IBIS The International Journal of Avian Science
BOU
Ibis (2010), **152**, 683–697

Review article

Potential impacts of wave-powered marine renewable energy installations on marine birds

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One potential approach to combat the impacts of climate change is the expansion of renewable energy installations, leading to an increase in the number of wave-powered marine renewable energy installations (MREIs). The consequences of increased use of these devices for birds are unknown. Here we describe the wave-powered energy-generating devices currently either operational or in development and review the potential threats and benefits of these to marine birds, their habitats and prey. Direct negative effects include risk of collision, disturbance, displacement and redirection during construction, operation and decommissioning. Above-water collision is a particular concern with wind-powered devices, but, because of their low profiles, the collision risk associated with wave-powered devices is likely to be much lower. Conversely, wave devices also pose the novel threat of underwater collision. Wave-energy-generating devices may indirectly impact marine birds by altering oceanographic processes and food availability, with implications for trophic cascades. Through appropriate mitigation, wave-powered MREIs offer the potential to enhance habitats. Direct positive effects may include provision of roosting sites, and indirect positive effects may include prey aggregation due to suitable substrates for sessile organisms or because they act as *de facto* protected areas. The cumulative effect of these could be the improvement and protection of foraging opportunities for marine birds. Recent studies have been critical of the methods used in the assessment of wind-powered MREI impacts, which lack sufficient sample sizes, controls or pre-development comparisons. Here we suggest solutions for the design of future studies into the effects of MREIs. Wave-powered MREIs are certain to become part of the marine environment, but with appropriate planning, mitigation and monitoring they have the potential to offer benefits to marine birds in the future.

Keywords: environmental impacts, experimental design, marine protected areas, offshore renewable energy, power analysis, seabirds, wave energy converters.

It is generally accepted that a significant proportion of increasing greenhouse gas emissions are derived from anthropogenic sources, and although the consequences of such global change are under debate, the evidence is that environmental change can have global-scale impacts on avian biodiversity, population dynamics and phenology (Pounds & Puschendorf 2004, Thomas *et al.* 2004, Huntley *et al.* 2006, IPCC 2007).

Marine renewable energy installations (MREIs) offer the potential to generate clean, low carbon energy without the problems associated with finding suitable sites on land (Taylor 2004, Fox *et al.*

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2006, Oxley 2006, Markard & Petersen 2009), providing a solution to reducing the current dependence on fossil fuels and a method of meeting national targets for sustainable development. The UK has large offshore wind and wave resources and, in line with other EU member states, has seen a rapid increase in the number of energy-generating devices, predominantly wind-powered, on and around its shores (Gill & Kimber 2005, Desholm *et al.* 2006). However, further expansion of the renewables sector will require diversification to prevent reliance on any one technology.

Wave energy is a promising new method for marine energy generation, representing a widely obtainable and consistent energy source with a potentially low environmental impact, although this has yet to be quantified (Leijon *et al.* 2003, Henfridsson *et al.* 2007). New MREIs will be positioned to maximize potential energy return: shallow areas of ocean that experience either high annual wind speeds for utilization by wind-powered MREIs, or regular large swell or tidal current races for, respectively, wave- or tidal-powered MREIs. These neritic areas (between low-tide level and the continental shelf) are important habitats for a number of taxa, and any potentially negative impacts of MREIs need to be mitigated or avoided. To date, few data have been collected offshore due to the expense of at-sea surveys (Desholm & Kahlert 2005), leaving a lack of information on habitat utilization of potential development areas.

Although many taxa may be impacted by MREI development, marine birds (seabirds, sea ducks, divers and grebes) are easily studied because they are relatively abundant, conspicuous and occur above water. Also, as apex predators, they integrate conditions over broad spatio-temporal scales, and are often used as convenient models for studying the effects of environmental change (Furness & Camphuysen 1997). To date, work has focused on how changes in extrinsic factors such as fisheries (Frederiksen *et al.* 2004, Votier *et al.* 2004, 2010, Phillips *et al.* 2006), climate (Votier *et al.* 2005, Frederiksen *et al.* 2007a, Rolland *et al.* 2008, Grémillet & Boulinier 2009) and pollution (Votier *et al.* 2005, 2008, Altwegg *et al.* 2008) can shape marine bird behaviour, foraging, movements and population dynamics, but few studies have investigated the implications of offshore development.

The ecological impacts of the expanding offshore wind industry have been the focus of much research (Desholm & Kahlert 2005, Chamberlain *et al.* 2006, Desholm *et al.* 2006, Dierschke *et al.* 2006, Drewitt & Langston 2006, Hüppop *et al.* 2006, Masden *et al.* 2009), although the impact of offshore windfarms on the population dynamics of birds remains unclear (Stewart *et al.* 2007). By contrast, there are few data on the environmental impacts of offshore wave or tidal energies on biodiversity (but see Langhamer *et al.* 2010). Here we discuss the potential impacts of wave-powered MREIs on marine birds. Due to a paucity of studies it is not possible to conduct a conventional quantitative review. Instead, we describe the range of devices currently operational or under development, assess how they might affect marine birds directly or indirectly via their prey and habitats, and then consider possible population-level impacts, using evidence from wind-powered MREIs when wave-powered examples are unavailable. Moreover, we answer some methodological criticisms of ecological impact monitoring at MREI sites in general, and wave-powered devices in particular, with suggestions for appropriate experimental design.

WAVE ENERGY CONVERTERS

Wave-powered MREIs differ from wind turbines in many ways (Fig. 1) and use a variety of technologies and methods to harness wave energy, with a range of possible impacts on marine birds, their habitats and prey. There are six main groupings of wave energy converters; point absorbers, attenuators, overtopping devices, submerged pressure differentials, oscillating wave surge converters, and oscillating water column devices.

A point absorber is a floating device that sits on the surface and absorbs energy in all directions as it moves with the waves. There are a number of different power take-off methods to convert this motion into useful energy, but one method is to convert the directional movement into a stroking motion, which in turn will drive a hydraulic ram. Examples of point absorbers include the PowerBuoy device from Ocean Power Technologies (http://www.oceanpowertechnologies.com), and the Fred Olsen Buldra/FO^3 concept (http://www.seewec.org) (Fig. 1).

Attenuators either sit high in the water column, or float on the surface, operating perpendicular to the wave direction. Wave movements are transported down the length of the device as it rides the waves. Devices can be articulated, as in the case of Pelamis (Fig. 1), currently being developed

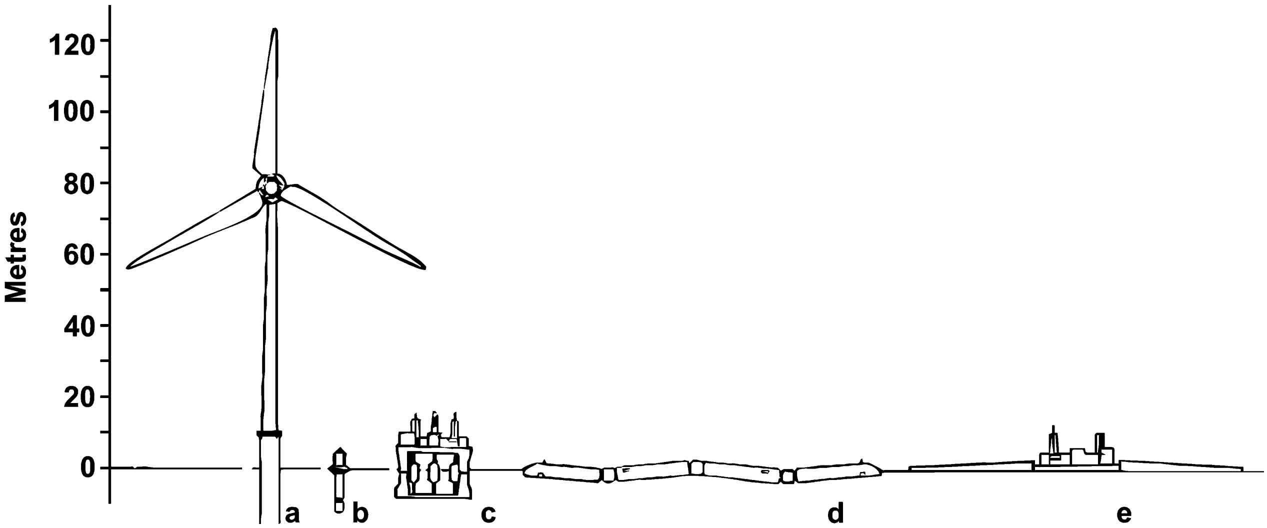

Figure 1. Wind turbines (a) offer a much more significant collision risk due to their height and extended sweep of the rotors. Wave-powered MREIs such as the OPT Powerbuoy (b), Fred Olsen Buldra (c), Pelamis (d) and Wave Dragon (e) present a much smaller collision risk to seabirds by being semi-submerged and offering a reduced profile.

by Pelamis Wave Power Ltd (http://www.pelamiswave.com). This uses hydraulic rams positioned between the articulations, and compressed by the movement of the device, to generate electricity.

Overtopping devices use a floating reservoir that collects water from waves as they break over the device. This water is held in the reservoir and then returned to the sea through low-head turbines, thus generating electricity, much like existing hydroelectric systems. The Wave Dragon, constructed by Wave Dragon ApS (http://www.wave-dragon.net) is such a device (Fig. 1).

Submerged pressure differential devices operate in a similar manner to point absorbers, but are fully submerged. Wave motion forces the device up and down, creating a pressure differential which can be used to pump hydraulics and generate electricity. AWS Ocean Energy (http://www.awsocean.com) is currently designing the AWS-III/Archimedes Wave Swing (Fig. 2).

Oscillating wave surge converters use a pendulum that sits in the water column: as the wave surge passes, the pendulum oscillates on a pivot, which in turn drives hydraulic pistons. A commercial example is the Oyster device, developed by Aquamarine Power Ltd (http://www.aquamarine-power.com) (Fig. 2).

Oscillating water column devices are semi-submerged in the water column, encapsulating a pocket of air in a chamber while being open to the sea below. Waves cause the water level to rise and fall, compressing the air and forcing it through a turbine. This technology has been successfully deployed by Hydro Wavegen Ltd (http://www.wavegen.co.uk), and a Limpit device has been installed on Islay, Inner Hebrides, Scotland (Fig. 2).

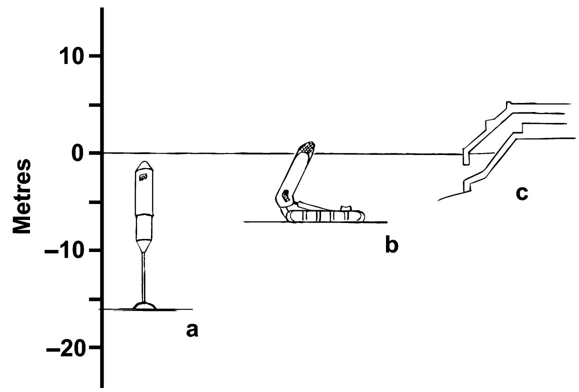

Figure 2. Wave-powered MREIs will be highly mobile underwater, e.g. Archimedes Wave Swing (a) and Oyster (b) pose the novel threat of underwater collision, or will contain chambers that may trap marine birds, e.g. Limpet devices (c).

POTENTIAL NEGATIVE INTERACTIONS WITH MARINE BIRDS

Risk of collision above water

It is now well established that the greatest threat of wind turbines to birds is the risk of collision

(Hüppop *et al.* 2006, Montevecchi 2006). However, because wave-powered devices have a much smaller profile, they may represent a much lower collision risk. For example, attenuators, point absorbers and other buoy-like wave-powered MREIs are unlikely to extrude more than 4 m from the water surface (Michel *et al.* 2007), in contrast wind turbines may be over 120 m tall (Fig. 1). However, not all devices will have a small footprint and, unlike wind turbines, many will contain mobile components both on and below the water surface, with consequences for birds in flight and whilst diving.

The existing literature on wind turbine impacts has shown avoidance ability and vulnerability to collision to vary as a function of species and size (Brown *et al.* 1992, Garthe & Hüppop 2004, Lucas *et al.* 2008), and nocturnal or crepuscular species may be more affected by being active during periods of low light (Larsen & Guillemette 2007, Arnett *et al.* 2008). Furthermore, age and reproductive stage may affect collision risk (Henderson *et al.* 1996), and differential mortality between age classes would affect population dynamics (Votier *et al.* 2008). These differences in collision risk may also apply to the, albeit low, risk of collision with wave-powered devices.

Even so, few studies have quantified how collision risk might vary with environmental conditions, particularly during bad weather when marine birds would be at greater risk due to reduced visibility and manoeuvrability. Further work is required to quantify the potential collision risks posed by these devices, and how risk may vary between species and environmental conditions, allowing mitigation of any effect to be incorporated at an early stage in the process.

Risk of collision under water

Wave-powered MREIs represent an underwater collision risk to diving birds. Fixed structures under the surface pose little risk due to their ease of navigation; however, the energy converters, anchor chains and cabling are highly mobile and so harder to navigate (Wilson *et al.* 2007) (Fig. 2). No work to date has quantified the potential collision risks to marine birds associated with wave-powered MREIs, although tidal energy converter turbines have low rotational speeds (*c.* 15 rpm) and are unlikely to cause injury during a collision event (Fraenkel 2006). Risk will be highest when marine birds are diving for prey, and so sensitivity will depend on the ecology of the species, with the highest potential for interaction occurring when a device is placed within the foraging range of a colony and at a depth within the dive profile. It is important therefore to understand the distribution and behaviour of prey species in response to these devices, to allow a better understanding of the potential conflicts between marine birds and wave-powered MREIs.

Sensitivity will also vary as a function of avoidance ability: surface divers have typically slow and controlled dive profiles, whereas plunge-diving species have a lower margin for avoidance and so may be more threatened (Ropert-Coudert *et al.* 2004, Thaxter *et al.* 2009). Turbidity will increase around the moving parts of a wave-powered MREI (Langhamer *et al.* 2009), thus reducing visibility and increasing the potential collision risk. While diving behaviour has been linked to both visibility (Haney & Stone 1988, Henkel 2006) and tide (Holm & Burger 2009), no work to date has investigated the collision risk associated with underwater structures, although attempts have been made to quantify mortality around offshore oil platforms, which present a collision and pollution risk (Wiese *et al.* 2001).

Risk of entrapment

Devices that use pressure differentials to drive internal turbines, such as oscillating water columns (Fig. 2) or overtopping devices (Fig. 1), will contain enclosed chamber sections that are partially exposed to the open ocean. These openings pose a risk of entrapment to marine birds that are capable of entering the chamber and could be killed either by the turbines or by the propulsion of water from within the device. These risks would differ between the device and installation type, but could be mitigated simply by covering openings with a protective mesh.

Disturbance

Any impact of operational noise will be most significant during installation of the devices, and subsequent maintenance activities (Madsen *et al.* 2006). Devices capable of floating rather than being fixed in the seabed would minimize the impact of noise during construction by negating the need for pile driving, an activity that has the potential to cause auditory damage to wildlife in the vicinity

(Thomsen *et al.* 2006, Snyder & Kaiser 2009). Nevertheless, wave-powered MREIs will require the construction of extensive moorings and anchorage to maintain efficient operation. Natural wariness to anthropogenic activity might exclude animals from the critical area during construction, thus reducing the potential impact (Burger 1988, Koschinski *et al.* 2003), but responses vary with the stimuli and are hard to quantify (Hill *et al.* 1997).

A wide range of operational noise will be produced by the equipment and associated anchorage and cabling; the potential impacts of these are unknown and there are no studies currently quantifying wave-powered MREI noise, or the impacts on marine birds. Studies suggest the noise produced by wind turbines may mask biologically significant sounds or even damage acoustic systems in a range of species (Southall *et al.* 2000, Gill & Kimber 2005), although there is evidence of habituation after construction in geese (Madsen & Boertmann 2008) and marine mammals (Madsen *et al.* 2006). Further work should focus on understanding the baseline soundscape in these environments before development to allow a comparison with noise levels after installation, as has been done in urban environments (Habib *et al.* 2007).

Displacement

The area of seabed directly impacted during the construction of wave-powered MREIs will be small, limited to impacts from cabling and anchorage (Langhamer & Wilhelmsson 2009). Nevertheless, some devices, such as oscillating wave converters, will require a fixed base. This is similar to the impacts suggested during wind turbine construction; however, the construction and decommissioning of the devices themselves differ substantially and loss of habitat throughout these phases is likely to be less extensive (reviewed by Gill 2005).

Disturbance and removal of habitat may lead to displacement of animals from the vicinity of the development site. Displacement will take two forms: (1) birds may avoid areas containing man-made structures (Petersen *et al.* 2006, Larsen & Guillemette 2007) or (2) foundations and associated cabling around MREIs may alter the hydrological process and make the environment unsuitable for prey species (Kaiser *et al.* 2006a).

For marine birds that are restricted to forage in shallow sandy areas suitable for MREIs, displacement could have a disproportionately negative impact (Snyder & Kaiser 2009). Moreover, wave-powered MREIs, which either float on the water surface or are stable in the water column and are anchored to the sea bed, are likely to have less of an impact than pile-driven turbines (Mueller & Wallace 2008, Inger *et al.* 2009). Furthermore, impacts during construction are time-bound; in contrast, fishing activities such as trawling are repetitive, leading to cumulative impacts on the benthos, as the habitat is not allowed to recover (Kaiser *et al.* 2006b).

Redirection

Developments have the potential to form extensive barriers to movement (Gill 2005), and marine birds may be forced to navigate around wave-powered MREIs in the same way that they avoid wind-powered MREIs, increasing both distance travelled and energy expenditure (Desholm 2003, Masden *et al.* 2009). However, the energetic requirements of wind farm avoidance are limited unless repeated regularly; navigating around a medium-sized wind farm extended the migration distance of Common Eider *Somateria mollissima* by approximately 500 m (0.04% of their total migration) at a negligible cost to body condition. To achieve a loss in body mass in excess of 1% this response would need to be repeated 100 times (increasing the migration distance by 4%) (Masden *et al.* 2009). Therefore, it is unlikely that multiple wind-powered MREI sites will impact migration routes, and for wave-powered MREIs with inherently low profiles, the impact will be negligible. However, not all devices have a low profile; commercial-scale developments such as the Fred Olsen Buldra/FO^3 concept (Fig. 1) house a number of point absorbers in a more traditional offshore rig that will be 24 m high. Work is required to investigate the re-directional effect of devices with differing heights.

Many marine birds have altricial young and so are confined to centrally placed foraging during the breeding season. Conflict may arise if installations are sited between feeding, breeding and roosting grounds, and navigated frequently (Langston & Pullan 2003, Desholm & Kahlert 2005, Masden *et al.* 2010b). Changes in energy balance may affect fitness, but need to be placed in the context of the wider energetic pressures on a population (Masden *et al.* 2010b).

Pollution

Wave-powered MREI devices contain substantial amounts of oil and lubricant for effective operation at sea, which carries a spill potential. There is currently no evidence to determine how frequently this occurs or whether it would have any impact, but major oil pollution events are known to have population-level consequences for marine birds (Votier *et al.* 2005, 2008).

POTENTIAL POSITIVE INTERACTIONS WITH MARINE BIRDS

Roosting

The construction of new structures in the marine environment creates roosting sites that are quickly used by marine birds, as found around oil platforms (Wiese *et al.* 2001). If wave-powered MREIs were to act as roosting sites they could potentially increase foraging ranges of certain species, or provide resting sites for migratory terrestrial birds normally unable to land on the water. However, manufacturers are likely to design buoys deliberately to deter roosting, as prolonged use may cause damage and reduce device efficiency (Michel *et al.* 2007), and aggregation around a device is likely to increase collision risk.

POTENTIAL NEGATIVE INTERACTIONS WITH HABITATS AND PREY

It is harder to predict the indirect impacts that wave-powered MREIs may have on local habitats and prey species, but these could be of equal importance to direct impacts on marine birds, leading to population-level changes.

Changes to oceanographic processes

There is the potential for wave-powered MREIs to reduce foraging opportunities for birds through trophic changes resulting from altered oceanographic processes (Frederiksen *et al.* 2007b). Attenuators such as Pelamis may extract up to 23% of the incidental energy from a wave (Palha *et al.* 2010), although the efficiency of energy extraction will differ between devices and wave states. The area of ocean affected by the wave shadow produced by an array will also move relative to the prevailing wave and wind direction (Millar *et al.* 2007). A reduction in wave energy could impact transport processes (Pelc & Fujita 2002) and might be detrimental to spawning or nursery sites (Gill 2005). Conversely, reducing the ability of currents to move sediment would lead to the accumulation of organic matter, increasing biodiversity by providing habitat for deposit and suspension feeders such as polychaetes (Fabi *et al.* 2002). In coastal sites there is also the potential for a scale-dependent reduction in the wave energy that reaches the shore, which could lead to changes in sedimentation and shoreline processes (Millar *et al.* 2007).

The potential bottom-up effects of these impacts and their scale are unknown, but if predicted changes to the micro-scale tidal climate within an MREI were to have a detrimental impact on spawning and larval recruitment in the surrounding area (Gill 2005), the likely outcome would be a reduction in food availability for higher trophic level animals such as birds. Further work is required to quantify both the wave shadow produced by large arrays of devices, and the environmental consequences.

Changes in food availability

Foraging opportunities for birds could be altered through detrimental changes to local-scale habitat around wave-powered MREIs, although there may also be beneficial effects through enhancement of small-scale hydrographic processes such as eddies. Novel structures placed in areas with little or no hard substrate will enable the colonization of sandy areas by hard bottom-dwelling species (Bulleri *et al.* 2003). Studies on the colonization of wind-powered MREIs show them to be dominated by Blue Mussels *Mytilus trossulus* and Acorn Barnacles *Balanus improvisus*, with altered fish communities having a higher abundance but lower species diversity (Wilhelmsson *et al.* 2006). Invasive species typically colonize more rapidly than indigenous species following disturbance (Bulleri & Airoldi 2005), which could impact marine birds if invasive species outcompeted preferred prey species, but could also offer benefits if the monocultures were exploited (see Positive Interactions below).

The installation of tidal turbines in the Bay of Fundy has negatively affected migratory fish populations, with potential consequences for the marine animals reliant on this seasonal resource (Dadswell & Rulifson 1994). The redirection of fish migration routes away from areas with large arrays would have obvious deleterious effects for piscivorous bird species. An increase in fish mortality due to collision or entrapment would have a long-term negative effect, although there may be short-term benefits for scavenging species.

POTENTIAL POSITIVE INTERACTIONS WITH HABITATS AND PREY

Habitat enhancement

Wave-powered MREIs could attract marine organisms through the addition of hard substrate to the ecosystem and formation of artificial reefs (Baine 2001, Whitmarsh *et al.* 2008). Wave- and wind-powered MREIs provide anchorage for a number of sessile species such as Blue Mussels and Acorn Barnacles (Sundberg & Langhamer 2005, Wilhelmsson & Malm 2008, Langhamer *et al.* 2009). This offers potential benefits to shellfish-eating species such as Common Eider, which could capitalize on the increased food resource. Nevertheless, invasive species are quick to colonize new habitats and may out-compete native prey species (Fridley *et al.* 2007); however, due to the complex nature of trophic linkages (Anthony *et al.* 2008) the effects of such change could be very difficult to predict.

Colonization will cause conflict if it interferes with equipment performance (Michel *et al.* 2007), and experimental studies estimate the level of biofouling may be as high as 150 kg of biomass per 3-m-diameter buoy (Langhamer *et al.* 2010), but scouring to enhance efficiency may not be cost-effective (Langhamer *et al.* 2009).

Aggregation

Floating wave-powered MREIs could act as fish aggregation devices (FADs), attracting and recruiting fish species seeking protection and food (Hunter & Mitchell 1968, Nelson 2003, Sundberg & Langhamer 2005). Wind turbine monopiles have been shown to act as both artificial reefs and FADs as they are positioned vertically in the water column, increasing the density of fish within the vicinity, although there may be consequences for community structure, species richness and diversity (Wilhelmsson *et al.* 2006). Both species richness and assemblage size are positively correlated with FAD size (Nelson 2003), so large wave-powered MREIs will be better at recruiting fish species, providing foraging opportunities for piscivorous birds.

De facto MPA designation

Navigational aids and buffer zones will be installed around the MREI to limit boat traffic and prevent either fouling of the machinery by fishing gear, or vessel collisions. Larger installations with a number of devices, especially wave and tidal energy converters, will have enforced closures and 500-m exclusion zones to protect the deployed equipment (SWRDA 2006), and it is unlikely that fishing vessels will enter the array due to the risks of entanglement. Indeed, current regulations will exclude commercial fishing from development sites, providing refugia from fishing (Gill & Kimber 2005) but the response of local stakeholders is unknown. No-take zones are increasingly promoted by both conservationists and ecologists to reduce the overexploitation of fish stocks (Sanchirico *et al.* 2006).

This potential for protection, combined with the provision of novel hard substrate by device installation, could increase biodiversity as lower trophic species recruit to colonize the new habitat, offering an aggregated and effectively protected resource for marine birds. As a result, MREIs may act as *de facto* marine protected areas (MPAs) (Sundberg & Langhamer 2005, Inger *et al.* 2009), with potential benefits for marine birds. However, any potential benefit to local-scale fish abundance could lead to ‘fishing the line’ (Kellner *et al.* 2007, Stobart *et al.* 2009), by attracting fisheries to the edges of the exclusion zone due to spill-over effects.

POPULATION-LEVEL AND SYNERGISTIC EFFECTS

Trophic cascades have been shown to affect seabird populations by altering food supplies in complex ways (Österblom *et al.* 2006, Frederiksen *et al.* 2007b). Therefore as well as the effects of changes in food availability mentioned above, there may be unforeseen community-level changes in trophic interactions, although the magnitude of any effect will determine to what extent these might have consequences at the population level (Elphick 2008). It is also unclear how the ecosystem will respond to such perturbation, and further work is required to investigate how the potential positive and negative effects may offset one another.

While mortality due to collision will affect only a small proportion of the population (Lucas *et al.* 2008, Desholm 2009), there is the potential for cumulative indirect effects for the entire population, for example through reduction in body condition of all breeding adults through the inappropriate placement of multiple installations on a migration flyway (Masden *et al.* 2009). The potential for cumulative negative impacts could potentially constrain development of multiple wave-powered MREIs, and consideration would be required through both environmental impact assessment (EIA) and strategic environmental assessment (Devereux *et al.* 2008, Masden *et al.* 2010a).

PROSPECTUS FOR FUTURE RESEARCH

The existing data on potential impacts of wind-powered MREIs is expansive, but inadequate experimental designs make comparisons problematic (Stewart *et al.* 2007). Gaining a better understanding of impacts requires further analyses, but crucially these require common methodologies. Due to the slow development of other types of MREI, information on the impacts of wave- and tidal-powered MREIs is poor, and the available information on wind farms does not translate well into wave-powered technologies. However, recognizing the errors made during the study of wind farms is critical in preventing the same mistakes being made in the development of studies into wave-powered MREI effects. It is vital to involve stakeholders through the process of developing and managing an MREI site. In this way the science can be built in from the start, allowing for appropriate monitoring programmes to be managed throughout the lifespan of an MREI.

More data are required to elucidate the causes of observed changes in fauna around existing MREIs and to predict the potential effects of future developments. Stewart *et al.* (2007) and Langston *et al.* (2006) call for better standards of EIA and post-construction monitoring, as much of the reviewed work in Stewart *et al.* (2007) did not include either controls or pre-development comparisons, but this is now being addressed (Pearce-Higgins *et al.* 2009, Masden *et al.* 2010a). Studies that focus on one site, with no control for a comparison, lack the power of more complex studies. The use of before-after-control impact (BACI) assessment (Underwood 1992) should be the minimum standard in future research studies of MREI impacts. Including a minimum monitoring period of 1 year before impact to ensure monitoring of any annual cycles in species, and monitoring of the construction area over 5–10 years for any long-term post-construction effects (Langston & Pullan 2003). Stewart *et al.* (2005) call for BACI designs to incorporate replicated and balanced experimental designs with randomized sampling regimes. Future developments need to incorporate well-designed and replicated monitoring from the initial planning stages through to completion. This should be followed by long-term monitoring of the site to examine both immediate and longer-term changes. In combination, this will enable robust examination of changes at the individual site level, as well as providing the criteria for multi-development level comparisons.

Theoretical considerations

Marine birds are highly K-selected, exhibiting low birth rates and prolonged development, and so are sensitive to changes in adult survival (Sæther & Bakke 2000). The majority of mortality occurs during the inter-breeding period (Barbraud & Weimerskirch 2003), but the impacts of wave-powered MREIs during the non-breeding season are currently unknown. Furthermore, many current seabird declines are attributed to reproductive failure due to low food availability (e.g. Frederiksen *et al.* 2007b). Future studies should focus on understanding the potential for wave-powered MREIs to increase adult mortality or alter food supplies during the breeding season, but teasing apart the effects of MREIs over and above other factors is not straightforward.

A population-level response is ultimately determined by individual-level choices, ranging from disturbance, migration and predation to habitat patch utilization (Sutherland 1996, Inger *et al.* 2006). Only by understanding the individual-level responses to MREIs can the population-level effects be elucidated. This will require individual-based studies (e.g. mark/recapture and animal tracking) to identify the survival for whole and sub-sections of populations as well as demographic studies to understand sensitivities to mortality (Desholm 2009). Marine bird populations contain large non-breeding components, which can buffer changes in population size caused by temporary increases in adult mortality (Votier *et al*. 2008); however, due to the ephemeral nature of this age class, little is understood of their movements away from the colony.

During the breeding season most seabirds act as centrally placed foragers and are restricted in the foraging habitat they can exploit. Therefore, an important question is to link breeding colonies with specific foraging areas before being able to mitigate the potential effects of building MREIs in these areas. If MREIs were to act as FADs/MPAs then they could offer benefits to colonies if placed strategically. However, marine birds also have different breeding and wintering ranges, which would require consideration at the planning stage.

Practical considerations

There is a clear need for the integration of multi-disciplinary scientific research, necessitating the use of a number of techniques to expand on the potential impacts of MREIs on seabird populations. In addition to BACI standardized survey methodology, gaining a detailed understanding of seabird movements and habitat utilization would allow the mitigation of potential conflicts with offshore site designation and device operators.

Wave-powered MREI technology is still in its infancy, and to date there are only a limited number of active sites in the UK and Ireland. As technology develops, consideration of the spatial distribution of sites will help to mitigate any cumulative device impact while maximizing the potential benefits. Figure 3 illustrates the potential overlap between seabirds (from Mitchell *et al.* 2004) and currently planned or operating MREIs: the Round 3 Offshore Wind Development Zones;

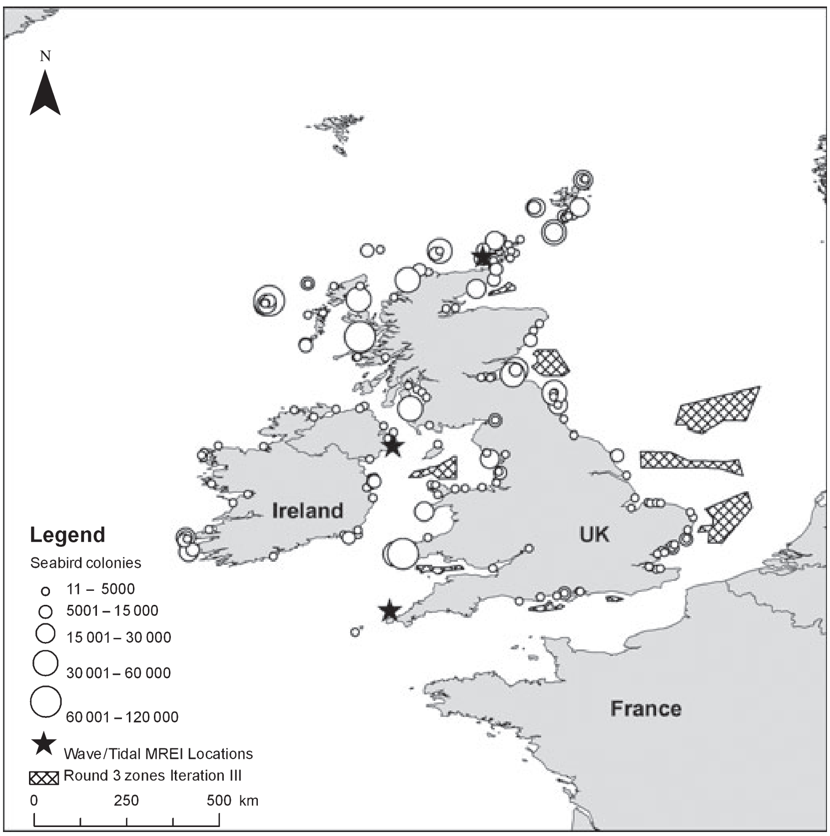

Figure 3. Spatial overlap between key seabird colonies and MREI installations in the UK and Ireland. Locations are shown for colonies containing at least 1% of the UK and Irish breeding population for a species, scaled to represent population size (equivalent to pairs). Extant wave and tidal MREI locations are Wave Hub (St Ives, Cornwall), SeaGen (Strangford Lough, Ireland) and EMEC (Orkney, Scotland). Wind-powered MREIs are represented by The Crown Estate Round 3 designations for offshore wind farm development.

the European Marine Energy Centre (EMEC) in Orkney, Scotland (http://www.emec.org.uk/); the site of SeaGen in Strangford Lough, Northern Ireland (http://www.seageneration.co.uk/); and Wave Hub, Cornwall, UK (http://www.wavehub.co.uk/), which appears to have the lowest potential overlap. To understand the use of these areas by seabirds, as well as other marine birds, will require the integration of land-based surveys to pinpoint colonies potentially impacted by developments, with tracking studies to understand movements from those colonies. In the UK, the establishment of the Seabird Monitoring Programme and its outputs (e.g. Mitchell *et al.* 2004) provide these data, which could then be used to model hotspots of activity, and in turn provide comparisons with existing at-sea surveys.

Experimental design

The lack of available data and the small number of devices currently operational at a global scale highlight the need for robust survey methods optimized to detect ecologically significant changes in bird species abundance and distribution, should they occur. Critically, early adoption of broad-scale standardized methods would allow the involvement of science in the design and installation of future MREI sites. One study currently underway looks at the biodiversity impacts of the Wave Hub project (http://www.primare.org), the UK's first large-scale offshore test facility for wave energy conversion devices. To refine the experimental design for monitoring potential impacts on marine birds, we undertook a prospective power analysis after completing five at-sea surveys at the proposed Wave Hub site. This allowed us to gain a better understanding of the variability of seabird numbers at the site, thus enabling the determination of an appropriate number of replicates with which to detect any future statistically significant changes in abundance.

Power typically represents the probability of rejecting a null hypothesis when it is false (Gerrodette 1987), and power analysis provides a useful tool in the planning phase of ecological experiments and the interpretation of non-significant results (Di Stefano 2003). We constructed a power analysis in R 2.6.2 (R Development Core Team 2008) to evaluate the effect of sample size and effect size on power, demonstrating how increases in sample size change the ability to detect a signal. The test was a comparison of the mean bird

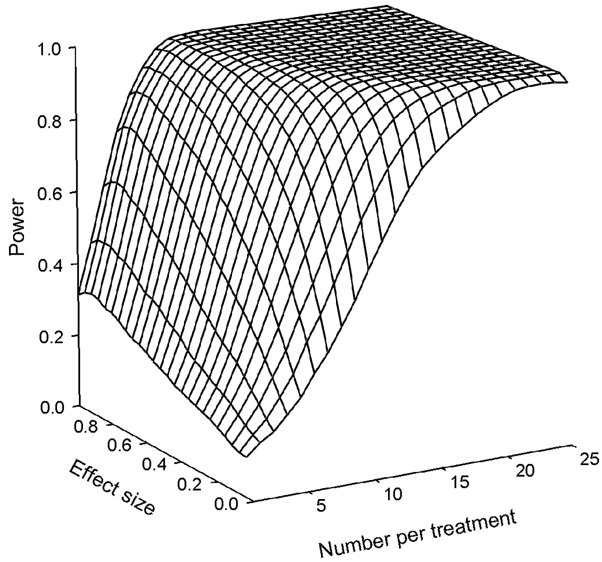

Figure 4. Impact of effect size and treatment size on the ability to detect a signal during EIA surveys, the smoothed results of a power analysis. Surveys including up to 10 replicates would detect moderate effect sizes with reasonable power.

abundance between two groups: control (point counts of bird abundance outside the wave-hub site) and experimental (point counts of bird abundance within the wave-hub development), with varying numbers of replicates within the groups. The experimental effect was a percentage reduction in the mean number of birds within a replicate (Fig. 4). Replication is vital to detect potential impacts, as power increases with replication: for moderate effect sizes, small increases in the sample sizes would have larger implications for the power of the study. However, if the effect size signal is very small then there is little chance of detection even with relatively large numbers of treatments. For a power of 80% and a minimum of 10 replicates per treatment, our analysis would suggest a statistically significant reduction in the mean abundance of marine birds by 35% would be detectable.

This model does not consider spatial autocorrelation within the site, as the analysis considered the averaged effect between replicates; we recommend consideration of autocorrelation in future prospective power analysis. Power analysis may not always be helpful: for those studies that may never be able to expand beyond $n = 1$, we propose that analysing the gradient change in distribution across a site and developing forms of randomization tests and simulations might prove to be more useful (see Seavy & Reynolds 2007).

CONCLUSION

An increased reliance on meeting energy requirements with renewable resources will put pressure on the development of alternative technologies, including the exploitation of wave energy. Vital to this will be developing an understanding of the potential ecological impacts that these technologies represent. To date, due to the prevalence of wind turbines, much work has focused on the potential for collision risk (i.e. Garthe & Hüppop 2004, Fielding *et al.* 2006, Fox *et al.* 2006, Perrow *et al.* 2006), and the cumulative effect a number of installations may have on migration pathways (Desholm & Kahlert 2005, Masden *et al.* 2009, 2010b). For wave-powered MREIs with low operational profiles this risk will be reduced, although with this comes an increased risk of underwater collision.

Wave-powered MREIs are likely to cause some disturbance during construction, maintenance and decommissioning. However, impacts related to construction activities are likely to be minimized in wave-powered MREIs, which do not require the pile driving associated with current wind technologies. MREIs also have the potential to change environmental processes indirectly around the devices, which in turn may alter habitat assemblages. Disturbance can have deleterious impacts on foraging efficiency, however; if MREIs offer the potential to act as FADs and MPAs, then the reverse may be true, as birds could profit from an increase in food availability.

With appropriate mitigation, wave-powered MREIs may also enhance habitats through the provision of novel hard substrate and the FAD effects of buoys, which may prove more effective than found with wind-powered MREIs (Wilhelmsson *et al.* 2006). Unlike wind-powered MREIs, wave-powered MREI structures will provide roosting sites that could help marine birds to exploit an aggregated and protected resource.

The level to which other impacts listed here will affect marine birds is unclear. It is vital to expand this knowledge base, and this will require the broad-scale acceptance of common methods within the sector to develop comparable studies. The incorporation of common EIA methods at the early stages of MREI development would allow each site to act as its own control, giving better depth to the assessment of impacts. In developing a better understanding of the potential threats MREIs may pose, ecological principles could be built into MREIs at the development stage, thus allowing for the mitigation of some effects and potentially scaling down the requirement for monitoring programmes in the future. However, a large gap exists in our knowledge of how individual-level effects become population-level changes (Sutherland 1996, Elphick 2008), and without standardized methods the meta-analysis required to investigate potential population-level changes is not possible.

We must also consider that renewable energy generation displaces traditional forms of energy production, leading to a positive environmental benefit through a reduction in fossil fuel use. Any negative impact should therefore be put in the wider context of continued reliance on fossil fuel-powered energy production. MREI impacts are likely to be spatially discrete, whereas the climate impacts from fossil fuels are wide-scale and indiscriminate (Stewart *et al.* 2007, Elphick 2008, Snyder & Kaiser 2009).

We repeat calls by Gill (2005) and Inger *et al.* (2009) for the integration of multi-disciplinary scientific research to develop an understanding of the implications an expanding MRE industry may have on the environment, and mitigate any threat to the ecology of development areas. Wave-powered MREIs are certain to become a part of the marine environment; however, with appropriate planning, mitigation, and monitoring they have the potential to offer benefits to marine birds in the future.

This work was supported by PRIMaRE, an independent research organization funded by the South West of England Regional Development Agency and the EU (ERDF). W.J.G. is supported by a PRIMaRE PhD studentship at the University of Plymouth. M.J.W. is a Post-doctoral Research Fellow supported by PRIMaRE at the University of Exeter. R.I. was supported by NERC standard grant NE/F021690/1. We would like to thank the editorial team and two anonymous referees whose comments greatly improved this manuscript.

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Received 25 November 2009;
revision accepted 30 June 2010.