Article

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Offshore Windmill Farms: Threats to or Possibilities for the Marine Environment

A massive development of offshore windmill farms has been planned along the European coastline. This raises important questions about the possible effects on the marine environment. Effects during the construction period may be minimized to a negligible impact if care is taken to avoid areas containing rare habitats or species. Disturbance caused by noise, vibrations, and electromagnetic fields during windmill operation may, with present knowledge, be considered to be of minor importance to the marine environment. The reef effect (i.e. addition of a hard substratum), is believed to cause the largest impact on the marine environment and at different scales: the micro scale, which involves material, texture, and heterogeneity of the foundation material; the meso scale, which involves the revetments and scour protection; and the macro scale, which encompasses the level of the entire windmill farm. Effects on these scales are discussed in relation to results obtained from natural habitats, artificial reefs, and other man-made constructions at sea.

INTRODUCTION

In the search for clean and renewable energy sources that may partly replace fossil fuels and nuclear power, wind energy has become a serious alternative during the last decade. With increasing demand for sites for windmills, interest has been directed toward erecting windmills on offshore locations, often as groups of several turbines making up a windmill farm. Further advantages of offshore wind power include the option to erect larger plants and the opportunity to produce more energy per unit due to stronger and steadier airflows above the relatively smooth sea surface. Several Western European countries are planning a massive development of offshore windmill farms (OWFs) along the European Atlantic Ocean coast. The total development plans anticipate the generation of nearly 50 000 megawatts of power until 2030 (1) (see Fig. 1).

Offshore wind energy plants are a new technique and few farms are yet in operation (1). A thorough assessment of their effects on the environment is therefore hard to carry out at present. The environmental impact of an OWF can be divided into two classes of effects: effects during the construction period and effects during the much longer operation period. Effects during the construction period may further be divided into three categories: destruction, dredging, and disturbance. All these effects, except destruction, may be considered temporary. In contrast, effects during the operation of the windmill can be regarded as relatively permanent. They consist of disturbance, diversion of water flow, and altered habitat quality—the so-called reef effect—meaning the effect the additional structures will have on habitat and species composition (2), irrespective of whether or not they mimic genuine reef habitats (3). The revolving wings of the windmills that induce noise, vibrations, and shadows, together with the electromagnetic fields from the electric cables, will potentially disturb organisms both below and above the water surface. The environmental effect will depend on local conditions (i.e. whether an OWF occupies an area that hosts rare or important organisms or whether an OWF, for example, is situated in a strait, where water flow alterations may be of importance).

EFFECTS DURING CONSTRUCTION

In the seafloor area that will be covered by footings and scour-protecting revetments, all organisms will, of course, be eradicated. However, when comparing the area actually occupied by the physical constructions (less than one percent) in relation to the total area of the OWF, destruction effects can be considered small or negligible unless the structures are placed directly atop rare species or habitats. Dredging operations when establishing the windmills and cables, and in some locations during compensatory excavations, will result in temporary loss of habitats, release of sediment-bound substances, and increased sedimentation in the immediate surroundings. Construction operations will disturb fish, marine mammals, and bird populations.

Because few OWFs have been established, little is known of their specific impact on the marine environment. Even so, likely effects may be deduced from experience from other man-made constructions in the marine environment. The construction of the fixed link across the Øresund sound between Denmark and Sweden may serve as an example. The fixed link consists of an artificial peninsula, a 4-km-long immersed tunnel, and an 8-km-long bridge. To prevent reduced water flow in the Øresund by the construction, additional compensating dredging operations amounting to 7.5×10^6 m^3 were performed. A comprehensive monitoring program was set up for a number of different variables (4). The overall results show no major temporary or permanent impact of the construction on water quality (nutrient concentration, oxygen consumption, or hygienic standards),

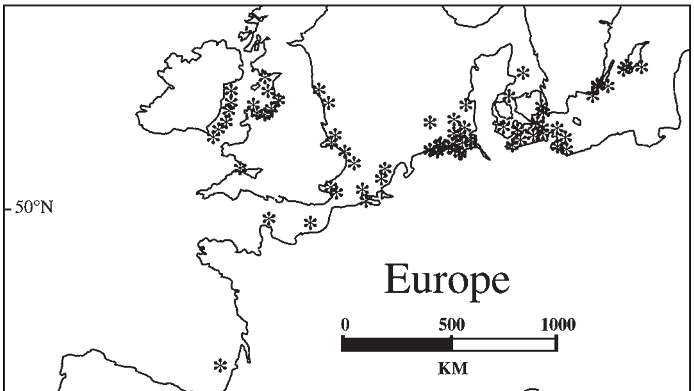

Figure 1. Stars indicate sites of planned, projected, and operational offshore wind farms in the European Union (2002) according to the European Wind Energy Association.

sediment characteristics, benthic vegetation, mussel populations, benthic fauna, migratory fish (herring), or on a nearby population of common seal. A few incidents of bird displacements were observed, but the populations of the most common bird species in the area have not been affected. Hydrographical conditions have been changed, but the effect is reduced to local effects around the bridge pillars and the artificial island (4).

On this background, it can reasonably be assumed that construction of an OWF will cause only minor environmental impact. Recent studies at a Danish OWF confirm this assumption (5). A number of potential environmental impacts during operation are more or less specific to all OWFs. These are disturbance caused by the revolving blades, the magnetic fields generated by connecting electric cables, and the reef effect. In this paper we will focus on the effects below the water surface and only indirectly point out effects on bird life.

DISTURBANCE EFFECTS

Transmission of electricity through cables—such as the frequently used high voltage direct current (HVDC) cables—will lead to the generation of electric and magnetic fields. Most marine organisms can sense electric fields (6) and it is assumed that elasmobranches in particular are sensitive to magnetic fields (6). It has also been suggested that some fish species such as eel may use magnetic fields as a tool for orientation (7). In a comprehensive study of electromagnetic field (EMF) emissions, it was concluded that the current state of knowledge is too variable and inconclusive to make any conclusions with regard to any possible environmental impact of EMF in the range detected by organisms sensitive to electric and magnetic fields (8). Based on direct measurements and models of EMF, it was further concluded that with perfect shielding electric fields will not be generated directly, but that magnetic fields will be generated and that these in turn will generate induced electric fields within the lower range detectable by electro-sensitive species (8). Use of mitigating measures such as improved cable armor and sheath or burial of the cables can reduce the impact. Thus, there might be a minor disturbing effect of EMF on sensitive species, but with current knowledge, the impact will likely be small, which is also confirmed by one of the few studies on HVDC cables (9). Similarly, it was concluded from initial investigations at the Nysted OWF, that a 132-kV alternating current cable did not affect the overall distribution or migration patterns of fish around the cable (10).

Sound is very well transmitted through water and noise generated by the rotors, especially at low frequencies, and potentially can be expected to affect marine organisms. In general, fish are sensitive to sound or noise and a number of species are even sensitive to very low frequencies (11). Vibrations and pressure changes associated with noise may also affect invertebrates such as crustaceans (12). The noise emitted by OWFs is currently not very well described, nor in particular how the noise interacts with other sources of sound. Further, because sound affects marine animals in various ways, it is currently difficult to predict any environmental impact of noise caused by OWFs.

In conclusion, the scale of effect regarding disturbance during the operation period are yet to be clarified, but it can be assumed with the present knowledge that these effects are of minor importance and that technological improvements may further reduce the impact.

REEF EFFECT

Hard substratum in a coastal area provides variable surfaces and microhabitats for establishment and growth of benthic organisms. It is well known that fish and other marine species are attracted to solid man-made structures placed on the seabed, as they will act as artificial reefs. The construction and deployment of different materials, ranging from specially designed concrete or steel units, to scrap materials such as car tires and shipwrecks, is widely used to enhance fisheries, to mitigate damage to the environment, to protect or rehabilitate certain habitats, or to increase the recreational value of an area (13). The wind turbine foundations and scour-protecting revetments can be considered hard substratum that will increase heterogeneity in the area and create a substrate for colonization by fouling organisms. The footings of windmill plants are formed in various ways. The two types that dominate in Western Europe are concrete caissons and steel monopiles, driven or drilled (1). There are, however, no standard solutions on the footing problem, the shape of the constructions varies slightly between different projects and vertical, horizontal, and sloping surfaces may occur. Further, boulders are often used to protect against erosion. It has been suggested that built structures may act as reefs (2), but deployment of artificial structures can damage fisheries due to redistribution of stocks and accelerate species introduction by providing stepping stones for spread, whereby local fisheries may be endangered (14). A built structure such as an OWF may thus be an equally possible threat to local biodiversity.

To our knowledge, reef effects have not been a part of environmental impact assessments (EIAs) on any major construction works for bridges or similar man-made constructions at sea. Recently, reef effects have been reported from the Denmark-Sweden Øresund fixed link, where a huge biomass of blue mussels has colonized the bridge pillars (15), but the documentation is at the moment scarce. Preliminary reports also exist from two Danish OWFs (10, 16). Recently, reef effects have been reported from two wind power farms in the Strait of Kalmar, in the central Baltic Sea. A huge biomass of blue mussels has colonized the monopiles (see Fig. 2) and abundant shoals of small pelagic fish species, primarily juvenile two-spotted goby (*Gobiusculus flavescens*), surround the pile (Wilhelmsson, unpub. data). There is, however, substantial literature on artificial reefs (2, 13, 17). From the existing knowledge, the reef effect can be anticipated to be important on several scales: the micro scale, which involves material, texture, and heterogeneity of the foundation material; the meso scale, which involves the revetments and scour protection; and the macro scale, at the level of the entire OWF.

MICRO SCALE

Several recent studies have revealed that the chemical composition (18–20) and relief (21, 22) of hard substratum play an important role in the structure of epibenthic communities in the marine environment. The diversity and biomass of the submerged parts of OWFs may be at least partly controlled by the choice of material and its roughness.

The term biomineralogy has been suggested (23) to explain the interrelationship between biological systems and minerals at different hierarchical levels (cell, organism, species, and community). Subsequent studies showed that biomineralogy might play a significant role in benthic community development, affecting not only primary colonization, but also the late stages of community development (19). The composition of benthic bacteria and other microorganisms (designated as "biofilm"), which are the primary colonizers of pristine surfaces in the sea, rely to a large extent on the chemical composition of the substrate. Microorganisms at hydrophobic surfaces form tightly packed biofilms, whereas sparse colonies grow on hydrophilic surfaces (20). A well-developed biofilm may facilitate the settling of macroscopic organisms such as

Figure 2. An example of reef effects. Blue mussels that have colonized a monopile at a wind power farm in the Strait of Kalmar, central Baltic Sea.

barnacles (24), mussels (25), and serpulid polychaetes (26). Biofilm is a problem for submerged infrastructure constructions because it induces metal corrosion and microbial-induced weathering of stone and cement (27).

The boundary layer at a concrete substratum has high alkalinity due to leaching of $Ca(OH)_2$ that favors settlement of benthic organisms. This chemical signal is strong enough to induce settling even without a biofilm (18). However, to prevent weathering, submarine concrete constructions are generally coated with silane/silicone products that chemically bind to the concrete to prevent water and salt intrusion and as a nontoxic, antifouling coating (28). Consequently, even if unprotected concrete may increase settling of various organisms due to leaching of calcium hydroxide, the silane-treated material may have a limited value as a reef builder on infrastructure constructions. This problem may partly be counteracted if it is possible to increase the surface heterogeneity of the concrete surface.

In general, smooth rock surfaces favor the establishment of filamentous algae with small propagules as green algae, whereas rough rock surfaces favor perennial algae with larger propagules such as *Fucus* spp. (29). Sessile animals such as barnacles preferentially settle in depressions (30), but some species such as the Bay Barnacle (*Balanus improvisus* Darwin) actively choose smooth surfaces when settling (31). Responses to small-scale topographic variations explain variation in numbers of recruits of intertidal gastropods where some species prefer rough rock surfaces while other species aggregate on smooth rock surfaces (32).

The attachment strength of seaweed germlings that grow on smooth surfaces is significantly less compared with the strength of those grown on rough surfaces (33) or corraline algae (34). Adult kelp specimens were firmest when they were attached to sandstone and granite, and weakest when attached to limestone (35). Thus, rough concrete footings of windmills may be colonized by seaweeds of various types, however, with low adult survival because the materials resemble the physical and chemical characteristics of limestone. The smooth monopiles of steel, often painted, are likely to be colonized primarily by sessile animals in the northeastern Atlantic Ocean, particularly by *B. improvisus* and annual filamentous algae.

The substratum structures also influence competition (36) and predation interactions (31) between littoral organisms. Crevices play an essential role for the survival of juvenile macro algae when subjected to grazing (37) and ice scraping (38). For many mobile and sessile animals, crevices are important refuges from waves and desiccation (39) and from predators (40). The final community structure on the windmill footing will not only depend on the material of the construction but also on the unique biodiversity in the area where a particular OWF is erected. The dense cover of *Mytilus edulis* (L.) of the monopiles observed in the Baltic Sea (Wilhelmsson unpub. data) may thus be a result of lack of competition and predation from other species. The potential number of colonizers is much greater in more saline waters, and it is therefore impossible to extrapolate the results from one OWF to another without taking the biological interactions into consideration.

MESO SCALE

The composition of living organisms in the coastal zone will be determined by a number of factors beside the substrate, of which tide, depth, and exposure are some of the most important. For example, macroalgae show a clear depth zonation of different species relating to light intensity, but exposure is also of great importance in determining the associations. Other factors of importance in determining the composition of the natural living associations are variations in topography with vertical faces and overhang (41), and steepness of the shore (42) giving the natural community a more wave-exposed appearance (e.g. resulting in associations with benthic animals and less foliose algae) compared with a more gently sloping rock (43). As with natural habitats, distinct zones of different animal and algae assemblages will cover the windmill footings, rising from the sea bottom up to the sea surface. The biomass and species composition of these communities will depend on the material of the footings, the depth, slope, and wave exposure. It is most likely that a species-impoverished, animal-dominated community consisting of barnacles, mussels, and filamentous algae will cover the smooth and vertical surfaces of the monopiles. There is probably a greater opportunity to develop a richer community of animals and algae on concrete caissons provided that some surfaces have a limited slope and that it is possible to manipulate the surface structure of the concrete. A low diversity of the fouling assemblage on the pillars of the Öland Bridge was suggested to be due to a combination of the vertical slope, the very smooth surface, and the silan-treated concrete surfaces (44).

Boulders provide habitat for a diverse suite of species. The types and abundances of animals and algae found on or under boulders can be influenced by features of the boulders themselves, or by features of the substratum on which a boulder lies. Boulders can be colonized by larvae and spores, or by adult or juvenile animals drifting in the water column or crawling up from the substratum (45). In the northern Atlantic Ocean, cobble and boulder substrata have, for example, been identified as important habitats for lobsters. The habitats serve both as nursery grounds for early benthic juveniles and as a home range for adult specimen (46). The heterogeneity of bolder fields also promotes species richness of mobile species such as stone reef fish, for example (47). Perennial algae are, on the other hand, not favored on boulder fields. At exposed sites with a high turnover rate of the stones, filamentous algae replace kelp and wrack. The quality of the habitat also depends on the size of the boulders and on the size of the reef. It has been shown experimentally (48) that animal diversity in stone reefs increases with the number of layers of boulders and that the combined diversity of animals and algae increases with increasing size of the boulders (49).

Especially on soft and sandy bottoms, it is important to protect the footings of the windmills from erosion by a pile of large boulders. This scour-protecting revetment may be more efficient as an artificial reef than the windmill footing itself given that care is taken to provide a heterogeneous environment. If the water depth is moderate (i.e. less than ten meters), the scour protection will, with time, host a luxury macroalgal assemblage in areas that today are dominated by sand. Fouling of the scour protection will in itself create a huge secondary heterogeneity that can give rise to settling and attraction of both plants and animals and will attract fish (2).

MACRO SCALE

Abundance and diversity in natural assemblages of the rocky shore environments are variable through different spatial and temporal scales. These variations may be caused by abiotic factors that may be regular and predictable, such as light and tide (50), or irregular and unpredictable (51). Variability in time and space may also occur because of differences in population dynamics among separated unsynchronized populations living in discrete patches throughout a mosaic of different habitats (52). The structure, sizes, and spacing of patches of habitat are each very important in determining abundances of local populations and their rates of change (53).

Constructing OWFs will, on a macro scale, lead to creation of new habitats irrespective of the existing environment in the area of construction. An introduction of new habitats has the potential of increasing local species diversity (54), and especially in areas with little or no hard substrate may construction of an OWF completely alter the characteristics of local species composition. However, reports indicate that new structures may have a very low diversity and primarily host a few dominating opportunists (55), which is in accordance with the "intermediate disturbance hypothesis" (2). With present knowledge, little is known about the physical and biological processes underlying either high or low diversity or the dynamics of different assemblages on man-made structures in the marine environment, but the temporal factor of most impact studies may be a part of this knowledge gap (55, 56). From long-term studies on artificial reefs it has been the experience that it takes approximately 5 y before stable communities are established (13). Irrespective of whether diversity is high or low, there seems to be mounting evidence that filter-feeders dominate the faunal part of the fouling assemblages (2, 13, 55) and they can with their high biomass alter the biological structure on a local level and introduce a large secondary production.

The distance between natural reefs and a natural hard substrate to artificial reefs are of great importance in determining the composition of the fouling assemblages that can be expected to colonize an OWF. In an analysis of colonization of few identical artificial reefs, it could be shown that the capacity of the artificial reefs was a function of reef size and that diversity and density were highest at reefs closest to natural reefs (57). The mechanism behind this observation is probably that natural substrata represent a source of migrating juveniles and settling spores and larvae of organisms associated with hard substrate. A reverse effect can also be expected. Reef inhabitants feeding on sediment organisms will tend to feed close to the reef, resulting in increased density of prey organisms with increasing distance from the reef (2).

It has been suggested that given sufficient time, the composition of the assemblages associated with OWFs or other built structures with features similar to natural material will resemble natural hard substrate assemblages (2). There is, however, mounting evidence that constructed structures such as pontoons and pilings will not host the same species as a natural hard substrate (3, 58, 59). The causes for the differences are not fully understood, but choice of material may be one explanation, because sandstone walls did not differ from natural sandstone reefs (59), placement in the water column could be another explanation (59, 60), whereas time appeared to be of lesser importance (59, 60), although the presented evidence is not conclusive. These observations from urban structures in Australian waters indicate that provision of a resource, in this case habitat/space and especially the right water depth, makes the local environment more susceptible to invasion of species either lesser abundant in the local area or by non-native species (61). The consequence is that because disturbances or abrupt increases in supply of a limiting resource will make environments more susceptible to invasion (61), an OWF can potentially be considered time bombs of non-native species invasion and thus a possible serious problem (14, 61). In fact, a reanalysis of Australian data revealed that a disproportionately large number of taxa on constructed structures are non-native and do not occur on adjacent natural coasts (Glasby et al., unpub. data). A special case in this connection is the potential problems arising in connection with relocation of underwater structures either with decommissioning or major repair/service that cannot be achieved at sea and that potentially will lead to spread and redistribution of non-native/invasive species on the local scale (60).

It is known that fish aggregate around reefs, whether natural or man-made constructions, but it is heavily disputed, and it has not been finally settled whether this represents attraction or new production (2, 17, 62). An argument in favor of new production is that reefs increase available food, increase feeding efficiency, increase survival of larvae and spores that would have otherwise been lost, and offer increased protection against predation. On the other hand, it is well known from behavioral studies that fish are attracted to reefs (17), and new production on an area level have only rarely been demonstrated (2). Construction projects such as OWFs will, in any case, offer an opportunity for fouling assemblages to develop, and especially in habitat-limited areas, will represent new production. It can further be argued that aggregation of fish in an OWF will represent a change in local biomass or density. Using recently developed techniques for tracking parental signatures via otolith chemistry (63) may be a way of enabling calculations of percentage contribution of different locations to a local fishery and thereby advance the discussion of production *vs.* attraction.

Habitats such as soft or sandy sediment, macroalgae, and seagrass beds and hard substrate are very different, but the boundaries between them are imprecise and there are well-documented cases of organisms in one habitat living on resources provided from another habitat (64). The influence of a hard substrate such as reefs or an OWF on the surrounding sediment communities can stem from changes in hydrodynamic conditions that lead to changes in erosion/sedimentation patterns and altered transport of, for example, nutrients, organic material deposition from production on the reefs, and the structuring effect of the organisms inhabiting the reef (2). Changes in benthic fauna have been observed in the vicinity of both natural rocky reefs (64) and artificial hard substrate constructions (65, 66).

OWFs can be anticipated on the macro scale to result in alterations to local biodiversity and biological structure, aggregation of fish, and alterations to the sediment community in the vicinity of each turbine foundation. The exact changes and their implications for the local environment will depend on specific local conditions, but because distance to other reefs or hard substrate communities will be of importance for the composition of the fouling and associated assemblages, OWFs can act as stepping stones for the spread of epibenthic organisms and thus also for alien species (3).

DISCUSSION AND CONCLUSIONS

Construction of OWFs will have impacts on the marine environment. Traditional EIAs focus on effects whose common denominator is that they assess destructive and disturbing effects. These effects are the results of the destruction and disturbance during construction and the specific effects of transmission cables and rotor blades during operation. If proper care is taken in siting an OWF and construction operations, it can be assumed that negative effects on the marine environment during construction will be minimal. Similarly, disturbances during operation can be regarded as being of minor importance to the marine environment if proper technology is implemented and further developed. It should be noted, however, that our current knowledge with regard to the effects of EMF and noise is quite limited.

In contrast, the potentially most pronounced effect of man-made constructions such as an OWF (i.e. the reef effect), has received very little attention in EIAs. As documented from studies of other types of artificial hard substrate—especially the large amount of literature on artificial reefs—an OWF will have a significant effect on local species composition and biological structure. By designing the shape of the windmill footings and the arrangement of the single turbines in a farm it may be possible to direct or limit the impact an OWF may have. However, there are large gaps in our knowledge in how to design a windmill footing for specific biological purposes. Research is needed into the habitat requirements of key species, species interactions, energy flows within a farm system, and an understanding of scale (i.e. how will several or many windmill footings in a farm interact with each other and the surrounding natural community?).

The lack of management awareness on the reef effect of OWFs is puzzling because an environmental impact must be defined as any change from average natural conditions, and changes in species composition is indeed an impact (3). If the management decision is that of avoiding or minimizing potential impacts of OWFs, the focus should be on surfaces and arrangements that result in the least settlement of organisms, and cleaning of the construction materials should be considered as a mitigating action. If the decision is the opposite and OWFs are seen as means of welcomed increase in diversity, restoration of previous lost habitats or creation of production grounds for fish/shellfish and tourist attractions, then the focus should be on the mounting evidence that artificial substrates apparently attract a different species assemblage than natural substrates. In any case, in areas with little or no hard substrate, OWFs will provide not only new habitats, but also create a stepping stone for the spread of hard substrate organisms and thereby facilitate the spread of non-native and invasive species. A main point is, however, that basic knowledge of this potentially huge impact is almost absent in the literature and not a well-integrated part of EIAs.

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