REVIEW

Offshore renewable energy: ecological implications of generating electricity in the coastal zone

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Summary

1. Global-scale environmental degradation and its links with non-renewable fossil fuels have led to an increasing interest in generating electricity from renewable energy resources. Much of this interest centres on offshore renewable energy developments (ORED). The large scale of proposed ORED will add to the existing human pressures on coastal ecosystems, therefore any ecological costs and benefits must be determined.

2. The current pressures on coastal ecology set the context within which the potential impacts (both positive and negative) of offshore renewable energy generation are discussed.

3. The number of published peer-review articles relating to renewable energy has increased dramatically since 1991. Significantly, only a small proportion of these articles relate to environmental impacts and none considers coastal ecology.

4. Actual or potential environmental impact can occur during construction, operation and/or decommissioning of ORED.

5. Construction and decommissioning are likely to cause significant physical disturbance to the local environment. There are both short- and long-term implications for the local biological communities. The significance of any effects is likely to depend on the natural disturbance regime and the stability and resilience of the communities.

6. During day-to-day operation, underwater noise, emission of electromagnetic fields and collision or avoidance with the energy structures represent further potential impacts on coastal species, particularly large predators. The wider ecological implications of any direct and indirect effects are discussed.

7. *Synthesis and applications.* This review demonstrates that ORED will have direct and, potentially, indirect consequences for coastal ecology, with these effects occurring at different scales. Ecologists should be involved throughout all the phases of an ORED to ensure that appropriate assessments of the interaction of single and multiple developments with the coastal environment are undertaken.

Key-words: coastal ecology, coastal environmental impact, enhancement, habitat disturbance, resilience, stability

Introduction

The generation of electricity from renewable energy resources is fast becoming a key objective of many countries. The driving force behind this is the link between non-renewable fossil fuels and environmental degradation (Dincer 1999; Chow, Kopp & Portney 2003). Climate change is a major concern, leading to predictions of a global temperature rise of 3–5 °C within 50 years and an increase in climatic variability (Houghton *et al.* 2001). Although the consequences of climate change are currently the subject of much debate, from an ecological standpoint the concern arises from evidence of geographical shifts in the distribution of species (Pounds & Puschendorf 2004), predictions of a sharp increase in extinction probability for many plant and animal species (Thomas *et al.* 2004)

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and wider impacts on ecosystems (Leemans & Eickhout 2004). Add to this the predicted decline in the amounts of non-renewable resources over the next few decades (Pimentel *et al.* 2002) and it is clear that alternatives to fossil fuels are needed.

Countries with coastlines have particularly valuable renewable energy resources, in the form of tides, currents, waves and offshore wind. Coastal waters are extensive and the associated renewable energy resources are plentiful and predictable (Pelc & Fujita 2002). In addition, the perceived aesthetic problem of siting large numbers of energy-generating devices (e.g. wind turbines) in terrestrial landscapes is reduced by locating them offshore. Not surprisingly, therefore, considerable attention is now being directed towards coastal waters in an effort to harness offshore renewable energy sources.

Coastal zones, however, are already under significant pressure from human activity as a result of their high biological productivity and accessibility (Blaber *et al.* 2000) and their provision of valuable ecosystem services and functions (Costanza *et al.* 1997). It is imperative, therefore, that the implications of generating electricity from offshore renewable sources are appropriately assessed with regard to the current ecological status of the coastal zone and the potential consequences.

EXISTING COASTAL ECOLOGICAL STATUS

Major changes to coastal ecosystems are attributable to human activities. Pressure from fisheries has dramatically reduced biomass, changed diversity, altered local trophic and community structure, and degraded habitat (Blaber *et al.* 2000; Pauly *et al.* 2002). Large-scale oil and gas operations have been implicated in the perturbation of the coastal environment (Holdway 2002), and other industrial processes have led to bioaccumulation of contaminants (Matthiessen & Law 2002), abnormal development of invertebrates (Fichet, Radenac & Miramand 1998), endocrine disruption (Tyler, Jobling & Sumpter 1998), nutrient enrichment, toxic algal blooms and deoxygenation (Carpenter *et al.* 1998).

A variety of terrestrial land uses and near-shore activities (Mason 2002; Matthiessen & Law 2002) have led to local habitat loss and disturbance, changes to nutrient status and cycling, loss of food supplies, erosion, reduced sediment supply, changes in the level of sea inundation and increased exposure to natural disturbances (McLusky, Bryant & Elliott 1992; Schekkerman, Meininger & Meire 1994; Rogers & McCarty 2000).

Offshore renewable energy developments (ORED) will also impact on coastal ecosystems because single developments have ecological footprints extending over several square kilometres of near-shore waters. Larger ORED (with individual footprints approximately 20–50 km^2 or greater), located adjacent to each other, are planned for the future. Such developments will require proper consideration of any potential impact on the ecosystem at appropriate spatial and temporal scales. However, our current understanding
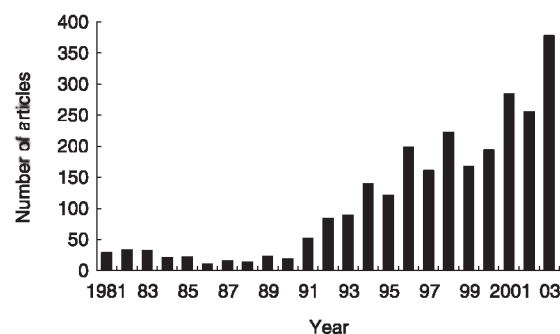
Fig. 1. The number of peer-reviewed articles with the term renewable energy (or derivative terms) published between 1981 and 2003. Web of Science data from the expanded Science Citation Index, Social Science Citation Index and the Arts and Humanities Citation Index.

of the effects of human activity on the coastal environment is limited and piecemeal (Mann 2000).

It was the aim of this study to provide an integrated review of the potential ecological implications of offshore renewable energy generation in the coastal environment at different scales.

CURRENT SCIENTIFIC KNOWLEDGE RELATING TO RENEWABLE ENERGY

The general growth of interest in renewable energy is well illustrated by the significant increase in the number of published scientific articles over the last 10 years (Fig. 1). However, only 7·6% of these articles related to environmental impacts, whether positive or negative, and just 4·0% have specifically considered the ecological implications of harnessing any renewable energy source. More importantly, less than 1% of the articles considered the potential environmental risks of renewable energy exploitation and none was specifically related to coastal ecology. Ecological factors are not being considered properly and are underrepresented in any discussion of the costs and benefits of adopting offshore renewable energy sources.

Offshore renewable energy developments

DIRECT EFFECTS ON COASTAL ENVIRONMENT

ORED currently encompass wind, wave, tidal and current power, with offshore wind power being the most actively pursued (Byrne & Houlsby 2003). All ORED convert a renewable energy source into electricity via energy-generation devices (e.g. turbines and hydrofoils). To convert sufficient energy to be economically viable requires a large expanse of seabed for the device foundations and related structures to fix the devices in place.

Different degrees of physical disturbance will occur during the three phases of the life of an ORED: 1, construction; 2, routine operation; 3, decommissioning. It is generally assumed that the direct effects of decommissioning a site will be similar to those associated with

construction. Two further specific considerations are the type and extent of seabed covered by the development, and the extent of cabling. These aspects are summarized in Fig. 2.

During construction and decommissioning the seabed will be disturbed by work on the foundations for the energy conversion devices and any associated substations and the underwater power cables between devices and the main connection to shore. Removal of sediments will lead to direct loss of habitats and there will be an increase in local water turbidity arising from suspended solids. Resuspended sediments will be transported by prevailing water movement during construction, which may also mobilize any contaminants within the sediments.

Mobilized sediments may smother the neighbouring habitats of sedentary species. For ORED using current or tidal energy, the effects of suspended sediment may extend downstream. Resuspension of sediments high in organic matter, such as in estuaries and tidal reaches of rivers, will probably temporarily reduce available oxygen because of an increased biochemical oxygen demand. No published studies have assessed the ecological implications of ORED construction, so evidence from benthic habitats that have been fished or subjected to marine dredging is used to discuss possible consequences (Fig. 2).

Species assemblages within sediments exhibit natural variation spatially and through time as a result of biotic interactions and environmental disturbance. Nevertheless, fishing- and dredging-related disturbance have been shown to alter local species diversity and population density (Blyth *et al.* 2004). The magnitude of the effects on the benthic community and the length of time that they are apparent depend on the duration and intensity of the disturbance (Van Dalfsen *et al.* 2000) and the resilience of the local infauna (Drabsch, Tanner & Connell 2001). Areas that suffer least from natural disturbance are affected by fishing activity to a greater extent (Kaiser & Spencer 1996).

After fishing or dredging has ceased, recolonization takes from months to years (Harvey, Gauthier & Munro 1998; Bradshaw *et al.* 2000). Small opportunistic species, such as polychaetes and amphipods, are the quickest to colonize after physical disturbance, while epifaunal species assemblages are likely to take longer (Harvey, Gauthier & Munro 1998; Newell *et al.* 2004). Change may be rapid with soft substrata, and new habitat can be created if the conditions are suitable. On coarse and more stable substrata, change is likely to be slower (Kaiser & Spencer 1996).

A conceptual model proposed by Jennings, Kaiser & Reynolds (2001) suggests that as sedimentary habitats become more stable, so the effects of fishing disturbance are more extreme and longer lasting. This applies both to the structure and composition of the benthic assemblage and the topography and physical structure of the sediment. Evidence from fishing shows that the level of disturbance can also affect composition of the

community at local and regional scales (Hall 1994), and removal of ecological engineering species can have devastating consequences for local biodiversity and ecosystem processes (Coleman & Williams 2002).

Assuming fishing- and dredging-related disturbance to be analogous to construction and decommissioning of an ORED, a local loss of sedentary infauna and reef builders would be expected, while non-sedentary marine benthos would be displaced. Ecologically it is important to understand the susceptibility of species and their resilience to the effects of ORED construction/decommissioning and the processes determining community recovery after the disturbance. Implicit in this understanding is knowledge of the stability of the substrata on which the ORED is constructed.

A major difference between ORED and other human impacts in near-shore waters is the extensive subsurface structures present following construction. These structures may affect local water movements, which are fundamental to some aquatic species (Montgomery *et al.* 2000) and also determine the transportation and deposition of sediments.

Although the effects of decommissioning an ORED are assumed to be the same as those associated with its construction, the one obvious difference is the removal of the existing undersea structures. Removal of long-established ORED will immediately reduce habitat heterogeneity and take out a large component of the benthic community. Indirect effects, such as changes to local food web interactions and habitat availability, may also occur, similar to those associated with fishing (Kaiser & Jennings 2002). This will depend on species and community susceptibility and resilience to the changes.

OTHER DIRECT EFFECTS

Significant marine noise and vibration will occur during construction piling and drilling, and noise will also be emitted during the operational phase, together with electromagnetic (EM) fields associated with electricity production. The significance of these two disturbances will strongly depend on their frequency, intensity and duration in relation to the sensitivity of the organisms and their ability to habituate to the noise or EM field. A further disturbance relates to organisms colliding with or avoiding the energy-generation devices.

Noise

Foundation construction and cable laying have been shown to produce noise up to 260 dB re: 1 µPa and 178 dB re: 1 µPa, respectively (Nedwell, Langworthy & Howell 2004). These significant sources of noise could cause damage to the acoustic systems of species within 100 m of the source, and are expected to cause mobile organisms to avoid the area (Nedwell, Langworthy & Howell 2004). Any effects of the noise will depend on the sensitivity of the species present and their ability to habituate to the noise, and will reduce when the level of
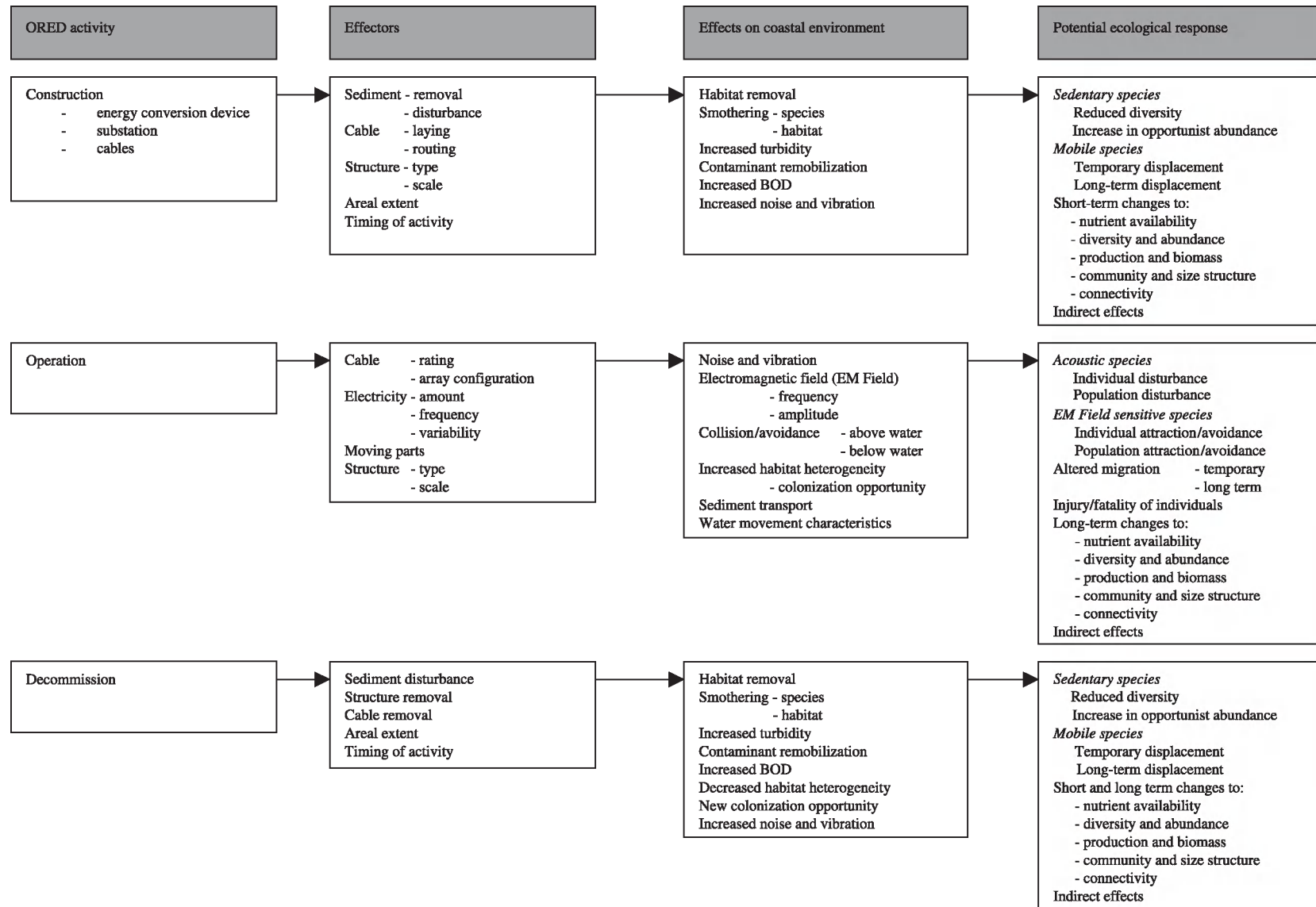
ORED activity	Effectors	Effects on coastal environment	Potential ecological response

Construction
  - energy conversion device
  - substation
  - cables
	Sediment - removal
	           - disturbance
	Cable - laying
	           - routing
	Structure - type
	           - scale
	Areal extent
	Timing of activity
		Habitat removal
		Smothering - species
		           - habitat
		Increased turbidity
		Contaminant remobilization
		Increased BOD
		Increased noise and vibration
			Sedentary species
			  Reduced diversity
			  Increase in opportunist abundance
			Mobile species
			  Temporary displacement
			  Long-term displacement
			Short-term changes to:
			  - nutrient availability
			  - diversity and abundance
			  - production and biomass
			  - community and size structure
			  - connectivity
			Indirect effects

Operation	Cable - rating
	           - array configuration
	Electricity - amount
	           - frequency
	           - variability
	Moving parts
	Structure - type
	           - scale
		Noise and vibration
		Electromagnetic field (EM Field)
		           - frequency
		           - amplitude
		Collision/avoidance - above water
		                   - below water
		Increased habitat heterogeneity
		      - colonization opportunity
		Sediment transport
		Water movement characteristics
			Acoustic species
			  Individual disturbance
			  Population disturbance
			EM Field sensitive species
			  Individual attraction/avoidance
			  Population attraction/avoidance
			Altered migration - temporary
			                  - long term
			Injury/fatality of individuals
			Long-term changes to:
			  - nutrient availability
			  - diversity and abundance
			  - production and biomass
			  - community and size structure
			  - connectivity
			Indirect effects

Decommission	Sediment disturbance
	Structure removal
	Cable removal
	Areal extent
	Timing of activity
		Habitat removal
		Smothering - species
		           - habitat
		Increased turbidity
		Contaminant remobilization
		Increased BOD
		Decreased habitat heterogeneity
		New colonization opportunity
		Increased noise and vibration
			Sedentary species
			  Reduced diversity
			  Increase in opportunist abundance
			Mobile species
			  Temporary displacement
			  Long-term displacement
			Short and long term changes to:
			  - nutrient availability
			  - diversity and abundance
			  - production and biomass
			  - community and size structure
			  - connectivity
			Indirect effects

Fig. 2. Renewable energy developments and ecologically relevant interactions (refer to text for details).

noise has decreased following completion of the construction (or decommissioning) phase.

The potential disturbances to birds and people from noise and vibrations generated by the operation of the wind turbines are also considered important in ORED environmental impact assessments. Current opinion is that by being located offshore the noise will be less detectable by humans. However, any effects of ORED operational noise on birds have not yet been investigated, although noise from human activity on land has been shown to reduce the local abundance of birds (Forman & Deblinger 2000; Fernandez-Juricic 2001). Breeding seabirds are known to be disturbed by human recreational activity (Dunnet *et al.* 1990; Beale & Monaghan 2004) and underwater noise has been used to reduce predation pressure on molluscs by waterfowl (Ross, Lien & Furness 2001).

Underwater, where a large number of species from very different taxa interact acoustically (e.g. cetaceans, pinnipeds, teleosts and crustaceans; Bradbury & Veherencamp 1998), the potential for disturbance from long-term ORED operation is high. Sound is used for communication (Lugli, Yan & Fine 2003), finding prey, echolocation (particularly by marine mammals; Tyack & Clark 2000), locating recruitment sites in fish (Simpson *et al.* 2004), finding potential mates and avoiding predators (Popper & Fay 1993). Fish have shown startle and alarm responses when encountering a loud noise (e.g. > 150 dB re: 1 µPa; Blaxter, Gray & Denton 1981; Pearson, Skalski & Malme 1992). More recent studies have demonstrated a link between underwater noise and changes to the auditory threshold of some species of freshwater fish (0·3–2·0 kHz, 142 dB re: 1 µPa; Scholik & Yan 2002). However, this is not the case for all species, as some freshwater fish have evolved a strategy using different parts of the sound spectrum for communication (around 0·1 kHz, 85–110 dB re: 1 µPa), effectively adapting to local ambient noise (Lugli, Yan & Fine 2003).

Research on the effects of anthropogenic noise in the coastal environment is limited (Popper *et al.* 2003) but studies suggest that marine species are exposed to noises from a variety of sources (Harwood & Wilson 2001). Research on existing offshore wind farms along Baltic Sea coasts (Hoffman *et al.* 2000; Fristedt, Moren & Soderberg 2001) has shown that the acoustic environment is added to by the operation of the wind turbines (0·001–0·4 kHz, 80–110 dB re: 1 µPa), and the level of acoustic disturbance is likely to be a function of the number of turbines and their operating procedure and timing at lower frequencies.

Clearly it is important to establish whether the type, frequency and intensity of sounds associated with ORED will have any implications (such as reaction or habituation) for the species that inhabit or migrate through the coastal environment. Analysis of the spatial and temporal behavioural of sensitive species in concert with measurements of the acoustic environment is required.

Electromagnetic fields

The high voltage alternating current (AC) and direct current (DC) cables that transmit power between devices and the mainland have the potential to interact with aquatic animals that are sensitive to electric (E) and magnetic (B) fields. This affects mainly fish, particularly the elasmobranchs, and marine mammals that use the Earth's magnetic field to navigate. In addition, some species utilize E fields behaviourally.

Industry standard AC cables effectively shield against direct E field emissions but cannot completely shield the magnetic component. The configuration of the cables and the leakage of B fields results in induced E fields adjacent to the cable independent of burial, as a result of magnetic properties (CMACS 2003). The EM field emissions are tiny from a human perspective (Fristedt, Moren & Soderberg 2001) but they come within the range of bioelectrical emissions utilized by electrosensitive species. EM fields relating to ORED with DC cables have yet to be determined, but the focus is likely to be on the current transmitted between sea electrodes (Walker 2001).

If the induced E fields emanating from submarine cables can be detected by electrosensitive species, then at levels that approximate the bioelectric fields of natural prey there is potential for these species to be attracted to them. Whether such species will be attracted or repelled by stronger fields is unknown at present, but will be dependent on them passing close to the E fields (Kalmijn 1982). Elasmobranchs are attracted to DC fields in the range 0·005–1 µV cm^{-1} and avoid DC fields of approximately 10 µV cm^{-1} or greater (Kalmijn 1982). There is little research to date on the effects of AC E fields (Kalmijn 1988) and only physiological studies of the frequency of emission detectable by electrosensitive fish (Bodznick & Boord 1986; Tricas & New 1998). Such studies suggest that low-frequency AC emissions in the environment are more likely to be detected (Kalmijn 1988). Electrosensitive species may be attracted or repelled by the E fields, potentially resulting in congregation or dispersal depending on the extent of the electrical environment where multiple cable arrays exist. Therefore, research into the effects of ORED-related E fields on sensitive species, particularly benthic ones, is required, especially when assessing the ORED environmental impact at important local feeding or breeding grounds or nursery areas.

Magnetosensitive species occur in coastal waters world-wide (e.g. migratory fish, elasmobranchs, mammals, chelonians and crustaceans) and these species are thought to be sensitive to the Earth's magnetic fields (Wiltschko & Wiltschko 1995). Whether there is any link between these organisms and the magnetic fields associated with an ORED is again unknown.

A B field equal to that of the Earth's magnetic field (approximately 50 µT) can be detected from DC electricity cables in the Baltic Sea at a distance of 6 m (Walker 2001). Such a field can affect a ship's compass

and has the potential to interact with the navigation and orientation of any animal relying on the Earth's magnetic field. Any effect may be transient as the organism moves through the area (possibly a confusion effect). Alternatively, magnetosensitive species may be attracted to or may actively avoid the area. The only published study to date on this subject suggested that the eel *Anguilla anguilla* could detect B fields emitted by DC cables but only a small proportion of these fish actively responded to them (Westerberg 1999).

Collision and avoidance

Organisms might collide with or actively avoid the energy-generating devices both above and below water, depending on the number, size and spacing of the devices and their moving parts, and whether the whole ORED is located along an organism's transit route. Coastal and migratory bird species are thought to be most at threat (Garthe & Huppop 2004), particularly species that undertake frequent, short low-level flights between feeding and roosting sites (Dirksen, Spaans & van der Winden 1996). Where large-scale migration routes coincide with ORED sites, the potential impact will only occur at certain times of the year. Increases in seasonal and local species mortality have been recorded at onshore wind turbine sites (Barrios & Rodriguez 2004).

At present little information exists concerning aquatic fauna colliding with or avoiding offshore energy-generation devices. The greatest impact is likely to be upon migrating species where underwater turbines are located in enclosed waters such as estuaries (Dadswell & Rulifson 1994) or where devices form an extensive barrier to movement. Any associated effects need to be considered in the context of the potential sensitivity of species, and behavioural time and energy costs in relation to the location and scale of the development (Garthe & Huppop 2004).

INDIRECT ECOLOGICAL EFFECTS

The extensive scale of ORED is expected to result in significant displacement of the most mobile fauna (fish, marine mammals, marine reptiles, coastal birds and possibly large crustaceans and molluscs) during construction and decommissioning. During operation, shifts in the temporal or spatial distribution of the mobile fauna or changes in their numbers may also occur as a consequence of changes in the local food web dynamics, species competition, predator–prey relationships and reproduction, which operate at different spatial and temporal ecological scales (May 1994).

Food availability

Bottom-up trophic effects are likely to occur following ORED construction and decommission as a result of significant changes in the type and abundance of ben-

thic species; this in turn will change food availability for higher trophic levels. The evidence from fishing and dredging, which operate at similar scales to ORED, suggests that opportunistic fauna will increase to take advantage of species that are displaced and vulnerable during physical disturbance. The large-scale removal of habitat and species following decommissioning is also likely to alter significantly local food web dynamics.

Coastal food resources have a patchy distribution (Hall, Raffaelli & Thrush 1994). The changes to the benthos associated with an ORED will probably increase local food availability and thereby add to the network of food patches. The importance of adding to food patches will depend on the extent and distribution of other patches and their connectivity.

The energetic requirements of the foraging fauna also need to be taken into account, particularly when considering the scale of the relationship between individual foragers and food availability (Mann & Lazier 1996). For example, larval fish are poor swimmers and have low energy reserves so will have a high dependency on locations with abundant resources at the right time or on short distances between food patches. A cetacean is less ecologically constrained, however, as it is able to move large distances between feeding areas and can eat a wide range of prey types and sizes. Hence changes to food availability associated with ORED may affect many species but the effect will be greater for the small, more geographically restricted organisms.

Competition

The number and extent of ORED will significantly change the local habitats and present new resource opportunities that may increase the use of the area by immigrant fauna. The relative density of competitors, their competitiveness and availability of alternative opportunities, will determine the ecological consequences, but the more adaptable species will be expected to dominate (Milinski & Parker 1991). Alternatively, if habitat degradation occurs over a wider area causing species aggregation around ORED sites, then density-dependent processes resulting from increased competition will be likely to have direct and cascading effects on the local faunal composition (Pimm 1991; Daskalov 2002).

Predation

The significant changes in prey type, size and abundance arising as a result of ORED are expected to affect the predator community. Density-dependent and top-down predatory effects may result in prey depletion (Pimm 1991) and trophic cascade effects (Pauly *et al.* 1998; Daskalov 2002). Additionally, if predators are perturbed by ORED and their mechanisms of recovery are slow, predator- or competitive-release may occur (Pauly *et al.* 1998; Dulvy, Sadovy & Reynolds 2003). Any changes that affect the dynamic link between

a predator and its prey may result in reduced allocation of energy to other activities (e.g. reproduction and refuge) and thereby strongly influence the behaviour of the predator (Gill 2003). With large-scale ORED we may therefore see responses in the local predator community that are additional to direct effects linked with noise and/or EM fields.

The ecological effects of competition and predation in coastal waters have been shown to be considerably altered by existing human activity (Jennings, Kaiser & Reynolds 2001; Ormerod 2003). For example, human impacts on coastal food webs have in some cases directly reduced food for seabirds, whereas in other cases, where fishing has removed larger predatory fish, seabirds have gained more food resources as a result of less competition for the smaller fish that they feed on (Tasker *et al.* 2000; Atkinson *et al.* 2003).

Hence, dynamic processes such as trophic linkage, competition and predation may be altered if the ecological changes associated with large-scale deployment of ORED are equivalent to those resulting from other industrial-scale human activities. Understanding how and when any change will manifest itself is crucial; a useful analytical approach could incorporate the effect of human activity into a trophic linkage model of coastal predators and their prey, as suggested by Stillman *et al.* (2001).

Reproduction and recruitment

The significant fluctuations in food and habitat availability arising through ORED could affect species reproduction, particularly species already under human pressure. There are examples of parental care species (e.g. seabirds and marine mammals) with reduced breeding success resulting from significant drops in prey abundance as a consequence of fishing (Barrett & Krasnov 1996).

Species with little post-reproduction parental investment could also be affected by local environmental changes linked to ORED. Many species of fish, for example, use specific spawning and nursery sites. During ORED construction and decommission early life stages may be vulnerable to burial and removal. Water movements could change as a result of the presence of a large number of ORED structures. This may redistribute new recruits locally or downstream and have wider implications for communities that are driven by species that disperse over regional scales (Kinlan & Gaines 2003).

Habitat degradation and loss is perhaps the single most effective way of slowing or preventing fish population recoveries (Dulvy, Sadovy & Reynolds 2003). It is a particular concern when spawning grounds or nursery areas are limited in their availability or extent and the species that rely on them have small numbers of recruits, long maturation periods (e.g. elasmobranchs) and are already being impacted by other human activities (Myers & Worm 2003).

ECOLOGICAL ENHANCEMENT

Once construction of an ORED is completed, the resultant physical structure could be a positive environmental enhancement because of an increase in the 3-D heterogeneity of the benthic habitat. An increase in habitat represents a greater colonization opportunity for benthos, opportunities for enhanced survival and growth, new trophic opportunities, recycling of local energy and increased refuge for juveniles of mobile species (Bohnsack & Sutherland 1985). For the juvenile stages of many species shallow coastal areas are crucial for promoting individual growth, refuge and survival until such time as they are able to recruit to the adult population (Gregory & Anderson 1997; Blaber *et al.* 2000). Habitats with greater physical heterogeneity have been shown to be functionally more important and increase fish abundance compared with more homogeneous areas of the same extent (Jenkins *et al.* 1997; Charbonnel *et al.* 2002).

Although no published data exist in the primary scientific literature, there are reports of existing ORED acting as artificial reefs that enhance the local ecosystem around the Baltic Sea coast (BorderWind 1998; Ecoserve 2000). Fishing records indicate an increase in yields post-construction that is assumed to be the result of extensive invertebrate colonization attracting fish (BorderWind 1998; Hoffman *et al.* 2000). The artificial reef effect therefore appears to offer evidence of a positive impact on the ecology of the area where the ORED is located. To be generally ecologically beneficial, however, ORED must do more than improve local biodiversity. There is a need to determine if enhancement is actually beneficial to the existing local populations of species by providing an additional, new source of recruits. Otherwise it may create wider problems by recruiting species to the site that would normally replenish the species populations of existing adjacent habitats on a regular basis. If the ORED acts as an ecological enhancement then daily management of operations, and particularly removal of habitat during decommissioning, will have to take this into account (Fig. 2). By extending this scenario to include multiple adjacent ORED then ecological changes will need to be determined not only on an ORED-by-ORED basis but also a cumulative basis, and include other existing habitats. Hence determination of local ecosystem connectivity, population (and possibly metapopulation) dynamics and food web interactions will require consideration of factors and processes at different spatial and temporal scales.

Conservation and protected status

Many coastal areas world-wide have some form of designation for the protection of species or habitats, while any ORED proposal will be required to consider the potential impact of the development on particular species and/or habitats. Often the species of concern

are birds and mammals or rare or 'flagship' species (Simberloff 1998). Unfortunately, relatively low priority is given to most of the remaining coastal flora and fauna. While rare species, birds and mammals have intrinsic appeal, ecologically it is more important to consider impacts on the ecosystem structure and processes and key functional species (Simberloff 1998). This will require knowledge of which are the key species, how these species are affected as a result of an ORED, species resilience and how the ecosystem dynamics will respond both locally and in the wider context.

Ecological-based mitigation

True ecological mitigation has two main attributes: first it compels us to consider what would constitute an ecological stress; secondly, it provides us with an opportunity to determine how much of a stress we are prepared to allow. For industrial-scale ORED in coastal waters the most important ecological aspects to take into account concern ecosystem structure and function in terms of: habitat loss or gain, particularly the balance between species' requirements and habitat availability; effects on nutrient availability; changes in primary productivity and the consequent effect on production and biomass at different trophic levels; altered species diversity and composition; changes in size composition of the community; effects on species growth and mortality rate.

In order to minimize the impact on existing flora and fauna, ORED sites should have a sparse biological community, predominantly comprising opportunistic, resilient, colonizer species. Soft sediment communities are typically low in diversity and have species that are adapted to naturally unstable habitat conditions. However, locations that are used as a migratory or periodic habitat essential for life-history completion should be avoided. There may be a higher diversity of less resilient species at sites with more stable substrata and any ORED in such areas will affect a greater component of the ecosystem. Thus, from the outset, developments should take into consideration the ecological communities present and the ecologically relevant history of the area (e.g. previous degradation). In addition, an ORED should consider and if necessary mitigate against potential ecological problems throughout the construction, operation and decommission phases (Fig. 2).

INTEGRATING ECOLOGY INTO ORED PLANS

The stability of coastal ecosystems world-wide is under serious threat, hence ORED must be planned appropriately to protect the ecosystem from further degradation and to enhance it wherever possible. Ecologists must play a fundamental role in this process. Species may be adapted to a wide range of natural disturbances but disturbance related to ORED may still have positive or negative effects. As Hall (1994) points out in relation to fishing, although natural variation may be large this is no basis from an ecological stance to suggest that if human development is small it will have no effect.

As the number of ORED increases in the coastal zone, cumulative impact assessments are required to provide spatial and temporal assessment of the environmental impacts by taking account of the proximity of existing and planned future developments (Carryer & Deeming 1998).

The biggest single problem for the integration of ecology into the planning and decision process for ORED remains the lack of appropriate knowledge. A stepped precautionary approach, such as the incremental one used in integrated fishery management (Symes 2000), may be most appropriate for ecologically based planning and management of ORED.

Conclusions

There is an urgent need to consider the ecological effects of the large increase in ORED in the coastal zone. Initiatives are required that facilitate ORED with due regard to ecological considerations and natural processes. This will require a wide-ranging perspective, adaptable monitoring and research based on our best understanding of coastal ecology, in order to sustain the ecosystem composition, structure and function whilst also assisting the wider goal of global carbon management. Ecology needs to be part of the process of ORED and at the same time offshore energy extractors need to be made aware of their role within the coastal ecosystem.

Acknowledgements

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