Environmental impacts of marine renewable energy infrastructures: what can we learn from the wind energy sector experience?

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Abstract— **The potential effects of the ocean renewable energy sector on marine organisms have been comprehensively discussed and include effects on nearshore intertidal and benthic habitats, fish, fish habitats, large marine vertebrates (sea birds, marine mammals and large fish), oceanographic and coastal processes. However, due to the novelty of wave and tidal energy device deployments, most of these discussed effects and impacts are just potential and not observed, being the global picture still poorly known. On the other hand, the EIA procedures of the offshore wind energy sector, being the most mature among all the ocean renewables, has produced a significant amount knowledge and has many lessons to teach to the less mature ocean renewable sectors. Particularly, these studies provide significant insights concerning : 1) the area and the timing over which biological effects may occur, 2) the responses to disturbance of different target organisms; 3) the quantification of short- and long-term effects; 4) the recovery from impact in the long term. The monitoring studies concerning offshore wind parks (OWPs) which have been considered in this review show very little and only local impacts on the environment, either during their construction and during the operational phases. However, it is still open the question whether many little and local impacts may determine any biologically significant consequence at the population level. As the number and size of ocean renewable energy developments will increase, there will be a growing need to consider the population level consequences and cumulative impacts of these activities on marine species.**

Keywords— **Offshore wind parks, Environmental impact monitoring.**

I. Introduction

Ocean renewable energy sources are increasingly attractive in the perspective of satisfying the worldwide demand of clean energy. Research efforts have been increasing on the side of the technological development, however several non-technical barriers still need to be overcome. The most significant of these non-technical barriers is the necessity to comply with the EU Environmental Impact Assessment (EIA) Directive and associated national legislation, which requires regulatory authorities to make an informed decision on the proposed project and its potential environmental impacts at an early stage. The potential effects of the ocean renewable energy sector on marine ecosystem have been comprehensively discussed and include effects on nearshore intertidal and benthic habitats, fish, fish habitats, large marine vertebrates (sea birds, marine mammals and large fish), oceanographic and coastal processes [1], [2]. However, due to the novelty of wave and tidal energy device deployments, most of these discussed effects and impacts are just potential and not yet validated through observations, being the global picture still poorly known. On the other hand, the offshore wind energy sector is the most mature among all the ocean renewables, and a growing number of offshore wind-related environmental studies are being conducted worldwide [3]. Moreover, either the experience gained during the first EIA procedures for offshore wind farms, either the data made available from the environmental monitoring at the offshore wind farm sites, which now has been conducted for several years, have many lessons to teach to the less mature ocean renewable sectors. In the presented review the results from environmental monitoring conducted over several years at some wind farm sites, are presented and general recommendations are drawn which might be relevant also for the future monitoring of other marine renewable energies. Special attention has been given to the Danish experience since the long-term monitoring activities that have been conducted at the Danish wind farms are still unique, being these the only studies that may provide insights on long-term impacts.

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II. The literature on the environmental impacts of the offshore wind energy sector

The first wind turbines at sea were installed in Danish waters in 1991. The first real offshore North Sea wind park came into operation in Denmark in 2002, followed by The Netherlands in 2007, UK and Belgium in 2008 and Germany in 2010 [3]. For all these wind parks monitoring programmes to investigate the impacts on the surrounding marine ecosystems were started and many results have now been published [4],[5],[6],[7],[8],[9]. Environmental data collection on OWPs started around 2000, first in Denmark [10], [11]. These early studies indicated possible effects concerning the introduction of hard substratum fauna into a sand dominated environment, and some potential effects were predicted for seabirds and marine mammals [3]. Since then research effort at a European/global level has increased significantly, covering a wide range of potential impacts and all ecosystem components [6],[9]. All these investigations, over the last years, have contributed to a significant increase of the understanding of OWP potential effects. The scientific knowledge has been enhanced in some topic areas, particularly at the species level for some benthic animals, fish, birds and marine mammals and a good knowledge has been acquired on many of the general short-term effects on the marine system. Some knowledge has been also acquired about long-term changes that could be correlated with the interactions between OWPs and the environment. The main lesson that can be acquired from these monitoring activities, conducted all across Europe, is that OWPs do change the local environment and these changes concern all ecosystem components; however if some of these changes can be regarded as potentially negative (e.g. avoidance and collisions of birds), some other can be considered as potentially positive (e.g. increased biodiversity and local fish populations [9], [11], [12]). The major impacts of OWPs are focused on the most obvious changes within the local environment such as the very high sound levels produced during the construction phase [13], [14], the introduction of hard substratum [10], [15], [16], the rotating blades [17], [18] and the exclusion of fisheries, such as trawling [6], [19]. Knowledge has been gained on the short-term effects on benthos, fish, birds and marine mammals, including attraction to and avoidance of the OWPs (for references: see [6]), while on the effects and consequent changes over the longer term there is still to investigate. Long-term monitoring studies may be useful to detect various effects through time, e.g. the effect of trawling cessation on the benthos [6] or the displacement effects on seabirds [20]. Some studies have outlined how the basic monitoring by itself (e.g. following the BACI design of OWP versus reference area) may not be sufficient to disentangle specific cause–effect relationships, especially in systems with a high natural variability [21], [6]. Notwithstanding, it cannot be denied that targeted monitoring activities, such as the near turbine effects studies on benthos [22], the feeding behaviour of demersal fish in the wind park [23],[24],[25] or the escape behaviour of harbour porpoises during piling [26], have provided significant new and important knowledge on cause–effect relationships [27]. In many monitoring programmes, there has been the attempt to differentiate between 'positive' and 'negative' responses to OWPs. Ecologically 'negative' impacts may include the altered sediment characteristics, increased erosion of the natural sandy sediments around wind turbine foundations [28], an increase in the non-indigenous species on the hard substrata [29], an obvious disturbance of seabirds because of avoidance and collision [30], [20] and the increased sound pressure on the marine environment and its impact on marine mammals [20], [31], and fish [32], [33]. The 'positive' impacts include, for example, the enrichment and colonisation of the soft and hard substratum invertebrates and fish (e.g. [16], [22]).

III. Short-term or Long-term effects

Monitoring associated with the Environmental Impact Assessment is a requirement of environmental legislation across many countries. Basic monitoring focusing on the resultant effect of human activities, such as the construction and operation of offshore wind parks, is the most common type of monitoring in environmental impact studies. It allows keeping track of major and even unforeseen impacts and is therefore a suitable research strategy for a better understanding of the environmental impact of development. It may also trigger adjusting or even halting activities if unacceptable impacts occur. However, limitations and knowledge gaps of these monitoring studies have been outlined by past studies. So far, all ecosystem components investigated have already shown some degree of response to OWPs. However, most of the evidence has been interpreted as the altered ecosystem was still developing, and the patterns observed so far to be considered as short-term effects that probably reflect the initial stages of the ecological change and succession [6]. The rationale of these conclusions is that some impacts may not have been detected yet, because they are still not developed to the extent needed to become detectable. For instance, the enrichment of the soft-sediment macrobenthos observed close to the wind turbines, has been demonstrated to spatially extend through time [22] although it might not have reached the spatial extent to be picked up by the basic monitoring of macrobenthos, collecting samples at more than 200 m from the turbines [34],[35]. The long-term continuation of the basic monitoring of all ecosystem components is generally recommended to record any long-term effect but at the moment it is still unclear which is the discriminant between short-term and long-term effects, since it varies from component to component.

IV. The issue of Research Effort

It is well known that the likelihood of impact detection is strongly dependent on research effort, impact size and data variability. Research effort is mostly determined by the aim of the study, and it strongly affects the amount of observations or samples collected. Impact size is the degree of deviation from a defined reference condition and data variability is natural or sampling-induced variability in the data (e.g. [36], [37]). The low likelihood of impact detection has been pointed out as the main factor making difficult the detection of impacts of Belgian offshore wind parks on seabirds [38]. Also the difficulties in demonstrating consistent impacts on the soft-sediment epibenthos and fish throughout the first 6 years of monitoring in Belgian waters has been probably related to a combination of natural and sampling-induced variability

and the time scale over which sampling occurs in relation to physico-chemical and biological response [3]. The effort issue certainly would need a higher consideration when designing basic monitoring programmes and attention should be given to the statistical power needed to quantify the likelihood that an impact of a given extent can be detected, while methods on how to lower the variability in the data should be further explored. Some authors have concluded that natural variability may be lowered focusing data collection on one season and as such excluding seasonality [39] however this strategy may be effective only when dealing with short-term effects. Sampling-induced variability can be lowered by increasing the sample size. It has been speculated that a higher number of passive acoustic monitoring devices, inside and outside wind parks, could facilitate investigating possible harbour porpoise, *Phocoena phocoena,* repulsion or attraction to offshore wind parks [40], [41], [42], [43]. Moored equipment will allow recording long time series of underwater sound, during a broad range of weather conditions and various wind park development stages, and will hence increase the representativeness of underwater sound results [44]. Within a Before-After-Control-Impact (BACI) design, an appropriate balance in number of samples per group needs to be targeted.

V. CAUSE-EFFECTS RELATIONSHIPS

The Working Group on Marine Benthos and Renewable Energy Developments (WGMBRED) of the International Council for the Exploration of the Sea (ICES) reviewed the cause–effect relationships between offshore renewable energy installations, mainly OWPs, and marine benthos [45]. They outlined a wide variety of potential causal relationships in a context of the marine environment ecosystem services affected by renewable energy installations. Several of these cause–effect relationships have been investigated during the first decades of monitoring. For instance, the local enrichment of organic matter in the soft sediment close to wind turbines, which has been proven to cause an increase in benthos species richness and density [46]. Some fish and seabird species were also found to be attracted to the wind turbines as a consequence of the improved feeding conditions due to habitat alterations [25]. Stomach analysis of cod, *Gadus morhua* and pouting, *Trisopterus luscus,* have demonstrated that these species were primarily predating on the hard substratum epifauna generated by the OWP presence [23], [24]. Moreover, if the attraction-production hypothesis in artificial reefs has been investigated in detail for several fish [25]), far less investigated is the attraction-production for several invertebrate (e.g. edible crab, *Cancer pagurus* and European lobster, *Homarus gammarus*) and fish species common to OWPs [47] which prey on the hard substratum epifouling community. Biomass estimates of these prey species may be used to quantify food availability created by the whole wind park artificial reef [48]; [49]. Trawling cessation in the OWP area might also lead to changes in energy flow and trophic structure of soft-bottom benthos [19] since the soft-sediment macrobenthos in the vicinity of wind turbines may alter trophic connectivity, as the increasing abundance may start playing an important role in the artificial reef food web. Artificial reef effect itself may be different for the different types of foundation and types of foundations may differ between, and even within wind parks. Steel monopile, tripods and jacket foundations, the latter generally without erosion protection layer, are most common in European waters [50]; however substantial reef effect monitoring, especially concerning fish and megafauna attraction, has been performed respectively near concrete gravity-based foundations with an extended erosion protection layer (e.g. [24], [25]) or jacket foundations (e.g. [47], [49]).

The artificial reef effect may also explain the attraction of some bird species (e.g. common tern, *Sterna hirundo* or great cormorant, *Phalacrocorax carbo*) to the wind parks as it is hypothesised that these species benefit from a yet unexplored increased availability of pelagic fish [20]. Whether or not pelagic prey fish also attract marine mammals, such as harbour porpoises, remains not so clear [51]. Some studies documented not only that pelagic fish were scared away by construction sound but also proved decreased food gathering of mackerel in the OWP area [33]. Whether this might affect pelagic fish occurrences in the long run as potential food resources for higher trophic levels remains to be understood through future monitoring programmes.

Sectorial literature has debated that positive artificial reef effect of offshore wind parks may be partially neutralised by sound generated during the construction and by the generation of operational sound and electromagnetic fields (EMFs) [33], [52]. The most comprehensive assessment on the effect of electromagnetic fields on fish has been conducted at the Danish offshore wind park of Nysted [53]. For this purpose, specially designed setup and fishing gear were developed and applied to the area along the cable route connecting the wind farm with the shore. The design of fishing gear included two types of pound nets, bi-directional and quadri-directional, and one bi-directional and two quadridirectional pound nets were placed on each side of the cable. This setup made it possible to detect the migration direction of the fish and to estimate the number of fishes crossing the cable. As part of the survey programme at Nysted, the migration direction for common eel (*Anguilla anguilla*) was investigated through a mark and recapture programme. Eels caught in the pound nets were marked and released on the same side of the power cable. Fishermen then recaptured the tagged fish and reported the catches to the survey programme. A conceptual model was formulated representing an open system with bi-directional migration across and along the cable route. Two effects were considered: the asymmetry in the catches across the cable route indicating an east-west/west-east migration, and the potential effect on the individual fish behaviour, testing the hypothesis of a barrier or a blocking effect deriving from the cable route.

Concerning migration direction, significant impacts were found for some species (e.g. baltic herring, *Clupea harengus*, common eel, Atlantic cod and flounder, *Platichthys flesus)*, suggesting that the migration of some species across the cable route might be impaired. Concerning the effect on fish behaviour, significant results were only obtained for common eels, that were shown to react by leaving the area along the cable route, and for Atlantic cod, for which it was shown some accumulation close to the cable route. However, as in many other environmental assessment studies, the strength of the electromagnetic field around the cable was not measured at Nysted and it was assumed its proportionality with the power production at the wind farm. Correlations between the above mentioned effects and the power production were examined but a significant correlation was only found for flounders which apparently crossed the cable when the strength of the electromagnetic fields was estimated to be low, during calm periods. However, as the same authors of the study have clarified, the hypothesis that fish might be also reacting to the physical conditions along the cable route could not be excluded. The results of the mark-recapture study at Nysted strongly indicated that the eels prevailing migration was not altered by the presence of the wind farm.

The Danish experience on the long-term monitoring of seals and porpoises is also extremely relevant for documenting the effects from construction and operation of Horn Rev and Nysted, the first large offshore wind farms where a national demonstration program was activated. Concurrently to the construction and operation phases of these two OWPs, an ambitious environmental monitoring program was activated to assess potential negative effects on the marine environment, [53]. Although no simple conclusion was drawn, the monitoring study in general showed smaller effects on seals than on porpoises, and smaller effects at Horns Rev than at Nysted. No statistically significant effects were seen on seals, except for a decrease in the number of seals resting on land at Rødsand during pile driving operations. Satellite telemetry studies did not indicate differences in the seals' use of the wind farm area, when compared to the surrounding areas at Horns Rev. Moreover, no evidence of negative effect during the two OWP operation on the seal populations was found. As for seals, the effects on porpoises were mainly connected to the construction phase, and only for porpoises at Nysted the avoidance effect persisted through the first two years of operation. At Horns Rev, which is an important area to porpoises and with general high densities of animals, there was a weak negative effect of the construction period as a whole, and strong – but short term – reactions to pile driving operations. No effects were observed during normal operation at Horns Rev. At Nysted, an area with a lower abundance of porpoises, there were strong negative reactions to the construction, where animals left the wind farm area almost completely and the reference site 10 km away was also affected. As on Horns Rev strong reactions were observed to pile driving operations and recovery from pile driving took significantly longer than at Horns Rev. After two years of operation the porpoise activity in the reference area reverted to baseline levels, although the activity in the Nysted Wind Farm was still lower than expected. In general, at Horns Rev a large number of animals was affected but for a limited period of time (construction period), and even more animals were affected for an even shorter period of time during pile driving operations when the effects extended beyond the outer edges of the study area.

At Nysted the situation was reversed. Although a comparatively low number of animals was affected, the population of porpoises in the western part of the Baltic Sea is also smaller. Therefore, the relative impact on the population was higher at Nysted, both because the response to the wind farm was stronger and because the duration of the disturbance has been considerably longer than at Horns Rev, as it was extended into the operating period. A further monitoring study, meant to be the continuation of the national monitoring program [43], allowed to assess that the strong negative effect on porpoises observed in Nysted Offshore Wind Farm was gradually diminishing, possibly due to a habituation of the porpoises to the wind farm or enrichment to the environment favourable to porpoises due to less fishing and artificial reef effects [10]. Since the effects on harbour porpoises were different in magnitude at the three wind farms (i.e. Horn Rev, Nysted and the more recent Rødsand2 constructed close to Nysted) the study concludes that harbour porpoises may react differently to similar disturbances [43]. It was speculated that the stronger response at Nysted might be due to the fact that the area is a less important habitat to porpoises than

Horns Rev [43]. So the porpoises at Horns Rev might be more tolerant to disturbance, if the area is of great importance to their survival, whereas the porpoises around Nysted may not be particularly interested in the area. Another hypothesis is that, being the Nysted area relatively sheltered whereas Horns Rev is very exposed with higher background noise, the turbine noise from the wind farm at Nysted could be higher above the background noise than at Horns Rev so the porpoises were able to hear the turbines at greater distances at Nysted. The authors of the study [43] conclude that until more information will be made available on the actual cause of the observed difference, generalization of these results to other wind farms is not recommended. Finally, the Danish experience is worth to mention also for the development of a technology to measure collisions of birds (e.g. the "TADS" or "thermal animal detection system") which has been one of the major achievements of the Danish programme. Particularly, TADS provided empirical evidence that sea bird collisions were very rare events. Collision risk modelling and bird tracking by radar as well as visual observations in fact showed that many bird species tended to avoid the wind farm, changing flight direction some kilometres away to deflect their path around the site. Birds flying through the wind farm tended also to alter altitude to avoid the risk of collision. Under adverse weather conditions, which were thought to be likely to increase collision risk, results showed that birds tend to avoid flying. The strong avoidance behaviour results in very low estimates of collision risk suggesting instead increases in habitat loss and in costs of travel. The bird studies demonstrated also strong differences between bird species in response to the marine wind farms, with some species of conservation concern such as divers and scoters showing particularly high aversion to these structures [53].

VI. Impacts and Cumulative Impacts

The significance of the impact needs also discussion.

A certain degree of human-induced impacts on the marine environment needs to be accepted, as long as these impacts do not prevent sustainability. Exercises in the context of the European Habitats- and Bird Directives (Nature 2000), and the Marine Strategy Framework Directive (MSFD) to determine what is acceptable from a nature conservation point of view or from the MSFD: Good Environmental Status and Environmental Targets perspective, have been conducted, being the occasion for discussing meaningful impact limits. The cumulative habitat loss due to ongoing and planned offshore wind farm construction within the North Sea's exclusive economic zones of Germany, the Netherlands, Belgium and the United Kingdom has been analysed in context of the EU Marine Strategy Framework Directive [54]. The study highlights the varying experiences and legislative differences between neighbouring states or riparian states of a common Regional Sea, which may generate opposing priorities, goals, measurements and consequently assessments, and it shows the difficulties of implementing the MSFD requirements to assess cumulative impacts of OWPs at Regional Sea scale. Furthermore, the study points out the urgent need for harmonisation of conservation approaches and cooperation among riparian states of trans-national "management units" like the North Sea to successfully implement the Marine Strategy Framework Directive. A major challenge for all offshore renewable energy environmental monitoring programmes will be to assess cumulative impacts and to upscale locally observed impacts to the larger scale at which a number of ecological processes take place. Despite of that, most of the monitoring effort so far has been mainly focused on the environmental impact of a single wind park and specific receptors [6],[7[,[8]. Because the species that are affected are part of populations extending over larger areas, ecologists [3] recommend the focus of the impact investigation to be widened to consider the population level of those species (e.g. sea birds attracted to the wind parks, having an increased risk of collision with the wind turbine blades). Whether or not the number of collisions may actually put the sustainability of certain bird populations at risk can however only be reliably assessed when taking account of the multitude of wind parks throughout the range of their populations spatial distribution [55]. Similarly, the effect on the population of harbour porpoises avoiding areas of pile driving e.g. [31] should be assessed in a cumulative OWP context throughout their distributional range. Even the effects anticipated to be positive from a local perspective, such as the improved feeding condition for demersal fish attracted to the wind turbines, according to some authors [25] would be needed to be evaluated at the population level before final conclusions on the attraction-production hypothesis can be drawn. However, to accomplish that, scientifically sound threshold ranges for acceptable overall mortality or habitat loss should be defined, based on investigations at the spatial scale relevant to the population of each species under consideration and at the scale of the local food web. Moreover, OWPs are only one of the many human activities in the marine environment that also influence ecosystem structure and functioning [56], [57]. Assessing the combined effect of all these activities, framing the observed impact of wind parks in a broader setting, would demand a holistic approach which is believed to be of major importance for the management of the marine ecosystem. However, research designs, to appropriately tackle the issue, are largely lacking and the available knowledge may not be enough. The monitoring of basin wide cumulative effects is in fact very ambitious and it cannot satisfactorily be dealt with by a single country or research team. It would require a close collaboration between scientists and administrators, preferably across country borders, to assemble and comprehensively analyse all information that is needed. Future monitoring programmes should therefore attempt to upscale their surveys in a cumulative and in-combination context, searching for international collaboration to develop the strategies needed (see e.g. [54]).

VII. Conclusions and "Take-Home" Messages

The monitoring studies which have been considered in this review show limited and local impacts on the environment, either during their construction and during the operational phases. However, it is still open the question whether several little and locally related impacts may determine any biologically significant consequence at the population level. As the number and size of ocean renewable energy developments will increase, there will be a growing need to consider the population level consequences and cumulative impacts of these activities on marine species. Notwithstanding, some key lessons can be learned from the wind energy sector experience as far as their implications for the other ocean renewable are concerned. Particularly these studies provide significant insights for similar monitoring studies, such as: 1) the area and the time period over which biological effects may occur (e.g. concerning benthos or marine mammal); 2) the measured responses to marine renewable energy infrastructures construction and operation in terms of both positive and negative effects concerning different target organisms; 3) the recovery over the years from the impacts (e.g. harbour porpoises at the Nysted OWP site).
Moreover, general conclusions may be drawn across the offshore wind farm sector, which might be relevant also for the future monitoring of other marine renewable energies:

- Environmental impact monitoring programmes are generally designed to show whether habitats change due to the presence of OWP, or marine organisms avoid the wind farm areas or change their occurrence in the surrounding area affected by the construction and operation of the wind farms. Such studies are not able to detect which of the specific factors (such as noise, turbine presence, boat traffic or change in prey availability) are responsible for the observed effects;
- Construction activities (e.g. pile driving operations) were found to produce the highest level of disturbance, involving also considerable boat traffic, with associated underwater noise, as disturbance to the seabed with resuspension of sediment etc.;
- To date no study on wind farms has been able to measure the impact on the population level of any target investigated species; on the other hand, offshore wind farms were shown to have very little impact on the environment, and if population level effects exist, it is unlikely their impact could be large.
- The Danish experience at the Nysted and Horns Rev sites is very important since these are the only studies where long-term effects could be evaluated. Some differences have been found between Nysted and Horns Rev, concerning harbour porpoise responses to both construction and operational phases of the plants: at Nysted the effect persisted during the operational phase and the recovery was particularly slow, although measurable signs of recovery have been documented;
- the Danish experience was also relevant for the technological tools developed, especially for the study of behavioural responses of marine mammals (e.g. the T-POD system for recording porpoise sound production underwater) and birds (e.g. the "TADS" or "thermal animal detection system" of a technology to measure collisions of birds,), which will be very useful for researchers working on new offshore installations in other locations and can be applied for studying a wide range of focal species;

We believe that the offshore wind experience may support the future monitoring activity concerning the other MREs if the following ***take-home messages*** will be acquired:

1. Short-term effects do not necessarily reflect long-term effects. Long term monitoring activities are fundamental to assess the possible recovery from short-term impacts;
2. Given that monitoring effort and sample size have been reasonably or statistically determined, if no effect can be detected because of the natural variability extent, the effect should be considered not relevant;
3. Future monitoring programmes should be designed to effectively detect the relative contributions of all the potential impacting factors which might responsible for the observed effects;
4. The experience on sea birds, which might not be relevant for most of the other MREs, in our opinion, teaches an important lesson which might valid also for other species: mortality risk modelling, especially when based on very cautious and conservative assumptions, may largely over-estimate the size of the effects. Collision risk, at least for sea birds, may appear a minor concern with respect to the potential habitat loss and increase of energetic travel cost that may affect the survivorship;
5. Concerning the potential EMF effect on marine organisms, if further hypothesis-driven research on this impact would be certainly needed to get a better understanding, the OWP experience suggests this impact being probably negligible for most of the MREs;
6. The studies on marine mammals and underwater noise outline that the habitat preferences of the species might affect their response to a disturbance; the importance of the site for the species ecology, and the percent of population affected should be considered when evaluating the impact;
7. Finally, being nowadays multiple the potential impacts of human activities at sea, the assessment of the combined effect of all these activities is required,

framing the observed impact of any new marine infrastructure in a broader setting. Future monitoring studies would require basin-wide regional or international cooperation and effective data sharing among stakeholders.

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REFERENCES

[1] A.E. Copping, N. Sather, L. Hanna, J. Whiting, G. Zydlewski, G. Staines, A. Gill, I. Hutchison, A. O'Hagan, T. Simas, J. Bald, C. Sparling, J. Wood, and E. Masden. "Annex IV 2016 State of the Science Report: *Environmental Effects of Marine Renewable Energy Development Around the World*," Ocean Energy Systems. 2016. [Online]. Available: https://tethys.pnnl.gov/publications/state-of-thescience-2016

[2] G. Boehlert and A. Gill, "Environmental and Ecological Effects of Ocean Renewable Energy Development: A Current Synthesis," *Oceanography*, vol. 23, no. 2, pp. 68-81, 2010.

[3] Lindeboom H., Degraer S., Dannheim J., Gill A.B., Wilhelmsson D. Offshore wind park monitoring programmes, lessons learned and recommendations for the future. *Hydrobiologia* (2015) 756:169–180, 2015.

[4] Elliott, M.The role of the DPSIR approach and conceptual models in marine environmental management: An example for offshore windpower. *Mar. Pollut. Bull.* 44(6): iii–iv, 2002.

[5] Wilson, J., M. Elliott, N. Cutts, L. Mander, V. Mendão, R. Perez-Dominguez, A. Phelps.. Coastal and offshore wind energy generation: Is it environmentally benign? *Energies* 3: 1383–1422, 2010.

[6] Lindeboom, H. J., H. J. Kouwenhoven, M. J. N. Bergman, S. Bouma, S. Brasseur, R. Daan, R. C. Fijn, D. de Haan, S. Dirksen, R. van Hal, R. H. R. Lambers, R. Ter Hofstede, K. L. Krijgsveld, M. Leopold, M. Scheidat. Shortterm ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. *Environ. Res. Lett.* 6(3): 035101, 2011.

[7] Degraer, S., R. Brabant (eds). Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Learning from the Past to Optimise Future Monitoring Programmes. *Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models, Marine ecosystem management unit,* Brussel: 239, 2013.

[8] Beiersdorf, A. & A. Radecke (eds). *Ecological Research at the Offshore Windfarm alpha ventus: Challenges, Results and Perspectives.* Springer, Wiesbaden: 201, 2014.

[9] Bergström, L., L. Kautsky, T. Malm, R. Rosenberg, M. Wahlberg, N. A. Capetillo & D. Wilhelmsson. Effects of offshore wind farms on marine wildlife – a generalized impact assessment. *Environ. Res. Lett.* 9(3): 034012, 2014.

[10] Petersen, K. J. & T. Malm. Offshore windmill farms: Threats or possibilities to the marine environment. *Ambio* 35: 29–34, 2006.

[11] Leonhard, S.B., C. Stenberg, J. Støttrup (eds). *Effect of the Horns Rev 1 Offshore Wind Farm on Fish Communities. Follow-up Seven Years after Construction*. DTU Aqua, Orbicon, DHI, NaturFocus. Report commissioned by The Environmental Group through contract with Vattenfall Vindkraft A/S. DTU Aqua-report No 246-2011. National Institute of Aquatic Resources, Technical University of Denmark: 66.

[12] Wilhelmsson, D., T. Malm, R. Thompson, J. Tchou, G. Sarantakos, N. McCormick, S. Luitjens, M. Gullstro¨m, J. K. Patterson Edwards, O. Amir & A. Dubi (eds). *Greening Blue Energy: Identifying and Managing the Biodiversity Risks and Opportunities of Offshore Renewable Energy*. IUCN (International Union for Conservation of Nature), Gland, 2010.

[13] Huddleston, J. (ed.) Understanding the Environmental Impacts of Offshore Windfarms. COWRIE 2010, London: 138.

[14] Norro, A., B. Rumes & S. Degraer. Differentiating between underwater construction sound of monopile and jacket foundations for offshore windmills: A case study from the Belgian part of the North Sea. *Sci. World J.* 2013: 7.

[15] Langhamer, O.. Artificial Reef Effect in Relation to Offshore Renewable Energy Conversion: State of the art. *Sci. World J* 2012: 386713.

[16] De Mesel, I., F. Kerckhof, A. Norro, B. Rumes & S. Degraer, 2015. Succession and seasonal dynamics of the epifauna community on offshore wind farm foundations and their role as stepping stones for non-indigenous species. *Hydrobiologia*, 756 : 37–50, 2015.

[17] Drewitt, A. L. & R. H.W. Langston. Assessing the impact of wind farms on birds. *Ibis* 148: 29–42, 2006.

[18] Mendel, B., J. Kotzerka, J. Sommerfeld, H. Schwemmer, N. Sonntag & S. Garthe.Effects of Alpha Ventus offshore test site on distribution patterns, behaviour and flight heights of seabirds. In BSH & BMU (ed.), *Ecological Research at the Offshore Windfarm Alpha Ventus – Challenges, Results and Perspectives.* Federal Maritime and Hydrographic Agency (BSH), Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (BMU), Wiesbaden: 96–109, 2014.

[19] Dannheim, J., T. Brey, A. Schröder, K. Mintenbeck, R. Knust & W. E. Arntz. Trophic look at soft-bottom communities – Short-term effects of trawling cessation on benthos. *J Sea Res.* 85: 18–28, 2014.

[20] Vanermen, N., T. Onkelinx, W. Courtens, M. Van de walle, H. Verstraete, E. W. M. Stienen. Seabird avoidance and attraction at an offshore wind farm in the Belgian part of the North Sea. *Hydrobiologia*, this issue. 2015 doi:10.1007/s10750-014-2088-x.

[21] Gray, J. S., M. Elliot. Ecology of marine sediments: from science to management. Oxford University Press, Oxford: 256, 2009.

[22] Coates, D. A., Y. Deschutter, M. Vincx, J. Vanaverbeke, 2014. Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. *Mar. Environ. Res.* 95: 1–12, 2014.

[23] Reubens, J. T., S. Degraer & M. Vincx. Aggregation and feeding behaviour of pouting (*Trisopterus luscus*) at wind turbines in the Belgian part of the North Sea. *Fish. Res.* 108: 223–227, 2011.

[24] Reubens, J., M. De Rijcke, S. Degraer & M. Vincx. Diel variation in feeding and movement patterns of juvenile Atlantic cod at offshore wind farms. *JSea Res.* 85: 214–221, 2014.

[25] Reubens, J., S. Degraer & M. Vincx, 2014. The ecology of benthopelagic fishes at offshore wind farms: a synthesis of 4 years of research. *Hydrobiologia* 727: 121–136, 2014.

[26] Haelters J., V. Duliére, L. Vigin & S. Degraer, 2015. Towards a numerical model to simulate the observed displacement of harbour porpoises Phocoena phocoena due to pile driving

in Belgian waters. *Hydrobiologia*, 756(1): 105-116, 2015. doi:10.1007/s10750-014-2138-4.

[27] Degraer, S., R. Brabant (eds). Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Learning from the Past to Optimise Future Monitoring Programmes. Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models, Marine ecosystem management unit, Brussel: 239, 2013.

[28] Vanden Eynde, D., M. Baeye, R. Brabant, M. Fettweis, F. Francken, P. Haerens, M. Mathys, M. Sas & V. Van Lancker. All quiet on the sea bottom front? Lessons from the morphodynamic monitoring. In Degraer, S., R. Brabant & B. Rumes (eds), *Offshore Wind Farms in the Belgian part of the North Sea: Heading for an Understanding of Environmental Impact*s. Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models, Marine ecosystem management unit, Brussels: 35–47, 2013.

[29] Kerckhof, F., S. Degraer, A. Norro & B. Rumes. Offshore intertidal hard substrata: a new habitat promoting nonindigenous species in the Southern North Sea: an exploratory study. In Degraer, S., R. Brabant & B. Rumes (eds), *Offshore Wind Farms in the Belgian part of the North Sea: Selected Findings from the Baseline and Targeted Monitoring.* Royal Belgian Institute of Natural Sciences, Management Unit of the North Sea Mathematical Models, Marine Ecosystem Management Section, Brussels, 2011.

[30] Busch, M., A. Kannen, S. Garthe & M. Jessopp. Consequences of a cumulative perspective on marine environmental impacts: Offshore wind farming and seabirds at North Sea scale in context of the EU marine strategy framework directive. *Ocean Coast. Manage.*71: 213–224, 2013.

[31] Dähne, M., A. Gilles, K. Lucke, V. Peschko, S. Adler, K. Krugel, J. Sundermeyer & U. Siebert. Effects of piledriving on harbour porpoises (Phocoena phocoena) at the first offshore wind farm in Germany. *Environ. Res. Lett.*8(2): 025002, 2013.

[32] Gill, A. B., M. Bartlett & F. Thomsen. Potential interactions between diadromous fishes of U.K. conservation importance and the electromagnetic fields and subsea sound from marine renewable energy developments. *J. Fish Biol.* 81: 1791, 2012.

[33] Krägefsky, S.. Effects of the Alpha Ventus offshore test site on pelagic fish. Chapter 10. In Beiersdorf, A. & A. Radecke (eds), Ecological Research at the Offshore Windfarm Alpha Ventus: Challenges, Results and Perspectives. Springer, Wiesbaden: 83–94, 2014.

[34] Coates, D., G. Van Hoey, J. Reubens, S. Vanden Eede, V. De Maersschalck, M. Vincx & J. Vanaverbeke. The macrobenthic community around an offshore wind farm. In Degraer, S., R. Brabant & B. Rumes (eds), *Environmental Impacts of Offshore Wind Farms in the Belgian Part of the North Sea: Learning from the Past to Optimise Future Monitoring Programmes*. Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section, Brussels: 87–97, 2013.

[35] Gutow, L., K. Teschke, A. Schmidt, J. Dannheim, R. Krone & M. Gusky,. Rapid increase of benthic structural and functional diversity at the alpha ventus offshore test site. In *BSH & BMU (ed.), Ecological Research at the Offshore Windfarm Alpha Ventus – Challenges, Results and Perspectives*. Federal Maritime and Hydrographic Agency (BSH), Federal Ministry of the Environment, Nature Conservation and Nuclear Safety (BMU), Wiesbaden: 67–81, 2014.

[36] Collie, J. S., S. J. Hall, M. J. Kaiser & I. R. Poiner. A qualitative analysis of fishing impacts on shelf-sea benthos. *J. Anim. Ecol.* 69: 785–798, 2000.

[37] Gray, J. S., P. Dayton, S. Thrush & M. J. Kaiser. On effects of trawling, benthos and sampling design. *Marine Pollution Bulletin* 52: 840–843, 2006.

[38] Vanermen, N., T. Onkelinx, P. Verschelde, W. Courtens,M. Van de walle, H. Verstraete & E. W. M. Stienen. Assessing seabird displacement at offshore wind farms: power ranges of a monitoring and data handling protocol. *Hydrobiologia*, this issue. 2015, doi:10.1007/s10750-014-2156-2.

[39] Rogers, S. I., P. J. Somerfield, M. Schratzberger, R. Warwick, T. A. D. Maxwell & J. R. Ellis. Sampling strategies to evaluate the status of offshore soft sediment assemblages. *Mar. Pollut. Bull.* 56: 880–894, 2008.

[40] Thompson, P. M., D. Lusseau, T. Barton, D. Simmons, J. Rusin & H. Bailey, 2010. Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. *Mar. Pollut. Bull.* 60(8): 1200–1208, 2010.

[41] Scheidat, M.. Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation. 6(3): 035101, *Environ. Res. Lett*. 2011.

[42] Brandt, M. J., A. Diederichs, K. Betke & G. Nehls.. Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. 421: 205–216, *Mar. Ecol. Prog. Ser.*, 2011.

[43] Teilmann, J. & J. Carstensen. Negative long term effects on harbour porpoises from a large scale offshore wind farm in the Baltic – evidence of slow recovery. *Environ. Res. Lett*. 7(2012): 10, 2012.

[44] Dazey, E., B. McIntosh, S. Brown & K. M. Dudzinski. Assessment of underwater anthropogenic noise associated with construction activities in Bechers Bay, Santa Rosa Island California. J. *Environ. Prot.* (3): 1286–1294, 2012.

[45] ICES Report of the Working Group on Marine Benthal and Renewable Energy Developments (WGMBRED), 19–22 March 2013, Caen, France. ICES CM 2013/SSGEF:17: 23.

[46] Coates, D. A., Y. Deschutter, M. Vincx &J. Vanaverbeke. Enrichment and shifts in macrobenthic assemblages in an offshore wind farm area in the Belgian part of the North Sea. *Mar. Environ. Res.* 95: 1–12, 2014.

[47] Krone, R., L. Gutow, T. Brey, J. Dannheim & A. Schroder . Mobile demersal megafauna at artificial structures in the German Bight – Likely effects of offshore wind farm development. *Estuar. Coast. Shelf. Sci.* 125:1–9, 2013.

[48] Joschko, T. J., B. H. Buck, L. Gutow & A. Schröder, 2008. Colonization of an artificial hard substrate by Mytilus edulis in the German Bight. *Mar. Biol. Res.* 4: 350–360, 2008.

[49] Krone, R., L. Gutow, T. J. Joschko & A. Schroder, 2013. Epifauna dynamics at an offshore foundation—Implications of future wind power farming in the North Sea. *Mar. Environ. Res.* 85: 1–12, 2013.

[50] EWEA, 2014. The European Offshore Wind Industry – Key Trends and Statistics 2013, European Wind Energy Association, www.ewea.org/fileadmin/files/library/publications/statistics/European_offshore_statistics_2013.pdf.

[51] Haelters, J., L. Vigin & S. Degraer. Attraction of harbour porpoises to offshore wind farms: what can be expected? In Degraer, S., R. Brabant & B. Rumes (eds), *Environmental Impacts of Offshore Wind Farms in the Belgian part of the North Sea: Learning from the Past to Optimise Future Monitoring Programmes*. Royal Belgian Institute of Natural Sciences, Operational Directorate Natural Environment, Marine Ecology and Management Section, Brussels: 167–171, 2013.

[52] Gill, A. B., I. Gloyne-Phillips, J. A. Kimber & P. Sigray.

Marine renewable energy, electromagnetic fields and EMsensitive animals. In Shields, M. & A. Payne (eds), *Humanity and the Sea: Marine Renewable Energy and the Interactions with the Environment*. Springer Science and Business Media, Dordrecht, 2014.

[53] Danish Offshore Wind: Key Environmental Issue. Published by DONG Energy, Vattenfall, Th e Danish Energy Authority and The Danish Forest and Nature Agency, November 2006. http://ens.netboghandel.dk

[54] Busch, M., A. Kannen, S. Garthe & M. Jessopp. Consequences of a cumulative perspective on marine environmental impacts: Offshore wind farming and seabirds at North Sea scale in context of the EU marine strategy framework directive. *Ocean Coast. Manage.* 71: 213-224, 2013

[55] Brabant, R., N. Vanermen, E. Stienen & S. Degraer. Towards a cumulative collision risk assessment of local and migrating birds in North Sea offshore wind farms. *Hydrobiologia*, 756(1): 63–74, 2015.

[56] Hooper, D. U., F. S. Chapin, J. J. Ewel, A. Hector, P. Inchausti, S. Lavorel, J. H. Lawton, D. M. Lodge, M. Loreau, S. Naeem, B. Schmid, H. Seta¨la¨, A. J. Symstad, J. Vandermeer & D. A. Wardle. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. *Ecol.Monogr*. 75: 3–35, 2005.

[57] Bremner, J. Species' traits and ecological functioning in marine conservation and management. *J. Exp. Mar. Biol. Ecol.* 366: 37–47, 2008.