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Marine renewable energy: potential benefits to biodiversity? An urgent call for research

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Summary

1. The evidence for anthropogenically induced climate change is overwhelming with the production of greenhouse gases from burning fossil fuels being a key driver. In response, many governments have initiated programmes of energy production from renewable sources.

2. The marine environment presents a relatively untapped energy source and offshore installations are likely to produce a significant proportion of future energy production. Wind power is the most advanced, with development of wave and tidal energy conversion devices expected to increase worldwide in the near future.

3. Concerns over the potential impacts on biodiversity of marine renewable energy installations (MREI) include: habitat loss, collision risks, noise and electromagnetic fields. These factors have been posited as having potentially important negative environmental impacts.

4. Conversely, we suggest that if appropriately managed and designed, MREI may increase local biodiversity and potentially benefit the wider marine environment. Installations have the capacity to act as both artificial reefs and fish aggregation devices, which have been used previously to facilitate restoration of damaged ecosystems, and *de facto* marine-protected areas, which have proven successful in enhancing both biodiversity and fisheries.

5. The deployment of MREI has the potential to cause conflict among interest groups including energy companies, the fishing sector and environmental groups. Conflicts should be minimized by integrating key stakeholders into the design, siting, construction and operational phases of the installations, and by providing clear evidence of their potential environmental benefits.

6. *Synthesis and applications*. MREI have the potential to be both detrimental and beneficial to the environment but the evidence base remains limited. To allow for full biodiversity impacts to be assessed, there exists an urgent need for additional multi and inter-disciplinary research in this area ranging from engineering to policy. Whilst there are a number of factors to be considered, one of the key decisions facing current policy makers is where installations should be sited, and, dependent upon site, whether they should be designed to either minimize negative environmental impacts or as facilitators of ecosystem restoration.

Key-words: artificial reefs, environmental impact, fish aggregation devices, marine-protected areas, wave power, wind farm, wind power

Introduction

It is now widely recognized that there must be a paradigm shift in energy production from fossil fuels to alternative energy sources if we are to mitigate the effects of anthropogenically induced climate change (King 2004; Rosenzweig *et al.* 2008). The marine environment represents a virtually untapped source of energy, which could, theoretically, meet the total global demand for power; offshore renewables are likely to play a major part in a suite of technologies (Pelc & Fujita 2002).

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Primary amongst these is wind power, which has rapidly increased in capacity in recent years (Herbert *et al.* 2007). Onshore wind farms are often in competition with other land users, and cause aesthetic concerns (Taylor 2004). This, coupled with the better wind conditions in offshore areas, has resulted in an escalation in the development of offshore wind farms (Michel *et al.* 2007). The potential to capture energy from waves has seen increasing interest, with pilot developments in a number of countries (Dal Ferro 2006; Cada *et al.* 2007; Boehlert, McMurray, & Tortorici 2008; Nelson *et al.* 2008). Although the technology is behind that of offshore wind power, it has the potential to provide a significant contribution to renewable energy production in countries with suitable wave conditions (Carbon Trust 2006; Kerr 2007).

Given the demand for renewable energy it seems likely that for countries with large offshore wind and wave resources, an increasing proportion of their offshore coastal water will be turned over to marine renewable energy production. Renewable energies are often viewed as environmentally benign, especially when compared with the current vilification of carbon based and nuclear energy supplies. While on a global scale the advantages of renewable energy are not in doubt, the impacts on the local environment must also be carefully considered. The coastal marine environment is currently experiencing unprecedented anthropogenic pressure [RCEP (Royal Commission on Environmental Pollution) 2004]. Areas including Western Europe, North America, and the Far East which are amongst the sites likely to be targeted for marine renewable energy generation, are also the areas experiencing a high degree of environmental stress (Halpern *et al.* 2008).

The increased development of marine renewables has been mirrored by an increasing number of studies highlighting the potential impacts on the local environment (Abbasi & Abbasi 2000; Gill 2005; Michel *et al.* 2007; Sutherland *et al.* 2008), and most have tended to concentrate on the potential negative effects. Although a number of large scale offshore wind farms are under development, the marine renewable sector is still in its infancy. As such, we are now ideally placed to assess the environmental impacts of current marine renewable energy installations (MREI) and hence shape the of future marine renewable development, learning from the mistakes made when assessing the impacts of terrestrial wind farms on birds (Stewart, Pullin, & Coles 2007).

Despite having been studied for over 10 years, the impacts of terrestrial wind farms on avian populations remains unclear. While a number of studies suggest that wind farms may have detrimental impacts on birds (e.g. Langston & Pullan 2003; Garthe & Huppop 2004; Barrios & Rodriguez 2004), a recent systematic review demonstrated that the evidence-base remains poor, largely because of methodological weakness and short time scales of previous studies (Stewart *et al.* 2007). Particularly worrying are the lack of both replication and baseline comparisons. The systematic review process produces an unbiased and objective synthesis from the available (potentially conflicting) findings in a given field, with the aim to guide decision making. This approach, along with good study design, should be central to assessing the impacts of MREI.

While it is clearly critical to assess, minimize and mitigate any detrimental effects, such effects should be considered within a wider context as a few studies have indicated the potential positive environmental impacts of marine renewables. Here we build upon the seminal review of Gill (2005) by reviewing the growing evidence base and discussing some of the conflicts that will need to be resolved if the sector is to move forward to best effect.

Possible negative impacts on biodiversity

Some potential negative impacts will be specific to the MREI, but there are also a number of generic threats, and impacts will differ significantly between the construction, operational and decommissioning stages (Gill 2005).

HABITAT LOSS/DEGRADATION

Habitat loss because of MREI will vary depending on the type and size of the installation, the location, whether it is situated in degraded or pristine habitat, and the stage of the life cycle of the installation. Tidal barrages may cause substantial habitat loss at a small number of sites (Clark 2006; Fraenkel 2006); however, tidal power is beyond the scope of this review in which we concentrate on coastal and offshore MREI. Offshore MREI are however generally considered unlikely to result in significant habitat losses, although inappropriate siting has the potential to cause deleterious effects for certain taxa. For examples sea ducks, whose restricted foraging habitat may also be suitable for MREI (Kaiser *et al.* 2002, 2006b; Larsen & Guillemette 2007), may be displaced from affected areas. Wave energy convertors will have less impact on the seabed than wind farms, as they generally float on the water surface or are suspended within the water column, and are only anchored to the seabed during operation (Mueller & Wallace 2008). Impacts will also vary during the lifetime of MREI with the greatest expected impacts during construction and decommissioning as a result of factors such as direct habitat destruction, noise and altered sedimentary process. While MREI may result in some habitat loss, the infrastructure associated with the seabed, particularly from wind turbine piles, may act as artificial reefs, thus increasing the amount of available habitat for some taxa (see below).

COLLISION/ENTANGLEMENT

The collision hazards presented by MREI are divided into two main sections: first, avian (and to a lesser extent bat: Arnett *et al.* 2008; Baerwald *et al.* 2008) collisions with sections of MREI above the water, particularly illuminated areas and wind turbines; and secondly, collision/entanglement of marine vertebrates with underwater structures. In this study we consider the current designs for wind turbines, although new designs to capture wind power at lower altitudes are already under development which may significantly reduce the collision risks for birds (Nova-Project 2009; http://www.nova-project.co.uk/). The effects of collisions with wind farms on birds are still a contentious issue, and a number of factors remain unclear. Importantly, it must be noted that the majority of studies so far have been conducted on terrestrial wind farms. The study of the impacts on offshore avian populations is likely to be more challenging and will require the development and application of novel detection strategies (e.g. Desholm & Kahlert 2005; Desholm *et al*. 2006; Perrow *et al*. 2006). In addition, MREI will carry navigation lights, which have the potential to attract seabirds, increasing the collision risks (Montevecchi 2006).

Research suggests that impacts are highly dependent on the site and the nature and conservation status of both resident and migratory species utilizing the area (Garthe & Huppop 2004; Drewitt & Langston 2006; Fox *et al*. 2006; Stewart *et al*. 2007; Lucas *et al*. 2008). Generally, wind farms have a negative impact on local bird abundance (Stewart *et al*. 2007). Given that actual levels of mortality caused by collisions with structures appears to be low (Drewitt & Langston 2006), reductions in abundance may be attributed to avoidance rather than the direct effect of collisions (Desholm & Kahlert 2005). Furthermore we are only just starting to investigate the non-lethal effects of wind farms, such as disturbance or reduction in habitat quality, although initial findings demonstrate that windfarms have minimal impacts (Devereux, Denny, & Whittingham 2008), and that birds are able to habituate to them (Madsen & Boertmann 2008).

Virtually nothing is known about the potential for collision between submarine animals and MREI. Wind turbines are unlikely to represent a significant risk, being large and static, whereas there is a vast array of designs for wave and tidal energy collectors which may pose greater hazards. The most advanced of these are only at the pilot stage, so understanding the impacts of large scale installations or arrays is difficult. Using analogies with other anthropogenic marine activities, Wilson *et al*. (2007) highlighted a number of factors which may be important; fixed submerged structures are likely to pose little collision risk, while cables, chain, power lines and components free-moving on the surface or in the water column will pose a much higher risk of collision. A number of proposed devices have rotating turbines, which have the potential to seriously injure or kill organisms. In addition, a variety of marine organisms are attracted to marine light sources (Marchesan *et al*. 2005; Harewood & Horrocks 2008) which may be present on MREI, and have the potential to increase collision risks.

NOISE

The impact of anthropogenic underwater noise and vibrations on marine life is a growing concern, with an increasing body of evidence demonstrating its adverse effect over a range of taxa (Horowitz & Jasny 2007; Dolman, Green, & Simmonds 2007 and refs within). MREI will undoubtedly introduce extra noise, which is likely to impact on local marine life (Croll *et al*. 2001; Nedwell, Langworthy, & Howell 2003; Nedwell & Howell 2004; David 2006; Thomsen *et al*. 2006), particularly acoustically sensitive species such as marine mammals (Nowacek *et al*. 2007). Disturbance will be most severe during construction (Madsen *et al*. 2006) with pile-driving having been observed to directly affect the behaviour of seals (Edŕen *et al*. 2004) and cetaceans (Henriksen, Teilmann, & Carstensen 2003; Tougaard *et al*. 2005; Carstensen, Henriksen, & Teilmann 2006), possibly through masking vocalization in the latter group (David 2006; Thomsen *et al*. 2006). Less information is available regarding effects of MREI on fish populations, although estimates suggest fish can detect pile-driving noise over large distances, and that the noise may affect intra-specific communication, or cause injury or mortality at close range (Popper *et al*. 2003; Thomsen *et al*. 2006).

Noise during the operational phase is likely to be less intrusive but significantly more research is needed to determine the potential for chronic, long term effects. Particular attention should be paid to identify the range of frequencies utilized by marine organisms and minimize the production of noise within this frequency range. Thomsen *et al*. (2006) estimate that the operational noise of wind turbines will be audible by harbour porpoises *Phocoena phocoena* at around 100 m, and by harbour seals *Phoca vitulina* at over 1 km, although no *in-situ* studies have as yet been published on marine mammals. Fish react to the noise generated by wind farms (Andersson *et al*. 2007), and during operation fish avoided wind turbines at a distance of 4 m; however, although noise may mask communication and orientation signals, they experience no destructive hearing effects (Wahlberg & Westerberg 2005). While the impacts of wind farms on bird abundances have received much attention, the behavioural mechanisms and cues used by birds to detect and avoid wind farms remains understudied. This is unfortunate given that these data are likely to increase the effectiveness of collision mitigation devices. Larsen & Guillemette (2007) found that neither turbine noise nor movement affected common eiders *Somateria mollisima* and concluded that they used vision to avoid the structures. Indeed, for birds, extra noise from turbines may provide an extra sensory input to aid in avoidance.

It is unclear how other marine animals will react to the presence of MREI. Anthropogenic noise is thought to be detrimental to sea turtles (Samuel *et al*. 2005), whilst sea otters *Enhydra lutris* and manatees (*Trichechus* spp.) are sufficiently restricted to inshore waters so as not to be significantly affected (Michel *et al*. 2007), and marine invertebrates are not thought to be affected (Vella *et al*. 2001).

Most work has been carried out on wind farms, yet the effects of noise from other MREI are likely to be highly variable. An important assumption made here is that minimization of noise from MREI is desirable; however the evidence based to make this assumption is currently not available. Hence we suggest that, when sufficient evidence becomes available, a systematic review be undertaken (Roberts, Stewart, & Pullin 2006) which will provide an unbiased, quantitative assessment of the overall noise impacts of MREI.

ELECTROMAGNETIC FIELDS

In addition to the structures used to harness marine energy, submarine electrical cables are needed to transfer power between devices, to transformers and to the mainland, producing a high concentration of cabling at MREI. These cables will produce electromagnetic fields (EMF) which may be detected by a number of marine organisms including electrosensitive fish (Walker 2001; Gill 2005; Gill & Kimber 2005; Gill *et al.* 2005). The magnetic component of EMF will be of similar strength to that of the Earth in close proximity to the cables (Walker 2001), and so have the potential to affect magnetosensitive species such as bony fish, elasmobranchs, marine mammals and sea turtles (Wiltschko & Wiltschko 2005; Luschi *et al.* 2007; Gould 2008). It is also possible that magnetic fields could affect animals using geomagnetic cues as an aid to navigation during migration, although the importance of these cues remains unclear (Lohmann, Lohmann, & Endres 2008). The evidence for actual effects again remains very poor, and presents an opportunity for future research (Gill 2005; Gill *et al.* 2005; Öhman, Sigray, & Westerberg 2007).

Possible benefits to biodiversity

The environment of our coastal waters is being increasingly compromised by anthropogenic activities, although this is not necessarily irreversible, and may be restored, to a degree, by establishing marine reserves, for example, which generally show some benefits (Halpern 2003). There is an increasing body of evidence to suggest that, with appropriate design, siting, and management, MREI may actually have the potential to produce (with some caveats) positive environmental impacts (Wilhelmsson, Malm, & Öhman 2006; Langhamer & Wilhelmsson 2007; Wilhelmsson & Malm 2008; Langhamer, Wilhelmsson, & Engstrom 2009). Of course, it should be noted that siting of MREI in pristine habitats not threatened by human activity would be unlikely to produce any benefits.

ARTIFICIAL REEFS

The proposed construction of MREI will increase the amount of hard substrate in coastal environments and thus may have a significant impact (Petersen & Malm 2006). Man-made structures placed on the sea bed attract many marine organisms. These 'artificial reefs' are often used to enhance fisheries, for habitat rehabilitation, for coastal protection and to attract ecotourists (Clark & Edwards 1999; Jensen 2002). Other anthropogenic structures fixed to the seabed whose primary function is not to act as artificial reefs, such as oil platforms and piers, have also been reported to attract marine organisms (Rilov & Benayahu 1999; Love, Caselle, & Snook 1999; Helvey 2002), and have been called secondary artificial reefs. The presence of novel structures effectively creates new habitat capable of supporting more epibiota and fish, and have consistently been demonstrated to increase both the density and biomass of fish when compared with surrounding soft bottom areas and even local natural reefs (Bohnsack *et al.* 1994; Wilhelmsson *et al.* 1998; Wilhelmsson & Malm 2008). The species composition of artificial reefs may, however, not be the same as natural reefs, and their presence may also influence the biodiversity of surrounding areas (Connell & Glasby 1999; Rilov & Benayahu 2000; Connell 2001). Artificial reefs may also promote the establishment and spread of non-native species (Bulleri & Airoldi 2005; Page *et al.* 2006) and harmful algal blooms (Villareal *et al.* 2007). In addition it remains unclear whether the artificial reefs facilitate recruitment in the local population, or whether the effects are simply a result of concentrating biomass from surrounding areas. If the latter is true then it has been suggested (Grossman, Jones & Seaman 1997) that artificial reefs may perhaps have deleterious effects by increasing both fishing effort and catch rates and by causing exploitation of previously unexploited stock segments, and concentration of currently exploited stock. However, this point becomes less significant if the artificial reefs are out of bounds to fisheries. Again, we would call for a systematic review process (Roberts *et al.* 2006) to be carried out to accurately assess the impacts of artificial reefs, and highlight the need for more targeted research.

It is highly likely that MREI have the potential to act as artificial reefs (Linley *et al.* 2007), and preliminary findings support this. Wilhelmsson *et al.* (2006) found greater abundances of fish within the vicinity of wind turbines than in surrounding areas, although the species richness and diversity showed little difference. Abundance was greater on the turbine monopiles, although species richness and diversity were lower than in surrounding areas. Preliminary evidence also suggests that the foundations of wave energy converters can act as secondary artificial reefs (Langhamer & Wilhelmsson 2007), with structures becoming rapidly colonized by both epibenthic assemblages and fishes. Additionally the diversity of species increased with time, and was dominated by species resident to the areas (Langhamer & Wilhelmsson 2007).

The extent to which these secondary artificial reefs attract marine life and the nature of the species attracted will largely be shaped by the design of the components of the installation, with structural complexity of exposed surfaces being a key driver of the extent of colonization (Petersen & Malm 2006). Also important is the extent to which they are designed to either attract any species, only attract local species [artificial reefs with similar structural features to local natural reefs will attract local fauna (Perkol-Finkel & Benayah 2007)] or repel colonization. Given that the desirability of artificial reefs still remains a matter of conjecture, it is important that factors including local species abundance and diversity be considered before deployment, particularly if MREI are sited in pristine sites where increased biodiversity may be undesirable.

FISH AGGREGATION DEVICES

While wind turbines are restricted to relatively shallow waters as current designs are attached directly to the seabed, a number of manufacturers are currently developing floating turbines (Musial, Butterfield, & Boone 2003; Fayram & de Risi 2007) which, along with wave energy devices, will be anchored to the sea bed, but will be free to move on the surface, or within the water column. These floating devices may well have extensive moorings and some underwater engineering that can still function as, perhaps, more of a patch reef, and are in addition likely to act as fish aggregation devices (FAD) (Vella *et al.* 2001; Wilhelmsson *et al.* 2006; Fayram & de Risi 2007). Many species of fish aggregate around floating objects and fishermen have known and taken advantage of this phenomenon to increase their catches for centuries (Castro, Santiago, & Santana-Ortega 2002; Massutí & Vidal 1997). Additionally, offshore mussel farms can attract fish, which are at similar scales to MREI. FAD are now utilized in numerous fisheries globally, particularly in tropical and subtropical waters (Castro *et al.* 2002). As with artificial reefs, our understanding of how FAD work remains unclear (Castro *et al.* 2002), and the implications for their use on individual fish stocks and wider ecosystems require further investigation (Dempster & Taquet 2004). Furthermore, as FAD act to concentrate fish stocks rather than increase recruitment, the possibility for resultant overexploitation is clear. The utility of FAD as a tool for conservation and ecological restoration therefore remains questionable, although if fish are being attracted to areas that are free from fisheries pressure, which we envisage being the case for MREI, the benefits appear more tangible.

MARINE-PROTECTED AREAS

The possibility of collision and gear entanglement means that even without enforcement the immediate vicinity of MREI will not be able to be fished using many gear types. Larger installations with multiple arrays of devices, especially wave energy and tidal stream generating sites, will probably be enclosed within enforced exclusion zones for both safety and protection of the installations and may act as *de facto* marine-protected areas (MPA) to most fisheries. MPA, where all fisheries and other forms of extraction are excluded, are increasingly being called for [RCEP (Royal Commission on Environmental Pollution) 2004, Roberts, Hawkins, & Gell 2005; Fayram & de Risi 2007] and used as a fisheries management, conservation and ecological restoration tool. As well as protecting and enhancing fish stocks, the implementation of such MPA will also enrich benthic biota, by lifting the pressure from towed-bottom fishing gear (Kaiser *et al.* 2006a), which have chronic effects on seabed communities and are likely to affect ecosystem function (Tillin *et al.* 2006). Indeed, Gill (2005) cited fisheries impact studies as analogues to illustrate the potential negative ecological impacts and consequences of MREI construction. It is noteworthy, however, that construction impacts are temporally discrete, whereas fishing grounds are often repeatedly trawled/damaged, leaving little chance of recovery (Kaiser *et al.* 2006a,b).

The efficacy of MPA, while controversial, is largely dependent on the management objectives. There is increasing empirical evidence to suggest that, under effective management, MPA do work (Hawkins *et al.* 2006; Russ *et al.* 2008), and represent a relatively cost-effective means of habitat restoration (Balmford *et al.* 2004). Despite this, much more targeted research is needed to fully understand the underlying mechanisms at work (Sale *et al.* 2005). Halpern (2003) synthesized the results of 89 previous studies and found that, in general, MPA were effective in increasing density, biomass, size of organism and diversity within reserves when compared with the surrounding areas. Additionally, even the smallest reserves had a positive impact, with effects increasing directly with the size of the reserve. More recent results strongly suggest, however, that both size and age of the MPA are important determinants of success, at least in the case of commercial fisheries (Claudet *et al.* 2008). In addition to size and age, the habitat type (Friedlander, Brown, & Monaco 2007a,b) and efficacy of the management regime (Burke, Selig, & Spalding 2002; Samoilys *et al.* 2007) are also key to success.

While MREI may act as MPA it is important to remember that the location, and hence habitat protected by the MPA, may not be particularly valuable in terms of conservation, restoration or fisheries management. The siting of MREI will be influenced by the strength of the energy resource to be harnessed, suitability of the sea-bed, ease of connecting the infrastructure to the main-land, and consideration of other stake-holders in the marine environment. Even so, MPA which have previously been designed and sited with no intent to conserve biodiversity or enhance fisheries have still been shown to protect fish stocks within the MPA (Friedlander *et al.* 2007a).

It is also important to consider the role of MPA within the context of the wider marine environment. Marine species show high levels of connectivity with individuals moving between populations at various life stages, hence MPA are likely to act as a source providing benefits outside the MPA. In fisheries terms the net export of fish larvae, termed recruitment subsidy (Gerber *et al.* 2003), and juvenile and adult fish, termed spillover (DeMartini 1993), have the potential to bolster fisheries surrounding MPA, and also protect against over-exploitation (Sale *et al.* 2005).

INTERACTION OF POSITIVE AND NEGATIVE IMPACTS

MREI have the potential to produce significant anthropogenic influence on marine ecosystems, and the positive and negative impacts on the marine environment will certainly interact in complex and unpredictable ways. These impacts may also be cumulative, both in time, and with the introduction of increasing number of MREI, hence it is critical that we consider a wider marine ecosystem rather than focusing on the effects of individual installations. Furthermore, for all taxa of marine organisms, including birds whose flight paths may be affected by MREI, it is critical that we assess whether effects on individuals, at specific sites, are strong enough to produce population level effects (Elphick 2008).

Given that MREI have the potential to create additional habitat (by creating artificial reefs), attract marine organisms (via artificial reef and FAD effects) and create an area free from fisheries pressure, it seems possible that the overall effects on marine fauna will to be positive. There is increasing evidence to suggest that trophic cascades play a pivotal role in ecosystem function, and have recently been invoked as a mechanism by which lower trophic levels are impacted by anthropogenic disturbances at higher levels (Casini *et al.* 2008). Conversely, conditions at lower trophic levels have the capacity to significantly influence the dynamics of higher level organisms (Votier *et al.* 2004; Frederiksen *et al.* 2006; Johnson, Fleeger, & Deegan 2009). Hence by enhancing conditions at lower trophic levels we suggest that higher trophic levels including predatory fish, marine mammals and birds may also benefit from well-managed MREI. A key consideration here is that we seek to restore and enhance species native to the area, rather than encourage an increase in non-native or invasive species, which may be more competitive in colonizing new habitats created (Dafforn, Johnston, & Glasby 2009).

The scale over which these effects will propagate is also important and will be strongly affected by fisheries pressure in the vicinity. Recent work has demonstrated that networks of MPA have a rapid positive effect on fish abundance (Russ *et al.* 2008) and, as such, the introduction of networks of MPA associated with MREI may provide a powerful tool for restoration ecology. We suggest the potential linkage of conservation needs and renewable energy generation requirements should be explored to create such a network. Paradoxically, if potential benefits of certain MREI can be demonstrated, siting of these developments within areas requiring conservation may assist in the protection of wider areas of the marine environment.

Conflicts and solutions

There are a number of key conflict areas associated with MREI, because of the large number of stakeholders with conflicting interests and objectives. Therefore, we suggest that a fruitful line of future research may be modelling a number of management strategies within a multi-objective optimization framework, as have been used in previous environmental management scenarios (Higgs 2006; Stirn 2006; Kennedy *et al.* 2008).

ENVIRONMENTAL CONCERNS

Petersen & Malm (2006) raise a pertinent question: should marine renewable devices be designed to have minimal negative environmental impacts, or to attract and increase biodiversity? It is critical that policy makers and stakeholders rapidly come to some agreement. The worst possible outcome would be designs that are neither intended to produce a minimal impact nor enhance biodiversity. As we have highlighted here, there is an urgent need for targeted research programmes, particularly into the potential negatives of MREI, but also the prospect of MREI for habitat enhancement and even environmental recovery. It is essential that currently deployed MREI are studied appropriately to quantify impacts and benefits, the results from which can then be fed back into the design and deployment stages of future installations and used to model the likely impacts of larger scale developments.

Whether designed to be relatively environmentally benign or to enhance biodiversity, it is critical that all stakeholders, including energy companies, engineers, local communities, governmental and non-governmental organizations, fisheries, and academic institutions, are involved at all stages from design, siting, pre-construction monitoring/impact assessment, construction, operation and decommissioning. Furthermore research should be, as far as is commercially viable, transparent, with results published in scientific journals, to both maintain the scientific credibility, and accessibility to other researchers. Environmental monitoring of wind farms is already a condition of licence requirements in many EU counties, and MREI should be designed with this in mind.

Finally, it is critical that we consider the longer term future of MREI. If MREI are engineered to enhance biodiversity, particularly in degraded habitats, then we must ensure these enhancements are not lost during decommissioning. Consideration should be given to leaving new habitat forming infrastructure in situ and building this factor into the consenting process.

FISHING CONCERNS

The potential loss of access to areas containing and surrounding MREI will be a prime concern to the fishing sector, which should be involved as a key stake-holder from the earliest consultation stages. Outreach and training programmes should also be in place to highlight the potential benefits of MREI, which should also facilitate with the enforcement of fisheries exclusion from MREI. While there will be loss of some fishing areas, this may be countered by spill-over effects (McClanahan & Mangi 2000; Sale *et al.* 2005; McClanahan *et al.* 2007), and recruitment subsidies (Gerber *et al.* 2003; Sale *et al.* 2005). Indeed it has been suggested that MPA may in fact increase fisheries profitability in comparison to other forms of fisheries management (White *et al.* 2008), although this has yet to be demonstrated convincingly (Hart & Sissenwine 2009). Additionally it has been suggested there may be the opportunity for some forms of aquaculture, such as macroalgae or mussel/shellfish farming, within MREI (Linley *et al.* 2007).

Operators

The primary objective of MREI operators will be financial, although many either are or aspire to be environment-friendly, hence additional environmental benefits are desirable. Biodiversity enhancing features of MREI, however, may represent a number of technical problems for operators, such as the potential for biofouling to damage infrastructure and components. For larger devices consideration should be given, at the design stage, to the potential for birds using the structures as roosts, or seals using them as haul-out sites.

Conclusions

Undoubtedly MREI will increasingly be part of the seascape of tomorrow. It is clear that decisions made in the near future as to whether installations should be sited, sized and engineered to either minimize negative environmental impacts or maximise biodiversity and fisheries yield in coastal seas, will have impacts on the state of the marine environment in years to come. Since an earlier review by Gill (2005) some progress has been made in our understanding of how marine renewable energy will affect the marine environment and, as outlined above, there may be positive as well as negative effects. For example, the positive effects of MPA are becoming better understood (Hawkins *et al*. 2006; Russ *et al*. 2008) as is evidence that MREI will act as artificial reefs (Wilhelmsson *et al*. (2006); Langhamer & Wilhelmsson 2007). It is also becoming evident that wind farms may not have such a detrimental effect on avian populations as earlier studies suggested (Desholm & Kahlert 2005; Drewitt & Langston 2006; Stewart *et al*. 2007; Devereux *et al*. 2008; Madsen & Boertmann 2008). Despite this, the evidence-base for the impacts, both positive and negative, of marine renewables remains poor and there exists an urgent need for additional multi and inter-disciplinary biodiversity orientated research ranging from engineering to policy. Given the diverse number of stakeholders interested in the coastal seas, all such initiatives must take an inclusive approach for best effect. Given the already seriously degraded nature of our coastal seas we suggest that, if research and development programmes are targeted at identifying and promoting environmental benefits, marine renewable energy has the capacity to enhance biodiversity in degraded marine habitats, thus, representing an excellent example of 'win–win ecology' (Rosenzweig 2003).

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