OPEN ACCESS
IOP Publishing

Environmental Research Letters

Environ. Res. Lett. 9 (2014) 034012 (12pp)

doi:10.1088/1748-9326/9/3/034012

Effects of offshore wind farms on marine wildlife—a generalized impact assessment

Lena Bergström[1], Lena Kautsky[2], Torleif Malm[2], Rutger Rosenberg[3], Magnus Wahlberg[4], Nastassja Åstrand Capetillo[2] and Dan Wilhelmsson[5]

[1] Department of Aquatic Resources, Swedish University of Agricultural Sciences, Skolgatan 6, SE-74242 Öregrund, Sweden
[2] Stockholm University Baltic Sea Centre, Svante Arrhenius väg 21a, SE-106 91 Stockholm, Sweden
[3] Department of Biological and Environmental Sciences, University of Gothenburg, Kristineberg 566, SE-45178 Fiskebäckskil, Sweden
[4] Marine Biological Research Centre, University of Southern Denmark, Hindsholmsvej 11, DK-5300 Kerteminde, Denmark
[5] The Royal Swedish Academy of Sciences, Swedish Secretariat for Environmental Earth System Sciences, Box 50005, SE-104 05 Stockholm, Sweden

E-mail: lena.bergstrom@slu.se, lena.kautsky@su.se, Torleif.malm@gmail.com, rutger.rosenberg@bioenv.gu.se, magnus@biology.sdu.dk, nastassja.astrand.capetillo@su.se and dan.wilhelmsson@sseess.kva.se

Received 29 November 2013, revised 25 February 2014
Accepted for publication 26 February 2014
Published 19 March 2014

Abstract

Marine management plans over the world express high expectations to the development of offshore wind energy. This would obviously contribute to renewable energy production, but potential conflicts with other usages of the marine landscape, as well as conservation interests, are evident. The present study synthesizes the current state of understanding on the effects of offshore wind farms on marine wildlife, in order to identify general versus local conclusions in published studies. The results were translated into a generalized impact assessment for coastal waters in Sweden, which covers a range of salinity conditions from marine to nearly fresh waters. Hence, the conclusions are potentially applicable to marine planning situations in various aquatic ecosystems. The assessment considered impact with respect to temporal and spatial extent of the pressure, effect within each ecosystem component, and level of certainty. Research on the environmental effects of offshore wind farms has gone through a rapid maturation and learning process, with the bulk of knowledge being developed within the past ten years. The studies showed a high level of consensus with respect to the construction phase, indicating that potential impacts on marine life should be carefully considered in marine spatial planning. Potential impacts during the operational phase were more locally variable, and could be either negative or positive depending on biological conditions as well as prevailing management goals. There was paucity in studies on cumulative impacts and long-term effects on the food web, as well as on combined effects with other human activities, such as the fisheries. These aspects remain key open issues for a sustainable marine spatial planning.

Keywords: offshore wind farm, marine ecology, environmental impact, surveillance programme, marine spatial planning

1. Introduction

Global demand for renewable energy is increasing, as motivated by our challenge to reduce carbon dioxide loading and mitigate global warming, as well as to reduce risks for radioactive pollution, the dispersal of harmful substances, and the depletion of non-renewable resources. Wind energy is often described as a suitable alternative from all of these perspectives (Martínez *et al* 2009a, 2009b, Saidur *et al* 2010, Esteban *et al* 2011, Leung and Yang 2012). Expectations on the offshore areas are particularly high, as wind conditions are often stronger and more stable over sea. Further, OWF can allow for larger units and a higher total level of energy production, and large units may be transported and constructed more easily (EC 2008, EWEA 2012).

Importantly, potential conflicts of interest with other sectors of society are also less pronounced in the marine landscape than on land (Pedersen *et al* 2010). Although visual disturbance can be decisive for the consenting processes in many cases (Zoellner *et al* 2008, Ladenburg 2009), conflicts of interest further away from land are often related to conservation and fisheries issues (OSPAR 2004, HELCOM 2010). Whereas the effects on fisheries' distributions and landings can be assessed by vessel monitoring systems (VMS) and spatially explicit landing reporting, the effects on marine biodiversity are harder to encompass. Assessing effects on biodiversity is limited both by information on natural distribution patterns of species and habitats, and by ecological understanding of the sensitivity of species to the presence of an OWF.

Our understanding on the potential effects of offshore wind farms (OWF) on the function of marine ecosystems, as well as marine biodiversity, is steadily improving as empirical evidence from operational wind farms is accumulating (Leonhard *et al* 2011, Lindeboom *et al* 2011, Mann and Teilmann 2013). However, the potential risk this may entail to marine ecosystem structure and functioning are only rarely assessed systematically, as may be required in order to inform ecosystem-based marine management and spatial planning efforts.

In the present study, we have synthesized the current state of knowledge on the effects of OWF on marine and aquatic wildlife. We based the study on published records of empirical observations at global level, and translated the findings into a generalized impact assessment for Swedish waters. The Swedish coastline covers aquatic ecosystems of various salinity, gradually changing from marine (30‰) to nearly fresh waters (2‰). By this, the assessment covered various types of ecosystems, and made it possible to compare local and general impacts. Based on the conclusions, we highlight future key issues for the OWF sector from the conservation perspective.

2. Methods

Information for the synthesis was obtained from empirical studies addressing either the effects of OWF directly, or addressing some pressure identified as potentially influential on marine wildlife during OWF construction or operation. These were identified by searches in scientific databases, but also by directed searches over the internet for reports produced by consultant agencies or governmental authorities in connection to monitoring programmes of existing OWFs, as these encompass a significant part of the total written volume on the topic. An important background material in this respect was provided by the compiled literature review by Wilhelmsson *et al* (2010). The initial material included over 600 reports and publications. These were screened for relevance in relation to the delineations of this study (main pressures and ecosystem components, as outlined below). Key papers referred to in the text were selected to as far as possible represent peer-reviewed publications, or reports summarizing main findings from a specific topic or surveillance programme.

2.1. Generalized impact assessment

The assessment was made separately for different main pressures, identified as the ones most frequently mentioned in the studied literature. For the construction phase, the main pressures included were; *acoustic disturbances* and *increased sediment dispersal*, and for the operational phase; *habitat gain*, *fisheries exclusion*, *acoustic disturbance*, and *electromagnetic fields* (figure 1). In order to compare general versus more local effects, the assessment was made separately for three geographical subareas (see below). Effects were assessed separately for three different ecosystem components in each subarea. Impacts during the third stage of an OWF life cycle, decommissioning, were not assessed, as little or no research has hitherto been directly dedicated to evaluating this stage. However, available studies indicate that impacts during decommissioning are likely to be similar to those of the construction phase.

Probable impact on marine species was assessed with respect to the following aspects; (i) temporal extent, (ii) spatial extent, and (iii) sensitivity of species within each ecosystem component. The magnitude of impact was valued by scores from 1 to 3, where higher scores implied higher impact, using the categorization criteria described in table 1. In order to facilitate comparisons across pressures and geographical areas, the sum of all scores was calculated as an indicator of overall impact. A total sum of 3–4 indicated low overall impact (mainly low scores and no high scores for any of the specific aspects), whereas a total sum of 5–6 indicated moderate overall impact (predominantly moderate scores, or high scores for one aspect combined with at least one low score for the other aspects). A total sum of 7–9 indicated high overall impact (moderate to high scores for all aspects, or high scores for more than one aspect). In addition, the level of certainty in the assessment was evaluated based on how well the conclusions were supported by the peer-reviewed part of literature (table 1, cf Wilhelmsson *et al* 2010).

2.2. Geographical area

The assessed area ranged from the Skagerrak in the North Sea region to the inner Baltic Sea (figure 2). This was divided into three subareas with more similar species richness and species composition; the Skagerrak–Kattegat coast with near marine conditions (salinity 15–30‰, hereafter SK), the Baltic Sea proper with brackish conditions (6–12‰, hereafter BP) and the Gulf of Bothnia with near freshwater conditions (2–5‰, hereafter GB). The sounds connecting SK and BP are characterized by fluctuating salinity (8–15‰) due

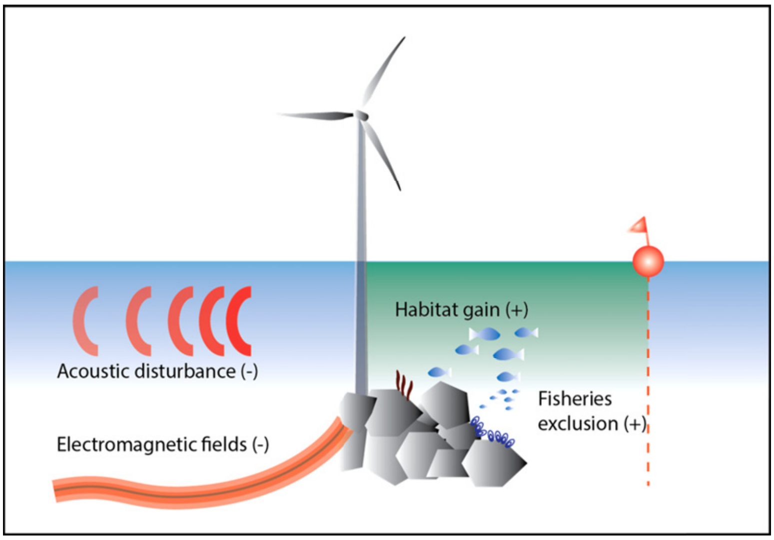

Figure 1. Overview of main pressures from OWF during the operational phase. Expected effect on the local abundance of marine organisms is indicated as (+) aggregation/increase, (−) avoidance/decrease.

Table 1. Criteria for assessing the probability of impact on marine life from pressures associated with offshore wind farms. The evaluation was made separately for each pressure (acoustic disturbance during construction, sediment dispersal during construction, habitat gain, fisheries exclusion, acoustic disturbance during operation, and electromagnetic fields). Spatial extent was defined as the expected dispersal of the pressure from its source, temporal extent as its expected duration. Sensitivity was assessed in relation separately for each ecosystem component (marine mammals, fish, and benthic species) and geographical area (Skagerrak–Kattegat, Baltic Proper, and Bothnian Sea). The level of certainty was assessed based on the level of documentation in peer-reviewed literature.

Score	Spatial extent	Temporal extent	Sensitivity	Certainty
1 (low)	<100 m	During construction	Minor or no effects on the abundance and distribution of local species	Limited or no empirical documentation
2 (moderate)	<1000 m	Throughout operational phase	Effects on the abundance and distribution of local species, no effects on food web	Documentation available, but results of different studies may be contradictory
3 (high)	>1000 m	Permanent	Effects on the abundance and distribution of local species, effects on food web	Documentation available, relatively high agreement among studies

to irregular mixing of marine and brackish water masses, and were included in SK because it holds several marine species that do not extend into the BP (HELCOM 2012). The subareas were defined based on salinity, as the salinity gradient is clearly correlated with changes in species richness and species composition (Ojaveer *et al* 2010), as seen for various species groups (HELCOM 1996, Snoeijs 1999, Bonsdorff 2006, Nohrén *et al* 2009, HELCOM 2012, Olsson *et al* 2012). Although there are also other environmental differences among subareas, for example changes in climate and topographical variation, these aspects are not decisive for differences in species composition at the current scale of study (Ojaveer *et al* 2010). The Swedish Energy Authority has identified suitable locations for OWF in all subareas. The results were typically representative for offshore areas with a depth of 5–40 m, reflecting the hitherto prevailing sites for OWF establishment.

2.3. Ecosystem components assessed

The assessment was made separately for the following species groups: marine mammals, fish, and benthic species. These were represented by different dominant species in the different subareas, and also varied in conservation status. The study was delimited to underwater pressures. Hence, it did not include impacts on seabirds and bats, which are also of high concern for the planning of OWF. These are mainly affected by pressures relating to above-surface properties of the OWF, and including them would have unduly increased the scope of the study.

Marine mammals were represented by four species. The harbour porpoise (*Phocaea phocaea*) and harbour seal (*Phoca vitulina*) are found mainly in SK and to some extent in BP. Grey seal (*Halichoerus grypus*) is found in all subareas but mainly in BP and GB. The ringed seal (*Pusa hispida*) is mainly found in the GB and parts of BP (Gulf of Finland and Gulf of Riga) (Härkönen *et al* 1998). Harbour porpoise is considered a vulnerable species in all subareas where it occurs (Swedish Species Information Centre 2010). The seals have been strongly decimated as a result of hunting and pollution until the past decades, but the west-coast harbour seal and the Baltic grey seal populations show strong recovery trends today (Hårding *et al* 2007, Olsen *et al* 2010). The ringed seal and

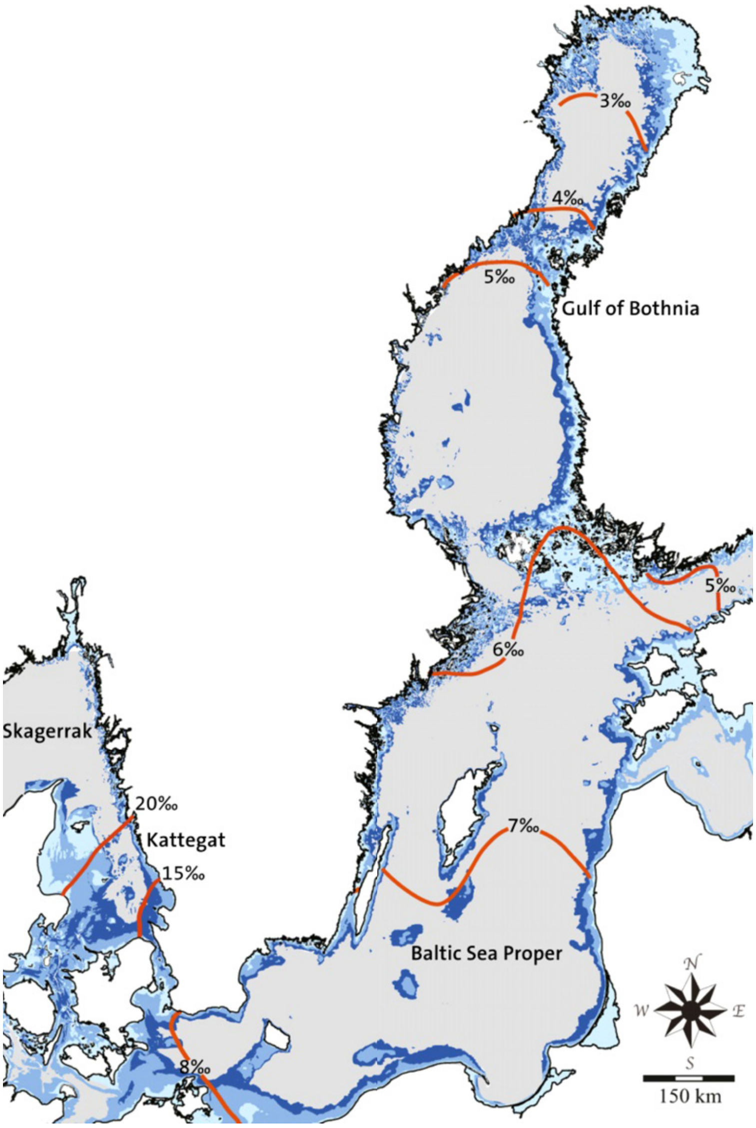

Figure 2. The assessed area was composed of the geographical subareas; Skagerrak, Kattegat including the sound area (SK in the text), Baltic Sea Proper (BS), and the Gulf of Bothnia (GB). Figures denote salinity limits (isohalines). Colour shadings indicate depth: light blue = 0–20 m, medium = 20–30 m, dark blue = 30–40 m depth. Areas with grey shading are deeper than 40 m.

local populations of harbour seal in the BP are still considered near threatened and vulnerable, respectively (Swedish Species Information Centre 2010). Pollution and fisheries by-catch are identified as the most important anthropogenic threats to the marine mammals (Hårding and Härkönen 1999, Härkönen and Isakson 2010).

Fish communities are the most diverse in SK, with about 80–100 regularly occurring species, decreasing gradually to around 50 species in BP and 30–50 in GB (HELCOM 2012). Marine species dominate in SK and occur increasingly side by side with species of freshwater origin in BP and GB. Many fish populations are decimated by overfishing, especially in SK and to some extent BS (Cardinale *et al* 2011, Bartolino *et al* 2012), which has also lead to cascading effects in other parts of the food web (Casini *et al* 2009, Eriksson *et al* 2011). Fish species often highlighted in relation to impacts from OWF are cod (*Gadus morhua*), herring (*Clupea harengus*), eel (*Anguilla anguilla*) and flatfishes (Pleuronectiformes). These occur in all subareas; however cod, eel and flatfishes are infrequent in GB (HELCOM 2012). Elasmobranchs (sharks and rays) mainly occur in deeper areas of SK.

Benthic species also decrease in diversity from SK to GB (HELCOM 2012). Large crustaceans, as well as many attached invertebrates, such as ascidians, sponges, corals, echinoderms and many molluscs are only common in SK. A dominant invertebrate in offshore areas of BP is the blue mussel, *Mytilus edulis*. In the GB, attached invertebrates are scarce and mainly represented by barnacles, bryozoans and hydroids (*Balanus* spp., *Electra* spp., *Cordylophora* spp.). A similar pattern is seen for macroalgae and submerged aquatic plants, with a decreasing structural complexity and species richness from SK to GB.

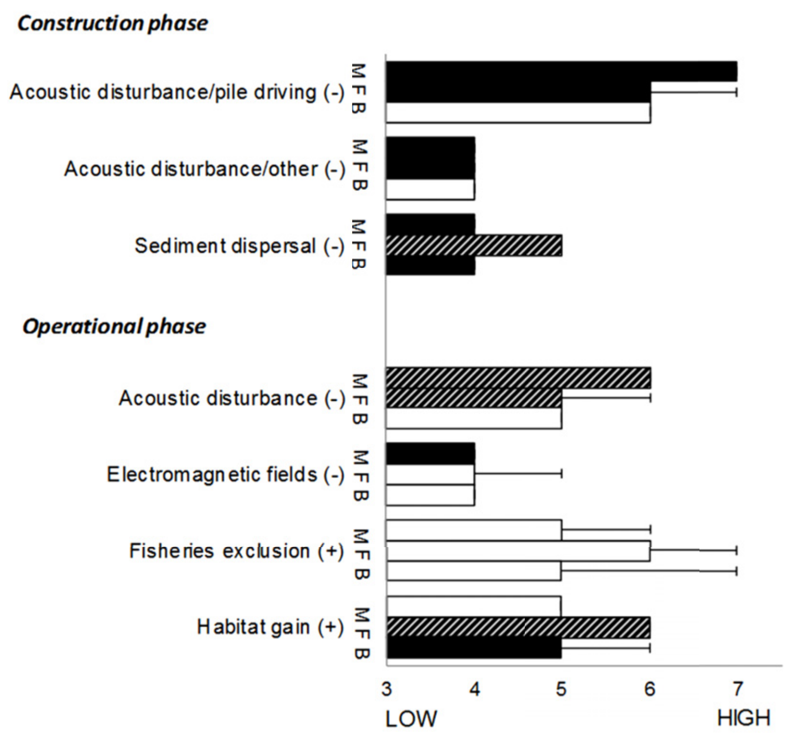

Figure 3. Summary of the generalized impact assessment. Probable impacts on marine mammals (M), Fish (F) and Benthos (B) are shown from LOW to HIGH for the main pressures associated with OWF construction and operation. Bars show median scores for all subareas. Error bars show maximum score in any subarea (for details see tables 2–4) A minus (−) sign indicates negative impact, a plus (+) sign predominantly positive impact. Level of certainty in the assessment is indicated by the colour of each bar; black = high, striped = moderate, grey = low certainty, based on criteria shown in table 1.

3. Results and discussion

3.1. Characterization of available studies

Empirical research on environmental effects of OWF has hitherto primarily been carried out in northern European marine waters (Belgium, Denmark, Germany, The Netherlands, UK and Sweden). Minor part of the studies has been conducted in the brackish Baltic Sea. The research field has gone through a rapid maturation and learning process, starting around year 2000. The initial years were characterized by broad monitoring programmes with relatively low precision, aiming at identifying or excluding impacts of OWF on marine species. Many early efforts were also aimed at developing survey methods. In later years, studies have become more targeted. Both the amount of studies, their topics and geographical coverage has increased rapidly. One remaining limitation is that the studies are typically restricted in spatial and temporal scope. Additionally, they have mainly focused on responses in single species, with little elaboration to ecosystem and seascape scales. Moreover, there is a considerable paucity of ecological baseline data for existing OWF areas, although this aspect seems to be gradually improving as more targeted monitoring programmes are being formed.

3.2. Construction phase

Studies on impacts during the construction phase were strongly focused on marine mammals, and to some extent fish. Very few studies addressed effects on sessile species, and none highlighted particular risks to these. The generalized assessment indicated a high impact from noise on marine mammals in all subareas, and on fish in SK. This was due to weak populations of many fish species that depend on shallow areas for recruitment, e.g. cod (Hammar *et al* 2014). The impact on fish in the other subareas was rated moderate, and for benthos low with low certainty, as strong differences among species may be expected.

The high scores were associated to extreme noise from pile-driving, which is mainly used in the deployment of OWF based on monopiles or jacket foundations. Pile-driving has been observed to cause significant avoidance behaviour in marine mammals (Richardson *et al* 1995, Carstensen *et al* 2006, Tougaard *et al* 2008, Bailey *et al* 2010, Brandt *et al* 2011, Dähne *et al* 2013), and is highly likely to cause mortality and tissue damage in fish (Popper *et al* 2003, Nedwell and Howell 2004, Popper and Hastings 2009). A considerably lower acoustic impact can be expected for OWF based on gravity foundations, which do not involve pile-driving (Hammar *et al* 2008). In these cases, acoustic disturbance is mainly expected from sea floor preparing activities, such as drilling or dredging, as well as an intensified vessel traffic (expected for all construction types). Available studies indicate that fish and marine mammals react to low intensity noise from these sources (Jensen *et al* 2009, Scheidat *et al* 2011, Spiga *et al* 2012; see also review in Wahlberg and Westerberg 2005), and may respond by leaving the area. However, the intensity

Table 2. Synthesis of potential impact on marine life from main pressures during OWF construction. Values give scores for probable impact (1 = low, 2 = moderate, to 3 = high) in relation to each of the criteria spatial extent, temporal extent and sensitivity. 'Total' denotes their sum. 'Certainty' indicates the level of literature documentation to support the evaluation. For definitions, see table 1. SK = Skagerrak–Kattegat, BP = Baltic Proper, GB = Gulf of Bothnia. The scores are based on a subjective evaluation of the cited literature and should be updated as new relevant results become available. Total scores are colour coded as: 3–4 = low, 5–6 = mod, 7–9 = high.

	Area	Spatial extent	Temporal extent	Sensitivity[a]	Total	Certainty
Acoustic disturbance (−)						
Marine mammals	SK	2–3	1	2–3	**4–7**	**3**
	BP	2–3	1	2–3	**4–7**	**3**
	GB	2–3	1	2–3	**4–7**	**3**
Fish	SK	2–3	1	2–3	**4–7**	**3**
	BP	2–3	1	1–2	**4–6**	**3**
	GB	2–3	1	1–2	**4–6**	**3**
Benthos	SK	2–3	1	1–2	**4–6**	**1**
	BP	2–3	1	1–2	**4–6**	**1**
	GB	2–3	1	1–2	**4–6**	**1**
Sediment dispersal (−)						
Marine mammals	SK	2	1	1	**4**	**3**
	BP	2	1	1	**4**	**3**
	GB	2	1	1	**4**	**3**
Fish	SK	2	1	2	**5**	**2**
	BP	2	1	2	**5**	**2**
	GB	2	1	1	**4**	**2**
Benthos	SK	2	1	1	**4**	**3**
	BP	2	1	1	**4**	**3**
	GB	2	1	1	**4**	**3**

[a] The higher score refers to pile driving and the lower score to other activities (drilling, dredging).

of disturbance is low, and animals are likely to return soon after exposure has ended. Hence, low impact can be expected, provided that significant habitats and seasons are avoided.

On the other hand, gravity foundations involve higher impact from sediment dispersal, due to dredging. Although organisms inhabiting wave-exposed sites typical for OWF establishment can generally be expected to be tolerant of turbidity, some studies indicate that elevated turbidity may harm sensitive organisms, such as juvenile fish (Auld and Schubel 1978, Lake and Hinch 1999, Partridge and Michael 2010). The impact of sediment dispersal was rated low to moderate, with good to moderate certainty (table 2).

In summary, available studies suggest that construction activities should not take place in important recruitment areas for marine mammals and fish, and that actions to reduce exposure to damaging noise levels should always be undertaken. For migrating species, this could potentially be solved by timing construction activities outside of biologically sensitive periods of the year. Ways to induce avoidance behaviour in fish and marine mammals have been addressed in some studies (Nedwell and Howell 2004, Mueller-Blenkle *et al* 2010, Andersson 2011). However, the ability to avoid harmful noise levels is probably reduced in young life stages with more limited mobility (Knudsen *et al* 1992, Wahlberg and Westerberg 2005).

3.3. Operational phase

In contrast to the construction phase, pressures during the operational phase entailed both positive and negative impact (figure 3). In addition, many studies emphasized the importance of local environmental conditions. This infers that the valuation of a certain pressure into causing either positive or negative impact is dependent on existing values and prevailing management goals. At the generalized level, the probability of negative impact during the operational phase was rated low to moderate, whereas potential positive impact was rated low to high (tables 3 and 4). The level of certainty was low to moderate, due to the high dependency on local conditions (variation within subareas). The result indicates a need for systematic studies across OWFs in different settings, in order to improve the scope for estimating outcomes under different environmental conditions.

Studies on the operational phase were early focused on the effects of habitat gain (Petersen and Malm 2006). These have mainly documented the colonization and aggregation of species close to the foundations, during the first years after establishment (e.g. Wilhelmsson *et al* 2006a, Maar *et al* 2009), although some more broad-scale studies have been conducted with respect to fish (Hvidt *et al* 2006, Degraer *et al* 2011, Leonhard *et al* 2011, Bergström *et al* 2013). Studies on acoustic disturbance have predominantly approached effects on habitat use of harbour porpoise (Scheidat *et al* 2011, Teilmann and Carstensen 2012). Research has to no or little extent investigated physiological effects on marine species, in response to e.g. elevated noise and EMF, or the effects of habitat gain on population fitness or reproductive success (Reubens *et al* 2014). Obviously, empirical studies in OWFs are bound to study combined effects to various extent, as the

Table 3. Synthesis of potential positive impact on marine life from the OWF operational phase. For explanations to the table, see table 2.

	Area	Spatial extent	Temporal extent	Sensitivity	Total	Certainty
Habitat gain (+)						
Marine mammals	SK	2	2	1	**5**	**1**
	BP	2	2	1	**5**	**1**
	GB	2	2	1	**5**	**1**
Fish	SK	2	2	2	**6**	**2**
	BP	2	2	2	**6**	**2**
	GB	2	2	1	**5**	**2**
Benthos	SK	1	2	3	**6**	**3**
	BP	1	2	2	**5**	**3**
	GB	1	2	1	**4**	**3**
Fisheries exclusion (+)						
Marine mammals	SK	2	2	2	**6**	**1**
	BP	2	2	1	**5**	**1**
	GB	2	2	1	**5**	**1**
Fish	SK	2	2	3	**7**	**1**
	BP	2	2	2	**6**	**1**
	GB	2	2	1	**5**	**1**
Benthos	SK	2	2	3	**7**	**1**
	BP	2	2	1	**5**	**1**
	GB	2	2	1	**5**	**1**

Table 4. Synthesis of potential negative impact on marine life from main pressures during the OWF operational phase. For explanations to the table, see table 2.

	Area	Spatial extent	Temporal extent	Sensitivity	Total	Certainty
Acoustic disturbance (−)						
Marine mammals	SK	2	2	2	**6**	**2**
	BP	2	2	2	**6**	**2**
	GB	2	2	1	**5**	**2**
Fish	SK	2	2	2	**6**	**2**
	BP	2	2	1	**5**	**2**
	GB	2	2	1	**5**	**2**
Benthos	SK	2	2	1	**5**	**1**
	BP	2	2	1	**5**	**1**
	GB	2	2	1	**5**	**1**
Electromagnetic fields (−)						
Marine mammals	SK	1	2	1	**4**	**3**
	BP	1	2	1	**4**	**3**
	GB	1	2	1	**4**	**3**
Fish	SK	1	2	2	**5**	**2**
	BP	1	2	1	**4**	**1**
	GB	1	2	1	**4**	**1**
Benthos	SK	1	2	1	**4**	**1**
	BP	1	2	1	**4**	**1**
	GB	1	2	1	**4**	**1**

partial effects of different pressures are difficult to disentangle in real field studies (Lindeboom *et al* 2011).

3.3.1. Habitat gain. Habitat gain typically enhances local species abundances, which may entail positive or negative impacts on conservation and biodiversity values. This so called artificial reef effect is well known from other anthropogenic marine structures and is utilized to improve local habitats for supporting biodiversity (Mikkelsen *et al* 2013), tourism (Wilhelmsson *et al* 1998, 2006b), or fisheries (Claudet and Pelletier 2004, Seaman 2007). Increased species abundances have been observed in several studies close to OWF foundations (Wilhelmsson *et al* 2006a, Wilhelmsson and Malm 2008, Maar *et al* 2009, Andersson and Öhman 2010, Leonhard *et al* 2011, Reubens *et al* 2011, Bergström *et al* 2013, Reubens *et al* 2013), and have typically been associated with positive values. However, a negative effect may emerge if the OWF will function as introduction platforms for non-indigenous species (Bulleri and Airoldi 2005, Page *et al* 2008, Brodin and Andersson 2009). The OWF may also alter local biodiversity patterns and lead to undesired effects, if some species are benefited much more than others, such as jellyfish (Janßen *et al* 2013) or the blue mussel (*Mytilus edulis*). The blue mussel is a dominant invertebrate species on rocky substrates in the Baltic Proper, and is often seen in high densities on turbine foundations (Wilhelmsson and Malm 2008, Maar *et al* 2009, Malm and Engkvist 2011, Krone *et al* 2013). It could be additionally benefited by predatory release, as diving ducks, which are common blue mussel feeders in the BP, may be excluded from OWF areas (Drewitt and Langston 2006, Busch *et al* 2013).

Observations on increased abundances were mainly made at small spatial scale, i.e. close to the turbines, and none of the reviewed studies reported impacts at entire OWF scale. This can be explained by the fact that the turbine foundations (the added habitats) typically cover only minor part of the total OWF area (Hammar *et al* 2008, Malm and Engkvist 2011). It also implies that effects on species abundances may be left unobserved if the scale of study is not matched with the expected scale of impact. Studies on fish show that several species, such as pouting (*Trisopterus luscus*), cod (*Gadus morhua*), horse mackerel (*Trachurus trachurus*) and two spotted goby (*Gobiusculus flavescens*) can reside in high densities at distances of metres to tens of metres from the turbines (Wilhelmsson *et al* 2006a, Reubens *et al* 2011, Bergström *et al* 2013, Reubens *et al* 2013). For prey species, aggregation processes might also be masked by predation, if predatory species are attracted to the OWF area (Bergström *et al* 2013). Clearly, regular fishery by an added habitat could have a strong effect on local fish densities, by increasing local mortality (Pickering and Whitmarsh 1997, Seaman 2007), but created habitats are also used as feeding areas by natural predators (Mikkelsen *et al* 2013). Such impacts, involving food-web interactions, can only be addressed by coordinated studies on different ecosystem components.

The extent of impact also depends on the relative increase in habitat complexity, in comparison to the original substrate (Charton and Ruzafa 1998, Hunter and Sayer 2009). The use of a scour protection, which increases habitat complexity (Hammar *et al* 2008, Wilson and Elliott 2009), was probably decisive in many cases. For invertebrates, the type of construction material may influence succession patterns. Benthic communities have been observed to be less diverse on foundations made of steel than of concrete (Qvarfordt *et al* 2006, Wilhelmsson and Malm 2008), although total abundances and biomasses were not necessarily affected. The level of colonization of species onto the new substrate is also related to the local species pool, in particular the presence of species with motile juvenile stages. In the generalized assessment, this translated into lower scores in the less diverse GB and BP, compared to SK, for fish and benthic species (table 3).

The hitherto observed impacts were primarily related to increased aggregation by the turbines, reflecting behavioural preferences of the species. As studies have only been conducted during the first few years of operation, it remains to be seen if an increase in habitat or food availability will lead to increased productivity of resource-limited populations of time (Bohnsack 1989, Pickering and Whitmarsh 1997, Reubens *et al* 2014). For this to occur, conditions within the OWF would probably have to be significantly more benign than in surrounding areas, and any negative pressures on the species of small magnitude within their full migration distance (Bohnsack 1989, Palumbi 2004).

3.3.2. Fisheries exclusion. Fisheries are not routinely excluded from OWF, but may be restricted as a consequence of excluding shipping for safety reasons (other than that related to maintenance). Fisheries exclusion is likely to increase local species abundances by reduced mortality rates of both target species and by-catch (Leonhard *et al* 2011, Lindeboom *et al* 2011, Wilhelmsson and Langhamer 2014), whereas increases in overall productivity and potential spill over effects to adjacent areas are more uncertain (Gell and Roberts 2003). In areas where bottom-trawling were previously conducted, beneficial effects on local benthic species can be expected (Thrush and Dayton 2002). However, empirical evidence from existing OWF is limited, due to restrictions in study design, as available references areas have generally not allowed separating effects of fisheries exclusion from other effects, such as habitat gain. Hence, the probability of a positive impact from fisheries exclusion was rated moderate to high with low certainty (table 3). In contrast, combining OWF with fisheries may be expected to increase local mortality rates of fish, if an increased aggregation close to the foundations serves to enhance catch rates (Polovina 1989, Grossman *et al* 1997, Pickering and Whitmarsh 1997, Reubens *et al* 2014). A particular challenge for marine spatial planning is to assess the effects of trade-offs at a larger geographical scale. If the fisheries is reallocated to other geographical areas when an OWF is established, the new fishing area could be either less or more resilient to fishing.

3.3.3. Acoustic disturbances. Vibrations in the turbine towers generated by the gearbox mesh and the generator typically cause underwater noise of 80–150 dB re 1 μPa, at wavelengths that are within in hearing range of both fish and mammals. The tower will also transmit vibrations through the sea floor but this effect is in most cases highly local and therefore considered of minor importance (Nedwell *et al* 2003, Andersson 2011). In addition, acoustic disturbance may increase due to increased boat traffic for service and maintenance.

Impacts of acoustic disturbances from OWFs were evaluated early (Nedwell *et al* 2003, Wahlberg and Westerberg 2005, Madsen *et al* 2006, Tougaard *et al* 2009), but no empirical studies have hitherto revealed clear negative effects of turbine-generated noise on marine species (Mueller 2008, Båmstedt *et al* 2009, Andersson 2011, Scheidat *et al* 2011). However, effects on behaviour are likely, as evident from studies indicating avoidance of the OWF area by harbour porpoise, and possibly a habituation over time (Teilmann and Carstensen 2012). The hearing and processing of sound can be expected to differ strongly among species (Popper and Hastings 2009), many of which have not been studied, and a knowledge gap remains regarding the nature and detection levels of noise from wind turbines and OWF associated boat traffic (Mueller 2008 and Andersson 2011). Also, the extent of the pressure may vary depending on local conditions. Stronger impacts might be expected in pristine areas compared to areas where ambient noise is already high (Scheidat *et al* 2011). On the other hand, the impact of cumulative effects in such areas remains unclear (Slabbekoorn *et al* 2010). Hence, probable impact was rated as moderate, with low to moderate certainty (table 4).

3.3.4. Electromagnetic fields. Shielded electric transmission cables do not directly emit electric fields, but are surrounded by magnetic fields that can cause induced electric fields in moving water (Gill *et al* 2012). Probable negative impact from electromagnetic fields (EMF) was generally rated low, but the level of certainty varied among ecosystem components (Gill *et al* 2012). A higher score was given for fish in SK, due to the presence of cartilaginous fish, which use electromagnetic signals in detecting prey (Gill 2005, Kimber *et al* 2011). EMF could also disturb fish migration patterns by interfering with their capacity to orientate in relation to the geomagnetic field, as indicated by empirical studies on eel (Westerberg and Begout-Anras 2000, Westerberg and Lagenfelt 2008, Gill *et al* 2012). The extent of EMF can potentially be mitigated by adequate cable design. Only few studies have addressed electroreception in marine mammals (Czech-Damal *et al* 2012) or invertebrates (Karlsen and Aristharkhov 1985, Aristharkhov *et al* 1988, Bochert and Zettler 2004), and no significant effects have been shown to date (table 4).

4. Conclusions

Whereas the construction phase was consistently associated with negative impact, pressures during the operational phase may impose both negative and positive effects, depending on local environmental conditions as well as prevailing management targets.

The assessment was made in three subareas with clear differences in species composition and abundance, but revealed similar general results. Thus, we conclude that the results may also facilitate initial impact assessments in other aquatic systems. The matrix in which the results are presented is highly simplistic, but transparent and adjustable to a finer geographical scale where local biodiversity patterns are well known, as well as to knowledge increase. It may also be used for comparing pressures, if combined with similar impact assessments for other marine activities, such as oil and gas extractions, fisheries, aquaculture, or other options for energy provision.

The strongest remaining uncertainties were seen for acoustic disturbances during the operational phase and effects of fisheries exclusion. As most empirical information today is from short-term studies in relatively small-scale OWF's, it is likely that conclusions made today will change when information accumulates from larger OWFs, over longer time scales, or when techniques to diminish negative impacts are developed. Current studies have to no or limited extent addressed combined effects, such as the effects of several marine activities within the same area, or long-term effects on the food web.

Many potential negative effects of OWF can be reduced within the planning process, by avoiding important recruitment habitats and by timing construction activities outside of important breeding seasons. Obviously, such measures should be based on real knowledge on the distribution and population status of local species and habitats. Given the high dependency of the obtained conclusion on local environmental conditions, a fundamental issue for the sustainable development of OWF is the availability of reliable seafloor and habitat maps and information on population connectivity.

The synthesis revealed a clear scope for research to identify holistic targets for marine management. In some cases it was not possible to value the anticipated impact into being either positive or negative, as this would depend on prevailing management goals. As there are obvious overall limits to human utilization of marine landscapes, it is clear that such comprehensive approaches are key to ensuring their sustainable management. OWF constitute a relatively new mode of usage of marine resources, and knowledge on its impacts has accumulated only in recent years. In this time, however, the development has provided a significant incentive for efforts to improve integrated coastal management strategies and marine spatial planning, and raised issues on long-term risks of human activities on marine habitats and species that are highly applicable also to other marine sectors.

Acknowledgments

This study was financed by the Swedish Energy Agency through the Vindval research programme. We are thankful to two anonymous reviewers for constructive comments on an earlier version of this paper.

References

Andersson M H 2011 Offshore wind farms—ecological effects of noise and habitat alteration on fish *PhD Thesis* Department of Zoology, Stockholm University, Stockholm, p 48

Andersson M H and Öhman M C 2010 Fish and sessile assemblages associated with wind-turbine constructions in the Baltic Sea *Mar. Freshwater Res.* **61** 642–50

Aristharkhov V M, Arkhipova G V and Pashkova G K 1988 Changes in common mussel biochemical parameters at combined action of hypoxia, temperature and magnetic field *Ser. Biologisceskaja* **2** 238–45

Auld A H and Schubel J R 1978 Effects of suspended sediment on fish eggs and larvae: a laboratory assessment *Estuar. Coast. Mar. Sci.* **6** 153–64

Bailey H, Senior B, Simmons D, Rusin J, Picken G and Thompson P M 2010 Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals *Marine Poll. Bull.* **60** 888–97

Båmstedt U, Larsson S and Stenman S L Å 2009 Effekter av undervattensljud från havsbaserade vindkraftverk på fisk i Bottniska viken (Effects of underwater noise from offshore wind farms on fish in the Gulf of Bothnia) *Naturvårdsverket. Rapport* 5924 (available at: www.naturvardsverket.se/Documents/publikationer/978-91-620-5924-8.pdf)

Bartolino V, Cardinale M, Svedäng H, Linderholm Hans W, Casini M and Grimwall A 2012 Historical spatiotemporal dynamics of eastern North Sea cod *Can. J. Fish. Aquat. Sci.* **69** 833–41

Bergström L, Sundqvist F and Bergström U 2013 Effects of an offshore wind farm on temporal and spatial patterns in the demersal fish community *Mar. Ecol. Prog. Ser.* **485** 199–210

Bochert R and Zettler M L 2004 Long-term exposure of several marine benthic animals to static magnetic fields *Bioelectromagnetics* **25** 498–502

Bohnsack J A 1989 Are high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? *Bull. Mar. Sci.* **44** 631–45

Bonsdorff E 2006 Zoobenthic diversity-gradients in the Baltic Sea: continuous post-glacial succession in a stressed ecosystem *J. Exp. Mar. Biol. Ecol.* **330** 383–91

Brandt M J, Diederichs A, Betke K and Nehls G 2011 Responses of harbour porpoises to pile driving at the Horns reef II offshore wind farm in the Danish North Sea *Mar. Ecol. Prog. Ser.* **421** 205–16

Brodin Y and Andersson M 2009 The marine splash midge Telmatogon japonicus (Diptera; Chironomidae)-extreme and alien? *Biol. Inv.* **11** 1311–7

Bulleri F and Airoldi L 2005 Artificial marine structures facilitate the spread of a non-indigenous green alga, Codium fragile ssp. tomentosoides, in the north Adriatic Sea *J. Appl. Ecol.* **42** 1063–72

Busch M, Kannen A, Garthe S and Jessopp M 2013 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 Coastal Management* **71** 213–24

Cardinale M, Bartolino V, Llope M, Maiorano L, Sköld M and Hagberg J 2011 Historical spatial baselines in conservation and management of marine resources *Fish Fish.* **12** 289–98

Carstensen J, Henriksen O D and Teilmann J 2006 Impacts of offshore windfarm construction on harbour porpoises: acoustic monitoring of echolocation activity using porpoise detectors (T-PODs) *Mar. Ecol. Prog. Ser.* **321** 295–308

Casini M, Hjelm J, Molinero J-C, Lövgren J, Cardinale M, Bartolino V, Belgrano A and Kornilovs G 2009 Trophic cascades promote threshold-like shifts in pelagic marine ecosystems *Proc. Natl Acad. Sci. USA* **106** 197–202

Charton J A G and Ruzafa A P 1998 Correlation between habitat structure and a rocky reef fish assemblage in the Southwest Mediterranean *Mar. Ecol.* **19** 111–28

Claudet J and Pelletier D 2004 Marine protected areas and artificial reefs: a review of the interactions between management and scientific studies *Aq. Liv. Res.* **17** 129–38

Czech-Damal N U, Liebschner A, Miersch L, Klauer G, Hanke F D, Marshall C, Dehnhardt G and Hanke W 2012 Electroreception in the Guiana dolphin (*Sotalia guianensis*) *Proc. R. Soc.* B **279** 663–8

Dähne M, Gilles A, Lucke K, Peschko V, Adler S, Krügel K, Sundermeyer J and Siebert U 2013 Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany *Environ. Res. Lett.* **8** 025002

Degraer S, Brabant R and Rumes B 2011 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 Unit: Brussels* 157

Drewitt A L and Langston R H W 2006 Assessing the impacts of wind farms on birds *IBIS* **148** 29–42

EC 2008 *Offshore Wind Energy: Action Needed to Deliver on the Energy Policy Objectives for 2020 and Beyond* (Brussels: Europen Commission) p 11 (available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2008:0768:FIN:EN:PDF)

Eriksson B, Sieben K, Eklöf J, Ljunggren L, Olsson J, Casini M and Bergström U 2011 Effects of altered offshore food webs on coastal ecosystems emphasize the need for cross-ecosystem management *Ambio* **40** 786–97

Esteban M D, Diez J J, López J S and Negro V 2011 Why offshore wind energy? *Renew. Energy* **36** 444–50

EWEA 2012 *Seanergy 2020 Delivering Offshore Electricity to the EU: Spatial Planning of Offshore Renewable Energies and Electricity Grid Infrastructures in an Integrated EU Maritime Policy* European Wind Energy Association p 80 (available at: www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/Seanergy_2020.pdf)

Gell F R and Roberts C M 2003 Benefits beyond boundaries: the fishery effects of marine reserves *Trends Ecol. Evol.* **18** 448–55

Gill A B 2005 Offshore renewable energy: ecological implications of generating electricity in the coastal zone *J. Appl. Ecol.* **42** 605–15

Gill A B, Bartlett M and Thomsen F 2012 Potential interactions between diadromous fishes of UK conservation importance and the electromagnetic fields and subsea noise from marine renewable energy developments *J. Fish Biol.* **81** 664–95

Grossman G D, Jones G P and Seaman W J 1997 Do artificial reefs increase regional fish production? A review of existing data *Fisheries* **22** 17–23

Hammar L, Andersson S and Rosenberg R 2008 Miljömässig optimering av fundament för havsbaserad vindkraft (Adapting offshore wind power foundations to local environment) *Naturvårdsverket Rapport* 5828, p 103 (available at: www.naturvardsverket.se/Om-Naturvardsverket/Publikationer/ISBN/5800/978-91-620-5828-9/)

Hammar L, Wikström A and Molander S 2014 Assessing ecological risks of offshore wind power on Kattegat cod *Renew. Energy* **66** 414–24

Hårding K C and Härkönen T J 1999 Development in the Baltic grey seal (*Halichoerus grypus*) and ringed seal (*Phoca hispida*) populations during the 20th century *Ambio* **28** 619–27

Hårding K C, Härkönen T J, Helander B and Karlsson O 2007 Status of Baltic grey seals: population assessment and extinction risk *NAMMCO Sci. Publ.* **6** 33–56

Härkönen T and Isakson E 2010 Status of harbour seals (*Phoca vitulina*) in the Baltic proper *NAMMCO Sci. Publ.* **8** 71–6

Härkönen T, Stenman O, Jüssi M, Sagitov R and Verevkin M 1998 Population size and distribution of the Baltic ringed seal (*Phoca hispida botnica*) *NAMMCO Sci. Publ.* **I** 167–80

HELCOM 1996 Coastal and marine protected areas in the Baltic Sea region *Balt. Sea Environ. Proc.* **63** 230

HELCOM 2010 Ecosystem Health of the Baltic Sea 2003–2007. HELCOM Initial Holistic Assessment *Balt. Sea Environ. Proc.* **122** 68

HELCOM 2012 Checklist of Baltic Sea Macro-species *Balt. Sea Environ. Proc.* **130** 206

Hunter W R and Sayer M D J 2009 The comparative effects of habitat complexity on faunal assemblages of northern temperate artificial and natural reefs *ICES J. Mar. Sci.* **66** 691–8

Hvidt C B, Leonhard S B, Klaustrup M and Pedersen J 2006 Hydroacoustic monitoring of fish communities at offshore wind farms, *Horns Rev Offshore Wind Farm, Annual Report 2005 Vattenfall Document* No 2624-03-003 *Rev2.doc* p 54 (available at: www.vattenfall.dk/da/file/Hydroacoustic-Monitoring-of-F_7840985.pdf)

Janßen H, Augustin C B, Hinrichsen H H and Kube S 2013 Impact of secondary hard substrate on the distribution and abundance of *Aurelia aurita* in the western Baltic Sea *Marine Poll. Bull.* **75** 224–34

Jensen F H, Bejder L, Wahlberg M, Aguilar Soto N, Johnson M and Madsen P T 2009 Vessel noise effects on delphinid communication *Mar. Ecol. Prog. Ser.* **395** 161–75

Karlsen A G and Aristharkhov V M 1985 The effect of constant magnetic field on the rate of morphogenesis in a hydroid *Clava multicornis* (forskal) *Zurnal Obscej Biologii* **5** 686–90

Kimber J, Sims D, Bellamy P and Gill A 2011 The ability of a benthic elasmobranch to discriminate between biological and artificial electric fields *Mar. Biol.* **158** 1–8

Knudsen F R, Enger P S and Sand O 1992 Awareness reactions and avoidance responses to sound in juvenile Atlantic salmon, *Salmo salar* L *J. Fish Biol.* **40** 523–34

Krone R, Gutow L, Joschko T J and Schröder A 2013 Epifauna dynamics at an offshore foundation—implications of future wind power farming in the North Sea *Mar. Environ. Res.* **85** 1–12

Ladenburg J 2009 Visual impact assessment of offshore wind farms and prior experience *Appl. Energy* **86** 380–7

Lake R G and Hinch S G 1999 Acute effects of suspended sediment angularity on juvenile coho salmon (*Oncorhynchus kisutch*) *Can. J. Fish. Aquat. Sci.* **56** 862–7

Leonhard S B, Stenberg C and Støttrup J 2011 Effect of the Horns Rev 1 offshore wind farm on fish communities. Follow-up seven years after construction *DTU Aqua Report No* 246-2011 (available at: wwwx.dtu.dk/upload/aqua/publikationer/forskningsrapporter/246-2011_effect-of-the-horns-rev-1-offshore-wind-farm-on-fish-communities.pdf)

Leung D Y C and Yang Y 2012 Wind energy development and its environmental impact: a review *Renew. Sustain. Energy Rev.* **16** 1031–9

Lindeboom H J *et al* 2011 Short-term ecological effects of an offshore wind farm in the Dutch coastal zone; a compilation *Environ. Res. Lett.* **6** 035101

Maar M, Bolding K, Petersen J K, Hansen J L S and Timmermann K 2009 Local effects of blue mussels around turbine foundations in an ecosystem model of Nysted off-shore wind farm, Denmark *J. Sea Res.* **62** 159–74

Madsen P T, Wahlberg M, Tougaard J, Lucke K and Tyack P 2006 Wind turbine underwater noise and marine mammals implications of current knowledge and data needs *Mar. Ecol. Prog. Ser.* **309** 279–95

Malm T and Engkvist R 2011 Bentiska processer på och runt artificiella strukturer i Sveriges kustvatten (Benthic processes at and close to artificial structures in Swedish coastal waters) *Naturvårdsverket Rapport* 6414 p 35 (available at: www.naturvardsverket.se/Om-Naturvardsverket/Publikationer/ISBN/6400/978-91-620-6414-3/)

Mann J and Teilmann J 2013 Environmental impact of wind energy *Environ. Res Lett.* **8** 035001

Martínez E, Sanz F, Pellegrini S, Jiménez E and Blanco J 2009a Life-cycle assessment of a 2-MW rated power wind turbine: CML method *Int. J. LCA* **14** 52–63

Martínez E, Sanz F, Pellegrini S, Jiménez E and Blanco J 2009b Life cycle assessment of a multi-megawatt wind turbine *Renew. Energy* **34** 667–73

Mikkelsen L, Mouritsen K N, Dahl K, Teilmann J and Tougaard J 2013 Re-established stony reef attracts harbour porpoises *Phocoena phocoena Mar. Ecol. Prog. Ser.* **481** 239–48

Mueller C 2008 Behavioural reactions of cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*) to sound resembling offshore wind turbine noise *PhD Thesis* Humbolt University, Berlin p 214

Mueller-Blenkle C, McGregor P K, Gill A B, Andersson M H, Metcalfe J, Bendall V, Sigray P, Wood D and Thomsen F 2010 Effects of pile-driving noise on the behaviour of marine fish *COWRIE Ref: Fish 06-08, Technical Report* p 62 (available at: www.offshorewindfarms.co.uk/Assets/COWRIE%20FISH%2006-08_Technical%20report_Cefas_31-03-10.pdf)

Nedwell J and Howell D 2004 A review of offshore windfarm related underwater noise sources *Cowrie 544 R 0308* p 63 (available at: www.subacoustech.com/information/downloads/reports/544R0308.pdf)

Nedwell J, Langworthy J and Howell D 2003 Assessment of sub-sea acoustic noise and vibration from offshore wind turbines and its impact on marine wildlife; initial measurements of underwater noise during construction of offshore windfarms, and comparison with background noise *Cowrie 544 R 0424* p 68 (available at: ftp://150.241.234.1/resto/Referencias%20BIMEP/Nedwell_et_al_2003%20(E68).pdf)

Nohrén E, Pihl L and Wennhage H 2009 Spatial patterns in community structure of motile epibenthic fauna in coastal habitats along the Skagerrak–Baltic salinity gradient *Estuar. Coast. Shelf Sci.* **84** 1–10

Ojaveer H, Jaanus A, MacKenzie B R, Martin G, Olenin S, Radziejewska T, Telesh I, Zettler M L and Zaiko A 2010 Status of biodiversity in the Baltic Sea *PLoS ONE* **5** e12467

Olsen M T, Andersen S M, Teilmann J, Dietz R, Edrén S M C, Linnet A and Härkönen T 2010 Status of the harbor seal (*Phoca vitulina*) in Southern Scandinavia *NAMMCO Sci. Publ.* **8** 77–94

Olsson J, Bergström L and Gårdmark A 2012 Abiotic drivers of coastal fish community change during four decades in the Baltic Sea *ICES J. Mar. Sci.* **69** 961–70

OSPAR 2004 Problems and benefits associated with the development of offshore windfarms *OSPAR Commission, Biodiversity Series* ISBN 1-904426-48-4

Page H M, Culver C S, Dugan J E and Mardian B 2008 Oceanographic gradients and patterns in invertebrate assemblages on offshore oil platforms *ICES J. Mar. Sci.* **65** 851–61

Palumbi S R 2004 MARIne reserves and ocean neighborhoods: the spatial scale of marine populations and their management *Annu. Rev. Environ. Resour.* **29** 31–68

Partridge G J and Michael R J 2010 Direct and indirect effects of simulated calcareous dredge material on eggs and larvae of pink snapper Pagrus auratus *J. Fish Biol.* **77** 227–40

Pedersen E, Forssén J and Persson Waye K 2010 Human perception of sound from wind turbines *Naturvårdsverket Rapport* 6370 p 40 (available at: www.naturvardsverket.se/Om-Naturvardsverket/Publikationer/Publications-in-English/)

Petersen J K and Malm T 2006 Offshore windmill farms: threats to or possibilities for the marine environment *Ambio* **35** 75–80

Pickering H and Whitmarsh D 1997 Artificial reefs and fisheries exploitation: a review of the ‘attraction versus production’ debate, the influence of design and its significance for policy *Fish. Res.* **31** 39–59

Polovina J J 1989 Artificial reefs: nothing more than benthic fish aggregators *ColCOFI Rep.* **30** 37–9

Popper A N, Fewtrell J, Smith M E and McCauley R D 2003 Anthropogenic sound: effects on the behavior and physiology of fishes *Mar. Technol. Soc. J.* **37** 35–40

Popper A N and Hastings M C 2009 The effects of human-generated sound on fish *Integrative Zoology* **4** 43–52

Qvarfordt S, Kautsky H and Malm T 2006 Development of fouling communities on vertical structures in the Baltic Sea. Estuarine, Coastal and Shelf Science *Estuar. Coast. Shelf Sci.* **67** 618–28

Reubens J T, Braeckman U, Vanaverbeke J, Van Colen C, Degraer S and Vincx M 2013 Aggregation at windmill artificial reefs: CPUE of Atlantic cod (*Gadus morhua*) and pouting (*Trisopterus luscus*) at different habitats in the Belgian part of the North Sea *Fish. Res.* **139** 28–34

Reubens J T, Degraer S and Vincx M 2011 Aggregation and feeding behaviour of pouting (*Trisopterus luscus*) at wind turbines in the Belgian part of the North Sea *Fish. Res.* **108** 223–7

Reubens J T, Degraer S and Vincx M 2014 The ecology of benthopelagic fishes at offshore wind farms: a synthesis of 4 years of research *Hydrobiologia* 1–16

Richardson W J, Greene C R, Malme C I, Thomson D H, Moore S and Wursig B 1995 *Marine Mammals and Noise* (London: Academic)

Saidur R, Islam M R, Rahim N A and Solangi K H 2010 A review on global wind energy policy *Renew. Sustain. Energy Rev.* **14** 1744–62

Scheidat M, Tougaard J, Brasseur S, Carstensen J, van Polanen Petel T, Teilmann J and Reijnders P 2011 Harbour porpoises (*Phocoena phocoena*) and wind farms: a case study in the Dutch North Sea *Environ. Res. Lett.* **6** 025102 6

Seaman W 2007 Artificial habitats and the restoration of degraded marine ecosystems and fisheries *Hydrobiologia* **580** 143–55

Slabbekoorn H, Bouton N, van Opzeeland I, Coers A, ten Cate C and Popper A N 2010 A noisy spring: the impact of globally rising underwater sound levels on fish *Trends Ecol. Evol.* **25** 419–27

Snoeijs P 1999 Marine and brackish waters *Acta Phytog. Suec.* **84** 187–212

Spiga I, Fox J and Benson R 2012 Potential effects of long-term exposure to boat noise on the growth, survival, and nutrient retention in juvenile fish *The Effects of Noise on Aquatic Life* ed A N Popper and A D Hawkins (Berlin: Springer) pp 255–7

Swedish Species Information Centre 2010 The red list www.slu.se/en/collaborative-centres-and-projects/artdatabanken/the-red-list/

Teilmann J and Carstensen J 2012 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** 045101

Thrush S F and Dayton P K 2002 Disturbance to marine benthic habitats by trawling and dredging: implications for marine biodiversity *Annu. Rev. Ecol. Syst.* **3373** 449–4

Tougaard J, Henriksen O D and Miller L A 2009 Underwater noise from three offshore wind turbines: estimation of impact zones for harbor porpoises and harbor seals *J. Acoust. Soc. Am.* **125** 3766–73

Tougaard J, Madsen P T and Wahlberg M 2008 Underwater noise from construction and operation of offshore wind farms *Bioacoustics* **17** 143–6

Wahlberg M and Westerberg H 2005 Hearing in fish and their reactions to sounds from offshore wind farms *Mar. Ecol. Prog. Ser.* **288** 295–309

Westerberg H and Begout-Anras M 2000 Orientation of silver eel (*Anguilla anguilla*) in a disturbed geomagnetic field *Advances in Fish Telemetry: Proc. 3rd Conf. on Fish Telemetry Centre for Environment, Fisheries and Aquaculture Science (Lowestoft)* ed A Moore and I Russel pp 149–58

Westerberg H and Lagenfelt I 2008 Sub-sea power cables and the migration behaviour of the European eel *Fish. Manag. Ecol.* **15** 369–75

Wilhelmsson D and Langhamer O 2014 The influence of fisheries exclusion and addition of hard substrata on fish and crustaceans *Marine Renewable Energy Technology and Environmental Interactions* ed M A Shields and A I L Payne (Berlin: Springer) pp 49–60

Wilhelmsson D and Malm T 2008 Fouling assemblages on offshore wind power plants and adjacent substrata *Estuar. Coast. Shelf Sci.* **79** 459–66

Wilhelmsson D, Malm T and Öhman M C 2006a The influence of offshore wind power on demersal fish *ICES J. Mar. Sci.* **63** 775–84

Wilhelmsson D *et al* 2010 Greening Blue Energy: Identifying and managing the biodiversity risks and opportunities of offshore renewable energy *IUCN* Gland, Switzerland

Wilhelmsson D, Öhman M C, Ståhl H and Shlesinger Y 1998 Artificial reefs and dive tourism in Eilat, Israel *Ambio* **27** 764–6

Wilhelmsson D, Yahya S A S and Öhman M C 2006b Effects of high-relief structures on cold temperate fish assemblages: a field experiment *Mar. Biol. Res.* **2** 136–47

Wilson J C and Elliott M 2009 The habitat-creation potential of offshore wind farms *Wind Energy* **12** 203–12

Zoellner J, Schweizer-Ries P and Wemheuer C 2008 Public acceptance of renewable energies: results from case studies in Germany *Energy Policy* **36** 4136–41