the hoped-for ecosystem benefit from a wider regional perspective. Restrictions and displacement will be challenging for the fishing industry, however, if well managed as part of a coherent MPA network, these areas can potentially benefit the industry via enhanced larval recruitment and spillover effects of increased number of fish in none restricted areas.

3 Floating Offshore Wind Infrastructure

The development of FOW turbines has predominantly taken place in Europe to date, with the first installation of a floating ‘spar’ turbine by Equinor in Norway, 2009, with a single 2.3 MW turbine anchored in 220 m depth. This turbine has survived 40 m^{-s} winds and 19 m waves to date (Vicente, 2020). The first wind farm with five 6 MW turbines, also using the Equinor spar design, was installed off the Scottish coast, by Hywind Scotland, and is operational since 2017. Subsequent FOW developments include WindFloat Atlantic, off the Portuguese coast, and Kincardine Offshore Wind Farm, off the eastern Scottish coast, both using a semi-submersible concept design developed by Principle Power Inc. The Kincardine array (commissioned in 2021) is currently the largest floating wind farm in the world, comprising 5 turbines with a capacity of 9.5MW each (Chitteth Ramachandran et al., 2022).

The aforementioned and planned FOW farms use a number of design concepts at different levels of technology readiness: these 1) include buoyancy stabilized barge or semi-submersible platforms, 2) ballast stabilized spar buoy platforms, and 3) tension leg platforms (Gavin & Doherty Geosolutions, 2022; Zountouridou et al., 2015) (Figure 1). Each design aims to achieve stability through a combination of ballast, buoyancy, and mooring tension (Ikhennicheu et al., 2021). The ultimate design chosen at a particular site will depend on numerous factors including depth, significant wave height and wind speeds (metocean conditions), seabed characteristics, capacity of the nearest port, local supply chain capacity, and costs. For example, the spar buoy used by Hywind Scotland, with a draft of 78 m, are optimized for deep water and require deep-water harbouring for construction, integration, and wet storage. As such, they are well suited to deep fjords, e.g., Norway, but unsuitable for the shallow depths in Irish ports. In fact, many ports across Europe and all Irish ports, except for Belfast, lack the depth and facilities to support the ORE industry (Gavin & Doherty Geosolutions, 2022). Platforms can be manufactured using steel or concrete and the choice of material is likely to be influenced by design applicability, cost, carbon footprint and local supply chains. The type of material used by a project will likely come down to careful consideration of the factors outlined above and how they may impact on the development's CAPEX/OPEX costs, timeline, longevity, and ability to consent.

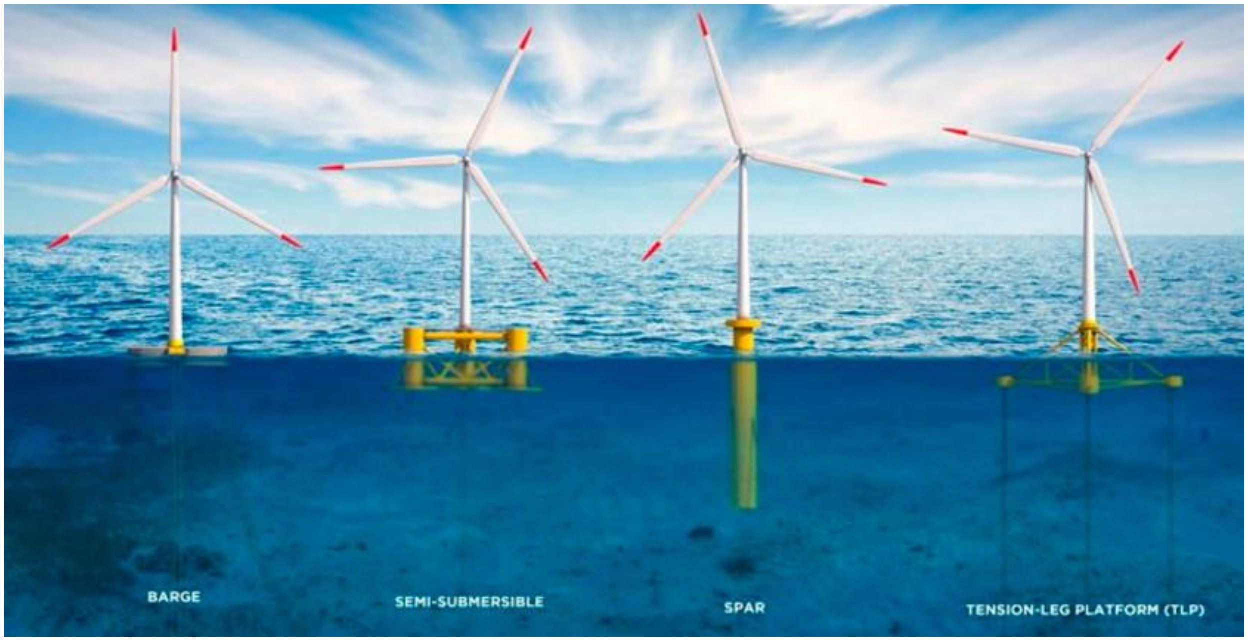

Figure 1. Semi-submersible and spar concepts are the most progressed in terms of Technology Readiness Level (TRL) with the Equinor and Principle Power Inc. designed projects that have been deployed to date, as discussed above. While these deployments have been largely successful, they are not considered optimal in all circumstances.

Mooring systems will be influenced by many of the same factors already outlined above, namely, depth, substrate type, metocean conditions etc. Commonly used anchoring systems include dead weight (gravity), driven pile, drag anchor, suction pile, torpedo pile, and vertical load anchor

(Figure 2). In addition, the configuration of these mooring systems can vary considerably, with catenary moorings needing a greater ‘swept area’ of seabed when compared with taut moorings. TLP floaters will typically involve vertical or near-vertical mooring lines (See TPL in Figure 1), but other floater concepts may also consider taut moored solutions with greater splay angles, and ultimately the anchor type will depend heavily on the mooring configuration chosen (Ma et al., 2019).

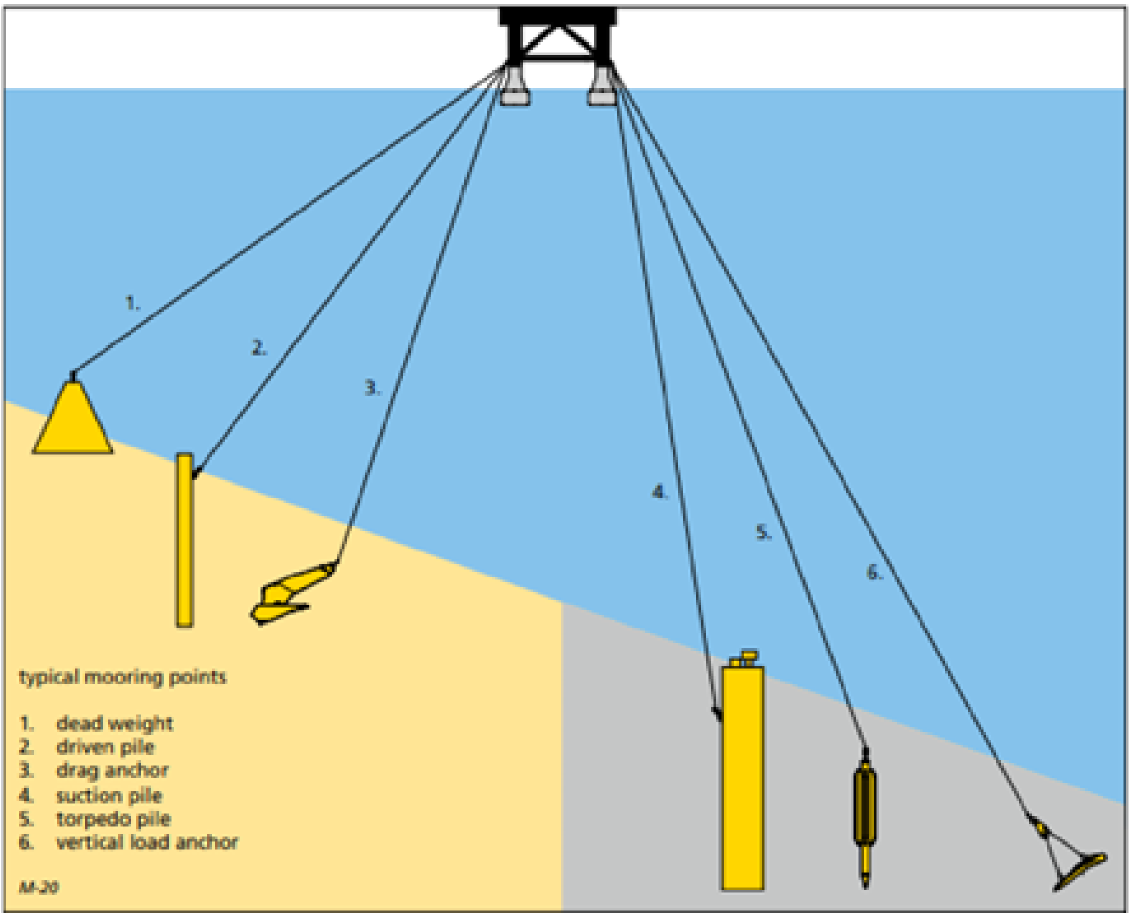

Figure 2. Commonly used anchoring systems for offshore floating infrastructure.

Each platform design and its respective anchoring system will present different characteristics to the receiving marine environment, influencing the type of biofouling and reef community that will develop on the foundations, and the way in which large mobile vertebrates might use it. Catenary mooring lines will need greater area and literally sweep across the sea floor, whereas, taut or TLP mooring lines will rise immediately away from the sea floor. Each anchor type will present a variable area of hard surface for colonization, with different 3-dimensional shapes that may or may not act as a refugia for cryptic species.

4 Potential Ecosystem Benefits of Floating Offshore Wind

Considering all the known ecosystem impacts of offshore energy developments (Section 2), there is general acceptance that **habitat modification** and the **fisheries exclusion** have the potential to confer substantial ecosystem benefits (Gill et al., 2020; Hammar et al., 2016; Inger et al., 2009; Wilson et al., 2010; Wilson and Elliott, 2009). In addition, **changes to the atmosphere and ocean** are tentatively identified as potentially having some ecosystem benefits. These factors can positively effect biodiversity, abundance, biomass, and biogeochemical cycling (incl. carbon sequestration). These are fundamentally important for ecosystem functioning and services and can have positive effects over local and regional scales as offshore renewable energy is scaled up through the creation of artificial reefs on novel hard structures and the restoration of benthic and pelagic ecosystems.

The offshore floating wind industry is nascent, with the largest floating wind farm currently consisting of 5 turbines in Kincardine, Scotland (Chitteth Ramachandran et al., 2022), and therefore, the evidence for proven and potential ecosystem benefits must be gleaned from elsewhere. Substantial fixed bottom OWFs have been operational in the North Sea for 10 years or more and a lot of the studies presented in this report are based on fixed bottom wind turbines in < 30 m of water. While some insights can undoubtedly be gleaned from fixed offshore turbines, the introduction of FOW turbines is likely to impact the ecosystem in different ways. Moored structures will move horizontally and vertically to some extent, and will not have an intertidal zone, which is likely to influence the biofouling and reef community that develops. Cables and mooring lines will introduce hard structures at far greater depths than current fixed bottom turbines (maximum 60 m depth) and are likely to develop different biofouling communities (Karlsson et al., 2022). The distance from the intertidal/coastal zone and increasing depth mean that the species community which colonize and associate with these artificial reefs may be unlike the nearest natural reef communities. Pelagic species are likely to use and aggregate around infrastructure, however, it is not clear that aggregation means an actual increase in abundance or biomass. Many of the potential ecosystem benefits that might arise from the installation of offshore floating wind are also identified as being knowledge gaps; artificial reef effects, changing fish community assemblages, the creation of ‘no-take’ or ‘reduced-take zones’ are all identified as topics in need of research (Wilson et al., 2010; Wilson and Elliott, 2009). Where developments take place is likely to be important: while the negative impacts of existing OWF have been less severe than predicted, caution is being advised in regions where there is no expansive shelf, diverse and vulnerable benthic habitats, and protected areas that might be impacted (Lloret et al., 2022). Looking towards the oil and gas industry which has constructed and operated thousands of platforms across the world is useful for trying to predict the impact of FOW infrastructure, however, the number of empirical studies on this type of infrastructure is relatively small and gives us limited insight (McLean et al., 2022; Todd et al., 2016).

5 Fisheries Exclusion

Offshore renewable energy developments are in competition for maritime space and commercial fisheries will most likely be the sector most effected (Gill et al., 2020; Methratta et al., 2020). FOW developments are likely to displace some fishing activities and force a partial or complete ban on fishing activities within the boundaries of the development. Depending on the country and specific health and safety concerns, fixed bottom developments exclude trawling, but may allow static gear like tangle nets and pots etc. Because of the complex mooring systems and cables in FOW developments it seems most likely that all mobile gear will be excluded from a FOW array area due to difficulties with navigation, safety, physical obstruction, snagging gear, all of which may impact insurance cover (Gill et al., 2020; Inger et al., 2009; Methratta et al., 2020). This will essentially create non-statutory marine protected areas, also called Other Effective Area-based Conservations Measures (OECMs), which are designated areas that preclude damaging human activities, despite the designation not explicitly being a conservation measure (IUCN, 2018). A broad definition states: “*Private, local, community managed and non-statutory protected or semi-protected areas that are managed in a way that has conservation benefits all qualify as OECMs*” (Diz et al., 2018). This is distinct from MPAs which are created and putatively managed for the purpose of conserving and/or restoring nature by conferring a higher level of legal protection compared with the surrounding area (Humphreys and Clark, 2020). MPAs can be placed on a scale of protection level - there is a 4-point scale from minimally protected to fully protected with zero extractions allowed (Grorud-Colvert et al., 2021). Presently, society is failing to meet marine conservation targets (Nature, 2020): the UN Convention on Biological Diversity (CBD) Aichi target 11, protecting 10% of coastal and marine areas by 2020 has not been achieved and there is a recognition that MPAs alone will not achieve future conservations goals. Arguably, OECMs and MPAs can be complementary in achieving protection for greater areas of the marine environment, if managed within a coherent marine spatial planning (MSP) framework (Diz et al., 2018; Estradivari et al., 2022; Rodríguez-Rodríguez et al., 2021).

5.1 Impacts of Commercial Fishing

Over-exploitation and damage from bottom trawling results in a substantial decrease in diversity, abundance, and biomass, particularly on benthic biogenic reef habitats (Dias et al., 2020; Freiwald et al., 2004; Kaiser et al., 2006, 2000; Maldonado et al., 2017; Ponti et al., 2021; Sala et al., 2021; Tillin et al., 2006). Without fishing pressure, it is estimated that the North Sea would have 100 times more large fish (Hoffmann, 2005; Jennings and Blanchard, 2004; Lotze and Worm, 2009). Moreover, the changes inflicted on the physical structure of the benthic habitat and the species community have negative implications for fundamentally important ecosystem functions and services (Jennings and Kaiser, 1998; Kaiser et al., 2006; Middelburg, 2018; Tillin et al., 2006).

Natural, pristine benthic habitats are rich diverse ecosystems with meiofauna (animals between 500 – 40 µm in size, e.g., nematode worms), large infauna (bivalves – clams etc), and epifauna (seapens, cnidarians (corals and anemones), sponges) living within and on the sediment. Epifauna and infauna (burrowers, diggers, also called bioturbators) are integral to the oceanic biogeochemical cycles and benthic-pelagic coupling and bottom trawling demonstrably reduces their abundance (Middelburg, 2018; Olsgard et al., 2008; Pikesley et al., 2021). The substrate type influences the type of community present; for example, mud and coarse sediments may be dominated by infauna and epifauna, respectively, however, in either case, trawling results in a reduction in the biomass and abundance of large slow growing species that provide structure and complexity which are positively associated with biodiversity (Olsgard et al., 2008; Pikesley et al., 2021). Damage from trawling is variable, depending on gear type and substrate type, ranging from partial to complete destruction, particularly where repeated trawling takes place. Intense trawling results in smaller, faster growing, faster maturing species, characterised by mobile scavenging fauna (Pikesley et al., 2021), whereas lightly trawled areas have larger bodied, slow growing and maturing species, dominated by sedentary fauna (Tillin et al., 2006). Intensely trawled areas are influenced by disturbance, whereas, pristine habitats are more influenced by interspecific competition for space and resources (Tillin et al., 2006), resulting in a more diverse and complex community, that create a more complex substrate – water boundary (i.e., benthic-pelagic coupling), which in turn encourages the presence of other epifauna to occupy the niches created.

5.1.1 What is Benthic-pelagic coupling – why is it important?

Benthic–pelagic coupling refers to the transfer and processing of energy, oxygen, nutrients, and biomass between the pelagic and benthic habitats, and it influences biological productivity, community structure, and ecosystem or foodweb stability (Griffiths et al., 2017; Marcus and Boero, 1998; Rodil et al., 2020; Rowe et al., 1975). The substrate type (mud, sand, gravel, rock etc) and the infaunal and epifaunal species found therein have important implications for biogeochemical cycling (Ehrnsten et al., 2020; Middelburg, 2018; Norkko et al., 2013). Small species (e.g., nematodes) can double nutrient fluxes, while macrofauna (e.g., benthic clams) can increase nutrient fluxes by a factor of 2 – 10 times (Griffiths et al., 2017). Size can be an important, larger macrofauna have a disproportionate effect through enhanced bioturbation (Norkko et al., 2013). Bioturbation is the constant mixing and disturbance of the sediment, encouraging microbial growth which is vital for remineralizing nitrogen and silicate back into inorganic form, readily transferrable back into the water column (Olsgard et al., 2008). Macrofauna are tightly coupled to the pelagic ecosystem and primary production, responding rapidly to increases in phytoplankton growth and subsequent deposition of biomass to the seafloor (Rodil et al., 2020). The response varies between species and also varies depending on the life stage or maturity of a single species, with some species profiting directly from deposition while others profit from degraded/processed deposition made more available through meiofaunal or microbial action (Rodil et al., 2020). Furthermore, different species have variable effects on different nutrients, e.g., polychaete worms have a negligible effect on denitrification, but do enhance phosphorus retention in sediments (Norkko et al., 2013).

5.1.2 Important ecosystem engineers – biogenic habitats

Several groups of animals are particularly important at creating benthic habitat and thus likely to be important in restoring a natural ecosystem and benthic-pelagic coupling (Figure 3). These so called ‘ecosystem engineers’ build habitats that increase biodiversity by creating complex structure, creating shelter/refugia, enhancing settlement of other larvae, and enhancing foraging opportunities for mobile species (Bradshaw et al., 2001; Griffiths et al., 2017; Kaiser et al., 2006; Marcus and Boero, 1998; Miatta and Snelgrove, 2022; Tillin et al., 2006). Cold water corals (e.g., *Lophelia pertusa*) are emblematic of this group, but sponges, cnidarians, and sea pens (also sea feathers) are also important ecosystem engineers. Cold water corals can be found from 40 m depth down to 1000s m depth, and are often found in otherwise soft, muddy benthos, analogous to an island in an otherwise homogenous ecosystem – a biodiversity hotspot (Freiwald et al., 2004; Roberts et al., 2006). They are slow growing and fragile which make them particularly vulnerable to modern bottom trawling. Like their tropical counterparts, cold-water corals are home to thousands of other species, in particular animals like sponges, polychaete, crustaceans, molluscs, echinoderms, and fish. Although corals are generally associated with hard substrates at depths below 200m, they have been recorded growing on oil and gas structures in the North Sea at approximately 70 m depth and fishing records from different regions suggest coral and sponge by-catch is not uncommon (Shester and Ayers, 2005).

What impact FOW sites may have on cold water coral restoration is highly uncertain, but it is reasonable to suggest that the benthic and dynamic FOW structures could be settled by coral larvae and encourage colonies to grow (Roberts, 2000) (See section 4.4 for this topic). Sponges are important reef building organisms, a wide range of species are found from the sub-tidal to the abyssal and they can form substantial long-lived reefs on soft mud, sand, and gravel benthos (Maldonado et al., 2017). They can filter large quantities of water, removing bacteria and particulate organic matter, and are integral to biogeochemical cycles, storing nitrogen, carbon etc, and providing a complex habitat and foraging opportunities for other taxa (Maldonado et al., 2017). Similarly, sea pens are found from the intertidal to the abyssal and are particularly adaptable, finding purchase in homogenous soft sediments such as mud, sand, fine rubble, or abyssal ooze (Williams, 2011). Their ability to form dense sea pen fields in these habitat types makes them unusual, as most other reef builder require some hard substrate to thrive.

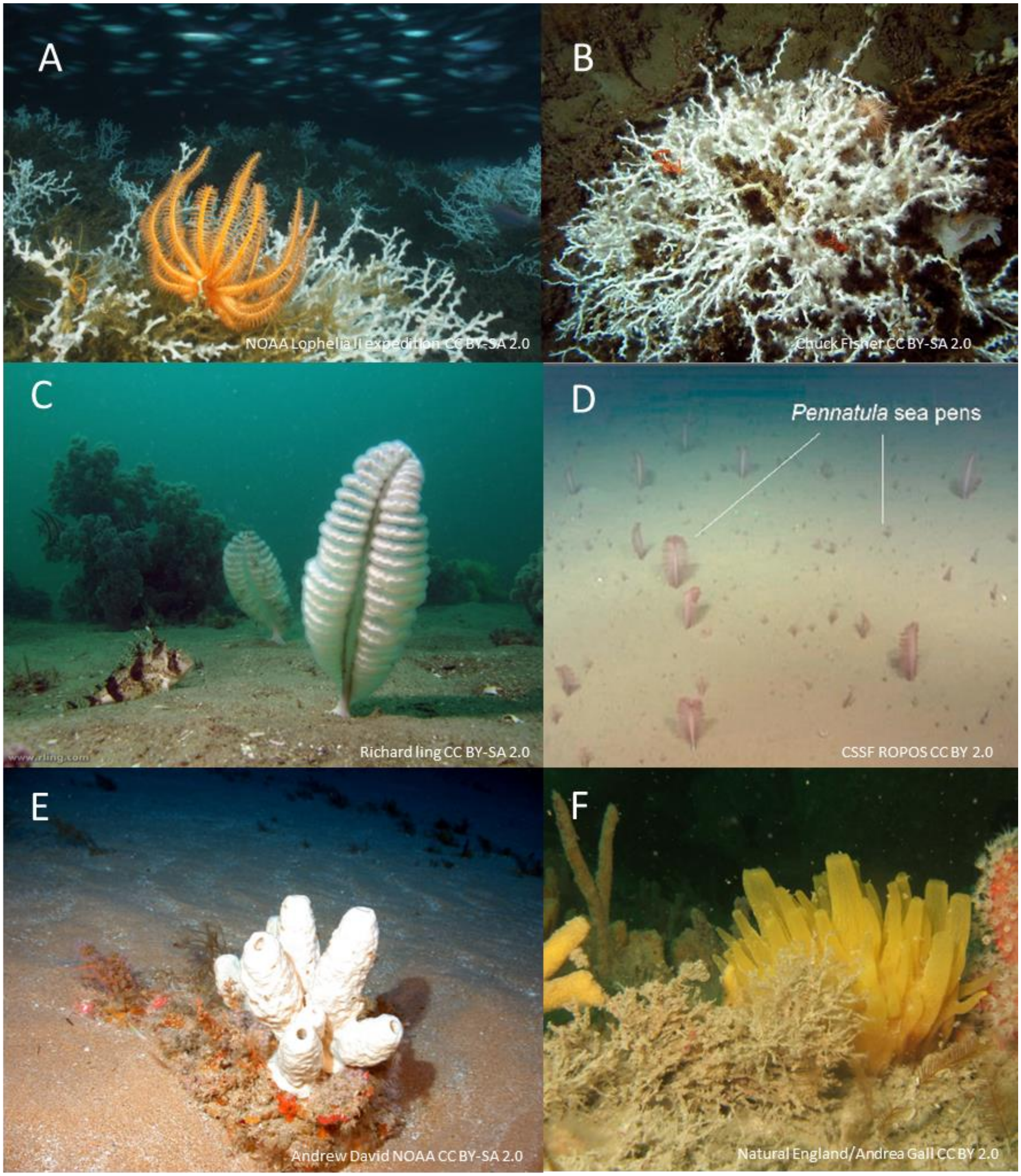

Figure 3. Biogenic reef building organisms: (A) *Lophelia pertusa* at 450 m in Viocsa knoll, with orange backet star. (B) *L. pertusa* thicket on upper slope, Gulf of Mexico, with galatheid crabs, sea urchins, and sea lilies. (C) Kidney sea pens *Carcopyilus grandis*. (D) Sea pen field in the Laurentian Channel MPA. (E) Sponge, Southeast U.S. shelf/slope region. (F) Sponge community on circalittoral shelf, UK.

These suspension feeders can alter flow, enhance the retention of nutrients, stabilize the substrate, and create a complex habitat for other species including some commercial fish species (Miatta and Snelgrove, 2022).

5.1.3 Benthic ecosystem recovery

The reported partial recovery time for some benthic fauna, e.g., cnidarians and sponges, after scallop dredging is greater than 2 years (Kaiser et al., 2006). This is consistent with a 2–5-year recovery time of biogenic fauna on the Georges Bank and in the Irish Sea after closing the scallop fisheries (Collie et al., 1997; Kaiser et al., 2006). Partial recovery post trawling can be rapid, although there is large uncertainty over the time needed for a full recovery, or indeed if some systems can ever recover fully. Areas closed to fishing are relatively uncommon and in fact most MPAs allow fishing, nonetheless, there is growing evidence suggesting that closures have positive ecosystem effects. Closed areas off Cornwall supported a greater abundance of sedentary large slow growing fauna (pink sea fans and branching sponges) compared with actively trawled areas (Pikesley et al., 2021). Similarly, an area (>200 km^2) closure in Lyme Bay, off Plymouth, resulted in positive changes in species richness and the total abundance of 13 important taxa, including definite evidence of a recovery in three indicator species (*Pentapora fascialis*, *Phallusia mammillata* and *Pecten maximus*) (Sheehan et al., 2013). Even the closure of relatively small areas can have a positive effect: a 2 km^2 area in an intensively trawled (for scallops) part of the Irish Sea allowed the scallop population to recover to some extent, although after 5 years it was clear that it would take longer to reach a normal population structure (Bradshaw et al., 2001). Bradshaw et al. (2001) suggested that for sedentary fauna with planktonic larvae, protected areas would be beneficial. The studies cited here are to some extent fisheries centric and looking to the broader MPA literature reveals the broader ecosystem benefits through area protection.

5.2 Ecosystem Benefits of Area Protection

Marine protected areas positively impact diversity, abundance, organism size, and abundance compared with surrounding unprotected areas, even when protected areas were relatively small (Lester and Halpern, 2008; Toonen et al., 2013; Turnbull et al., 2021). The positive effects are highly dependent on habitat type, location, levels of allowed anthropogenic activity, and the duration of protection, with size, age, and level of protection being the most important factors

(Edgar et al., 2014; Lester and Halpern, 2008; Sala and Giakoumi, 2018; Toonen et al., 2013; Turnbull et al., 2021). Where some level of extraction is allowed, i.e., partial protection, outcomes are far more variable with some studies indicating some benefit (Lester and Halpern, 2008), whereas others demonstrate no increase in fish diversity or biomass compared with fully open areas (Edgar et al., 2014; Turnbull et al., 2021). From a review of 87 MPAs globally, Edgar et al. (2014) described five key features which increased MPA efficacy; 1. no take, 2. Enforcement, 3. More than 10 years old, 4. More than 100 km^2, and 5. Isolated by deep water or sand. Fully protected small island MPAs were the most successful (Edgar et al., 2014). One may well question the relevance to FOW developments situated over homogenous sea-floor habitats, however, Edgar et al. (2014) did statistically control for the island effect and the presence of multiple large floating platforms, and their artificial reefs may well be analogous to some small island reef characteristics.

Most notably, when three or less of the key criteria were present, ecosystem benefits diminished. When three or more criteria were present, benefits were statistically significant. Similarly, Sala and Giakoumi, (2018) carried out a meta-analysis showing that fully protected reserves increase fish assemblage biomass by 670%, while partially protected areas increase fish assemblage biomass by 343% - though often not statistically different to unprotected areas. A large proportion of MPA studies are bias towards fish and vertebrate species, nonetheless, there is good evidence that protection also benefits crustacean species. Full area protection, with restocking, allowed European spiny lobster to increase in abundance in just 2 years in Sardinian waters (Cau et al., 2019). Off California, 6 years of protection at the Santa Barbara Channel Islands lead to a 4- 8-fold increase in abundance and a 5-10% increase in carapace length for lobsters (Kay et al., 2012).

5.3 Ecosystem Benefits - Fixed Bottom Offshore Wind Farms

It is difficult to speculate on what these studies can tell us about the likely high level of protection that will be in place around an operational FOW farm. Many MPA studies investigate feature specific protected areas associated with an island, a reef, and some valued benthic habitat. Studies on existing fixed bottom wind farms may be more revealing, although these are not deeper than 30 m and therefore there are ecological and physical difference between current fixed and planned FOW sites. Since 2005, monitoring at a Belgian OWF has revealed substantial reefs effects and a refugium effect, although the fish assemblage did not change significantly due to the wind farm

(De Backer et al., 2020). The reef effect was very pronounced and many reef associated species (inc. mussels and brown crab) present after installation of the turbines were not present pre-construction. One fish species, sea bass, was only found after installation (De Backer et al., 2020), suggesting these new reef habitats have attracted at least one new species to the area. These results are broadly similar to other studies showing little change in highly mobile fish species and significant change in reef associated species (Bergström et al., 2013; Krone et al., 2017; Vandendriessche et al., 2015). Notably, natural spatial and temporal variation in the epibenthic and fish assemblages was greater than any turbine/foundation effect – analysis indicated that seasonality, climate indices and substrate type influence fish populations (De Backer et al., 2020). Although no large-scale changes in fish populations are evident, demersal, and pelagic fish do utilise artificial reefs at OWFs (Mavraki et al., 2020).

5.4 Local, Regional, and Cumulative Effects

Protected areas will not only confer some level of protection to a particular area but may work as a network if there are several or many such protected areas connected by oceanographic currents. For example, off the south coast of Ireland, a seasonal coastal current flow around the periphery of the Celtic Sea and up the west coast. This feature will potentially connect FOW sites in the Celtic Sea with sites on the western shelf area.

5.4.1 Spill-over and larval subsidy

Spill over and larval subsidy are similar processes that refer to the export of adult and larval/juvenile fish and invertebrates from a protected area to the surrounding unprotected area (Cudney-Bueno et al., 2009; Gerber et al., 2005; Russ, 2002). The literature on this topic is extensive and spill over effects are demonstrated repeatedly, with increases in the size, maturity and abundance of reef associated fish and crustaceans (e.g., lobster) seen beyond MPA boundaries (Qu et al., 2021; Roberts et al., 2001). Qu et al. (2021) found that 10.6% of newly settled juvenile snapper recruits up to 55 km from an MPA were the offspring of snapper within the MPA. Positive effects can occur rapidly: a network of small marine reserves in Florida and St Lucia increased fish catches by 46 – 90% in adjacent areas after 5 years, with trophy fish caught up to 100 km from the Florida reserve (Roberts et al., 2001). Other species will need more time to generate a spillover effect, for example, after an 8 – 17-year period of protection at the Columbretes Islands Marine

Reserve, there was positive migration of lobster from the MPA, and the net gain to the fishery in weight exceeded the losses from lost fishing area (Goñi et al., 2010). Goñi et al. (2010) noted that intense fishing effort along the MPA edge likely limited the spillover effect, and this ‘fishing the line’ behaviour has been demonstrated to negatively affect other species within the border zone of MPAs (Ohayon et al., 2021). The impact on non-reef associated species is not so unequivocal. Extensive monitoring studies in some North Sea OWFs suggests there is no significant difference between commercial fish communities inside and outside OWFs (Bergström et al., 2013; De Backer et al., 2020), which suggests spill over is unlikely, although longer periods of protection allied to benthic recovery may change this.

5.4.2 Displacement of fishing effort

A potential consequence of area closures and MPAs is the displacement of fishing effort as fisheries will seek to shift their fishing effort to other areas and/or other species to maintain their catches and income. Fishing the line, as described above, is an example of displacement. Experience to date, across many jurisdictions, suggests that displacement is hard to predict, with individual fisher experience, boat type, gear type, metocean conditions and bathymetry all influencing how and where fishing effort will be reallocated (Slijkerman and Tamis, 2015; Greenstreet et al., 2009; Dinmore et al., 2003). It is possible that area closures due to FOW developments could displace fishing effort into areas which were previously lightly fished or unfished, with negative implications for habitats and ecosystems, undermining any ecosystem benefits gained from the area closure (Greenstreet et al., 2009). The introduction of the “cod box” in 2001, to conserve cod during spawning season, displaced beam trawling effort with substantial damage to benthic communities that would take >10 years to recover (Dinmore et al., 2003). The greatest amount of damage from bottom trawling occurs during the initial effort (Jennings and Kaiser, 1998) and therefore, even short-term displacement can have long term ecosystem consequences. Situating FOW sites in lightly fished areas can mitigate negative ecosystem impacts by ensuring that displacement is minimised and where it does occur, fishing effort is displaced into already fished areas.

5.4.3 Scale

In the context of protected areas, size is one of the most important criteria as the evidence shows that the larger MPAs are more effective and more cost effective to govern and monitor (Edgar et al., 2014; Toonen et al., 2013). In Europe, most MPAs are near the coast, typically feature, habitat or species specific, and generally small (5 - 30 km^2) (Toonen et al., 2013). Proposed FOW farms will likely be greater than 100 km^2 and a network of FOW farms, if managed as OECMs (see section 3), will considerably enhance Europe’s protected area network. While the positive impact on benthic habitats is more certain (see section 3.1), the positive impact on demersal fish species many of which are migratory and commercially fished is less certain. High adult dispersal means area-based protection will be less effective, however, nursery areas where larval/juvenile dispersal, even of migratory species, is low could still confer some protection (Gerber et al., 2005; Murawski et al., 2000). Conversely, where there is long-distance larval dispersal, any positive effect will be hard to detect (Pelc et al., 2010). Large scale closures of the Georges bank ground fishery also demonstrate limited impact for migratory species, being most successful where a large proportion of the population was located inside the closed area year-round (Murawski et al., 2000). It’s important to note that other fishery restrictions like reduced effort, catch limits, and gear selectivity were also deemed important contributors to the George’s Bank management effects (Murawski et al., 2000). There is some evidence that some exploited fish populations in the Northeast Atlantic are recovering, due to a reduction in fishing effort since the early 2000s (Fernandes and Cook, 2013), therefore further area restrictions may enhance their recovery, although to what extent is difficult to predict. This being the case, the positive impact of FOW protected areas may be harder to detect, as they will operate in an already improving background. This should not detract from the likely ecosystem benefit of restoring natural benthic habitats and benthic-pelagic coupling across large areas of shelf habitat. Multiple large, protected areas across a contiguous shelf habitat are likely to have substantial cumulative effects in terms of biogeochemical cycling, with bottom-up ecosystem benefits for benthic and pelagic species. It is important to bear in mind that continental shelf ecosystems may not recover to a previous state with a historic species assemblage. Recovery in the Clyde Sea has favoured smaller forge fish – crudely speaking, spratt have replaced herring since the late 1980s (Lawrence and Fernandes, 2021). It is very likely, there will be unforeseen consequences which will be difficult to predict.

6 Habitat Modification

6.1 Artificial Reefs

The European artificial Reef Research Network (EARRN) defines an artificial reef as "a submerged structure placed on the substratum (seabed) deliberately, to mimic some characteristics of a natural reef" (Baine, 2001; Jensen, 2002). Artificial reefs can be made from natural or artificial materials and have historically been used to enhance fisheries, although in recent years they have been used for recreational diving, trawling prevention and conservation (Baine, 2001; Jensen, 2002). The development of a reef from a blank structure to a living ecosystem is complex and begins with biofouling, which starts immediately after a hard surface is placed in the marine environment (Callow and Callow, 2011). Any hard surface including concrete, glass, metal, and plastics will be fouled by a complex community of invertebrate species and algae, which in turn provide habitat and food for mobile invertebrates (e.g., crabs, sea stars) and vertebrate species including highly mobile megafauna (large fish, seabirds, marine mammals). The process of biofouling is complex, dependent on location, climate, exposure, depth, and season, resulting in great variation in both the initial and mature reef communities. There is substantial variation in reef communities between fixed bottom OWFs (De Backer et al., 2020; Zoë L. Hutchison et al., 2020; Mavraki et al., 2020), and also variation between fixed bottom turbines within the same site (Zoë L. Hutchison et al., 2020). Some variation is likely due to the "founder effect" which states that the initial settlers will have a competitive advantage and thus dominate the fouling community, although it is most likely that over time reef communities within an area of broadly shared characteristics will start to converge on similar communities, despite early differences. A sub-category of artificial reefs is Fish Aggregating Devices (FADs), which are buoyant floating structures.

6.1.1 Fish aggregating devices - FADs

Floating objects in the marine environment are known to attract fish and other large mobile animals, and although the reasons for this behaviour are poorly understood, predator avoidance, food availability, and social grouping are thought to be some of the behavioural drivers (Castro et al., 2002; Dempster and Taquet, 2004; Karama and Matsushita, 2019; Wilson et al., 2020). FADs come in many forms, from large buoys to small collections of plastic bottles (Yusfiandayani et al., 2014).

They are often intentionally deployed by small scale artisanal and large-scale pelagic fisheries in tropical and sub-tropical regions to increase the catch efficiency of commercially valuable fish species (Cabral et al., 2014; Guillotreau et al., 2011). Anecdotal observations suggest that sharks, turtle, and marine mammals are also attracted to much larger offshore structures (floating and fixed) and their presence is not always linked with foraging behaviour/opportunities; however, this also remains poorly understood (Todd et al., 2018).

6.2 Ecosystem Benefits of Artificial Reefs and Fish Aggregating Devices

Artificial reefs increase habitat complexity, which positively influences biodiversity by providing refugia, nursery grounds, enhanced larval settlement and this is particularly the case when structures are situated in homogenous habitats, e.g., sand and mud. FADs on the sea surface, although they are generally simpler structures, can have similar benefits by also introducing habitat complexity into an otherwise homogeneous pelagic environment (Blasi et al., 2016; Sasikumar et al., 2015; Taquet et al., 2007). Floating offshore turbines have the potential to act as both artificial reefs and FADs through the introduction of hard structures such as floating foundations, cables and mooring lines, and anchoring systems (see section 3). The type of community that colonises these surfaces will vary depending on the surface physio-chemical properties, depth, degree of motion, and current velocities (Callow and Callow, 2011; Karlsson et al., 2022; Perkol-Finkel et al., 2008; Todd et al., 2020). The degree to which FOW devices will act as FADs and artificial reefs is not well understood, however, recent surveys on the Hywind Scotland spar turbines recorded 121 species, from 11 phyla, including 48 epifouling and 73 mobile species (Karlsson et al., 2022). Notably, this included two species of cold corals, *Desmophyllum pertusa* and *Lophelia pertusa*, situated on a cable at 73.5 m depth. In general, epifaunal colonisation reached almost 100% coverage on all structures, although community composition on the turbines, moorings, anchors, and cables varied substantially, with distinct vertical zonation (Karlsson et al., 2022) (Figure 4). Painted sections on the Hywind turbines were different to unpainted, suggesting coating and particularly antifouling coatings will impact the epifouling community. This will favour some species, like mussels and hydroids, which can tolerate high levels of toxicity. These results suggest that FOW infrastructure can foster artificial reefs and have a substantial positive effect on biodiversity, although uncertainly remains over different devices and technologies in different locations. There is a comprehensive body of literature in relation to existing offshore structures from which one can draw further inferences on potential ecosystem benefits.

6.2.1 Artificial reefs on oil and gas platforms

Oil and gas platforms are among the most productive marine fish habitats, comparable with designed reef habitats (Smith et al., 2016). Locally, platforms benefit both demersal and pelagic fish by acting as an artificial reef, leading to higher fish abundances, diversity, and creation of additional hard structure from shell mounds (Fabi et al., 2004; Love and York, 2006; Schroeder and Love, 2004). Fish rapidly colonise new structures: in the North Sea, a new platform was surveyed pre and post installation and within 4 days, fish diversity and biomass has increased (Todd et al., 2020). Platforms also increase recruitment of demersal fish species like rockfish, by acting as a nursery and refugia (Snodgrass et al., 2020). Although, localised reef populations are usually the beneficiaries of platforms, multiple platforms over a wide area can lead to regional benefits for fish populations (Fabi et al., 2004). For example, platforms off the coast of California are estimated to contribute over 90% of the total fish biomass and annual somatic production for the region (Meyer-Gutbrod et al., 2020). Oil and gas platforms host diverse invertebrate communities, which vary substantially between locations and between adjacent platforms, and invariably have distinct vertical zonation (Forteath et al., 1982; Love et al., 2019; Todd et al., 2018). Mussels, barnacles, cnidarians (inc. hydroids and anemones), bryozoans, sponges, macro algae and polychaete worms are some of the main taxa found on structures (Page et al., 2008; Todd et al., 2018). In the North Sea, mussels and algae dominated a natural gas platform above 10m depth, encrusting bryozoans increased dramatically from 10-15m, and anemones dominated below 15m with an increase in barnacles at 45-50m (Todd et al., 2018). The cold-water corals *Lophelia pertusa* were found on submarine cables, shipwrecks, the Brent Spar buoy, and Beryl Alpha SPM2. On the Brent Spar *L. pertusa* was found, during ROV surveys, on single point mooring, at >70 m depth, which was below the seasonal thermocline, growing an estimated 5 mm annualy (Roberts, 2002). Roberts (2002) suggested that the platforms provided a refuge for this species that was no longer present in the North Sea. It is reasonable to suggest that any area with an Atlantic influence and a suitable hard structure below the thermocline may be a suitable substrate for *Lophelia pertusa* (Roberts, 2002). The ecosystem benefits of *L. pertusa*, a protected reef building species, are discussed in the previous section (4.1.2).

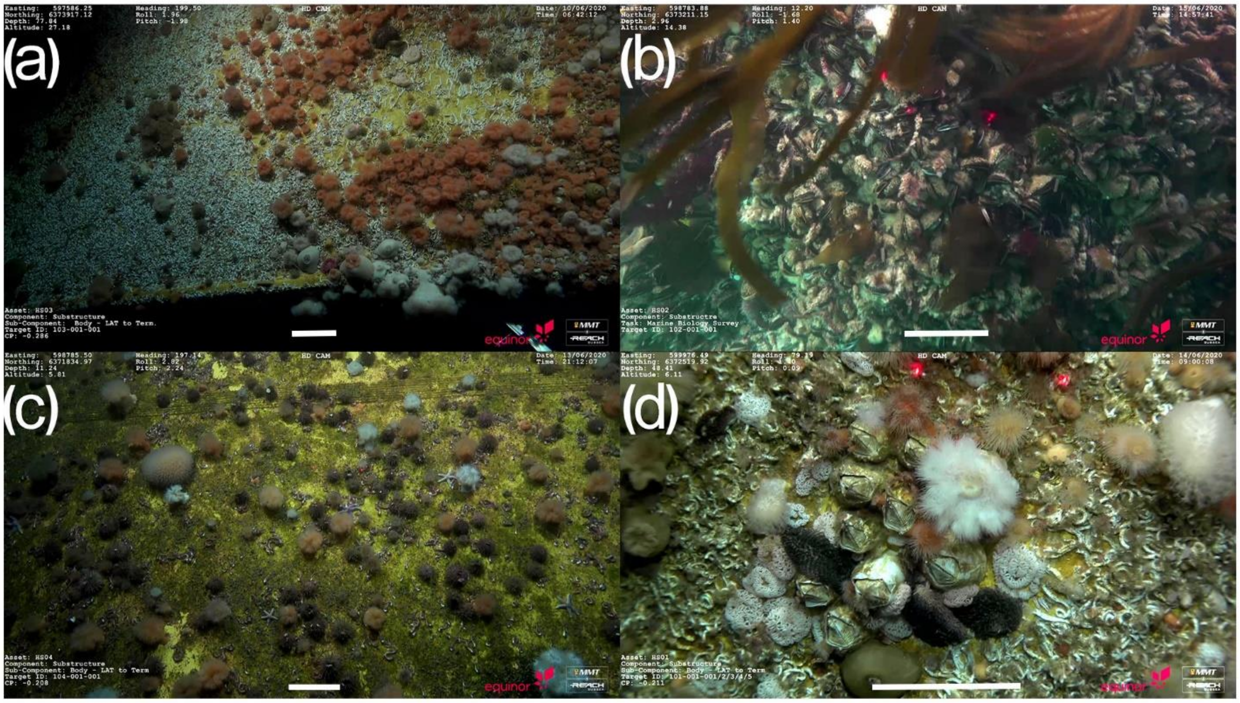

Figure 4. Example of epifouling colonisation on turbine substructures. (a) *Spirobranchus* sp. and *M. senile* at the bottom of the HS03 substructure. (b) Substructure HS02, with *Mytilus* spp., *Laminaria* sp. and potential amphipod tubes at 3 m depth. (c) Substructure HS04, with grazing sea urchins and biofilm at 11 m depth. (d) Substructure HS01, with nudibranchs (*A. papillosa*) and barnacles (Balanoidea) at 48 m depth. Scale bar: 10 cm. Image and text is taken from *(Karlsson et al., 2022)*.

6.2.2 Artificial reefs and offshore wind farms

Like oil/gas platforms, offshore marine renewable energy devices also function as artificial reefs (Ashley et al., 2014; Dannheim et al., 2020; Wilhelmsson et al., 2006). Offshore wind farms and tidal energy devices have been shown to have higher biodiversity compared to sandy bottoms in the surrounding area (Broadhurst et al., 2014). Both sessile and mobile invertebrate species colonize MRE device structures. Crustaceans and mussels were the most abundant organisms on the monopiles of wind turbines with mussel growth leading to local enrichment of organic material and formation of mussel beds on the seafloor (Langhamer, 2016; Wilhelmsson et al., 2006). Prey species such as brown crabs and brown shrimp demonstrated increased abundance across multiple studies (Ashley et al., 2014). Colonization by sessile invertebrates (e.g., mussels, anemones) creates a more complex habitat and may provide a food source for large fish species. Fish assemblages surrounding MREs are diverse, but large, commercially viable fish are less abundant. A meta-analysis of 31 studies related to wind farms, revealed small positive effects for commercially important cod and gadoids but mostly positive effects for small fish like wrasse (Ashley et al., 2014). Similarly, in the Strait of Kilamar, juvenile gobies made up 99.7% of fish captured around wind turbines with abundance and diversity significantly different from sandy bottoms (Wilhelmsson et al., 2006). In the North Sea, the pelagic mackerel and horse mackerel were found in close proximity to wind farms at high densities (Mavraki et al., 2021). Horse mackerel were recorded feeding on epibenthic invertebrates colonizing wind farm structures.

6.2.3 Floating aggregating devices

FADs attract a diverse range of species, including fish, sharks, reptile, marine mammals, and turtles (Snodgrass et al., 2020; Todd et al., 2016). Castro et al. (2002) divided FAD associated fish into two groups: large adult pelagic fish which are transient visitors to FADs, and post-larval and juvenile fish that live beneath a FAD until they are large enough to leave the refuge provided by the FAD. Proximity to the FAD is dependent on species and life stage: small, younger coastal and pelagic fish aggregate at shallower depths, closer to the FADs, compared to larger, older fish which seem to have a loser association with FADs (Josse et al., 2000; Sinopoli et al., 2011). Small fish seem to use FADs strictly for predator avoidance, while there is some evidence that larger individuals feed on aggregating prey items (Deudero and Morales-Nin, 2001; Malone et al., 2011). Fish species may also exhibit asymmetrical distribution at FADs as a result of social interaction (Robert et al., 2013; Sempo et al., 2013). Fish aggregations can be diverse, with FAD aggregations off the coast of Panama including 16 families of both pelagic and structure associated species, including shark species (Pinnix et al., 2013). Behaviour at FADs can be complex: silky sharks in the Indian Ocean stayed near FADs for extended periods of time (days to weeks), staying close during the day and leaving the FAD at night, most likely to forage, before returning again (Filmalter et al., 2015). Other FAD associated behaviours are very specific, for example, cuttlefish in the Arabian Sea attach their eggs to FADs (Sasikumar et al., 2015). Loggerhead turtles are attracted to FADs in the Mediterranean as they can be a source of food, i.e., alga and invertebrate species (Blasi et al., 2016).

6.3 Local, Regional, and Cumulative Effects

It is generally accepted that artificial reefs of all types can have pronounced local effects, increasing biodiversity and biomass across taxonomic groups, although, the weight of published evidence is heavily biased towards fish species, and particularly fish species of commercial or recreational importance. Reefs in protected areas provide clear benefits for reef associated species which include egg, larval and adult spillover into local surrounding areas, possibly 10s – 100 km away. Artificial reefs on O&G structures may assist the recovery of some fish stocks through site-specific protection and enhanced productivity leading to some spillover effect (Love and York, 2006; Streich et al., 2017). How important this spillover is in terms of local or regional population increases remains uncertain and centres around the ‘production Vs attraction’ debate (Bohnsack, 1989), and whether regional biomass would be significantly lower if structures were removed (Claisse et al., 2014; McLean et al., 2022; Wu et al., 2019). There is evidence that at least some fish (cod and lumpsucker) and one invertebrate a species (whelks) does appear to gain a reproductive benefit due to a platform in the North Sea (Todd et al., 2018). In terms of genetic diversity, oil and gas platforms appear to be less beneficial, with invertebrate genetic diversity in O&G populations representing a small subset of wider natural populations (Atchison et al., 2008; Fauvelot et al., 2012, 2009; Sammarco et al., 2012). This loss of genetic diversity may be due to the founder effect when a small new number of individuals establishes a new population and suggests that these artificial communities should perhaps not be considered analogous to natural reef communities.

Evidence on the impact of O&G structures on highly migratory fish species is very limited (McLean et al., 2022; Snodgrass et al., 2020; Todd et al., 2016). Although there is a reasonable amount of anecdotal evidence suggesting many different species spend time in the vicinity of large structures, the nature of, and duration of, their interaction with structures remains poorly understood (Snodgrass et al., 2020). It is often suggested that they present a foraging opportunity, however, large predatory fish do not seem to use FADs for foraging (Karama and Matsushita, 2019). Because FOW platforms will be numerous, there may well be a cumulative increase in the productivity of some migratory species, but this will depend on the spatial overlap between the infrastructure and species distribution, which will be species specific. The semi-permanent (25+ years) nature of FOW infrastructure means some species may adapt to its presence, using them as navigation waypoints and possibly for seasonal residency: some tuna can be semi-resident at mesoscale geographic features (Snodgrass et al., 2020). There are likely to be important links between the artificial reef effect and the 'wake effect' (see section 6). The wake effect may extend the area of influence of FOW infrastructure or amplify the attraction for migratory species by creating ocean hotspots of productivity. There is no published evidence on this topic – most literature on the wake effect of FOW is modelling or remote sensing studies with no biological component.

7 Wake Effects

In the context of FOW and existing fixed bottom OWFs, there are two main mechanisms that will create a wake in the lee of a wind farm. 1) Current flows flowing around infrastructure will create a wake effect, and 2) wind flow over and around an array of turbines will create a wind shear that can generate vertical rotation in the water column, i.e., upwelling and downwelling (Ludewig, 2015). Current flows will create variable flows around individual pieces of infrastructure, with individual wakes, increased vertical mixing, potentially scour around benthic structures, and resuspension of sediments, i.e., increased turbidity (Lange et al., 2010; Ludewig, 2015). Wake turbulence driven by wind shear is a cumulative effect of the entire turbine array and will create upwelling and downwelling on the downstream side (leeward side) of the wind farm (Ludewig, 2015). Predicting the impact of an FOW farm wake on the marine environment is difficult at this time and likely will only become possible once large FOW arrays are in place. There is comprehensive body of literature based on laboratory and modelling studies which suggest that the ecosystem impact of fixed bottom OWF or floating MRE devices will be relatively small (Carpenter et al., 2016; Cazenave et al., 2016; Copping et al., 2016; Farr et al., 2021; Lass et al., 2008).

7.1 Ecosystem Benefits of The Wake Effect

All marine organisms regardless of size are influenced by natural heterogeneity in the marine environment. Primary productivity (i.e., phytoplankton growth) is often higher at mesoscale ocean features like eddies, fronts, or indeed any sharp physical gradient where vertical mixing can occur (Benoit-Bird et al., 2019; Chang et al., 2013; McGillicuddy, 2016; Simpson et al., 1979). Large mobile fauna are known to preferentially forage at these oceanic 'biodiversity hotspots' and may gain an energetic advantage by doing so (Abrahms et al., 2018; Cox et al., 2018; Hays et al., 2016; Lieber et al., 2019). Small islands also create a wake or turbulent flow called the 'island mass effect' and this can create both enhanced primary productivity and enhanced foraging opportunities for larger mobile species (Chang et al., 2013; Doty and Oguri, 1956; Genin, 2004). Three processes lead to enhanced primary productivity: 1) phytoplankton from deeper water are brought to the surface, i.e., passive advection, 2) upwelled nutrient supply simulates phytoplankton growth, sometimes a bloom, in the surface waters. The bloom can lag the nutrient input by weeks with peak growth appearing some distance downstream (possibly 100s km) of the island, and 3) a weaker boom immediately in the lee of the island (Hasegawa et al., 2009; Messié et al., 2020). For planktivorous fish and larger predatory species, the turbulence and differential flows aggregate prey and creates areas of low current speed where animals can rest (Genin, 2004).

Modelling suggests that large FOW farms will, through the wind shear effect, create relatively large upwelling and downwelling zone that could deform the pycnocline and enhance vertical mixing downstream of the farm (Ludewig, 2015). Enhanced vertical mixing, bringing cooler nutrient rich water to the surface can enhance primary productivity, with positive implications for other higher trophic levels (Broström, 2008; Hasegawa et al., 2009). This type of upwelling and the associated bottom-up influence on the foodweb is well studied in coastal regions and along sea ice margins, and the impact on phytoplankton can be rapid, with the upwelled nutrients (nitrates and ammonia) being consumed within days (Dugdale et al., 2006). Therefore, there is a possibility of creating permanent hotspots for primary production and thus enhanced opportunities for lower trophic levels e.g., copepods. Weather and tidal changes will likely drive short duration changes in the upwelling intensity and it is clear that certain swarming zooplankton do respond rapidly to such changes by intensifying and relaxing swarm densities (Benoit-Bird et al., 2019). Changing spatial distribution of zooplankton prey will also influence the distribution of higher trophic predators (e.g., jellyfish, sea birds and fish) and therefore rapid changes in primary productivity can spread from the bottom up through the entire food web. Seabirds foraging in the wake of a tidal turbine at Strangford Lough showed a demonstrable preference for the wake zone, most likely because prey were made more available in the turbulent water, rather than more abundant (Lieber et al., 2019). Other natural tidal streams generated by topographic features are also recognised as foraging hotspots for sea birds and marine mammals, driven by prey availability and enhanced abundance (Benjamins et al., 2015). Cox et al. (2018) compile a comprehensive list of features which can create discrete oceanographic turbulent zones and some including headlands and small islands are similar in scale, and sometime much smaller, than proposed FOW developments.

7.2 Local, Regional, and Cumulative Effects

An assessment of a fixed bottom OWF off Germany, using hydrodynamic modelling, demonstrated no major impact of a monopile turbine on turbidity, nor was there a cumulative effect of multiple monopiles found (Lange et al., 2010). Evidence for the extent of oceanographic wake effects and turbulence created by OWFs is quite variable. Some modelling exercises have found that large OWFs may create large wake effects including eddy formations lasting several days (Paskyabi and Fer, 2012), with others indicating that wake effects will extend 100 km in the lee of an OWF and upwelling and downwelling cells will approach 15 km in size (Ludewig, 2015). In contrast, other modelling work on monopiles indicates a very limited wake and eddy formation, not more than 10 times the monopile diameter, and not extending far in the lee of the pile (Lass et al., 2008; Rennau et al., 2012). Where models have investigated large scale OWFs, they do demonstrate slowing current velocity and increasing vertical mixing, which could possibly disrupt seasonal stratification if OWFs become more extensive than at present (Carpenter et al., 2016; Cazenave et al., 2016). The ecosystems effects of these oceanographic changes are very uncertain at present, however, changes to stratification and vertical mixing can influence primary productivity. Enhanced vertical mixing can stimulate primary production, but if turbulence increases turbidity, light penetration is reduced, thus reducing primary productivity.

Increased turbidity is a recognised as a pressing ecological issue in recent years (Blain et al., 2021; Herbert-Read et al., 2022). Increasing wave energy, land use, and coastal eutrophication are causing increased turbidity in coastal regions globally and this has negative implications for fundamental ecological processes such as primary productivity and biogeochemical cycling. In the context of FOW developments, a large-scale reduction in bottom trawling will most likely reduce turbidity as trawling re-suspends sediment and organic matter (Linders et al., 2018). Conversely, increased vertical mixing and upwelling because of multiple large FOW farms may increase turbidity, however, this is purely speculative at this time.

8 Concluding Remarks and Recommendations

The current weight of evidence indicates that offshore renewable energy, either fixed or floating, will have limited negative impacts on the environment (Hammar et al., 2016; Inger et al., 2009; Wilson et al., 2010). The most likely ecosystem benefits will accrue because of area protection in combination with the artificial reef (and FAD) effect. There are possible positives and negatives associated with any oceanographic wake effect and the scale and magnitude of these is uncertain at present.

Area protection results in important ecosystem benefits which are positively associated with increasing levels of protection, i.e., complete protection from human exploitation achieves the best conservation outcomes. Industrial fishing methods, particularly bottom trawling, driven by societal demand have resulted in severe damage to benthic and pelagic ecosystems. Restricting or closing FOW developments to these activities can lead to habitat restoration, increased biodiversity, abundance, and biomass of many species, although it is important to consider and plan for the unintended negative consequences of fisheries displacement. Area closures are likely to be unpalatable and disruptive to some sectors within the fishing industry, however, there is robust evidence that area closures can result in significant gains for commercial fishing, if managed well within a coherent MSP framework. Benthic habitat recovery can take several years, but as infaunal and epifaunal communities recover, habitat complexity is restored, and this encourages recruitment of other algae, invertebrate and vertebrate species. Some animal groups have particular significance – these ecosystem engineers further enhance the organic structural heterogeneity of the benthic habitat, creating living reef systems that encourage very high levels of biodiversity compared with homogeneous benthic habitats. Some of these reef builders may also occur on subsurface FOW structures, e.g., cables and mooring lines. Furthermore, the restoration of a diverse complex benthic habitat will enhance nutrient flux across the sediment-water interface, transferring more carbon into organic biomass and sequestering more carbon into the sediment.

The surface and subsurface hard structures associated with FOW will create habitat complexity that increases the biodiversity, abundance, and biomass of invertebrate and vertebrate species, i.e., the reef effect. This will occur on floating, mid-water and benthic structures, resulting in different reef habitats with distinct vertical zonation and distinct species assemblages. Artificial reefs will most likely benefit reef associated species with restricted home ranges, i.e., non-migratory species. Large migratory species will almost certainly use the structures for navigation, resting, foraging, and socialising, although for many taxa these behaviours are poorly understood and thus any ecosystem benefit remains poorly understood.

Large FOW farms will almost certainly create a wake and change local oceanography to some extent. The increased turbulence (upwelling and downwelling) driven by wind and currents flowing around multiple turbines is likely to create localised changes in primary productivity and aggregate zooplankton prey species. These bottom-up changes in the foodweb, in turn, create new opportunities small zooplanktivorous fish and larger mobile predators. Natural features of a similar scale create oceanographic features that are recognised as diversity hotspots and can provide enhanced foraging for some large mobile species. The scale of FOW created wakes remains uncertain, and the ecosystem benefit is likely to depend on location, season and vary significantly across different species.

8.1 Knowledge Gaps

Large knowledge gaps exist across the entire domain of environmental impacts resulting from ORE, particularly for FOW, but also for fixed bottom OWFs and floating or fixed MRE devices. Considering how rapidly the industry is expanding (Global Wind Energy Council, 2022), research and monitoring efforts must scale up accordingly and future research should be coordinated across state borders and fully embrace an ecosystem-based approach (Dannheim et al., 2020).

Current monitoring and research programmes are generally focused on four receptors: marine mammals, sea birds, fish, and benthic habitats and therefore lack a holistic ecosystem-based approach (Dannheim et al., 2020; Maclean et al., 2014; Wilding et al., 2017). Furthermore, the targeted, time limited monitoring and sampling of single licensed areas is often not relevant to the spatial or temporal scale at which many ecosystem processes and functions occur, and therefore are unable to detect ecosystem level changes, positive or negative (Wilding et al., 2017). Ambiguities in the legislation and a lack of guidance on how legislation should be implemented means that determining the significance of ecosystem impacts may be flawed (Maclean et al., 2014; Willsteed et al., 2017). Wilding et al. (2017) argue that current benthic monitoring is often costly, does not capture ecosystem changes at relevant scales and has resulted in stakeholders being "data rich, information poor" (DRIP), meaning unacceptable levels of ecosystem change are not detected (Wilding et al., 2017). Robust detection and understanding of relevant ecosystem changes because of ORE expansion demands a more holistic scientific approach, at different ecologically relevant scales (Dannheim et al., 2020; Wilding et al., 2017; Willsteed et al., 2017).

Recommendations to enhance monitoring include: 1) begin with a clear objectives metrics and clearly defined spatial/temporal domains, 2) have pre-defined thresholds of unacceptable change, 3) metrics, thresholds, and confidence in chosen methods should be agreed with relevant stakeholders before sampling begins (Wilding et al., 2017). Detailed knowledge of the natural spatial/temporal variability of benthic ecosystems is currently lacking and collaboration between projects and research groups/institutions could broaden the scope of knowledge acquisition, improving the ability to detect large scale ecosystem changes (Dannheim et al., 2020). Equally important, is the need for targeted field studies on ecologies processes at smaller local scales (Dannheim et al., 2020).

8.2 Future Research

Despite a robust body of evidence demonstrating the potential ecosystem benefits of artificial reefs, including around OWFs, it is not included in EIAs and does not appear to be a major consideration in the ORE industry (Petersen and Malm, 2006). It is worth considering, should FOW be designed and managed to enhance the reef effect and promote ecosystem recovery (Inger et al., 2009)? To enable this proactive approach, existing infrastructure must be studied in greater detail, e.g., (Karlsson et al., 2022), producing information that can feed back into FOW design and installation, and be used to model the cumulative impacts of an expanded industry (Inger et al., 2009; Petersen and Malm, 2006). The shape, complexity, surface texture, and distance between structures are important factors that influence reef development (Petersen and Malm, 2006). While manipulating these elements on floating structures might be difficult, creating diverse additional anchoring structures, or possibly simply adding additional structures with no anchoring function, would seem to be a distinct possibility. Adopting this strategy requires more research on artificial reefs at depths above 60 m, research on the connectivity between reefs for different species, and research on how the increased biomass and biodiversity will impact ecosystems at the local and regional scales.

In terms of larger mobile species, e.g., tuna, a focus on single structures in the past means there is no clear understanding how these often-migratory animals will be impacted by multiple arrays of large floating structures (McLean et al., 2022). A poor ecological understanding of many large species, particularly those not protected by legislation, e.g., elasmobranchs (sharks), will hamper any efforts to understand potential population changes due to FOW developments. Research to develop a better understanding of the population structure, distribution, foraging behaviour, breeding behaviour, and migration patterns is urgently needed: field studies using biotelemetry, molecular and modelling techniques would help resolve some of these knowledge gaps. In terms of oceanographic changes and the wake effect, all the same techniques are relevant in seeking to understand how animals/ecosystems are influenced by the creation of permanent features in the pelagic ecosystem.

To fully understand the impact of FOW on marine ecosystems, research priorities need to switch from a narrow taxonomic focus and take a holistic ecosystem-based approach that can develop our understanding of functional marine ecology. Monitoring and research must begin to take account of habitats and species that are not limited by national boundaries, or indeed by the boundaries of a single FOW development. The ecosystem impacts of multiple FOW developments across large continental shelf regions remain highly uncertain and research priorities need to address cumulative spatial and temporal impacts at the population level of potentially impacted species. Achieving these goals will require greater collaboration at sectoral, regional, and international levels, working towards shared standards of data collection and analysis, and adapting the current regulatory approach to ensure ecosystem benefits can be detected in a cost-effective manner.

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