Marine renewable energy: The ecological implications of altering the hydrodynamics of the marine environment

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Review

Marine renewable energy: The ecological implications of altering the hydrodynamics of the marine environment

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ABSTRACT

Many countries now recognise the need for mitigation of climate change induced by human activities and have incorporated renewable energy resources within their energy policy. There are extensive resources of renewable energy within the marine environment and increasing interest in extracting energy from locations with either large tidal range, rapid flow with and without wave interaction, or large wave resources. However, the ecological implications of altering the hydrodynamics of the marine environment are poorly understood. Ecological data for areas targeted for marine renewable developments are often limited, not least because of the considerable challenges to sampling in high energy environments. In order to predict the scale and nature of ecological implications there is a need for greater understanding of the distribution and extent of the renewable energy resource and in turn, of how marine renewable energy installations (MREIs) may alter energy in the environment. Regional ecological implications of a MREI need to be considered against the greater and global ecological threat of climate change. Finally, it is recommended that the identification of species and biotopes susceptible to the removal of hydrokinetic energy could be a suitable strategy for understanding how a MREI may alter flow conditions.

1. Introduction

Countries worldwide now recognise the need to incorporate renewable energy resources within their energy policy as an alternative to finite fossil fuel resources, to achieve future energy security and to mitigate the effects of climatic change induced by human activities (MacKay, 2009). This change in energy policy has led to a growing interest in the extensive renewable energy resources available within the marine environment (Pelc & Fujita, 2002). Over the last decade there have been considerable advances in technologies for the extraction of energy from locations with large tidal range, rapid tidal flow or large waves (Wemyss, 2005). Little is known, however, about the ecological effects of the removal of kinetic energy from the marine environment. This review focuses on the potential ecological implications of altering the wave and/or tidal stream conditions experienced by benthic environments (Fig. 1).

Organisms living in energetic intertidal or subtidal zones have to contend with extreme hydrodynamic forces associated with breaking waves and/or tidal currents. Potential tidal energy sites are associated with tidal currents of 1–6 m s^{-1} and the swell and wind-waves that are necessary for a wave energy installation are associated with large orbital water velocities in the order of 5 m s^{-1}. High shear forces will exist where waves are breaking (at the sea surface in deep water, or in shoaling water at the surf zone), or in the boundary layer adjoining any solid surface (including the benthic boundary layer at the sea bottom or shoreline) where currents are strong. If an organism is unable to resist or evade large hydrodynamic forces, then mechanical failure will occur resulting in damage or dislodgement from the substratum (Vogel, 1994; Gaylord et al., 2001).

Withstanding or avoiding large hydrodynamic forces is only one aspect of adaptation to flow. Many sessile or sedentary organisms depend upon the flow of water for transport of gases, nutrients and food, and assisting with the dispersal of propagules and waste products (Abelson & Denny, 1997; Nowell & Jumars, 1984; Jumars & Nowell, 1984; Koehl, 1996; Denny et al., 1992; Gaylord, 2008). Specialised assemblages of species may exist in high energy sublittoral and littoral environments and these species are potentially vulnerable to the alteration of hydrodynamics.

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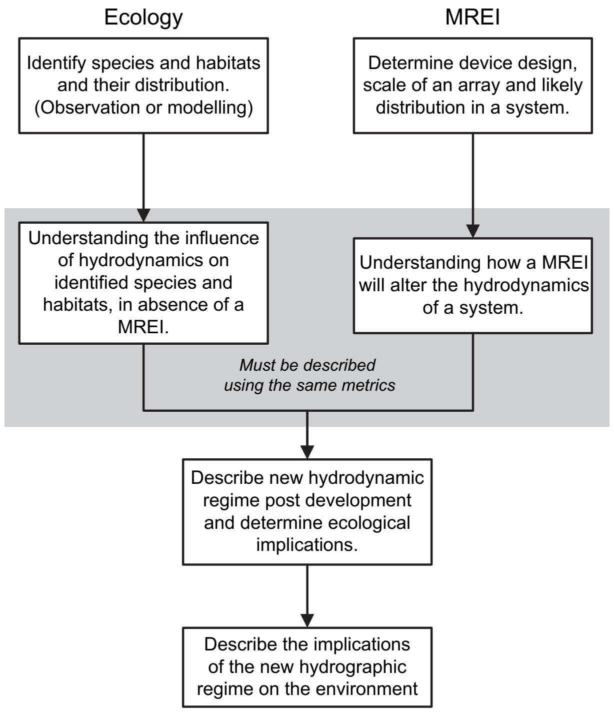

Fig. 1. Summary of the steps that should be taken when determining the potential implications of a MREI (Marine Renewable Energy Installation). Relating the hydrodynamics of a system to ecology.

The existence of data on ecological and environmental conditions prior to extraction of energy at any given location will be essential for understanding potential ecological impacts of any marine renewable energy installation (MREI). Many of the proposed locations for MREIs are where local environmental and physical conditions are poorly understood, largely due to the logistical difficulties associated with sampling in dynamic marine environments (Gill, 2005; Shields et al., 2008; Shields et al., 2009). Furthermore, understanding how marine renewable energy devices will influence near-field (<1 km), far-field (1–10 km) and regional (>10 km) flow conditions will be essential for mitigation of ecological impacts.

The majority of MREIs are at present composed of a single demonstration device and the industry is now progressing towards demonstration arrays (~10 devices) with the ultimate aim of installing large arrays (>100 devices). The spatial scale and magnitude of potential ecological implications associated with a single device will be very different from that of a large array of 100 devices. It is possible that a MREI may enhance local biodiversity by acting as an artificial reef and increasing habitat heterogeneity (Gill, 2005; Inger et al., 2009). When considering the potential ecological benefits of a MREI it is essential, however, not to overlook the importance of water flow and how alteration of energy in the environment may influence the distribution of species with dispersive juvenile stages reliant on transport by currents (Gaines et al., 2003). In order to incorporate water flow into spatial planning processes of MREIs and understanding of the hydrodynamics of a system and likely ecological responses to changing hydrodynamic conditions is required.

Here, we summarise (1) wave and tidal flow resources; (2) how wave and tidal energy devices can alter energy environments; and (3) how flow influences benthic ecology and the potential ecological implications of altering flow. Finally, as an example of potential regional effects of altering hydrodynamic energy, the waters of the Pentland Firth and Orkney Islands, Scotland will be discussed.

2. Understanding the resource

Studies focusing on potential ecological implications of a MREI must begin by understanding the hydrodynamic nature of the energy resource, before predicting how this may be altered by a MREI and then identifying the likely ecological response to any changes (Fig. 1). It is worth noting that wave and tidal stream resources, and the potential for their modification by MREIs, are fundamentally different in nature.

2.1. *Waves*

2.1.1. *Wave climate*

Ocean waves and swell are a result of the action of wind on the sea surface and favourable sites for the extraction of wave energy tend to be where ocean swell approaches the coast. For example, the Atlantic coast of Europe from Norway to Portugal benefits from swell produced by storms in the North Atlantic with average offshore wave “net power” of 40–50 MW km^{-1} (Mollison, 1994). Wave energy varies on similar timescales to that of the weather, exhibiting seasonal variations and inter-annual variations reflecting the variability of ocean winds. For example, the long-term UK wave climate features higher and more energetic waves in winter than in summer and also shows very strong variation among winters, paralleling variation among wet, windy winters and drier, calmer winters (Woolf et al., 1802).

Waves lose energy as they move from offshore to nearshore because of interactions with the seabed. This interaction is usually associated with a turbulent boundary layer which may result in resuspension and transport of sediment. These effects increase as waves approach the coast, where the associated stress and turbulence will be greater. The eventual shoaling and breaking of waves leads to particularly intense turbulence and the exertion of extreme loads associated with slamming forces.

2.1.2. *Wave energy devices*

The design of a wave energy device (WED) will vary depending on the location and method for energy conversion (Wemyss, 2005). Coastal methods for converting wave energy involve the attachment of a fixed device to the shoreline. The major advantage of a fixed coastal method is that the maintenance and installation of the device is less complicated than for offshore devices (Wemyss, 2005). Truly offshore devices are capable of operating in waters >50 m in depth and need to be operated at or near the surface, where the energy of the wave is greatest. Offshore devices are typically buoyant and require complicated mooring systems with electrical transmission cables that are vulnerable to damage.

2.1.3. *Modification of hydrodynamics by wave energy devices*

Individual WEDs in themselves will not extract large amounts of energy from the waves, but it is possible that an installation of many WEDs will reduce wave heights. Large waves will be usually propagating from seaward and any effects of WEDs on the kinematics of the wave can reasonably be assumed to be shoreward of the devices. Most WEDs are “tuned” to extract energy from swell or low frequency wind-waves, which generally represent a much greater source of power than higher frequency waves. Therefore, shoreward of a WED the energy (and thus height) of long waves will inevitably be reduced.

Models of a theoretical MREI (consisting of 270 WEDs; ~200 MW total installed power) moored in 50–70 m water depth off the coast of Portugal indicated that wave height at the 10 m depth contour may be reduced by 5 cm (Palha et al., 2010). Importantly, the relative percentage of wave energy removal by the MREI will exhibit seasonal variability and the proportion of

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energy removed will be greatest during the summer (Palha et al., 2010). A reduction in the height of long waves will reduce the associated stress on the seabed and sediment resuspension caused by wave action will be diminished. In addition, a reduction in wave energy will generally reduce the amount of breaking waves and associated turbulence. Often wave energy is expended at the shore and therefore the extraction of energy may be expected to have consequences for littoral and infralittoral environments rather than in the immediate vicinity of WEDs.

Perhaps the most important effect of WEDs will be on sediment suspension and sediment transport. In particular, long shore transport of material (and thus the sites where sediment accumulates or erodes) is dependent on the size and direction of incoming waves. Thus, by reducing waves in general and particularly those from a specific direction (i.e. downstream of the device), long shore drift of material and ultimately beach morphology, shallow water bathymetry and substrata may be altered (Defeo et al., 2009).

Many WEDs have a self-protective mode and will not operate during storm conditions. Energy is not, therefore, removed from large storm waves. Large waves are responsible for onshore erosion and offshore transport of sediment, resulting in the offshore migration of sandbars during storm events (Hoefel & Elgar, 2003). Energy from smaller waves will, however, be extracted by a WED and estimation of energy removal will be dependent on the frequency of the waves. These smaller waves are responsible for offshore erosion and onshore transport of sediment and consequently the onshore migration of sandbars (Hoefel & Elgar, 2003). It could therefore be expected that a reduction in energy of smaller waves, combined with no reduction to large waves by WEDs could result in the long-term migration of sediment offshore and the alteration of benthic habitats. It should be noted that all these processes are, however, already modulated by natural inter-annual variation of wave energy and direction (Woolf et al., 2002; Woolf et al., 2006) and by climate change (Harrison & Wallace, 2005; Tsimplis et al., 2005; Wolf & Woolf, 2006) on a regional basis. Near- and far-field effects of a MREI should each be considered in this context. In addition to extraction of energy by a MREI, there will be other effects, broadly associated with putting any large solid body in the water. It is difficult to generalise about these effects owing to the diversity of WED designs, but certainly where there are currents, devices will generate a wake similar to those for tidal energy devices (TEDs) discussed below.

2.2. *Tidal flow*

2.2.1. *The natural characteristics of tides*

Tides are an important part of the shelf sea environment and have been the subject of long and extensive study (Pugh, 1987), though paradoxically there have been relatively few studies in energetic tidal channels where currents are strongest. Tides are shallow water waves and their propagation is dependent on bathymetry and seabed characteristics. A tide, in common with any wave, cannot propagate indefinitely and a key feature of tidal dynamics is the frictional dissipation of energy. Dissipation of tidal energy is far from uniform and will be particularly great in some coastal areas, where strong currents interact with the seabed. Understanding these dynamics is essential to predict effectively any large-scale alteration of the tides that may occur where major engineering projects are undertaken.

Tidal amplitude can increase (and current speeds rise proportionately) where tidal waves are funnelled through a narrow gap or past a headland. Large currents in some narrow straits or channels may be regarded as a hydraulic response to the pressure difference owing to different tidal heights at either end of the strait. In another case, large tidal ranges and large currents may be attributable (e.g. Bay of Fundy) to a “near-resonant” interaction of the tide and bathymetry such that a large amplitude standing wave is created by the superposition of incident and reflected waves. Relatively few areas worldwide are likely to have conditions suitable for extraction of tidal stream energy and strong tides are certainly essential (Couch & Bryden, 2006). These areas will usually be well-mixed and this is unlikely to change, even with substantial energy extraction (Simpson, 1998).

2.2.2. *Tidal energy devices*

Tidal energy extraction can involve the construction of barrages or lagoons (Pelc & Fujita, 2002), but in this paper we limit the scope to tidal streams. Converting energy from tidal streams will depend on the (largely unmanipulated) natural flow of water to generate electricity via turbines or hydraulic devices (Wemyss, 2005). TEDs will be installed in locations where flow conditions are ideal (i.e. high velocity with low turbulence), normally around islands, in straits between two seas and round headlands where flow velocity will be enhanced by topography and bathymetry. Moorings of TEDs is currently an area of considerable research (Harris et al., 2004) and either gravity based moorings, anchor chains or piling are likely to be adopted; in all cases, interaction with the seabed will occur. Such interactions and their ecological implications, such as direct disturbance to the seabed, will require careful consideration (Gill, 2005).

2.2.3. *Near-field modifications of tidal flow*

Extraction of energy from the tidal stream necessitates placing an object or objects within the current flow. Both the physical presence of the TED and its actual extraction of energy will modify the flow. Modifications to flow will occur in the immediate vicinity of a device, i.e. near-field effects will occur at each TED within a MREI.

Near-field effects on flow can be modelled numerically or in physical laboratory simulations (e.g. (Batten & Bahaj, 2006; Myers & Bahaj, 2006)). For a single TED in a steady flow, there will be deceleration of flow immediately upstream of the device, a turbulent wake and reduced velocity downstream with accelerated flow around the device. Where an array of TEDs is placed in a steady stream, a staggered spatial arrangement can be used to exploit the accelerated flow from other devices upstream. In general, any objects associated with a MREI, including buoys, mooring lines and foundations will also have a wake, although this is likely to be minor in comparison to the effects of the devices themselves.

A MREI may modify absolute current (both near- and far-field) and intensity and spatial variability of turbulence (near-field). These modifications will feed through to the resuspension, transport and accumulation of sediment (thus altering habitats). The acceleration of flow between a TED and the seabed and the turbulent wake observed in simulations would be expected to affect the seabed. Note, however, that the reality of energetic tidal channels is that they are turbulent even without disturbance by a TED and that the nature of flow will usually be far more complicated than encountered in the laboratory or in simple numerical simulations (Lu & Lueck, 1999).

Understanding short-term fluctuations in tidal stream velocity, resulting from turbulence and wave–current interactions, is essential for proper evaluation of the performance of a TED and overall assessment of the MREI. In particular, fluctuations in turbulent flow across the rotor and entire structure of a TED, induced by the boundary layer, are crucial determinants of device performance and such characteristics are highly site-specific. *In situ* measurements of turbulence using Acoustic Doppler Current Profilers at the European Marine Energy Centre (EMEC) tidal stream test site in Orkney, Scotland have revealed complex turbulent flow, with the production of turbulent kinetic energy enhanced near the seabed (Osalusi et al., 2009b; Osalusi et al., 2009a).

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2.2.4. Far-field modifications of tidal flow

An important feature of the influence of TEDs on tides is that their effect may be more noticeable some considerable distance from the MREI. Whereas for waves, we expect effects only downstream of the development, introduction of a number of TEDs to a channel could influence the flow regime through the entire channel. In general these far-field effects are as yet unknown, but Karsten et al. (Karsten et al., 2008) estimated that, by pushing the system closer to resonance with the forcing tides, extraction of tidal energy from the Minas Passage in the Bay of Fundy has the potential significantly to alter tidal amplitude across the whole of the Gulf of Maine. In principle it is possible for a major MREI to influence ecology from deeper shelf waters to intertidal habitats. There will be a potential energy drop across the TEDs and applying a principle of continuity to a channel, the flow must be stronger where the water is shallower (for a given channel-width) and thus, the current-speed will be most strongly reduced upstream of the devices (Couch & Bryden, 2006).

The act of extracting energy from a source will reduce the energy in that source. However, there is potential for unexpected results from taking energy from tides. Since extraction of energy from tidal streams depends on the flux of kinetic energy (which is proportional to the cube of current velocity) across the TED, it is apparent that a reduction in current-speed will result in a loss of power production by the TED. However, by introducing TEDs to a tidal stream, energy is extracted by design and by necessity an obstacle to flow is introduced, usually resulting in a reduction of flow. A simple approach for calculating potential energy removal is to measure the kinetic energy flux in a channel and then to define a fraction of that flux which may be extracted, known as the “Significant Impact Factor” (SIF) (Bryden & Couch, 2007). It is important to note, however, that there are questions about how the kinetic energy flux and SIF relate to actual changes in flow conditions and the sensitivity of species and habitats to those changes. In addition, there are various estimates of total energy available from tidal resources (Blunden & Bahaj, 2007) and prior to predicting how a MREI will influence flow a greater understanding of the resource and local bed friction is required (Salter, 2009).

2.3. Potential ecological implications of a change in hydrodynamics

Potential ecological implications can be estimated based on existing knowledge of how hydrodynamics influences marine organisms and their environment. For example, a reduction in wave energy acting on the shoreline will reduce the overall height of the effective wetting level of the sea, thus reducing the area of habitat available for intertidal marine organisms (Lewis, 1964). Furthermore, tidal energy extraction may modify tidal dynamics on a regional scale. Tidal processes contribute significantly to horizontal dispersion of propagules (Zimmerman, 1986), directly through sheared and non-linear tidal transport and also through eddy generation. Therefore alteration of tidal flow and wave energy could have implications for dispersion of propagules, a key part of the life-cycle of many marine organisms, which in turn, could affect recruitment to and distribution of a variety of marine populations. Anthropogenic modifications of tidal currents could also alter sediment resuspension patterns, with concomitant effects on primary production or life-cycle couplings likely to be significant in seasonally varying photoperiodic environments of phytoplankton (Grist, 2000). The spatial and temporal scales at which these changes prevail will be dependent on both the hydrodynamics and bathymetry of the regional systems in question.

2.4. How drag and inertia forces interact with benthic organisms

Local flow conditions can influence body-size and shape of benthic organisms, limiting body-size in areas influenced by large hydrodynamic forces (Denny et al., 1985; Gaylord et al., 1994). The dominant force acting on very small or flat, encrusting organisms is skin friction, where water flowing across the surface resists being deformed in shear and exerts a force parallel to the surface of the organism and in the direction of the flow (Vogel, 1994). Organisms projecting into the water column are also subject to pressure drag and their presence influences water flow, creating a turbulent wake downstream (Vogel, 1994). A pressure drag forms when the dynamic pressure acting on the upstream side of the organism is less than on the downstream side. A small increase in flow-rate or body length can result in a large increase in drag acting on an organism (Vogel, 1994).

Waves breaking on the shore will create more complex forces acting on an organism than those in a tidal current. During the course of a wave, water accelerates in different directions creating an unsteady flow (Koehl, 1984). Any organism in an unsteady flow will be subjected to acceleration forces in addition to drag. When water accelerates past an organism that is subjected to gravity, the force acting on the organism is proportional to the mass of the water displaced by the organism (Koehl, 1984). As water accelerates past a sessile organism, the mass displaced will contribute to the total force experienced by the organism. Therefore the acceleration force on a sessile organism is a function of the organism’s volume, inertia, gravity and the acceleration of the water.

For benthic organisms to survive under the influence of large inertia and drag forces they must evade these forces or have adaptations that allow tolerance of mechanical stress. For example, barnacles, serpulid worms and stipitate kelps are permanently attached to the substratum. Other organisms attach with temporary, but strong attachments that permit limited movement; e.g. the byssus threads of the common mussel *Mytilus edulis.* Permanent or strong attachment to the substratum is not, however, always enough to survive mechanical stress and there are three mechanisms by which sessile organisms reduce the hydrodynamic forces applied to them (Denny et al., 1998):

I. Deformation or reorientation of an organism could result in an organism being more streamlined. Attachment to the substratum with byssus threads allows mussels to orientate according to the direction of flow (Denny et al., 1998).
II. Moving with the flow may reduce hydrodynamic forces acting on the organism as can be observed when stipitate kelps stretch out with increasing water velocity (Denny et al., 1998; Boller & Carrington, 2006).
III. When the motion of the organism is slowed by an elastic attachment to a stationary substratum then the motion of the organism will allow it to gain momentum which in turn will apply an inertial force to the organism. The stipe of a kelp provides an elastic attachment to the substratum that creates a restoring force when drag has caused substantial lateral swaying of the stipe and blades of the kelp (Denny et al., 1998). Variations in flow can also alter the forces associated with wave action (acceleration and drag) that would act on canopy-forming kelps (Gaylord et al., 2003).

2.4.1. Dispersal and settlement of propagules and flow

Water flow plays an important role in the distribution of species, particularly for those with a dispersive juvenile stage and flow should be considered in the planning of any marine development (Gaines et al., 2003; Gaylord & Gaines, 2000). The successful

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dispersal of propagules ultimately depends on settlement and alteration of hydrodynamics could have either positive or negative effects on this process. Downstream of any MREI, turbulence may increase, but information on the role turbulence can play in influencing external fertilisation and subsequent propagule settlement is limited (Abelson & Denny, 1997; Gaylord, 2008).

An increase in mixing associated with mild to moderate turbulence generated by a MREI may actually be advantageous for external fertilisation processes, particularly in surge channels where zygotes may concentrate (Denny et al., 1992; Gaylord, 2008; Denny & Roberson, 2002; Denny et al., 2002). However, the strong viscous shear associated with conditions of extreme turbulence could severely limit external fertilisation by disrupting the duration of vital interactions between egg and sperm (Gaylord, 2008; Mead & Denny, 1995; Gaylord et al., 2002). The negative influence of strong viscous shear on successful external fertilisation could be more significant when dense aggregations of organisms spawn simultaneously resulting in an important but brief period of high concentrations of gametes prior to dispersal (Gaylord, 2008).

Dispersed propagules encounter substrata through active swimming, passive transport by flow or via both processes. Flow can exert inertial and drag forces on settling propagules, which will potentially influence encounter with substratum and behaviour following encounter. In areas experiencing significant inertia and drag forces, the encounter of propagules with a suitable substratum will depend solely on passive transport with flow (Abelson & Denny, 1997). Propagules of many species, however, appear to be able to discriminate between substrata prior to settlement while being transported by laminar flow across substrata (Pawlik & Butman, 1993; Turner et al., 1994). Successful settlement under the influence of flow can be also be affected by predation of propagules by suspension feeders (Andre et al., 1993)or the presence of biogenic structures which provide complex three-dimensional habitats for other organisms (Eckman, 1983).

Flow can act as a settlement cue for some motile propagules or mediate various settlement cues (Abelson & Denny, 1997), in such cases successful settlement of propagules necessitates flow. Many propagules respond to dissolved settlement-inducing cues and if cues are detected in steady flow, then the propagule may immediately and actively move downwards, increasing the likelihood of selection of a suitable habitat (Tamburri et al., 1996). Even in unsteady flow, the brief detection of often intermittent dissolved settlement cues can enhance the settlement of propagules in suitable locations (Hadfield & Koehl, 2004) and many propagules have adaptations which increase residence time (Abelson et al., 1994). Following successful settlement, the feeding location for sessile species is established and feeding success for the organism will be influenced by local hydrodynamics and food particle flux (Jumars & Nowell, 1984).

2.4.2. *Feeding strategies and flow*

The growth and survival of suspension feeders depends on both the vertical and lateral flux of food particles, which in turn are influenced by local flow patterns (Nowell & Jumars, 1984; Wildish et al., 2008; Leichter & Witman, 1997). Suspended particle-size, food particle concentration and flow-rate can influence the feeding efficiency of suspension feeders (Okamura, 1990; Miller et al., 1992; Loo et al., 1996). Living in an area influenced by tidal currents can increase the daily food intake of suspension-feeding micro and macro-organisms (Simpson et al., 2007; Shimeta et al., 2001). In turn, the morphology of sessile organisms can influence the availability of food particles by altering flow-rate, local turbulence and particle movement in flow (Abelson & Loya, 1995; Abelson et al., 1993; Gardella & Edmunds, 2001). Feeding on fine particles is favoured by organisms that extend into the water column and have many branches (e.g. soft corals) that permit direct interception of fine food particles (Abelson & Loya, 1995; Abelson et al., 1993; Shimeta, 1993). Successful feeding on coarse particles can depend on gravitational deposition or inertial impactions of the coarse particles with the organism and is favoured by organisms with a low profile in flow (e.g. anemones) (Abelson & Loya, 1995). In the short term, an increase in resuspended sediments may occur due to disturbance of the seabed during the installation of a MREI (Gill, 2005)and potentially cause abrasion of organisms (Abelson & Denny, 1997)and/or interfere with filter feeders (Miller et al., 1992). However, any suspension feeders found in locations suitable for the development of TEDs or WEDs will be adapted for survival in a highly dynamic and harsh physical environment.

Predators may also be influenced by changes to flow conditions and turbulence associated with installation of MREIs. Some benthic predators rely on olfaction to locate prey when mechanical or visual stimuli are unavailable (Zimmer-Faust, 1989; Weissburg & Zimmer-Faust, 1993; Weissburg, 2000). Hydrodynamic processes can play an important role in the transport and modification of odour plumes and potentially influence the ability of a predator to locate prey when relying on olfaction (Weissburg & Zimmer-Faust, 1993; Ferner & Weissburg, 2005). Even in turbulent flow some organisms, such as stomatopod crustaceans can successfully detect and track odour plumes (Koehl et al., 2001; Stacey et al., 2002; Mead et al., 2003). Surprisingly, stomatopods can detect and track an odour plume more successfully in turbulent flow than in unidirectional flow (Mead et al., 2003).

2.4.3. *Ecology, sediment and flow*

Flow is known to influence both the onshore and offshore transport of sediments and alteration of flow conditions by a MREI could alter those transport patterns. For example, a near-field effect of a MREI could be the long-term deposition of sediment on exposed sublittoral bedrock around a TED (Neill et al., 2009). The deposition of sediment on exposed bedrock would alter the habitat to one of bedrock with a thin layer of sediment, potentially smothering sessile organisms already attached to the hard surface and ultimately changing the composition of the benthic assemblage. Far-field effects of altering hydrodynamics could be a change deposition and/or erosion patterns of intertidal sedimentary habitats, altering sediment heterogeneity and/or slope topography which in turn will influence the composition of assemblages (Defeo et al., 2009; McLachlan, 1996; McLachlan et al., 1984).

The erosion of particles by flow from intertidal sedimentary habitats can be influenced by the structure of the benthic assemblage. Some organisms can help stabilize sediments (e.g. *Mytilus edulis*), while the presence of other organisms may enhance erosion rates by destabilising sediments (e.g. *Macoma balthica* and *Hediste diversicolor*) (Widdows & Brinsley, 2002; de Deckere et al., 2001; Paterson & Black, 1999). Alteration to assemblages could have important consequence for long-term structure of sedimentary habitats. Any ecological changes related to far-field alteration of flow will ultimately depend on the sensitivity of benthic species and habitats to the alteration of energy in the environment and may, in effect, only alter species distribution with little or no overall effect to the ecosystem.

2.5. *Ecological understanding and management of energetic environments*

Many locations worldwide are recognised as being suitable for development for wave and/or tidal energy extraction. One such location is the waters of the Pentland Firth and Orkney Islands (Thorpe, 2001; Edwards, 2004; Black and Veatch, 2005; Faber Maunsell & METOC, 2007; Garrad Hassan & Partners Ltd, 2001;

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Bryden et al., 2004), where ten leases have recently been granted for a total of 1.2 GW of installed wave and tidal energy capacity by 2020. The development of the Pentland Firth region represents the largest commercial scale wave and tidal project worldwide in planning.

Within the Pentland Firth, there is a limited understanding of benthic ecology (Shields et al., 2009; Wilding et al., 2005). However, recent seabed surveys of this region have revealed a number of EUNIS habitats characteristic of high energy environments (Moore, 2009). The EUNIS classification system facilitates harmonised descriptions of data across Europe through the use of criteria for habitat identification. Habitat for this purpose is defined as ‘Plant and animal communities as the characterising elements of the biotic environment, together with abiotic factors operating together at a particular scale’ (EEA, 2009). The basis for the system is a database of information on species, habitats and sites to enable European governments to meet their obligations for relevant international conventions, such as the OSPAR Convention; Conservation of European Wildlife and Natural Habitats; IUCN Red Data Lista and CITES.

EUNIS Habitats that could be affected by a MREI and subsequent change in kinetic energy would be those that are generally subjected to the highest energy levels such as all those classified into the A1.1 High energy littoral rock. Depending on the magnitude of the reduction in energy, assemblages of species may become more like those in lower energy habitats (e.g. A1.2 Moderate energy littoral rock or A1.3 Low energy littoral rock). Changes to biotopes will also be influenced by other abiotic variables such as aspect, temperature or substratum and not only by alteration of hyrdodynamics. A list of all European habitats which may be altered by MREI and their effect on hydrodynamics is provided in Table 1.

Methodologies are being developed for seasonal ecological monitoring of rocky shorelines, specifically in areas suitable for WEDs (SuperGen-Marine, 2009). The identification of sentinel species sensitive to changes in hydrokinetic energy can help with the monitoring of potential impacts of a MREI. Several littoral species have been identified within the Pentland Firth region as potential sentinel species sensitive to changes in hydrokinetic energy and include species of limpet, topshell, barnacle and fucoid algae. For example, occurring near the EMEC wave test site on Orkney is the EUNIS biotope A1.121: [*Fucus distichus*] and [*Fucus spiralis*] f. [*nana*] on extremely exposed upper eulittoral rock (EEA, 2009). The seaweed *F. distichus* is rare in the UK and would be particularly subject to change due to its poor competitive advantage over more abundant species such as *Fucus vesiculosus* in a climate of less wave energy (Hiscock et al., 2001). If a change in *Fucus disitichus* populations was to be observed following a MREI then it is important not to overlook the possibility that the observed change may be a result of pressures associated with climate change and not the MREI. What is clear is that there is a need for greater understanding of how altering hydrodynamics of extremely energetic environments will influence benthic species and habitats.

Table 1
A list of EUNIS marine habitats at level 3 that may be altered by a change to hydrodynamics.

Habitat Type Code	Habitat Description
A1.1	High energy littoral rock
A1.2	Moderate energy littoral rock
A2.1	Littoral Coarse sediment
A3.1	Atlantic and Mediterranean high energy infralittoral rock
A3.2	Atlantic and Mediterranean moderate energy infralittoral rock
A4.1	Atlantic and Mediterranean high energy circalittoral rock
A4.2	Atlantic and Mediterranean moderate energy circalittoral rock
A5.1	Sublittoral coarse sediment
A5.6	Sublittoral biogenic reefs
B3.1	Supralittoral rock (lichen or splash zone)

The planning and management of a wave and tidal energy development needs to incorporate flow conditions. There is a marine spatial plan for the Pentland Firth and Orkney Waters being prepared, with the aim of providing regional local guidance and technical advice for developers and regulators of future wave and tidal developments (Scottish Government, 2009). The incorporation of modelled flow conditions along with environmental and socio-economic constraints for site selection purposes for wave and tidal developments can be included within a Geographic Information System (GIS) for management purposes (Dillon & Woolf, 2008a; Dillon & Woolf, 2008b). Furthermore, the development of the wave and tidal industry within the Pentland Firth and Orkney Waters can help to provide essential industry standards and environmental guidelines for the development of other suitable locations worldwide.

3. Conclusions

Waves and tides maintain shelf sea, coastal, estuarine and shoreline environments through associated advection, stirring and other processes. It is reasonable to suppose that removal of a small fraction of this energy at various locations need not have major ecological implications, but quantitative estimates of vulnerability and “safe limits” are not easily calculated. We are not yet able to say whether technically achievable levels of exploitation - variously estimated, but in the UK typically a few GigaWatts for each of wave, tidal impoundment and tidal stream – represent a threat to specific localities and ecological assemblages. Extraction of energy from waves will reduce the energy and height of waves. In principle, this reduction in energy could be detrimental to intertidal species adapted to wave exposed conditions, but further study of both biological and physical processes is needed to determine whether ecological responses would in practice be detectable against a background of natural variability. Reduction of waves from the direction of a WED array may alter sediment suspension and long shore transport near the coast, resulting in alteration of habitat. However, strong variation in wave exposure, shallow water bathymetry, substratum/habitat and beach morphology all occur naturally, so it is less likely that wave energy development will introduce a significant new threat.

Extraction of energy from tides can affect currents far from any construction, thus the regional effect (10s of km) may be greater than at the TED. Application of a rational approach to extraction of energy by tidal stream technology should avoid ‘greatly’ altering current speeds or tidal heights in general, but there may be more significant local effects. Also, overexploitation of some tidal stream sites is possible and may result in more dramatic alteration in tidal flow. The limits of safe extraction have been conceptualized for tidal stream in terms of a “flux-SIF approach” (Bryden & Couch, 2007) ~~(Karsten et al., 2008)~~. However, significant further effort is required to assess fully the resource potential in order to determine an acceptable level of resource extraction and to understand resulting ecological effects. For the purposes of protecting the marine environment, it is also important that research be directed specifically towards understanding how the energetic properties of the environment determine the nature and functioning of marine ecosystems. Identification of sentinel species susceptible to change in hydrodynamic conditions can help determine the influence of a MREI on both near- and far-field flow conditions. Such understanding is vital for effective marine spatial planning and impact

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assessment. Furthermore, natural variation in hydrodynamic conditions and the ecology of highly energetic environments, in addition to increasing pressures from climatic change, should not be misinterpreted as impacts from a MREI. Finally, care needs to be taken when considering potential regional ecological effects of a MREI and this should be considered against the global and greater ecological threat of climate change.

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