ARTICLE IN PRESS
EIR-05732; No of Pages 7
Environmental Impact Assessment Review xxx (2011) xxx–xxx
Contents lists available at ScienceDirect
Environmental Impact Assessment Review
journal homepage: www.elsevier.com/locate/eiar

The environmental interactions of tidal and wave energy generation devices

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ARTICLE INFO

Article history:
Received 23 February 2011
Received in revised form 31 May 2011
Accepted 20 June 2011
Available online xxxx

Keywords:
Wave energy
Tidal barrage and fences
Tidal streams
Electromagnetic field
Habitat change
Noise

ABSTRACT

Global energy demand continues to grow and tidal and wave energy generation devices can provide a significant source of renewable energy. Technological developments in offshore engineering and the rising cost of traditional energy means that offshore energy resources will be economic in the next few years. While there is now a growing body of data on the ecological impacts of offshore wind farms, the scientific basis on which to make informed decisions about the environmental effects of other offshore energy developments is lacking. Tidal barrages have the potential to cause significant ecological impacts particularly on bird feeding areas when they are constructed at coastal estuaries or bays. Offshore tidal stream energy and wave energy collectors offer the scope for developments at varying scales. They also have the potential to alter habitats. A diversity of designs exist, including floating, mid-water column and seabed mounted devices, with a variety of moving-part configurations resulting in a unique complex of potential environmental effects for each device type, which are discussed to the extent possible.

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doi:10.1016/j.eiar.2011.06.002

1. Introduction

The various nations within and bordering the Oslo-Paris Commission (OSPAR) region are all committed to significant reductions in CO_2 emissions in the near term. The EU has set a target that 20% of energy used within the EU should be generated from renewable sources by 2020 (see Directive 2009/28/EC). In addition to reducing CO_2 emissions, renewable energy generation could provide a means of reducing national dependencies on imported energy, increasing energy security and replacing diminishing domestic supplies of fossil fuels. Against this background energy demand continues to grow and the challenge is to move to a new low carbon economy where energy demands can be met while levels of CO_2 emitted are reduced (Umbach, 2010).

The term 'wet renewables' is commonly used to refer to offshore wind energy developments as well as tidal barrages/fences, tidal stream and wave energy schemes. For countries with significant areas of coastal waters the utilization of offshore and coastal energy resources is attractive. The World Energy Council estimates that if less than 0.1% of the renewable energy within the oceans could be converted into electricity it would satisfy the present world demand for energy more than five times over (World Energy Council, 2007). The reality is that the technology does not exist to utilize most of this energy resource, not least because of issues associated with the spatial mismatch of the areas of demand with regions of highest resource. Nevertheless, wet renewables are becoming increasingly economic and it is expected that offshore energy resources will become a significant source of renewable energy in the near future.

As offshore wind energy developments have advanced, attention has turned towards more predictable sources of marine renewable energy such as tidal energy associated with the change in water level in coastal bays, fjords or estuaries that might be harnessed by barrages or fences, devices to use the tidal stream energy in tidal currents and the energy associated with waves.

Electric generation from tidal height changes occurs commercially at the La Rance facility in France, operational since 1966, and at the Annapolis Royal Power Station on the Bay of Fundy, Canada, operational since 1984. The 'oil crisis' of the 1970s stimulated interest in such schemes and in the UK a large research programme was commissioned to look at the engineering and environmental issues associated with a tidal barrage across the Severn Estuary. This culminated in a public enquiry lasting several years and the publication of the 'Bondi Report' (Bondi, 1981). A new Severn Tidal Power scheme feasibility study is currently underway (http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/severn_tidal_power/feasibility/feasibility.aspx accessed 17 February 2011).

While there is now a growing body of data on the ecological impacts of offshore wind farms (Gill, 2005; OSPAR, 2004, 2006a,b, 2008a,b, 2009a,b,c), the scientific basis on which to make informed decisions about the environmental effects of other offshore energy developments is lacking. To date, tidal fences, tidal stream farms and wave energy capture devices have only been deployed on an experimental scale and so prediction of their impacts is based on very limited empirical data. A summary of environmental issues and knowledge gaps is provided in OSPAR (2006a) and suggests that many of these could be device design and site specific.

Here we consider the environmental impacts of tidal barrages and fences, tidal stream farms and wave energy capture devices. Given the paucity of direct evidence this review is largely based on the best available scientific knowledge from analogous activities. We examine three impact categories: 1) impacts on habitats and species, focusing on ecological changes, 2) direct impacts on reproduction and recruitment, and 3) impacts on water column processes and hydrology. For each we discuss the relative impacts of the various devices. Devices which produce impacts to the water column and hydrology (category 3) may have indirect effects on habitats and species (category 1) and in some cases also on reproduction and recruitment (category 2) which are affected by the physical environment. However, indirect effects derived from such interactions are often case specific and may be difficult to attribute to the original cause, and so they are only generally discussed here. We also examine two pressure categories 1) noise emissions, and 2) electromagnetic fields, common to all of the devices and summarize their known environmental and ecological impacts. This arrangement will allow decision makers to consider various alternatives given site-specific environmental issues.

2. Habitats and species

2.1. Tidal barrage/fence

Tidal barrages work like hydroelectric dams except water needs to flow in both directions. The sluice gates are opened to allow the tide to flood into a basin (estuary, fjord or bay); at high tide the sluices in the barrage are closed and the tide outside falls. Once a sufficient height differential has occurred the turbines are opened and the contained water flows out through the turbines. This continues until the tide turns and the differential head is eroded. The sluices are then opened to allow the basin to refill. This operation method, known as ebb generation, generates the most power. It is also possible to generate power on the flood tide by refilling the basin through the turbines, while this generates power for more of the tidal cycle it generates less power in total as there is less of a differential head. Both tidal flows may be harnessed in dual mode devices.

Building a barrage across a bay/estuary will destroy the former benthic habitat in the construction footprint. Construction and decommissioning activities can result in impacts to adjacent intertidal areas if used for construction of caissons or as staging areas. The presence of a barrage also influences habitats upstream and downstream of the facility. Upstream under ebb only generation, the upper intertidal remains submerged for a longer period, there is then a steady fall in tide level until the tide starts rising again (Fig. 1). The former lower shore remains submerged. These changes will shift the balance between marine intertidal species, with upper shore specialists potentially being squeezed out. The retention of water also significantly alters the exposure of tidal flats to feeding birds although the resource in the tidal flats when they are exposed may increase in quantity and quality. The availability of alternative feeding/roosting sites is therefore often critical.

Downstream of the barrage tidal range is often reduced close to the barrage but enhanced in other parts of the basin (Wolf et al., 2009). The outflow will delay the falling tide from around mid-tide downward, such that the tide falls as normal, or more rapidly, from high water until the turbines open at mid-tide after which the rate of fall declines or is halted. This has potential negative implications for birds, although this effect occurs at the same time as the flats above the barrage become exposed. Energy generation on the flood and ebb, dual mode, reduces considerably the changes in exposure of the intertidal area (Figs. 1, 2) and so reduces potential impacts on the bird community. The implications for tidally feeding fish are the opposite to those of the birds with greater periods for foraging available due to the retention/raising of water levels.

The economics of a barrage or fence scheme scale with the volume of the tidal prism and hence the most favoured schemes tend to involve large estuaries or bays. For example one option proposed in the Severn Tidal Power feasibility study could see up to 520 km^2 of the estuary impounded, compared with the 17 km^2 at La Rance and 6 km^2 at Annapolis Royal. Another UK scheme in the Mersey River would involve an impoundment of 61 km^2 but even this would be sufficient to generate changes in the tidal range at locations all around the Irish Sea (Wolf et al., 2009). The larger the scheme the more likely that there will not be alternative feed sites nearby. In the UK the quantity

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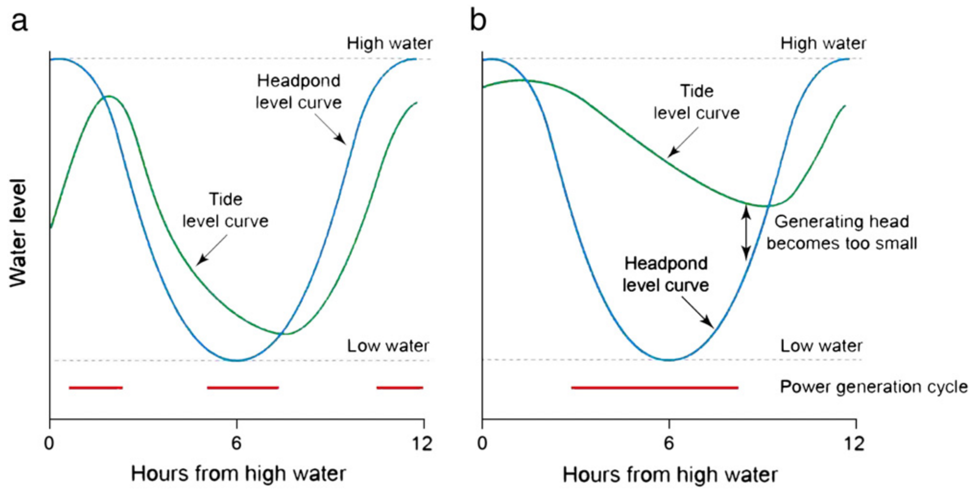

Fig. 1. The normal tidal curve and the modified tidal curve in the headpond above a tidal barrage in an estuary for (a) dual cycle generating and (b) ebb only generation. (Redrawn from Gray, 1992).

and quality of the food on the feeding grounds of over-wintering waders is the parameter that determines survival to the next breeding season (Burton et al., 2010; Duriez et al., 2009). Thus, reduced feeding areas, increased foraging costs (extra flights between sub-optimal grounds) or lower food quality will directly impact on population size.

Changed spatial flow patterns will result in altered patterns of sediment deposition and movement that will have impacts on benthic communities. The outflow will be constrained to a number of sites, where the turbines are, and in these areas sediments will be scoured and coarsened while upstream of the barrage the reduced flows and periods of no flow will lead to increased siltation and potentially an increasing quantity of fine material in the deposits. Changes in the nature of the habitats will alter their suitability as nursery or spawning areas for fish (see Section 3 below).

Tidal fences are not expected to alter the timing or amplitude of the tides.

2.2. Tidal stream farm

Energy generation using the tidal stream employs turbines or other devices placed in the water column to directly extract energy. The installation and operation of individual or multiple tidal stream devices, as with other forms of wet renewable energy systems, directly affect benthic habitats by altering water flows, wave structures, or substrate composition and sediment dynamics (e.g., Neill et al., 2009). Physical impact from small scale tidal stream generation pilot projects has been found to be reversible on decommissioning, especially as the areas most suitable for tidal power generation are located where high current flow causes natural disturbance to the sediments. However, the cumulative effect of multiple turbines needs to be considered with respect to far field impacts.

Large bottom structures will alter water flow and may result in localized scour and/or deposition. Because these new structures will affect bottom habitats, consequential changes to the benthic community composition and species interactions may be expected (Lohse et al., 2008). Changes in water velocities and sediment transport, erosion, and deposition caused by the presence of new structures will alter benthic habitats, at least on a local scale. Craig et al. (2008) report that deposition of sand may impact seagrass beds by increasing mortality and decreasing the growth rate of plant shoots. Conversely, deposition of organic matter in the wakes of tidal farms could encourage the growth of benthic invertebrate communities that are adapted to that substrate (Widdows and Brinsley, 2002). While the new habitats created by such structures may enhance the abundance and diversity of invertebrates, predation by fish attracted to artificial structures can greatly reduce the numbers of benthic organisms (Davis et al., 1982; Langlois et al., 2005).

Levels of direct mortality of fish passing through turbines can be high (e.g. Dadswell and Rulifson, 1994; Deng et al., 2011) and the disorientation might reduce species viability, as can be projected from instream fish behaviour in relation to turbines (Coutant and Whitney,

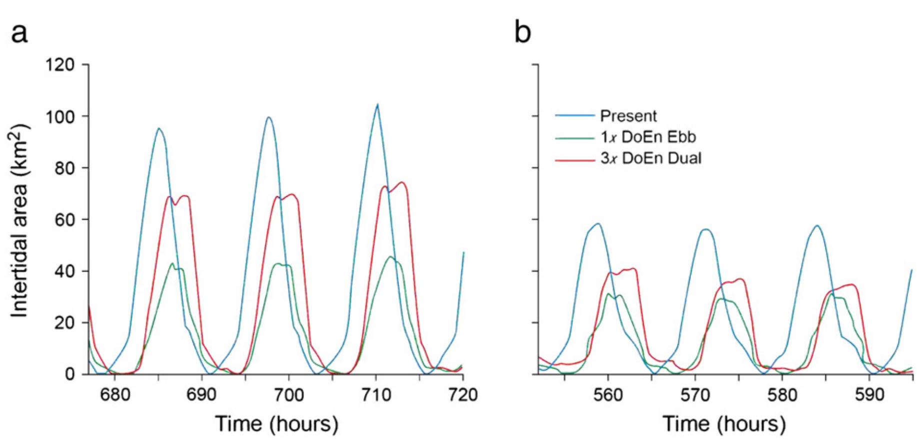

Fig. 2. Changes in the area of intertidal flats exposed in the Severn Estuary on (a) Spring and (b) Neap tides under no barrage (blue line), an Ebb only generation scheme (red line) and a Dual mode barrage scheme (green line). (Redrawn from Wolf et al., 2009).

2000). However there is considerable experience of engineering sluices, cooling water intakes and turbines to reduce fish entrainment (Coutant and Whitney, 2000) and such mitigation measures should be seen as a critical part of any system design. Turbine velocities in the range of 25–50 rpm are expected to minimize fish kills from physical contact with the blades (Pelc and Fujita, 2002).

Tidal stream farms operate in a very different manner to tidal barrage systems. In the latter a high speed turbine is mounted in a tunnel through which water flows at high speed and considerable pressure. Thus entrained organisms have little or no chance of avoiding passing thorough the turbine. In tidal stream farms the devices may not involve rotary turbines at all. Some rely on the see-saw oscillation of a beam with hydrofoils at each end (e.g., OSPAR, 2006b). When rotary turbines are used they are mounted in the open flow field and so the rate of revolution is much lower and organisms have plenty of opportunity to avoid direct contact.

There are insufficient data to state definitively how fish and fish habitat will be impacted by the operation of tidal stream power projects. No published data on the interactions between turbines and fish in the marine environment could be found except for some information from the Roosevelt Island tidal energy project on the East River in New York (Anon, 2008) that observed that the number of fish in and around the turbines was generally low (range of 16–1400 fish per day seen) and that the fish were predominantly small but still swam faster than the turbines rotated. Investigations into fish aggregation around submerged structures need to be considered for these devices (OSPAR, 2006a). There remain large information gaps concerning the collision risk of marine mammals with tidal stream farms. The literature reviewed suggests that the probability of cetaceans failing to detect and avoid a large static structure is considered to be extremely low, particularly for species that echo-locate and are agile and quick moving (US Department of Energy, 2009). The exact placement of tidal farms for species that frequent particular areas, either through site fidelity or seasonally, should be considered in mitigation and risk management.

The impacts of tidal stream farms on seabirds are also reported to be small (Anon, 2008). Risk of collision is expected to be minimal except for some deep diving species, for example, auks, guillemots, shags, which regularly dive to depths of 45–65 m (Thaxter et al., 2010). The slow turbine speeds relative to the agility of diving bird species would make the risk of mortality very low (Awatea, 2008). Diving birds may respond to the moving blades as potential prey and be attracted to their vicinity.

2.3. Wave energy farm

Wave energy farms show a wide variety of systems (see OSPAR, 2006a) at several stages of development, without it being clear which types will be most widely used (Falcão, 2010). As both pilot and commercial wave energy converting applications are limited, so are studies on habitat change. One Swedish study details the environmental effects over a five-year period after construction (Langhamer, 2010). The author concludes that the wave energy converters had only minor direct effects on the benthic community (macrofaunal biomass, densities, species richness and biodiversity) in relation to natural high variability. Langhamer and Wilhelmsson (2009) examined the function of wave energy foundations as artificial reefs (see also OSPAR, 2009a). They found a species-specific response to enhanced habitat complexity. Langhamer et al. (2009) demonstrated that foundations serve as colonisation platform with a higher degree of settlement on vertical surfaces. Analogous studies on colonization of offshore wind structures are reviewed by OSPAR (2006b, 2008a).

Fouled buoys may have positive effects on prey or forage species, which consequently cause an attraction of large predators, although complex underwater structures may provide refuges from predation (Dempster, 2005; Fedoryako, 1988; Relini et al., 2000). Conversely, lines on structures can cause the entanglement of marine mammals, turtles, larger fish and seabirds (Boehlert et al., 2007; DFO, 2009).

More critically, the dampening of waves may reduce erosion on the shoreline and may cause ecological changes. Further, arrays of devices may focus wave energies on the coastline thereby increasing erosion. However, sheltering due to wave devices will have a negligible effect on the largest waves, so that their ecological role as a disturbance that maintains biodiversity will be unencumbered (Pelc and Fujita, 2002).

3. Direct effects on reproduction and recruitment

3.1. Tidal barrage/fence

Construction of a barrage on or near a nursery or spawning area will clearly have an impact. These are site-specific considerations. Separation or constraining access to spawning and nursery grounds all have the potential for adverse effects at the population level. Barriers to the ranges of marine mammals and access to feeding, haul out, breeding and pupping areas all have the potential for adverse effects. Producing a barrier across the estuary/fjord the barrage will impact on migrations of anadromous and catadromous species including salmonids, eels and shad. For example, of river lamprey tagged below the Derwent River tidal barrage, only 1.8% was recorded at their spawning habitat, 51 km upstream of the scheme (North East England) where 98% of the spawning habitat occurred (Lucas et al., 2009). For fish, mitigation using salmon ladders is well developed and proven technology for hydroelectric dams (e.g., Gowans et al., 1999).

Tidal fences will also restrict fish and marine mammal passage through physical blockage, although there is room for mitigation through engineering of the fence structure to allow spaces for fish to pass between the caisson wall supporting the turbines and the rotors. Further, placement of the fence (in-parallel or in-series to water flow) can greatly influence impacts on species and habitats.

3.2. Tidal stream farm

These devices are unlikely to affect reproduction and recruitment processes unless multiple devices are very closely packed. In such cases there may be effects on larval transport and recruitment related to current and substrate changes.

3.3. Wave energy farm

Many fish species depend in part on currents to transport larvae, so wave energy devices that alter the currents between spawning grounds and feeding grounds could be harmful to fish populations (Boehlert et al., 2007). Conversely where biodiversity increases due to increased substrate availability, food availability increases and feeding efficiency is also higher, which could cause an enhancement of the larval recruitment in the area (Sánchez-Jerez et al., 2002). A complex substratum increases the spatial heterogeneity which can increase the species diversity of an area by providing more ecological niches, allowing more animals to recruit (Menge, 1976).

It has been hypothesized that noise might interfere with the ability of some fish species that locate their nursery areas by sound (Langhamer et al., 2010) although specific data were not presented. Breeding vocalizations are important for mate attraction in freshwater goby (Lugli et al., 1996), cod (Finstad and Nordeide, 2004) and haddock (Hawkins and Amorima, 2000). The successful settlement of coral reef fish depends on reef noise and can be affected by noise pollution (Simpson et al., 2008).

4. Water column processes and hydrography

4.1. Tidal barrage/fence

Downstream of the barrage during outflow and immediately upstream on inflow, the constraint of the flow will lead to turbulent flows that will increase mixing. Upstream for much of the tidal cycle the water in the basin will be fairly static and this could lead to stratification in summer, and changes in the phytoplankton dynamics. In the Severn Estuary, for example, the strong tidal flows lead to highly turbid conditions and hence low primary productivity. Underwood (2010) suggested that following construction of a barrage the increased water clarity upstream could lead to increased phytoplankton derived primary production.

Energy extraction may affect turbulent mixing, and change patterns of sediment distribution. Tidal fences in high energy coastal areas may encounter currents moving at 5 to 8 knots (9 to 15 km/h) producing intense mixing processes continuously in the water column. At lesser velocities some degree of water column stratification can be expected (Gray, 1992). This may also bring increased water clarity through reduced sedimentation.

4.2. Tidal stream farm

Tidal energy power generation devices will increase turbulence in the water column, which in turn will alter mixing properties, sediment transport and, potentially, wave properties. In both the near field and far field, extraction of kinetic energy from tides will decrease tidal amplitude, current velocities, and water exchange in a region in proportion to the number of units installed, potentially altering hydrography and sediment transport. Moving rotors and foils have been shown to increase mixing in systems where salinity or temperature gradients are well defined. Tidal energy turbines may also modify wave heights by extracting energy from the underlying current. The effects of structural drag on currents are not expected to be significant (Engineering Business Ltd., 2005; MMS, 2007), but few measurements of the effects of tidal/current energy devices on water velocities have been reported.

4.3. Wave energy farm

Wave power plants act as wave breakers, calming the sea, and the result may be to slow the mixing of the upper layers of the sea, which could cause an adverse impact on the marine life and fisheries (Pelc and Fujita, 2002). The energy devices remove energy from the wave train, affecting the tidal range, sediment deposition and ecosystem productivity (Hewitt et al., 2003). Similarly, erosion patterns along long stretches of coastline could be changed, the effect being beneficial or detrimental depending on the specific coastline (Pelc and Fujita, 2002). They may also modify some other local sediment transport patterns (including resuspension and deposition) by localized hydrodynamic changes due to presence of physical structures and from energy extraction. Depending on the location, scale, technological characteristics and dynamical processes, all these effects can be extended along the environment.

5. Noise

Tidal barrages, tidal stream farms and wave energy farms are all major civil engineering structures and construction (and decommissioning) activities will include considerable noise generating activities at levels potentially damaging to marine life. During construction noise and vibrations would affect different species in different ways (DFO, 2009; US Department of Energy, 2009). If installation involves pile driving, explosive or seismic work, which most pilot projects do, nearby noise levels are likely to exceed threshold values for the protection of fish and marine mammals. Even within the construction/decommissioning phases these are intermittent, short duration activities, but they have the potential to effect cetaceans (Madsen et al., 2006). At offshore wind farms in Denmark, Henriksen et al. (2004) and Tougaard et al. (2003) both found effects on the behaviour and abundance of harbour porpoises during pile driving activities. Fewer animals exhibited foraging behaviour and there was a short-term reduction of echolocation activity. These effects were documented up to 15 km from the impact area. These effects were short-lived once construction ceased (Carstensen et al., 2006). Studies suggest that high-level impulsive sounds have a greater effect on cetaceans than pinnipeds (Gordon et al., 2004; McCauley and Cato, 2003). Effects on other species would be less certain. Effects could be direct, by damaging sensory or sensitive tissues, or indirect, by changing behaviours. It is important when assessing noise effects that the cumulative effects of the entire system be evaluated and not just the levels produced by individual modules (US Department of Energy, 2009).

Operational noise of any of these installations is unlikely to be ecologically significant although there is very little information on the sound levels produced by the operation of tidal barrages, tidal stream farms or wave energy farms. There are also very few (if any) directed studies of the response of fish and marine mammals to noises and vibrations produced by operational (DFO, 2009). In the case of tidal stream farms the operational noise from a small number of units may not exceed threshold levels, but the cumulative noise production from large numbers of units has the potential to mask the communication and echolocation sounds produced by aquatic organisms in the vicinity of the structures. Resolution of the significance or otherwise of noise impacts will require information about the device's acoustic signature (e.g., sound pressure levels across the full range of frequencies) for both individual units and multiple-unit arrays, similar characterization of ambient noise in the vicinity of the farm, the hearing sensitivity of fish and marine mammals that inhabit the area, and information about the behavioural responses to anthropogenic noise (e.g., avoidance, attraction, changes in schooling behaviour or migration routes).

As for other effects, the type and scale of application determines the production of noise and subsequent effects (Boehlert et al., 2007). The constant low-intensity sounds from operating have also been compared to light to normal density shipping and a conventional ferry or subway (Anon, 2008), implying that effects may also be of a comparable magnitude. Behavioural reactions of marine mammals to noise must consider habituation effects (Langhamer et al., 2010).

6. Electromagnetic fields (EMF)

The environmental impacts of electromagnetic field (EMF) emissions from cables, switch gear and sub-stations are the same irrespective of the energy generating device and thus the lessons learned from offshore wind power developments are applicable to developments harnessing tidal stream or wave energy (OSPAR, 2008b). Electricity generated by the existing tidal barrage facilities is carried away by cables running on the top of the barrage and so has no marine environmental impact.

In a typical industry-standard cable it has been shown that EMF would fall to background levels (ca. 50 μT) within 20 m of the cable (CMACS, 2003). Marra (1989) showed that induced E fields of up to 91 μV were emitted from cables buried to 1 m in sediment. Cables carrying high voltage DC cables may produce fields of up to 5 μT at up to 60 m (Westerberg and Begout-Anras, 2000).

Some species of shark have been shown to respond to localized magnetic fields of 25–100 μT (Meyer et al., 2004). Westerberg and Lagenfelt (2008) found evidence that a 3-phase 130 kV cable (unburied) may be detected by migrating European eels (*Anguilla anguilla*) but did not disrupt their migration.

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Lohmann et al. (2008) report that given the important role of magnetic information in the movements of sea turtles (particularly loggerhead turtles), impacts of magnetic field disruption could range from minimal (i.e., temporary disorientation near a cable or structure) to significant (i.e., altered nesting patterns and corresponding demographic shifts resulting from large-scale magnetic field changes) and they suggest that this should be carefully considered when sites for tidal farms are authorised.

The survival and reproduction of several benthic organisms are not affected by long-term exposure to static magnetic fields (Bochert and Zettler, 2004). Evidence for marine mammal utilisation of EMFs is equivocal (Hui, 1994).

7. Conclusions

The world needs sources of energy that have low carbon demands and wet renewables represent a significant resource in the OSPAR region. All of the wet renewable devices reviewed impose changes to the environment which need to be balanced against the potential to deliver very significant quantities of low carbon energy.

Barrages and tidal fences require coastal locations with particular environmental conditions. Tidal barrages in locations where they will generate significant levels of power will alter tidal processes over large areas (potentially regional sea scales). The scale of the construction projects for barrages and fences is potentially large and many of the major impacts associated with this phase, for example noise from pile driving, can be mitigated by careful planning, for example by avoiding critical times of year for marine mammals and fish. While turbine life may be of the order of two decades the barrage structure will potentially have a design life of greater than 100 years and so impacts will be long term as well as far field.

The principle environmental effects produced from the operation of a tidal barrage are the changed tidal regime and its impact on bird communities and benthic habitat availability. The impacts on bird feeding habitat can be mitigated by the provision of new intertidal areas/lagoons which provide feeding grounds during the high water period landward of the barrage, and through the use of a dual cycle generation regime or the substitution of the barrage by a tidal fence. The latter options both give a lower energy yield. If the site was on a fish migration route (salmonids, eels, shad) appropriate provision would need to be provided by means of fish passes etc. The impacts on benthic habitats are not easily mitigated; a certain degree of loss of the regional habitat pool is inevitable.

The fact that wave energy and tidal stream devices are still in the experimental/trial phases means that there is no data on the environmental effects of commercial developments. It is at present not clear what the scaling-up from the limited observations on individual or small clusters of devices to commercial scale arrays will mean in terms of environmental effects and whether or not the effects observed to date are directly applicable. Tidal stream devices to generate significant power output will occupy large areas of sea for several decades. Although devices are likely to be well spaced within a farm, the sites themselves will have a large spatial footprint. Although of potential concern, there is little scientific literature to suggest that operation of underwater tidal stream energy devices will cause elevated levels of mortality to pelagic organisms such as fish and marine mammals, however, this is based on a limited data set.

Wave energy collectors have the potential to alter water column and sea bed habitats locally and by changes in the wave environment cause changes over some distances from the installation. The scale of the impacts will scale with the size of development and vary depending on the nature of the location selected. Most effects would be reversible, fairly rapidly, if an installation was removed. Appropriate scientific studies should accompany the licensing of the first commercial scale installations of these devices.

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Please cite this article as: Frid C, et al, The environmental interactions of tidal and wave energy generation devices, Environ Impact Asses Rev (2011), doi:10.1016/j.eiar.2011.06.002

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Please cite this article as: Frid C, et al, The environmental interactions of tidal and wave energy generation devices, Environ Impact Asses Rev (2011), doi:10.1016/j.eiar.2011.06.002