STRATEGIC ENVIRONMENTAL ASSESSMENT OF MARINE RENEWABLE ENGERY DEVELOPMENT IN SCOTLAND

Collision risks between marine renewable energy devices and mammals, fish and diving birds

Report to the Scottish Executive

12th March 2007

Suggested citation: Wilson, B. Batty, R. S., Daunt, F. & Carter, C. (2007) Collision risks between marine renewable energy devices and mammals, fish and diving birds. Report to the Scottish Executive. Scottish Association for Marine Science, Oban, Scotland, PA37 1QA.

SAMS RESEARCH SERVICES LIMITED

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

TABLE OF CONTENTS

Executive Summary

This report summarises the risks of injurious collision that marine renewable devices may pose to marine mammals, fish and birds using Scottish waters within the SEA assessment area. A collision is considered to be a physical contact between a device or its pressure field and an organism, that may result in an injury (however slight) to that organism. We did not consider the physical impacts of sound. Vertebrates may avoid collisions by moving away from the immediate area around a device (avoidance) or by escaping at close range (evasion, analagous to swerving to prevent collision with an obstacle in the road).

Other than barrages, neither wave nor tidal renewable devices have reached commercial scale deployment off Scotland. Consequently the precedent to evaluate vertebrate collision risks is severely limited. We therefore reviewed the known impacts of other industrial and natural activities with physical parallels. We considered shipping, fisheries, power station cooling intakes, fish aggregation devices, wind turbines and killer whale predation. The following generalities were identified:

- Collision risks are not well understood for any marine vertebrates. Of the three animal groups considered here, fish are best understood and diving birds least.
- Man-made collision risks are more diverse and common than generally supposed. The rate of whale–ship strikes is a significant example.
- Underwater collision risks typically become well studied after they have become a conservation concern.
- Animals may appear to behave illogically when faced with novel situations.
- Subtleties of gear design (shape, colour etc) as well as environmental conditions (turbidity, flow rate etc) can markedly change collision rates.
- Objects in the water column will naturally attract fish and their predators.
- Stationary objects in flowing water can herd fish upstream until they become exhausted limiting their behavioural options.
- The proximity and relative orientation to other objects will impact escape options and the combined collision risk while topography will impact escape options and animal approach angles.
- Collision risk will vary with age of organisms, with juveniles likely to be more at risk than adults because of reduced abilities or experience.
- The potential for animals to escape collisions with marine renewable devices will depend on their body size, social behaviour (especially schooling), foraging tactics, curiosity, habitat use, underwater agility and sensory capabilities.
- A variety of warning devices and gear adaptations have been developed for marine mammals and fish (although not as yet birds) in recognition of underwater collision issues.

For all species, vision is a primary sense (especially birds). Marine mammals are particularly reliant on sound while fish are responsive to sound (both pressure changes and particle displacement), and chemoreception. Other senses such as touch and the detection of electro-magnetic fields are likely but their use is less well known.

A wide variety of device designs have been proposed to extract wave and tidal energy from coastal waters. These are typically categorised firstly in terms of the type of energy they extract and then by the method of extraction. However for animals in the water column, the specific brands or mechanics of operation are of less relevance than the type and movement of the physical structures that they may encounter. From the perspective of collision risks, the structural components of marine renewable devices divide into fixed submerged structures, mooring equipment, surface structures, horizontal or vertical axis turbines (open, semi- or fully shielded) and structures that in combination have the potential to form traps.

Fixed submerged structures (such as vertical or horizontal support piles, ducts & nacelles) are likely to attract marine life in the manner of artificial reefs or fish aggregating devices. Collisions are most likely in high flow environments where flows can combine with swimming speeds to produce high approach velocities with consequently reduced avoidance or evasion response times. Instead of swimming around fixed structures in high flow environments, fish may hold station in front of them until they reach exhaustion and then passively be swept downstream towards them.

Mooring equipment such as anchor blocks and plinths are likely to function like other natural or artificial seabed structures and hence pose few novel risks for vertebrates in the water column. Cables, chains and power lines extending up through the water will have smaller cross-sectional area than vertical support structures and so produce reduced flow disruption and fewer sensory cues to approaching animals. Instead of being swept around these structures, animals are more likely to become wrapped around or entangled in them.

Many of the devices proposed, particularly wave related, will have significant surface components. Floating structures may simply be static boxes used to secure submarine equipment or guide waves or be composed of multiple articulated boxes. In collision terms, species most at risk are birds in flight, bird and mammal species that frequently cross the air-water interface to breath and haul-out and large fish that swim close to the surface (eg basking sharks). Semi-aquatic species are likely to use floating devices as landing/roosting/breeding or haul-out sites and risks of injury may be associated with getting onto/off the structures and any contact with exposed moving or articulated parts. While cetaceans do not haul-out, they do regularly surface for air and collisions could either occur with animals swimming into them or the structures pitching down onto breathing animals in heavy seas. Collision risks for surfacing mammals and birds will depend on the how aware they are of the presence of the surface structures.

Rotating turbines are the most intuitive contenders for significant collision risks with marine vertebrates. These devices move relative to both the seabed and to the water flow and their effective motion is that of a spiral with the blades travelling at angles < 90° to the water and suspended objects in their sweep. The blade tip is the fastest moving part and will likely move at or below speeds of around 12 ms^{-1}(23 knots). Greater speeds will incur efficiency losses through cavitation. Thus turbines have fundamental differences to wind turbines which are not speed limited by cavitation and ship propellers which are smaller but introduce energy into the flow rather than subtract it. Other than the rotation component, the velocity of rotor blades and especially their tips are therefore, in collision terms, more analogous to ships' bows or the keels of high-speed yachts. Both vessel bows and keels have been implicated in cetacean-ship strikes. These velocities are also comparable to those used by killer whales to swipe and fatally injure schooling fish. Thus turbines and especially their tip velocities are of marine vertebrate collision concern.

The structures described above are generally discrete objects that marine vertebrates can either collide with or avoid; however, the combination of several structures raises the possibility of traps being created. Traps are most likely to be a significant issue for species that need to surface regularly for air or where water flow is sufficiently high to limit the animal escape options once the trap has been entered.

To assess the magnitude of potential interactions between Scottish marine vertebrates and commercial scale developments of marine renewable devices we constructed a model to assess the potential encounter rate between 100 horizontal axis 8 m radius turbines operating off the Scottish coast and existing populations of herring and harbour porpoises. The model incorporated a number of assumptions about the vertical distribution of herring and porpoises, their swimming speeds and distribution. As escape (avoidance and evasion) behaviours by the fish and cetaceans to this type of device are currently unknown it was also assumed that the animals were neither attracted to nor avoided the immediate area around the turbine. While these assumptions could be further refined, the intent was to derive a ball-park figure for the number of *potential* physical encounters between rotors and animals. The model predicted that in a year of operation, 2% of the herring population and 3.6 to 10.7 % of the porpoise population would encounter a rotating blade. While the calculated encounter rates between herring and turbines is of relatively low significance compared to losses from fisheries, the rate for harbour porpoises is more noteworthy. However, it must be stressed that encounters are not collisions. An encounter *may* lead to a collision but only if the animal in question does not take appropriate avoidance or evasive action. At this point in time, there is no information on the degree to which marine animals will make appropriate manoeuvres. If lethal collision rates were to equate to the encounter rates then the calculated values for porpoises injuries would have scope to be unsustainable at the population level.

The difference between the proportion of herring and the proportion of porpoises encountering the turbines in the model (2% vs 3.6 %) is attributable to the greater swimming speeds and body size of the porpoises. Accordingly, larger species (basking sharks and whales) will have potential encounter rates that are greater still. The model predicted that in general, encounter rate as a proportion of population size increases with body size. Use of the model also highlights the immense importance of a better understanding of the processes of avoidance/attraction and evasion capabilities of marine vertebrates in assessing collision risk.

Rather than being oblivious to objects in the water column, marine vertebrates are likely to show behavioural responses to the presence of marine renewable devices. Responses are likely to occur on two scales. At long range they have the option to *avoid* the area of device placement (i.e. swim or fly around) and at closer range they can *evade* the particular structures (i.e. dodge or swerve). The balance between avoidance and evasion responses will depend on a product of the distances that these animals will be able to perceive the devices and their subsequent behavioural reactions. Little is known yet about behavioural reactions but detection distances can be determined. These will depend on the sensory systems of the species at risk, the visual, acoustic or other environmental signatures of the devices and background conditions. In daytime and clear waters, underwater structures may be visible at ranges of thousands of meters above the surface and tens of meters underwater, and hence give sufficient warning for visual species to exhibit avoidance and evasion if necessary. At night or in turbid environments, structures may be visually undetectable and provide little or no opportunity for a behavioural response. In addition to time of day and turbidity, other environmental variables are likely to be important. Depth will influence light levels as well as species' distributions and the amount of time air breathing species have to avoid devices. Season will influence light levels and species abundance, feeding ecology and life stage considerations. Water flow speed will influence relative approach speeds and reaction opportunities as well as the abundance of species at risk. The proximity and relative orientation to other devices will impact escape options and the combined collision risk while topography will impact escape options and animal approach angles.

Marine renewable devices have a potential range of ecological implications. They extend from no impacts, to the potential removal or injury of individuals and if rates are sufficiently high to declines in populations. If avoidance responses occur then habitat exclusion is possible while if structures provide foraging opportunities then positive exploitation may occur. If there are significant collision concerns then methods of mitigation are desirable. Measures that increase the options for avoidance are clearly advantageous as they will reduce the number of close encounters between device and animal but they also have to be considered in relation to their potential for habitat exclusion. For example, loud underwater acoustic alarms may give marine mammals or fish good warning of renewable devices but if too loud they may banish the animals from valuable habitat. Appropriate mitigation options will depend on the device design, species at risk and local environment and should be considered at the EIA level.

Given the uncertainties outlined in this report, there is a clear need for future development of this industry to be undertaken with caution and be coupled with research into the behaviour of animals towards and around devices. In terms of collisions, areas of particular focus should be a better understanding of how vertebrates perceive, avoid and evade devices, to quantify the potential rate of collisions, and to assess the consequences of physical injury arising from collisions and habitat exclusion on their populations.

1. A collision defined

For the purposes of this report, we consider a collision to be an interaction between a marine vertebrate and a marine renewable energy device that may result in a physical injury (however slight) to the organism. A collision may therefore involve actual physical contact between the organism and device or an interaction with its pressure field. We will not consider the physical impacts of sound. The marine vertebrates that we will consider are marine mammals (pinnipeds and cetaceans), marine birds and fish found in Scottish waters.

2. Existing collision risks in the sea: a review

Marine renewable devices are at a relatively early stage of development when compared to other renewable technologies such as wind turbines. There are few devices in the oceans and these are mainly developmental or test units. The collision risk to marine mammals, fish and birds from these devices is uncertain and may remain so until more devices are installed and monitored. However it is essential to consider the possibility of collisions before installation to highlight the potential areas of concern. This section will review key collision parallels in the marine environment and in doing so add a perspective to concerns about this potential new form of vertebrate-offshore industry interaction. Information on these collision parallels is itself limited and not available for each species group. We therefore concentrate on those parallels for which there are useful lessons to be learnt.

2.1 Marine mammals

2.1.1 Shipping

The common perception among the public is that ships do not pose a serious threat to marine mammals because of their swimming agility and developed sensory systems. However over recent years, evidence and resulting concern regarding marine mammal mortality from ship collisions has increased substantially.

Ship strikes are a known cause of mortality for both whales and dolphins worldwide (Pace D.S. 2006). Strikes are far from infrequent and the majority go unnoticed (David L. 2006). This global problem has been highlighted by focused work in the USA (Northern right whale) and in the Mediterranean (fin whale). Actual numbers of strikes are poorly known (Laist D.W. et al. 2001) and statistics on strike rates are likely to be underestimates as they can go unnoticed or unreported onboard ships, stranded carcases may show no obvious sign of a strike, and only a proportion of carcases actually wash up onto shore. Where in-depth studies that have been undertaken, the strike rates are often substantial accounting for between 12 and 47% of carcases recovered (Table 1).

Resultant injuries tend to fall into 2 categories, lacerations from propellers, and blunt traumas from impact with the hull. Blunt traumas result in fractured skulls, jaws or vertebrae, in conjunction with large haematomas (IWC 2006). It is probable that if these injuries do not cause the immediate death of the animal but they will leave it vulnerable to death from secondary infections, complications or predation.

Four main drivers that are thought to influence the number and severity of ship strikes:

- Vessel type, (ferry, tanker, sailing, pleasure, military, fishing vessel) and navigation speed.
- Underwater noise – high levels of ambient noise can result in difficulty in detection of approaching vessels. There may be habituation to underwater noise, and very loud noise can cause damage to hearing. The under water pathways of sound is also one possible reason that ships are not detected, for example, there are underwater reflections, multiple sound signals, hull blockage of sound from stern, bubbles by the propeller that absorb sound and the Lloyd mirror effect (an acoustic phenomenon in calm seas that reduces or cancels out low frequency noise at the surface where resting or feeding whales may be (Laist D.W. et al. 2001).
- Weather conditions and time of navigation – this can affect the ability of crew to locate whales and add to ambient noise.
- Whale behaviour – which is species specific. Juvenile and sick individuals appear to be more vulnerable.

Another factor in the occurrence of ship strikes is the apparent reduced perception by the marine mammals of a collision threat, perhaps by distraction during other activities such as foraging, or social interaction. (IWC 2006).

Table 1: Number of cetacean deaths detailed in existing literature.

Period	Species	Reported proportion killed by ship strikes	Location	Source
1986-1998	Fin whale *Balaenoptera physalus*	26% (11 / 42)	Italian stranding records	Notarbartolo-di-Sciara et al. 2003
1972-1998	Fin whale *Balaenoptera physalus*	16	French stranding records	Notarbartolo-di-Sciara et al. 2003
1970-1999	Northern Right whale *Eubalaena glacialis*	35.5%	USA	Ward-Geiger et al. 2005
1996-2000	Northern Right whale *Eubalaena glacialis*	0.8 whales per year	USA	Ward-Geiger et al. 2005
1970-1989	Northern Right whale *Eubalaena glacialis*	20%	Eastern USA and Canada	In Laist D.W. et al. 2001
1970-1998	Northern Right whale *Eubalaena glacialis*	35%	Eastern USA and Canada	In Laist D.W. et al. 2001
1991-1998	Northern Right whale *Eubalaena glacialis*	47%	Eastern USA and Canada	In Laist D.W. et al. 2001
1985-1992	Humpback whales *Megaptera novaeangliae*	30%	U.S. Atlantic coast	In Laist D.W. et al. 2001
Pre 1951	(species not detailed)	15 records	Global	In Laist D.W. et al. 2001
1986-1997	Fin whales, sperm whales (*Physeter catodon*), minke whales (*Balaenoptera acutorostrata*)	12%	Italy	In Laist D.W. et al. 2001
1972-1998	Fin whales	13%	France	In Laist D.W. et al. 2001
1963-1998	Southern right whale (*Eubalaena australis*)	20%	South Africa	In Laist D.W. et al. 2001
1972-2001	Fin whale	16%	Mediterranean	Panigada S. et al. 2006

Most lethal and serious injuries to whales are thought to have been caused by relatively large vessels (80 m or longer, Laist D.W. et al. 2001). Larger vessels (over 100m long) are unlikely to report collisions as they are unlikely to impede the vessel's passage. The most severe and lethal injuries have seemingly been caused by ships travelling at 14 knots (~7 $m.s^{-1}$) or faster, including relatively quiet sailing vessels.

Concerns for the high incidence of ship-strikes has received sufficient political recognition to warrant the establishment of a variety of legislative measures (see Table 2). These include methods of communicating information to mariners regarding areas frequented by cetaceans, and the introduction of geographical or seasonal restrictions on passage routing, ship speed regulations in certain areas and minimum approach distances. In addition, designation and protection of specific habitats have been made.

One method of mitigation not mentioned in the tables is acoustic mitigation, which includes ambient noise imaging sonar to detect whales. Stellwagon Bank National Marine Sanctuary (USA) has deployed an array of acoustic detection buoys. Likewise passive acoustic detection is being used for the Northern Atlantic Right Whales along the east coast of the US.

Table 3 details current intergovernmental organisations and programs in place for the protection of marine mammals. The information contained in the tables 2 and 3 was obtained from the International Whaling Commission Ship Strikes working group progress report (IWC, 2006).

Table 2: Current legislative measures associated with whale-vessel issues (IWC 2006). The table serves to illustrate the growing high-level recognition of this problem.

Country	Legislation/ Programme	Comments
Australia	Environment protection and Biodiversity Conservation Act 1999	• Within the Australian Whale sanctuary (encompasses the Australian EEZ). It is an offence to recklessly kill, injure, take, trade, move or interfere with a cetacean.
Australia	Environment protection and Biodiversity Conservation Act 2000	• Sets out how people must behave outside the sanctuary. Regulations impose restrictions on vessels while around cetaceans, including minimum approach distances.
Belgium	Royal decree 2001	• Protection of species in marine areas under Belgium jurisdiction. States that ships should avoid collision. Applicable in Belgian waters and to vessels navigating under the Belgian flag.
Canada	December 2002	• IMO approval of the Government of Canada proposed changes to shipping lanes in the Bay of Fundy. Action part of Canada's Right whale Recovery Plan (implementation 2007)
USA	Mandatory Ship Reporting systems (MSR)	• In waters off New England and the calving areas off Georgia and Florida. Operational since 1999. All ships of 300 gross tonnes and greater communicate via satellite, an automated message is sent detailing info on the Right Whale vulnerability, where they can get guidance on avoidance of collisions and any recent whale sightings. Reports are gathered and used to quantify ship traffic patterns.
USA	Proposed regulations	• Planned to regulate ship speed in same areas as above and to be in effect mid 2007.
USA	Realignment of the Boston traffic separation zone (2007)	• Expected to reduce ship strike risk.
USA	Endangered Species Act and the Mammal Protection Act	• Regulations prohibiting vessel to approach Right Whale within 500 yards
USA	Collision reporting	• Most US federal agencies (e.g. US navy / coastguard) require their vessel operators to report any ship strike.
USA	NOAA, supports or conducts aircraft surveys for Right whales.	• Information passed to mariners via email, notices to mariners. NOAA and coastguard issue warnings regarding Right Whale aggregations.
France/ Italy/ Monaco	Co-founders of the Pelagos Sanctuary for Mediterranean marine mammals	• Specially protected area of Mediterranean importance (SPAMI). Part of reason behind set up was to address increasing mortality of large whales from entanglement and collisions with vessels.
New Zealand	The development of a Marine Mammal Action Plan	• Plan to run from 2005 to 2010. In which the threat of collision is considered.
Spain	A programme to mitigate the impact of collisions started in 2006	• In Gibraltar strait. Information network of real time locations of fin and sperm whales, and an education programme for ferry crews.

Table 3: Current Intergovernmental organisations and programmes with interests in marine mammal-vessel collisions (IWC 2006).

Organisation / Programme	Comments
Agreement on the Conservation of Cetaceans of the Black Sea, Mediterranean Sea and the Contiguous Atlantic. (ACCOBAMS)	• In 2003 ACCOBAMS "recognised the potential threat of ship collisions to the conservation of some cetacean populations in the ACCOBAMS area, especially of large whales". Five mitigation measures advised (1) education and training for vessel crew, (2) independent observers on ferries (3) education of enforcement officials (4) information to shipping companies on "high use" areas by species and season (5) the creation of an international database of ship strikes
Agreement on the Conservation of Small Cetaceans of the Baltic and North Seas (ASCOBANS)	• ASCOBANS has been addressing the issue of ship strikes since 1999. Requests information on the development of high speed ferries (in excess of 30 knots)
United Nations Environment Programme (UNEP) Convention on the Conservation of Migratory Species (CMS)	• During its 8th Conference of Parties in 2005, the CMS adopted a resolution to review the extent that they are addressing adverse human induced impacts on cetacean, and to cooperate with IWC on ship strikes.
European Union	• EU 1992 Habitats Directive Annex IV protects all cetacean species, Article 12 § 4 of the directive stipulates that "Member States shall establish a system to monitor the incidental capture and killing of the animal species listed in Annex IV(a). In the light of the information gathered, Member States shall take further research or conservation measures as required to ensure that incidental capture and killing does not have a significant negative impact on the species concerned".
The International Association of Antarctic Tour Operators (IAATO)	• IAATO has issued a whale collision reporting form to be completed by expedition leaders in Antarctic waters.
The International Maritime Organisation (IMO)	• In 1998 IMO adopted a resolution (MSC.85) on mandatory ship reporting systems, aimed at reducing the impact of maritime traffic on the population of Northern Right Whales on the north-eastern and south-eastern coasts of the US
The International Whaling Commission (IWC)	• - Resolution 2000:8 – noted that the Northern Right Whale population is highly endangered with numbers at less than 300 individuals, and called for continued work with IMO. - Resolution 1999:7 – identifies ship strikes as a threat for some whale populations. - Resolution 1998:2 – that incidental catches along with collision with ships and other sources of human-induced mortality should be considered on a par with deliberate catches and counted towards total allowable removals.
The Secretariat of the Pacific Regional Environmental Programme (SPREP)	• The administrative organisation for the Memorandum of Understanding (MOU) for the conservation of cetaceans and their habitats in the Pacific (2006), the Action Plan will include migratory corridors, and maintaining a database on vessel strikes and investigation of potential approaches to mitigation.
The United Nations Environment Programme (UNEP)	• 1984 adopted a Global Plan of Action for the Conservation, Management and Utilization of Marine Mammals. Is currently being revised. Action Plan includes various measures regarding ship strikes.

2.1.2 Fisheries interactions

Cetacean and pinniped entanglement in fishing gear is not an insignificant occurrence. Incidental capture threatens whale (Panigada S. et al. 2006), dolphin and porpoise populations worldwide, and is likely to cause the imminent extinction of several species (Zollett E.A. & Rosenberg A.A. 2005). The first global bycatch estimate predicted that hundreds of thousands of marine mammals are incidentally captured annually (Zollett E.A. & Rosenberg A.A. 2005). Additionally it is probable that bycatch statistics are underestimates as not all fishers will report these events. Marine mammal bycatch is not limited to fishing methods and has been recorded for nearly every type of fishing gear (Zollett E.A. & Rosenberg A.A. 2005). Gillnets are the most significant source of mortality but accidental capture in other net types such as pair trawls, herring weirs and pound nets are also common and have more direct parallels to the potential trapping properties of marine renewable devices. There have been reports both in the US and UK of baleen whales being caught by the vertical lines used to mark traps or pots (Read A.J. et al. 2006). Similar vertical lines may also be used around marine renewable devices.

The reasons why marine mammals become entangled is not clear (Goodson A.D. 1996, Cox T.M. et al. 2003). Much of the research into bycatch mitigation has been focused on gear modification rather than understanding marine mammal fishing gear interactions underwater (Goodson A.D. 1996). Hence our understanding of why the bycatch events actually occur remains limited. It is clear however that marine-mammals forage around or interact with nets regularly and only occasionally become fatally entangled in them (Cox T.M. et al. 2003). It may be that marine mammals are taking advantage of the availability of food in the fishing gear or in close proximity (Cox T.M. et al. 2003, Zollett E.A. & Rosenberg A.A. 2005) foraging either on the target or associated species. It may be that juvenile animals are more susceptible to bycatch through curiosity or inexperience around fishing gear (Zollett E.A. & Rosenberg A.A. 2005).

A further issue associated with echolocating mammals (Odontocetes) is that if the animal is actively chasing prey with its sonar locked on to the prey or sea bed, echoes from the net may not be observed at all (Goodson A.D. 1996). As with ship-strikes, cetaceans may not always act logically. Large numbers of spinner and several other dolphin species, for example, have died over recent decades in the Eastern Tropical Pacific after being encircled by tuna nets. These dolphins will not jump over the surface float line despite being perfectly capable of doing so and end up being severely injured or asphyxiated as a result.

There has been much work into bycatch mitigation, and strategies include fishing gear and practice modification, acoustic alarms, time and area closures and post capture release (Kraus et al. 1997; Zollett E.A. & Rosenberg A.A. 2005).

2.2 Fish

2.2.1 Fisheries interactions

Fishers aim to catch fish, thus collisions in this instance are the desired end result, therefore understandably the existing literature is concentrated on understanding fish behaviour to maximise and improve fishing catch.

Fish are thought to respond to several sensory stimuli associated with the movement of trawls, including acoustic noise and visual recognition (Jamieson A.J. 2006). However, vision appears to be the main stimulus and it has been observed that fish do not perform as well when ambient light falls below critical levels (Ryer C.H. 2000). In one experiment it was shown that that herring avoided stationary obstacles using visual stimuli, but they collided with the same obstacles in the dark (Blaxter J.H.S. & Batty R.S. 1985). In another study it was found that juvenile walleye pollock hit an approaching net more frequently and swam closer to the net in darkness than in the light (Ryer C.H. 2000). Further evidence is provided by the fact that catch sizes vary according to the time of day (Jamieson A.J. 2006).

It has also been found that herring exhibit strong avoidance of a vibrating obstacle (Blaxter J.H.S. & Batty R.S. 1985) in the dark; when the object was stationary the fish swam past it; however when it was vibrating (at a sound intensity 70 dB above the threshold) most fish turned back and swam in the opposite direction (Blaxter J.H.S. & Batty R.S. 1985).

In the fish capture process, fish detect the sound of fishing vessel engines resulting in many fish moving to a deeper depth (Wardle 1986). Fish react to an approaching object such as a swimmer, by splitting left or right, keeping it in view and then regrouping after the object (Figure 1a). In poor visibility fish have been observed close to an obstacle only just evading collision, but in clear water the fish have been seen reacting further away from trawl otter boards (Wardle 1986). It has also been observed that fish avoid capture by swimming over, under or around the trawl path in good visibility conditions (Jamieson A.J. 2006).

However a trawl with otter boards moving over the seabed, produces a wall of sand spreading out behind the boards providing a stronger sensory stimulus, which has the effect of directing fish towards one side or the other of the board’s track, either toward the mouth of the net or to the outside and to freedom (Figure 1b).

The fish herded towards the net do not see the net until it comes into visual range (depending on visibility); on sensing the new hazard of the approaching net, fish are timid and unwilling to allow it past them. They therefore turn and swim forward in line with the hazard (Wardle 1986, Walsh S.J. 2003) (Figure 2). Fish have been observed to hold position with the net mouth only swimming at a speed to stop the net from overtaking them. The strategy of using the minimum speed required to avoid the object ensures that they have energy in reserve in the event of an escape response being required (Wardle 1986). Fishing gears are, however, towed at a speed exceeding the maximum endurance speed of fish; they will ultimately be exhausted. The larger the fish, the greater swimming endurance they have and it has been observed that larger fish can maintain their position in front of the net and avoid capture when the net is hauled in. Smaller fish, for example sandeels, have to swim harder to maintain their position and therefore tire sooner (Wardle 1986).

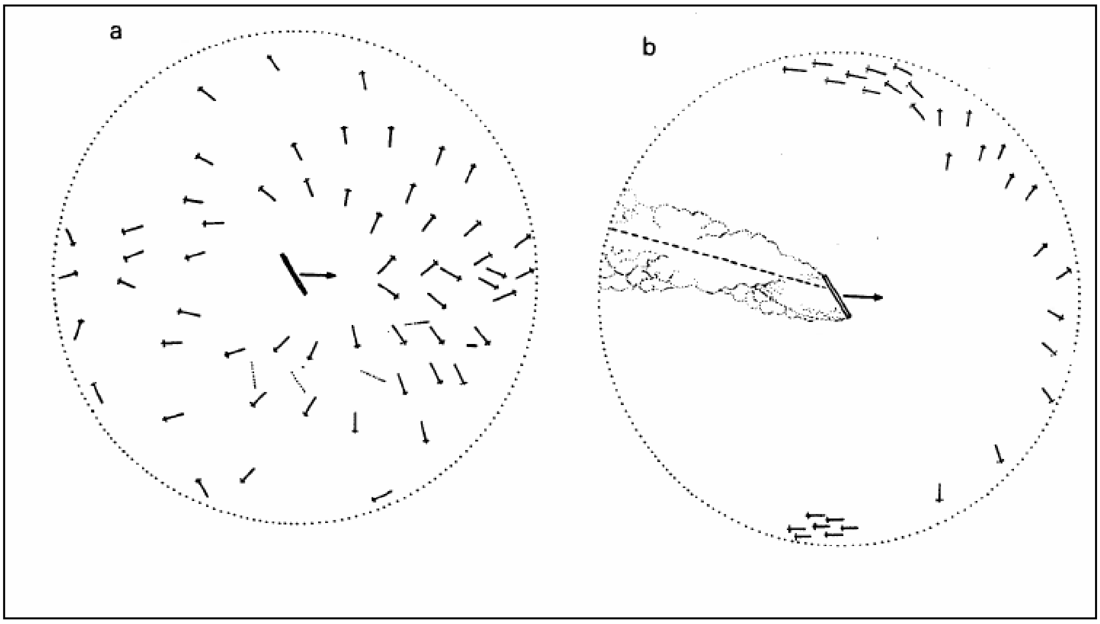


Figure 1: Visual appearance is important. Diagram of fish reaction to an approaching object (a) and the more substantial reaction when the same object disturbs the sea bed producing a larger visual barrier (b). (Wardle 1986).

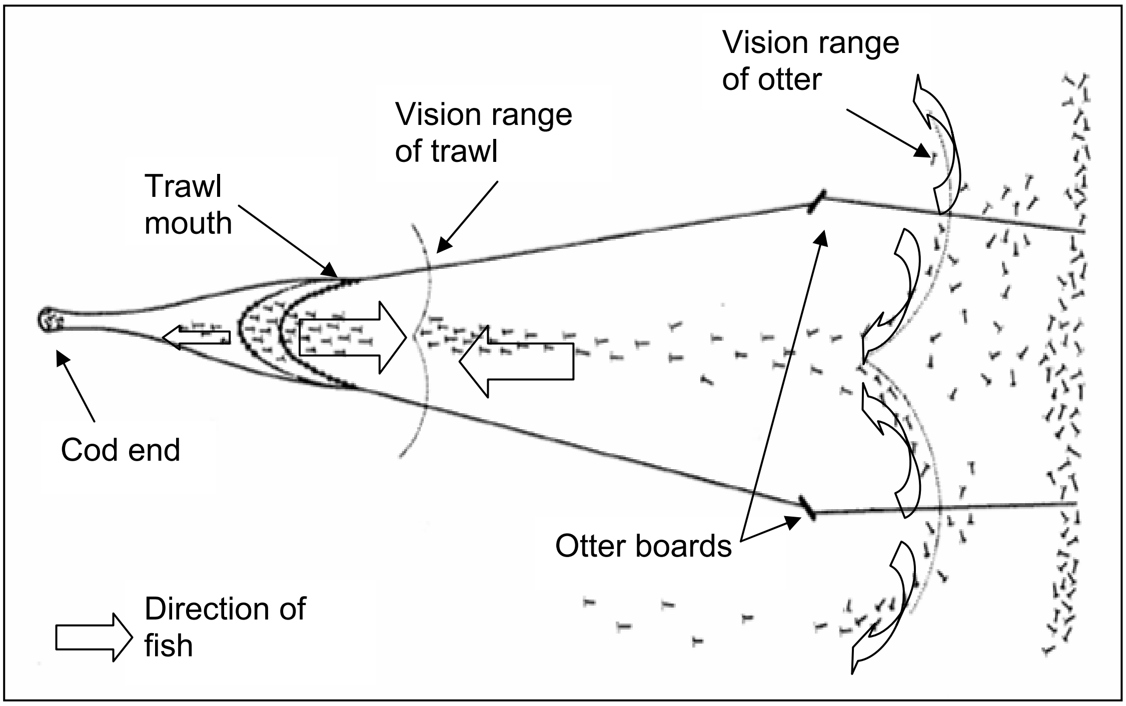


Figure 2: Diagram showing the reaction of fish to a trawl. Adapted from Wardle (1986).

On exhaustion, fish turn and allow the net mouth to overtake them (Wardle 1986, Walsh S.J. 2003, Breen M. 2004, Jamieson A.J. 2006) often turning to swim in the opposite direction, directly towards the cod end. Because of their range of vision the net looks like a clear passage through a circle of netting, the fish then swim avoiding the netting to the side until they become trapped in the cod end of the trawl net (Figure 2). Schooling fish react 'en masse' which can result in fish at the outer extreme of a school being caught in a net when otherwise, if they had acted as individuals, they would have escaped (Wardle 1986).

2.2.2 Power stations

Cooling water intakes are a known collision risk for fish. These are industrial pipes where water is pumped as a coolant from the marine or freshwater environment. They are typically found inshore at shallower depths, for example an intake pipe in California is situated *c.* 300m offshore at a depth of 15m (Helvey & Dorn 1987).

Cooling and hydroelectric power station intakes have become a notable conservation topic over the last decade (Sonny et al. 2006). The loss of various life history stages of invertebrates and fishes due to impingement on the mesh screens or entrainment within the cooling system has become a major concern (Maes et al. 2004). From the industry's viewpoint, the clogging of their system is a serious problem because it causes a reduction in water flow and results in high maintenance costs (Sonny et al. 2006).

As with interactions with fishing gear, fish vision is considered to be the most important sense (Helvey & Dorn 1987). A greater number of nocturnal species have been found impinged than those species more active during the day (Helvey & Dorn 1987).

Fish reactions to the intake structures can be categorised into five motor patterns (Helvey & Dorn 1987):

- Positive rheotaxis – this is the most common response observed, the fish orient themselves parallel to the flow swimming against the current. Fish then either hold position in the current or accelerate upstream against the flow.
- Negative rheotaxis – this behaviour is seen infrequently, the fish either passively drifts, or swims with the current.
- Perpendicular orientation – the fish orientates itself perpendicular to the flow when traversing the area.
- Oblique orientation – when swimming through the flow from either above or below the intake.
- Switching – is a variation of positive rheotaxis, and occurs when the fish drifts from general flow conditions into the intake flow, and reorients it body against the faster flow.

One study found that those fish that routinely interacted with the flow intake were rarely removed by it (Helvey & Dorn 1987). The removed fish were either transient fish unaccustomed to the flow or juveniles that were unable to swim against the flow. The study also suggested that visual acuity was the principle sense in intake avoidance as most impinged species occurred during the night or at times of poor visibility.

Different mitigation methods have been used to warn fish away from intakes and include visual stimuli (*e.g.* air bubble screens, lights and strobe lights), electrical shocks, acoustic deterrents and mechanical methods *i.e.* fine screens (Maes et al.

2004, Sonny et al. 2006). There are problems with each of the methods, for example visual deflection and electric shock methods do not work in regions of high turbidity and salinity, and mesh devices become clogged. Acoustic devices do have some success, but depend on the hearing abilities of the species involved.

2.2.3 Fish aggregation devices

A fish aggregation device (FAD) is a floating device placed in the water to attract fish (Dempster & Taquet 2004) and may closely parallel many of the designs of wave energy devices. This fishing method has arisen from a phenomenon where natural aggregations of fish form under and around floating objects. Such objects can attract both juvenile and adult fish, and their predators include logs, jellyfish, drift algae, man-made debris, rafts, purpose built FADs, oil platforms and coastal sea cage fish farms (Dempster & Taquet 2004). FADs can be free-floating or moored.

Pelagic fishes that live in a uniform environment are attracted by any physical anomaly, *e.g.* an object, bottom discontinuity, steep gradients etc, and fishermen have used these associations to increase their catch, as the fish occur in bigger schools and are easier to catch (Freon & Dagorn 2000). There have been many possible reasons suggested (Table 4) to explain why these floating structures attract marine life. It is thought that wave and tidal devices may also act as FADs, the difference being that these devices will have moving parts. It is possible that the presence of fish will also attract predators (such as marine mammals and birds) to these areas.

Table 4: Summary of different hypotheses proposed to explain the association with floating objects adapted from Fréon & Dagorn (2000).

Hypothesis	Description
Shelter from predator	Object is used as a refuge or can be a way of preventing the predator using the ‘blind zone’ of the prey in order to attack.
Concentration of food supply	A floating object or a seamount aggregates prey in its close vicinity on which large fish could prey.
Spatial reference	Floating objects, underwater structures or seamounts provide spatial references around which fishes can orient in the otherwise unstructured pelagic environment.
Comfortability stipulation	Fish station themselves near floating object to rest for regeneration after foraging in the area.
Indicator log	Natural floating objects are often indicators of productive areas.
Meeting point	The use of floating objects to increase the encounter rate between isolated individuals or small schools and other schools.
Seeking shade	Fish seek shade in order to limit predation and/or increase prey detection.
Schooling companion (=innate schooling)	Schooling fish use the object as a simple point of reference for optical fixation.
Substitute environment	The floating object functions as a substitute for species not adapted to pelagic life.
Cleaning station	Floating objects are cleaning stations where pelagic fishes have their parasite removed by other fishes.
Substratum for eggs deposition	Some fish species may use floating objects for depositing their eggs.

2.2.4 Killer whale tail swipes

Killer whales (*Orcinus orca*) exhibit a co-operative hunting strategy, "Carousel Feeding", whereby the whales swim around and under a school of herring, herding the school and moving it towards the surface. The whales periodically lunge at the school to maintain a tight school structure before slapping many fish with their tail (Domenici *et al*, 2000). Analysis of underwater video recordings of this behaviour showed that the lunging behaviour is merely a mechanism to direct the school into position ready for the whale's tail-slap. The impact of the tail stuns the fish, which are than fed upon by the killer whales.

The relevance of this behaviour is that the speed of the tail slap is broadly similar to the estimated speeds of the horizontal type turbine tips. The maximum rotor speed for one such device is estimated to be 10-12 ms^{-1} (Fraenkel 2006).

The velocity of tail slaps of approximately 8-13.6ms^{-1} is faster than the herring's predicted burst speed of approximately 2.5ms^{-1} for adult herring (Figure 3), therefore should a herring find itself in close proximity to a turbine blade, its swimming ability alone would be inadequate to escape a collision.

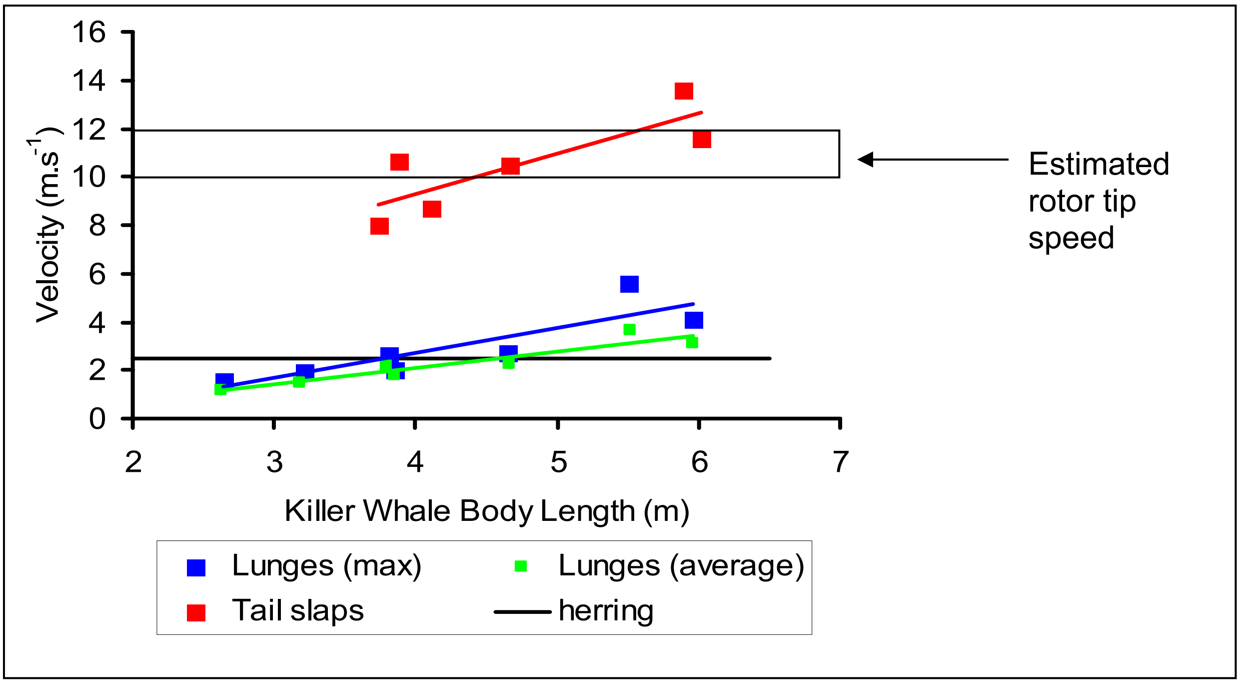


Figure 3: Lunging, tail slap velocities and the predicted burst speed of herring are compared to the predicted marine energy device rotor tip speed (adapted from Domenici 2001).

2.3 Birds

2.3.1 Shipping

Birds are generally more manoeuvrable than marine mammals but may also be at risk of collision with ships, especially at night. Collision typically occurs in two situations – flying birds colliding with the surface structures of ships or ships colliding with birds rafting on the surface. Risk is likely to be low for all species (see Table 5), and very low for cormorants since they spend the night on land (Daunt *et al.* 2006a).

However, no empirical data are available. There are also no data on strike rates when birds are foraging underwater.

Table 5: Surface collision risk from shipping

Species group	Risk from collision	Knowledge gaps
Divers	Low	No empirical data available
Grebes	Low	No empirical data available
Fulmar	Low	No empirical data available
Shearwaters	Low	No empirical data available
Storm-petrels	Low	No empirical data available
Gannet	Low	No empirical data available
Cormorants	Very low	No empirical data available
Red-necked phalarope	Low	No empirical data available
Sea ducks	Low	No empirical data available
Skuas	Low	No empirical data available
Gulls	Low	No empirical data available
Terns	Low	No empirical data available
Auks	Low	No empirical data available

2.3.2 Wind turbines

The collision risk to birds from offshore wind farms has been the subject of research in recent years (Richardson; Garthe & Huppop 2004; De Lucas *et al.* 2005; Desholm & Kahlert 2005; Greenwood 2005; Desholm *et al.* 2006; Drewitt & Langston 2006; Fox *et al.* 2006; Oxley 2006; Smales 2006). The work has followed on from the impacts of onshore wind farms on terrestrial birds. Models have been developed that quantify collision risk based on the structure and operation of turbines, number and size of blades, rotation speed and bird characteristics including size, flying mode, flight speed and avoidance behaviour (Band *et al.* 2005; Chamberlain *et al.* 2006). The collision risk of marine birds is deemed to be higher at night than during the day, but overall is deemed to be low because of their high visibility even in poor light conditions. Birds may also use the lights placed on wind farms to locate them. Collision risk is thought to be low in part because birds appear to show greater avoidance distance at night (Desholm & Kahlert 2005) Risk for gannets and terns can be considered as low/moderate – see Table 6.

Table 6: Collision risk from offshore wind farms

Species group	Risk from collision	Knowledge gaps
Divers	Low	No empirical data; risk based on collision risk models
Grebes	Low	No empirical data
Fulmar	Low	No empirical data
Shearwaters	Low	No empirical data
Storm-petrels	Low	No empirical data
Gannet	Low/mod	No empirical data; risk based on collision risk models
Cormorants	Low	No empirical data
Red-necked phalarope	Low	No empirical data
Sea ducks	Low	
Skuas	Low	No empirical data
Gulls	Low	No empirical data; risk based on collision risk models
Terns	Low/mod	No empirical data; risk based on collision risk models
Auks	Low	No empirical data

2.4 Lessons learnt from existing collision risks

The cryptic nature of marine vertebrates underwater means that identification of negative physical interactions with existing marine technologies is severely limited. The events typically become well studied when they are sufficiently common to be a significant concern for either the human activity or the species at risk. It is clear however that in the majority of circumstances, documented cases of physical interaction are considered to be underestimates of the true number that actually occur.

2.4.1 Marine Mammals

1. Collision threats with existing human activities are significant issues for many marine mammal populations. The phenomenon is receiving increasing scientific and political recognition.

2. Collision threats may be more diverse than generally thought (e.g. ships bows & static mooring lines as threats).

3. Marine mammals may behave apparently illogically when faced with novel circumstances. (e.g. buoyant ascents by right whales & dolphins unwillingness to leap nets).

4. Details make a difference (e.gs. vessel behaviour, net material, weather, ambient noise levels all impact collision rates).

5. A variety of warning devices and gear adaptations have been developed in recognition of underwater collision issues.

2.4.2 Fish

1. Ambient conditions are important for avoidance and evasion (especially flow speed, visibility, visual appearance, vibration etc).

2. Objects in the water column will naturally attract fish.

3. In a flowing environment, a stationary object has potential to herd fish upstream of it until exhaustion is reached whereupon fish will then turn and go with the flow.

4. Schooling can compromise the efficiency of avoidance and evasion behaviours of individuals.

5. Local fish species may adapt to collision risks but transient species may be at greater risk.

6. A variety of warning devices and gear adaptations have been developed in recognition of underwater collision issues.

2.4.3 Birds

1. Underwater collisions more poorly understood than the other species groups

2. Birds are particularly vulnerable to collisions above the water surface in poor light conditions. Light underwater is typically worse so collision risks will be potentially accentuated.

3. Fewer mitigation measures have been developed than the other species groups and these have been for above surface interactions.

3. Species at risk in Scottish waters (and their attributes)

2.5 Marine Mammals

The ecology and legal status of marine mammals (pinnipeds and cetaceans) that occur in Scottish on-shelf waters have been outlined in two previous reports to Metoc as part of the SEA renewables initiative (Wilson 2005; Hastie & Wilson 2006). All marine mammal species found in Scottish waters are likely to be capable of and regularly dive to the operating depths used by marine renewable devices on the continental shelf. While the species can be divided into those that forage within the water column (pelagic) and those that feed at or on the bottom (benthic), all breathe at the surface and so transit the water column on a regular basis. In collision terms, these species can be grouped into five broad categories (Table 7).

SPECIES GROUP DESCRIPTIONS
SEALS
Two species of seal occur in Scottish shelf waters. Both regularly haul-out on land and feed in shelf waters on a wide variety of fish and cephalopods. Common (or harbour) seals (*Phoca vitulina*) tend to range within 40 km of shore while grey seals (*Halichoerus grypus*) range more widely in the marine environment. While these species rest and breed in social groups, at sea they tend to feed alone. Feeding may occur within the water column but is more frequently at or near the sea bed. Compared to other marine mammals, seals are comparatively small to medium in body length ranging from 0.7 m for a harbour seal pup to 2.6 m for an adult male grey seal. They are highly manoeverable in the water and capable of rapid turns and also sculling backwards in confined spaces. In water they are curious and often approach novel items in their environment.

PORPOISE
There is only one species of porpoise that occurs in Scottish coastal waters– the harbour porpoise (*Phocoena phocoena*). This small species of toothed cetacean is the most numerous cetacean in shelf waters and typically occurs alone or in small groups. They feed on a wider variety of fish and squid species particularly small schooling species in the water column or near the bottom. Unlike other toothed cetaceans, porpoises rarely interact with human activities and are generally shy of unusual objects in the water. They are the smallest species of cetacean in Scottish waters, reaching around 180 cm in total length. Despite their size they are accomplished divers and can reach depths of 200m. Their diving is often to the bottom and areas of strong tidal currents are often use for foraging. The specific mechanisms that draw porpoises to tidal races are unknown.

DELPHINIDS
There are 5 species of delphinid (bottlenose dolphins *Tursiops truncatus*, common dolphins, *Delphinus delphis*, white-beaked dolphins, *Lagenorhynchus albirostris*, Risso’s dolphins, *Grampus griseus* and killer whales, *Orcinus orca*) that regularly occur in Scottish shelf waters and 3 additional species that use it occasionally (Atlantic white-sided dolphins, *Lagenorhynchus acutus,* long-finned pilot whales *Globicephala melas* and striped dolphins, *Stenella coeruleoalba*). Delphinids are typically social and associate in schools from several individuals to hundreds. They feed on a wide variety of fish and squid primarily in the water column but bottom

species such as flat fish are also taken. They are typically pursuit predators and may use complex social aggregations to herd or trap individual or schooling prey. Killer whales feed on fish and / or marine mammals in Scottish waters. Unlike porpoises, delphinids are often curious and frequently approach man made structures in the water.

LARGE ODONTOCETES

A variety of non-delphinid large odontocetes (including sperm whales, *Physeter macrocephalus*, northern bottlenose whales, Hyperoodon *ampullatus* and a variety of beaked whales, *Mesoplodon* spp.) occur in Scottish waters. The majority use waters offshore of the continental shelf break and so are of less relevance to renewable energy generation. However, these vagrants are known to venture onto shelf waters, sometimes entering shallow coastal waters. These events are typically regarded as abnormal and often lead to the deaths of the individuals concerned. However, because these species appear to be less accustomed to manoeuvring around structures in the water column they are potentially more vulnerable should they encounter such devices. Their large mass, particularly in the case of sperm whales (50 tons), may also have damaging effects for such devices should collisions occur.

MYSTICETES

Five species of mysticete, or baleen whale commonly use Scottish waters. These include the minke, *Balaenoptera acutorostrata,* fin, *B. physalus,* sei, *B. borealis,* blue, *B. musculus* and humpback whales, *Megaptera novaeangliae*. Of these, minke whales are most abundant and widespread. Minke whales are the smallest Scottish mysticete species but still reach 10 meters in length and weights of 8 – 10 tons. Mysticetes feed by engulfing entire schools of small schooling fish or crustaceans and typically concentrate on species living in the water column or near the surface. Mysticetes are not particularly social and generally occur alone or in small groupings. Of all the marine mammal species, their occurrence is the most seasonal and abundance in Scottish waters is lowest in winter. Minke whales are noted for their curiosity and often approach boats, and presumably other novel items in their environment. They also venture into constrained coastal waterways in search of their prey and may also congregate in areas of strong tidal mixing. They are surprisingly agile but like all other cetaceans unable to swim backwards. Furthermore, some species such as north Atlantic right whales (*Eubalaena glacialis*) appear to have limited abilities to control their buoyancy in surface waters and are highly positively buoyant when near the surface.

DISEASE, AGE & BLAME

So long as marine renewable devices do not significantly attract marine mammals for enhanced foraging opportunities, it is most likely that collisions will involve young, old, diseased or disorientated individuals. Similar demographic trends are seen in ship-strike and bycatch statistics. It is likely that young animals do not recognize the threat while old, ill, or disorientated animals have compromised abilities to either detect the threat or escape from it once it is perceived. While any fatal collisions between old, sick or vagrant animals may have little if any ecological impact on marine mammal populations, the occurrence of such events is likely to have adverse impacts on the public perception of the environmental safety of marine renewable devices. Consider if the disabled northern bottlenose whale that entered the Thames River in January 2006 had blundered into a tidal turbine. It is therefore important that should such event(s) occur, post-mortem infrastructure is in place to establish the prior health status of any animals that are known to have collided with these devices.

Table 7: Overview of marine mammals and collision risks. Dark shading represents significant knowledge gaps. Lighter shading signifies less important knowledge gaps.

					Knowledge gaps			
					Behaviour towards devices			
Species group	Foraging mode	Prey detection	Foraging modes	Collision concern	perception	attraction	avoidance	foraging exploitation
Seals	Bentho-pelagic	Visual/tactile/ passive acoustic	Sit and wait, burst pursuit	High	■	■	■	■
Porpoise	Bentho-pelagic	Active & passive acoustic/visual	Active pursuit	High	■	░	■	░
Delphinids	Pelagic	Active & passive acoustic/visual	Active pursuit, social tactics	High	■	■	■	■
Large odontocetes	Pelagic	Active & passive acoustic/visual	n/a coastal waters	Low	░	░	░	░
Mysticetes	Pelagic	Passive acoustic/visual	Gulp & skim feeding	High	■	░	■	░

3.1 Fish

When the full range of possible devices that may be used are considered it can only be concluded that almost all species of fish are at some risk. The group of species at risk will vary depending on the type of device and its location within the water column. Demersal fish, spending all their time near the sea bed will not be affected by the moving parts of wave power generating devices that act at the surface. It is possible that they may benefit from the habitat structure provided by the foundations and or moorings for these devices. Some species (plaice for example) may interact with turbines in mid water when they make excursions up the water column when using tidal stream transport during migration. Some devices, vertical axis turbines for example, may be placed in foundations on the sea bed in shallow water. Demersal species could be at particular risk with these machines. Table 8 details knowledge gaps.

Pelagic species of fish will however be at some risk of interaction with all types of device. Their diurnal vertical migration behaviour forces them to at some time of day occupy all depths in the water column; herring for example descend to 100 metres where depth allows. The Atlantic mackerel by contrast does not exhibit a distinct diurnal migration but is known to occupy depths greater than 100 m at times, the depth occupied varying with season and food availability.

Species at risk will vary with season as their geographic distribution changes, during migrations and spawning periods. Risk of collision with moving parts also varies with scale. Very small fish and certainly larval fish with very low inertia experiencing viscous flow regime are more likely to follow the flow streamlines around moving parts and thus avoid collision. The risk increases as animals increase in mass.

Schooling species may be at greater risk than those with a solitary habit. A school could be regarded as a large “superorganism” rather than simply a group of individuals. Schools of fish move together in polarised formations and their predator escape behaviour is coordinated. Responses may lead to some individuals evading contact with turbine blades; others could be directed into the path of a blade. It is important to bear in mind that turbine blades, either of the horizontal or vertical axis type present a threat quite unlike any predator that fish normally experience.

Table 8 Dark shading represents significant knowledge gaps. Lighter shading signifies less important knowledge gaps.

					Knowledge gaps			
					Behaviour towards devices			
Species group	Foraging mode	Prey detection	Attack detection	Collision concern	perception	attraction	avoidance	foraging exploitation
Pelagic Fish clupeids	Pelagic Visual biting or filtering	Visual, chemical, mechanical	Sound visual	moderate	░	░	■	■
Pelagic fish scombroids	Pelagic biting	Visual, chemical	Visual	moderate	░	░	■	■
Benthic fish round fish	Bentho-pelagic biting	Chemical, visual	Visual Sound	moderate	░	░	■	░
Benthic fish flatfish	Benthic biting	Chemical, visual, mechanical	Tactile mechanical Visual	Low	░	■	■	■

3.2 Birds

Appendix 1 lists the 53 marine and coastal bird species that are potentially at risk of collisions and therefore considered in this report. The criteria for inclusion was those species that use the seas around the UK and for which marine SPAs are being considered, because they are on Annex 1 of the Birds Directive 79/409/EEC or because they are migratory (see www.jncc.gov.uk/page-1414 for full details of rationale). The black guillemot Cepphus grylle is neither in Annex 1 of the Birds Directive nor is it migratory, but is included within this report for completeness.

Throughout this report the 53 species will be grouped into the following species groups, based on taxonomy/foraging ecology, in subsequent tables and text:

- divers
- grebes
- fulmars
- shearwaters
- storm-petrels
- northern gannet
- cormorants

- red-necked phalarope
- sea ducks
- skuas
- gulls
- terns
- auks

This section describes each group's foraging characteristics relevant to collision risk. A summary of the characteristics are given in Table 9 (see end of section).

There is likely to be considerable overlap between the proposed location of wave and tidal schemes and seabird foraging areas. Tidal schemes in particular are likely to be in areas that are favoured by marine birds, which preferentially forage in regions of high tidal activity (Daunt *et al.* 2006b). Therefore, marine birds are potentially at risk of collision with tidal and wave devices. Collisions may result in physical injury or death. The sensitivity of the species is likely to depend on:

- the extent of overlap between foraging locations and energy schemes
- the foraging mode, including depth attained in the water column and swimming speeds
- the diurnal rhythm of foraging
- the extent to which species location and behaviour varies with time of year
- the extent to which the species is attracted to the development e.g. for perching/nesting (Craik 2004)
- the effect of the scheme on turbidity
- the effect of the scheme on water flow

However, no empirical data exist on the impact of collisions from wave and tidal schemes on marine birds. Therefore, in assessing collision risk, we have resorted to assessing likely collision risk dependent on foraging ecology and importance of potential locations at different times of the year. There are also large gaps in our knowledge of the ecology of the species groups, including distributions, depth usage, diurnal rhythms, importance of tactile foraging methods, ecology in relation to time of year and ecology of younger age classes.

SPECIES GROUP DESCRIPTIONS

DIVERS

Species: red-throated diver, black-throated diver, great northern diver

Both red-throated and black-throated divers primarily use freshwater systems, but both species are known to forage in inshore marine waters during the breeding season, in particular the red-throated diver. The two species use the marine environment extensively outside the breeding season in sandy bays throughout the study area. Scotland holds very important numbers of great northern diver in winter. Divers dive through the water column to obtain food, propelling their bodies with their feet, obtaining food primarily by sight although tactile methods may also be used. Therefore, collision risk is likely to be higher than average in this group compared to marine birds as a whole.

GREBES
Species: Great-crested grebe, red-necked grebe, Slavonian grebe, black-necked grebe

These species are distributed almost exclusively in freshwater environments in the summer. However, all species forage in inshore marine waters outside the breeding season. The Slavonian grebe is the most marine of the grebe species outside the breeding season. The other species use inshore coasts and bays. Like divers, grebes are foot-propelled divers, obtaining food principally by sight but tactile methods may be used. Therefore, collision risk is likely to be higher than average in this group compared to marine birds as a whole.

FULMAR
Species: Northern fulmar

During the breeding season, the fulmar is principally an offshore feeder, but can also be found in considerable numbers in inshore regions. Furthermore, fulmars are the only British seabird that occupy their nest site throughout the winter, so presence in inshore waters close to the colonies occurs year-round. Northern fulmars are surface feeders, attaining depths no deeper than 2-3m during the breeding season (Garthe & Furness 2001). They forage principally during day light, with comparatively little foraging taking place at night. No data are available on depth usage at other times of the year. However, it is unlikely to dive to great depths at any time of the year so collision risk from underwater schemes is likely to be lower than average.

SHEARWATERS
Species: Cory's shearwater, great shearwater, sooty shearwater, Manx shearwater, Balearic shearwater

Shearwaters are principally offshore feeders. They also migrate along the coasts of Scotland. The manx shearwater is much the most common species although little is known about its foraging ecology. It is absent from the UK in winter. The other four species are all scarce in the study area, with birds present on passage in autumn (in particular sooty and great shearwaters), regularly seen on the same flying routes as the manx shearwater. Collision risk from shearwaters is hard to assess because of the lack of data on foraging depth usage, but whilst surface feeding is common, pursuit diving is likely also to occur, so overall risk is likely to be higher than for species that feed entirely at the surface.

STORM-PETRELS
Species: European storm-petrel, Leach's storm-petrel

These two species are found offshore in summer. In winter, both species migrate to the tropics and southern hemisphere. Storm petrels are surface, visual feeders, so collision risk is likely to be low.

GANNET
Species: northern gannet

The gannet is principally a pelagic feeder during the breeding season, capable of travelling several hundreds of kilometres on single foraging trips, but will also spend considerable time in close proximity to the colony for loafing and feeding (Hamer *et al.* 2000). Although much of the population disperses to southern Europe and western Africa in winter, birds can be seen in the vicinity of colonies and along coasts throughout the year. Foraging is achieved by plunge diving where birds reach considerable speeds (ca. 6ms^{-1}, unpublished data) before entering the water column; some plunges are followed by pursuit of prey underwater, propelling themselves with their wings (Garthe *et al.* 2000). Man-made objects are frequently used as perching posts by northern gannets, so they may be attracted to renewable schemes for this purpose. Collision risk is likely to be higher than many other marine birds because of the speed of travel during plunges. This species is one of the best studied, with data available on depth distribution and diurnal foraging rhythms (see later sections), although little is known about their ecology outside the breeding season or the ecology of younger age classes.

CORMORANTS

Species: great cormorant, European shag

Great cormorant foraging is divided between freshwater and marine habitats. Although precise locations of foraging at sea are poorly known, great cormorants typically feed inshore within a few kms of the coast. The European shag is exclusively marine and also feeds in the inshore zone. European shags feed within a few kms of the colony during the breeding season, and do not disperse widely in winter, remaining associated with rocky shores throughout the year. Both species are foot-propelled divers, using vision and tactile methods. Swim speeds underwater typically range from 1-2 ms^{-1} (Daunt *et al.* 2005; Watanuki *et al.* 2005), which is probably typically of other diving species that have not been measured for swim speeds. Man-made objects are frequently used as perching posts and sometimes breeding locations by this group, so they may be attracted to renewable schemes for this purpose. Collision risk is likely to be higher than average for this group than marine birds as a whole. The European shag is one of the best studied species of marine bird, with data available on depth distribution, diurnal foraging rhythms and foraging ecology throughout the year (see later sections).

SEA DUCKS

Species: greater scaup, common eider, long-tailed duck, common scoter, surf scoter, velvet scoter, common goldeneye, red-breasted merganser, goosander

Important numbers of common scoter, long-tailed duck, common eider and red-breasted merganser can be found in inshore waters and estuaries. Whilst the surveys have been patchy, the results suggest that these four species are the most common of the sea ducks in Scotland. Surf scoter, velvet scoter, common goldeneye and goosander are scarce in Scotland. Collision risk in sea ducks is higher than the average for marine birds because they are foot-propelled divers and use tactile foraging methods more extensively than other groups so may operate in areas where visibility is not of primary importance. There will be a spectrum of collision risks because this groups includes divers and pursuit divers.

PHALAROPE

Species: red-necked phalarope

This species is likely to fly across marine areas and feeds in marine environments in winter, but its risk of collision is likely to be low.

SKUAS
Species: pomarine skua, arctic skua, long-tailed skua, great skua

Although precise foraging locations are poorly understood, these species forage in close association with other seabird species such as black-legged kittiwakes, common guillemot, Atlantic puffin and northern gannets, from which they kleptoparasite food or, in the case of great skuas on the smaller seabird species, prey on them. As surface feeders, skuas are of lower risk from collision than divers. Skuas migrate in the winter, and the west coast is the main migration route, though precise locations are not well known.

GULLS
Species: Mediterranean gull, little gull, sabine's gull, black-headed gull, common gull, lesser black-backed gull, herring gull, Iceland gull, glaucous gull, great black-backed gull, black-legged kittiwake

Of the six common species (Mediterranean gull, little gull, sabine's gull, Iceland gull and glaucous gull are all scarce in the region throughout the year), black-legged kittiwake foraging ecology is the most widely studied (Wanless *et al.* 1992; Daunt *et al 2002)* and this species is the most pelagic of the six, foraging some distance from the colony during the breeding season, and dispersing away from the UK in the winter. Despite this, kittiwakes breeding in the region spend a considerable portion of time in the vicinity of the colony loafing and feeding. The remaining five species are more closely tied to the inshore zone than kittiwakes, rarely venturing further than 25 kms from the shore (Camphuysen 2005). With the exception of the greater black-backed gull, these species also spend a considerable portion of foraging time in terrestrial habitats, where they also breed in large numbers. All five species are resident with the exception of the lesser black-backed gull which migrates in the winter, and therefore is likely to pass through the study area on passage. Man-made objects are frequently used as perching posts and sometimes breeding locations by this group, so they may be attracted to renewable schemes for this purpose. As surface feeders, gulls, in particular those that spend a proportion of time in terrestrial habitats (especially herring gulls) and are not present in winter (lesser black-backed gulls, black-legged kittiwakes), are at lower risk from collision than divers.

TERNS:
Species: sandwich tern, roseate tern, common tern, arctic tern, little tern

During the breeding season, terns forage extensively in inshore regions, though precise locations are not well understood. In winter, all five species migrate so will pass through the region on passage. Man-made objects are frequently used as perching posts and sometimes breeding locations by this group, so they may be attracted to renewable schemes for this purpose. Roseate terns are scarce. As plunge divers, terns are likely to be at comparatively high risk of collision with underwater renewable schemes.

AUKS:
Species: black guillemot, common guillemot, razorbill, little auk, puffin

The first three species generally feed within 50kms of the breeding colony during the breeding season, and therefore spend a considerable portion of foraging time within the inshore zone. Furthermore, loafing and social activities take place in the vicinity of colonies. All three species disperse in winter, although common guillemots and razorbills will still be found close to the coast in large numbers. Puffins, on the other hand, are pelagic in winter and will therefore be rare within the study area at that time of the year. The black guillemot is an exclusively inshore foraging species, so is resident throughout the year. The little auk is a winter visitor only, but much larger numbers are found on the east coast of Britain. All species are wing-propelled divers, so risk of collision is higher than many other marine species groups. Swim speeds are typical for underwater divers, at 1-2 ms^{-1} (Watanuki *et al.* 2006). This group is one of the best studied, with data available on depth distribution and diurnal foraging rhythms (see later sections).

Table 9: Overview of marine birds and collision risk

Species group	Foraging mode	Prey detection	Foraging speeds	Collision risk	Knowledge gaps
Divers	Pursuit diver	Visual/tactile	Unknown	Moderate	Limited understanding of foraging ecology; no empirical data on collision impacts of underwater renewable schemes
Grebes	Pursuit diver	Visual/tactile	Unknown	Moderate	Limited understanding of foraging ecology; no empirical data on collision impacts of underwater renewable schemes
Fulmar	Surface feeder	Visual/olfactory	Unknown	Low	Limited understanding of foraging ecology; no empirical data on collision impacts of underwater renewable schemes
Shearwaters	Surface feeder / shallow diver	Visual	Unknown	Low/moderate	Limited understanding of foraging ecology; no empirical data on collision impacts of underwater renewable schemes
Storm-petrels	Surface feeder	Visual	Unknown	Low	Limited understanding of foraging ecology; no empirical data on collision impacts of underwater renewable schemes
Gannet	Plunge/pursuit diver	Visual	ca. 6 ms^{-1}	Moderate/high	Limited understanding of foraging ecology outside breeding season and in juveniles; no empirical data on collision impacts of underwater renewable schemes breeding season
Cormorants	Pursuit diver	Visual/tactile	1-2 ms^{-1} underwater	Moderate	Limited understanding of foraging ecology outside breeding season and in juveniles; no empirical data on collision impacts of underwater renewable schemes
Phalarope	Surface feeder	Visual	Unknown	Low	Limited understanding of foraging ecology; no empirical data on collision impacts of underwater renewable schemes
Sea ducks	Diver / Pursuit diver	Visual/tactile	Unknown	Moderate	Limited understanding of foraging ecology; no empirical data on collision impacts of underwater renewable schemes
Skuas	Surface feeder	Visual	Unknown	Low	Limited understanding of foraging ecology; no empirical data on collision impacts of underwater renewable schemes
Gulls	Surface feeder	Visual	Unknown	Low	Limited understanding of foraging ecology of some species; no empirical data on collision impacts of underwater renewable schemes
Terns	Plunge diver	Visual	Unknown	Moderate	Limited understanding of foraging ecology; no empirical data on collision impacts of underwater renewable schemes
Auks	Pursuit diver	Visual/?tactile	1-2 ms^{-1} underwater	Moderate	Limited understanding of foraging ecology outside breeding season and in juveniles; no empirical data on collision impacts of underwater renewable schemes

4. Structures of concern on marine renewable devices

A wide variety of device designs have been proposed to extract wave and tidal energy from coastal waters (see Appendix 2). These devices are typically categorised firstly in terms of the type of energy they extract (i.e. waves or tides) and then by the method of extraction (in-water turbines, articulated surface structures etc). However for marine vertebrates in the water column the specific brands or mechanics of operation are of less relevance than the type and movement of the physical structures that they may encounter. Thus it is helpful when evaluating collision risks to consider marine renewable devices from the standpoint of their component parts, motions and likely placement (see Figure 4). In the following section we outline the generalities of a variety of potential devices and draw structural parallels with the existing human activities reviewed in Section 2. Table 10 summarises these parallels

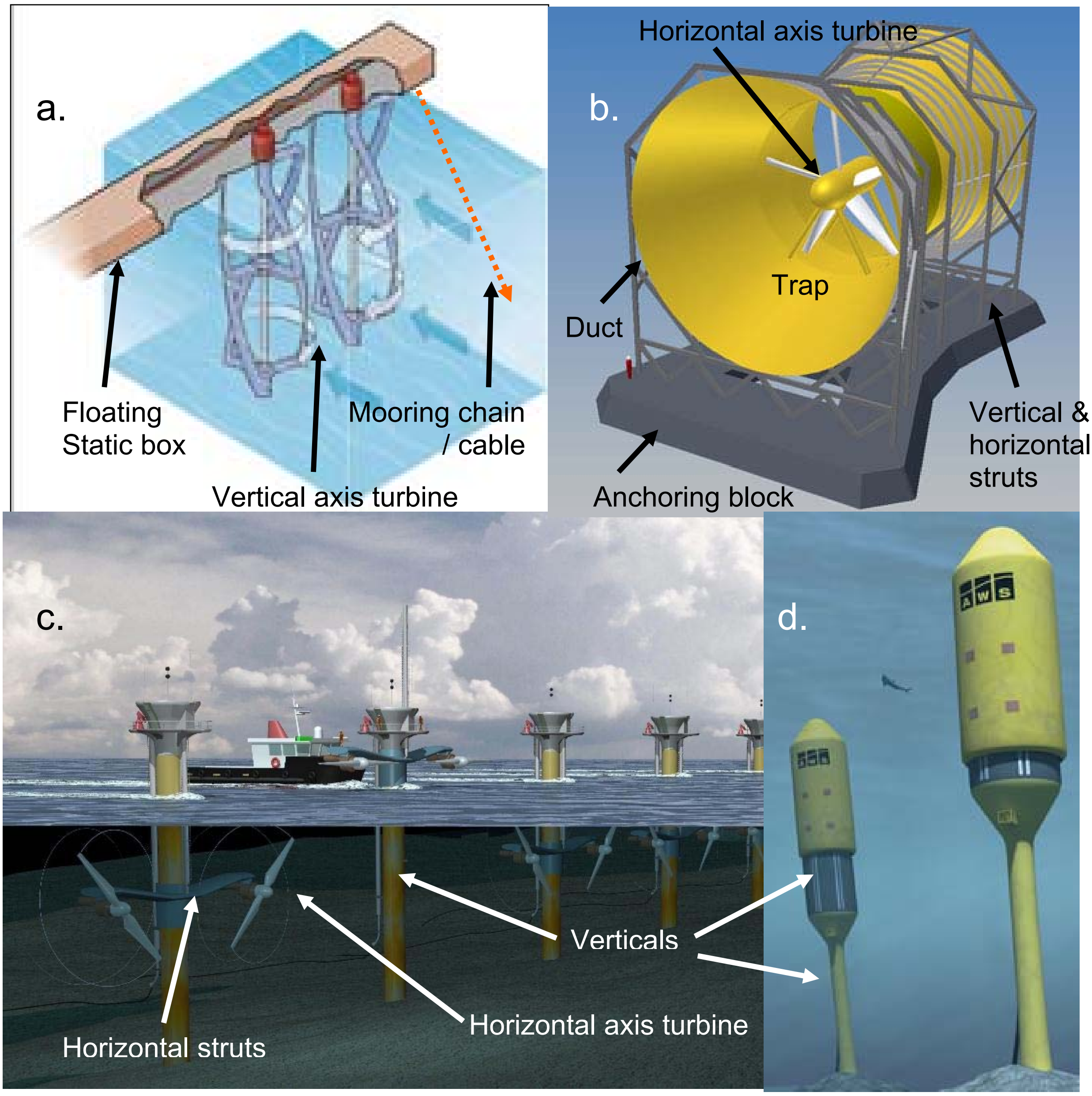


Figure 4. Four examples of marine renewable devices to illustrate how each combines several collision threat types. a) Gorlov helical axis turbine, b) Lunar Energy horizontal axis turbine, c) MCT Seagen d) Archimedes Wave Swing

4.1 Fixed submerged structures

A variety of both tidal and wave generators will utilize fixed structures submerged in the water column. Probably most common will be **Vertical support piles** for machinery attachment. These structures parallel established supports often for bridges, oil platforms etc and are most likely to pose most collision risks in areas of strong water movement, particularly areas of strong tidal flow or upper water-column wave motion. Because larger structures are likely to impinge more on the local water flow characteristics they are also likely to provide vertebrates in the water column with more cues to their presence and upstream escape options. **Horizontal support structures**, **ducts** and **nacelles** are likely to be less universal than vertical piles but pose broadly similar collision issues.

4.2 Mooring equipment

A wide variety of device designs, especially surface floating devices will require substantial mooring equipment. Seabed standing **anchor blocks** or **plinths** are likely to function like other natural or artificial seabed structures and hence pose little novel risks for vertebrates in the water column. **Cables** and **chains** extending up through the water column will have direct parallels with mooring devices used in other offshore industrial applications as well as static fishing gear but, by the nature of the industry, will be placed in more energetic sites than most other existing marine activities. By extending up through the water column, they will have some parallels in collision terms with vertical support piles but having a smaller cross-section will not disrupt the water flow to the same extent. This will have several implications. Firstly, by impinging less on any water flow they will generate different cues for marine vertebrates. With lower flow disruption, bow-wave effects in strong currents will be reduced but acoustic strumming or chain noise may be significant. As well as providing different sensory cues, the implications of collisions, should they occur, will also differ as vertebrate species of concern will be much larger relative to the structure and so be less likely to be swept around them by the flow. Finally, various cetacean species (particularly mysticetus) are known to become entangled in static lines used to mark crab creels so cables, chains or other lines anchoring renewable structures as well as power cables may have entanglement potential for such species. Mooring lines may also have **mid-water mooring floats** and **weights** to help them maintain station. These are likely to have similar collision properties to the small fixed submerged structures described above.

4.3 Surface structures

Many of the devices proposed, particularly wave related, will have a significant surface components. These may either be fixed to the sea bed and then pierce the surface or be anchored and float on the surface. Floating structures may simply be **static boxes** used to secure submarine equipment or guide waves or be composed of multiple **articulated boxes**. In collision terms, species most at risk are those that frequently cross the air-water interface, i.e. diving birds and marine mammals. Nearest equivalent natural structures are floating logs and sea ice while industrial structures include fish-farm cages, oil related floating storage and offloading structures and logging industry log-booms/rafts. As with these other industrial applications, semi-aquatic species are likely to use surface floating marine renewable devices as landing/roosting or haul-out sites and risks of injury may be associated with getting onto/off the structures and any contact with exposed moving or articulated parts. While cetaceans do not haul-out, they do regularly surface for air. Species that live in ice-bound areas typically do not have dorsal fins so it is likely that collision with surface floating objects is a significant issue for cetaceans. However little is currently known about the ability of cetaceans to detect passive floating objects and the nature of injuries should contact occur. Collisions could either occur with cetaceans swimming into the structures during surfacing manoeuvres or the surface structures pitching down onto them in heavy seas. Given the scale of current designs (and unlike log-booms), it is unlikely that structures be so large as to actually hinder marine birds or mammals from reaching the surface for air. This is so long as the ascending animals are aware of the presence of the structures.

4.4 Turbines

Rotating turbines are the most intuitive contenders for significant collision risks with marine vertebrates. These devices move relative to both the seabed and to the water column and have obvious parallels with wind turbine - bird strikes as well as ship - cetacean strikes. However, it must be stressed that unlike ship propellers these devices take energy from the medium around them rather than put energy in and so their rate of movement is slower relative to the ambient flow than active propulsion propellers. Furthermore, by being turned by the moving flow, the motion of the rotors is that of a spiral with the blades travelling at angles shallower than 90º to objects passing through their area of sweep. This means that the passing blade tips are as much pushing along the tube of water within which they are rotating (stream tube) as they are cutting through it.

Because turbine blades are solid structures the blade tip is the fastest moving part of the turbine and will move faster than the water flow but at or below speeds of around 12 ms-1(23 knots). Speeds greater than this are likely to be avoided in turbine manufacture as higher water flow speeds result in water cavitation and consequent efficiency losses. Thus turbines have fundamental differences to wind turbines which are not speed limited by cavitation and ship propellers which are smaller but introduce energy into the flow rather than subtract it. Other than the rotation component, the velocity of rotor blades and especially their tips are therefore, in collision terms, more analogous to ships' bows or the keels of high-speed yachts.

The majority of proposed designs have relatively narrow blades compared to the area that they sweep, however, there is at least one design (Openhydro, see Appendix 2) that has a higher ratio of blade to inter-blade space. Designs of this kind are likely to give different cues to approaching vertebrates and may elicit different avoidance/evasion responses as well as escape options.

Turbines can be mounted in positions that are open (i.e. entirely exposed to the environment), semi-shielded by a duct or fully-shielded within a larger device used to direct a concentrated flow of water towards them. Open and semi-shielded turbine types typically fall into two axes of operation. Horizontal axis turbines rotate in a plane like that of a plane propeller while vertical axis turbines turn like revolving doors at a building entrance. The majority of exposed turbine types are associated with tidal energy extraction but some turbine-based wave devices have also been proposed.

4.5 Traps

The structures described above are generally discrete objects that marine vertebrates can either collide with or avoid, however, the combination of several structures raises the possibility of traps being created. While most marine vertebrates are highly manoeuvrable, combined structures that restrict options of movement are likely to lead to higher risk of collisions occurring. Such structures include **ducts, venturi devices, combinations of turbines** and **surface corrals**. The placement of such devices in areas of water flow rates that are significant relative to the swimming speeds of the species of concern will accentuate any problems. Nearest industrial parallels include cooling water intakes for power plants and the mouths of fishing nets. In both of these situations, animals may enter such a trap either aware or unaware of the structure around them but begin to take counter-measures to avoid collision too late. Venturi devices and turbines housed in ducts are of particular concern in these circumstances.

4.6 Equivalents with existing collision threats

Table 10: Matrix of equivalents between Marine Renewable Devices and existing marine structures (See section 2) Black shading denotes an equivalent.

		Shipping	Fisheries interactions	Power station	Wind turbines	FADs	Whale tail swipes
Fixed submerged structures	Vertical piles	■	■		■		
	Horizontal supports	■	■				
	Ducts			■			
	Others						
Moorings	Cables/chains		■			■	
Floating surface structures	Static boxes					■	
	Articulated boxes					■	
	Screens					■	
	Ledges					■	
Turbines	Horizontal axis	■			■	■	■
	Vertical axis	■			■	■	■
Traps	Ducts			■			
	Venturi			■			
	Oscil. water column			■			
	Surface corral					■	

5. Close encounter probabilities

Since it is our aim to assess collision risk there may be some benefit from deriving a predictive model for encounters between marine animals and turbines. Such a model will also reveal gaps in present knowledge and sensitivity of encounter rate to the interaction of turbine location and design with animal behaviour. Encounters, however, are not collisions. An encounter may lead to a collision but only if the animal in question does not take evasive action or has already avoided encounter following detection of sensory stimuli emitted by a turbine. Avoidance and evasion are defined in section 8.

Our model predicts encounters rate but could later be extended to predict collision rate. Collision rate is a function of the encounter rate and the probabilities of avoidance and evasion.

$$C = Z.(1-P_a).(1-P_e) \qquad (1)$$

In equation 1, C is the collision rate, Z the encounter rate and the probabilities of avoidance and evasion are P_a and P_b respectively.

The probabilities of evasion and avoidance cannot be estimated without further research (see section 11) and rather than making a wild guess we have restricted our modelling effort to predicting encounter only. It will become apparent that by taking this approach the importance of assessing the magnitude of avoidance and evasion behaviour is very important.

5.1. The model

Encounter models have been used in ecology for many years to predict rates of predation in predator-prey interactions and there is a large literature including 3 dimensional models for the aquatic environment such as that derived by Gerritsen and Strickler (1977), which was modified by Bailey and Batty (1983) and applied to predation between medusae and fish that depend upon collision. Encounter rate Z for a single predator can be simply expressed as the product of the volume swept V by the predator and the density of prey D.

$$Z = V.D \qquad (2)$$

The volume swept can be calculated from the relative velocities of both parties (the predator and prey) and the encounter radius R, which may be the radius of a medusa's bell or the perceptual range of the predator.

$$Z = \pi.R^2.\ u.D \qquad (3)$$

The relative velocity u in equation 3 is a function of the mean velocities of the prey u_a and predator u_b. Gerritsen and Strickler (1977) derived the following formula for predator prey encounters in 3 dimensions assuming that predator speed is greater than that of the prey.

$$Z = \pi.R^2.\ (u_a^2 + 3u_b^2) / 3u_b .D \qquad (4)$$

In order to apply this type of model to encounters between marine animals and turbines (or other wet renewable devices) we need to know the density of the animals per cubic metre in the locale of the turbine, the velocities of both the animal and turbine blades and also the encounter radii of the animals and the turbine blade.

The density of fish species can be obtained from published data such as ICES reports on acoustic surveys. The ICES report on acoustic surveys of herring populations (ICES, 2006) provides information on the estimated total number of herring for both the North Sea and West of Scotland populations of herring. Further detail is given of numbers in quarter ICES rectangles (approximately 29km^2, varying slightly with latitude). From this data densities per km^2 can be calculated either as a local density or as a mean density for the whole area.

In order to have a density per cubic metre at the depth horizon of a turbine, we need to know both the depth of water and the behaviour of the animal in question: vertical distribution and diurnal vertical migration for fish. Herring vertical migration behaviour is well known (Blaxter, 1985); fish tend to spend the day at depths of up to 100m and move up to the surface at dusk, descending to the bottom again at dawn. This migration is of course restricted by water depth. We can therefore make reasonable predictions of the distribution of fish at a particular water depth, time of day and season. Density per cubic metre will then be the product of the probability of being within the depth range of the turbine rotor *P* and twice the blade length divided by mean water depth at the site *H*.

$$D = P.\ 2\ .\ R_b / H \qquad (5)$$

The encounter radius *R* or the encounter area and the velocity of the turbines' moving parts can be estimated from predictions of the flow through a turbine and the geometry and dimensions of the blades. The flow through turbines will be helical and the blades rotate against this helical flow with a small angle of attack. Although current velocity at locations where they may be deployed will vary, the maximum velocity relative to the water at the blade tips should be limited to prevent cavitations. Speed of rotation will therefore be limited to about 10 rpm (Fraenkel 2006) and, for example for a 16m diameter turbine in a current of 3.5 m.s^{-1}, the velocity of the blade tip against the water will be about 12.5 m.s^{-1}. The helical flow and the small angle of attack result in the blades having a small cross section of about 0.3 m normal to the helical flow. In the Gerritsen and Strickler model the encounter radius can be replaced by the encounter cross-sectional area *A* for collision encounters:

$$Z = A.\ (u_a^2 + 3u_b^2) / 3u_b .D \qquad (6)$$

Cross sectional area *A* is the product of the length of the blade and the width as defined above. The animal that is interacting with the turbine blades cannot, however, be treated as a non-dimensional point in space. Bailey and Batty (1983) dealt with this problem by calculating a collision encounter radius for the "prey". Assuming that orientation to the "predator" or blade in this case is random, the encounter radius of the animal can be treated as a sphere. This radius is half the length of the animal (its longest dimension) projected onto a plane normal to the path of the animal relative to the blade. Bailey and Batty (1983) found that by representing the body orientation to the path as spherical polar coordinates and integration that the animal's encounter radius R_a is:

$$R_a = 2L/\pi^2 \qquad (7)$$

This encounter radius should be added to both the cross-sectional width of the blade W relative to the water flow and the blade length R_b and the number of blades such that:

$$A = (W + R_a).(R_b + R_a).N \qquad (8)$$

The one remaining parameter required for the model is the velocity of the blades u_a relative to the water. In order to simplify the calculations we have made the assumption that the velocity will be the mean tangential velocity of all parts of the blade from the tip to the axis. At the axis the velocity will approximate to the free stream velocity. Current speed will vary with a sinusoidal pattern with the tide and we have therefore assumed that the mean velocity will approximate to the root mean square velocity of the mean tangential velocity of the blades. For a 16 m diameter turbine operating in water with a maximum current speed of 3.5 m.s^{-1} u_a will be 5.4 m.s^{-1}.

To explore the potential rates of interaction we have chosen a representative fish species and a representative marine mammal species for which there are comparatively high-resolution data (Table 11 details assumptions made). We have not studied a diving bird at this stage but do consider this to be feasible and could be done at a later stage when time and funding permit. The model would have to be adapted for diving birds; there are more variables to be included such as the number of dives per unit time, duration of dives, depth distribution of dives and orientation of swimming during dives. Furthermore, if collision rate were to be estimated (equation 1), and since birds generally only dive where prey (fish) are present, fish avoidance behaviour of all species prey upon by the bird in question would have to be included in the model.

5.2. Predicting encounters with herring

The ICES report of the planning group on herring surveys (ICES, 2006) which reported on 2005 surveys gave an estimated abundance of herring on the Scottish West Coast of 1,590 million in an area of 90828 km^2 giving a density of 0.0175 fish.m^{-2}. If we assume the mean length of adult herring to be 0.3 m and that their swimming speed is 0.45 m.s^{-1} and an even probability of occurring at any depth in 50 m with a 2 blade turbine of 16 m in diameter then our encounter model predicts that there will be 338,000 encounters per year. Scaling this up to 100 turbines and we have encounters with 2% of this herring population.

Some processes have been ignored. Herring are not evenly distributed throughout their range. Data reported by ICES (2006) found very large variations in density across the survey area, from 0 to 0.161 per square metre in an ICES quarter rectangle. Evasive behaviour is also important; some fish will detect and will successfully evade collision. The close spacing of fish in schools (Domenici et al, 2000, 2002) and the coordination of escape responses within them (Domenici and Batty, 1994, 1997) means that although escape responses may lead to evasion by some individuals others will be taken directly into the path of the turbine blade. Fish have not evolved to deal with this type of "predator". Some schools of fish may react to the turbine at a suitable distance and avoid any encounter. Lastly we have assumed an even depth distribution of fish when integrated over a 24 hour diurnal cycle. Herring tend to spend the day at the bottom or up to 100m deep and the night near the surface. The depth of water in which turbines are deployed and the size and depth of the turbine will have a very significant effect on the number of interactions, many more occurring when turbines are deployed in less than 30m.

When these other factors are considered, our estimate of 2% of the population encountering turbine blades in a year when 100 turbines are deployed can be considered the upper limit of the encounter rate. The expected impact on fish populations should be less than this figure, which is one tenth of fishing mortality F 0.19; that is 19% of the population.

Table 11: Assumptions used for herring / porpoise encounter model

	Herring	Harbour Porpoise	units
Mean fish / porpoise length	0.3	1.4	m
Stock number	1.59E+09	12,076	individuals
Area of sea (porpoises: SCANS-II block 'N')	90828	30650	km^2
Density per km^{-2}	17539	0.394	km^{-2}
Water depth at turbine location	50	50	m
Depth distribution of fish / porpoises	random	random	
Probability of being within turbine depth horizon	0.32	0.32	
Fish / porpoise density m^{-3}	0.000351	7.88E-09	.m^{-3}
Depth of turbine	10	10	m
Rotor diameter	16	16	m
Proportion per m depth	0.02	0.02	
Mean swimming speed (in body lengths)	1.5	1.43	L.s^{-1}
Mean swimming speed	0.45	2	m.s^{-1}
Mean rotor speed versus water	5.435975	5.435975	m.s^{-1}
Rotor diameter	16	16	m
Encounter radius	1.355545	1.355545	m

5.3. *Predicting encounters with harbour porpoises*

We have applied the encounter model to harbour porpoises with the same turbine deployed and hypothetical environment. In this case we have used a recent high quality estimate of porpoise density in the coastal waters of the west coast of Scotland (SCANS-II survey block 'N') of 0.394 individuals per square kilometre. We assume a mean body length of 1.4 metres and an average swimming speed of 2 m.s^{-1} (Table 11). The model predicts an encounter rate of 13 individuals per year per turbine. Scaling this for 100 turbines, we would expect 1300 porpoise turbine blade encounters per year. This rate would potentially represent encounters for 10.7 % of the porpoises in the area. It should be noted, however, that the survey block used for porpoises is smaller than that used in the herring study and therefore the relative density of the 100 hypothetical turbines is effectively greater. To afford direct comparison, of potential encounter rates, therefore, turbine densities over a similar area to the herring model would produce encounter rates for 3.6 % for the porpoise population.

It should be noted that encounter rate is not synonymous with collision rate. An encounter represents the opportunity for a collision to occur. Animals may detect at long range and opt to avoid the area around turbines or respond at close range and take evasive action when in the immediate vicinity of the structures. As the model assumes that the porpoises are swimming but otherwise passive to other objects in the water, avoidance and evasion behaviour have not been included and could be expected to reduce the rates described above. For example, in wind turbine collision risk modelling, avoidance/evasion rates of 95-99% are typically used. However the behavioural response(s) of harbour porpoises (and other marine mammals) to marine renewable devices is not yet known and clearly requires targeted research to better understand and quantify.

5.4. Encounter, animal size and risk to a species

We had predicted encounter rates for two example species (the herring and harbour porpoise). In an attempt to understand the risk of encounter across a wider range of species we have considered the effect of animal body size on encounter. Clearly density is dependent on the size of animal; biomass of small animals is greater than larger animals feeding at higher trophic levels and of course the smaller body size means that small animals occur in much higher densities in terms of numbers per unit volume or sea area. In Figure 5 we have applied the encounter model with the same assumptions used for herring and porpoises above (uniform depth distribution, same turbine parameters) and have also predicted swimming speed dependent on body length. In order to predict animal density we have assumed that size spectra will vary according to the theoretical model derived by Platt ad Denham (1977, 1978) for pelagic ecosystems, which predicts that biomass will scale with body mass$^{-0.22}$. On this basis, across a wide range of size, encounter rate is heavily dependent on the reduced density with increasing body size. The density prediction has been arbitrarily normalised for herring densities. The encounter rate for porpoises is much lower than our relationship, which is for all animals. This discrepancy between herring and porpoise is entirely due to their actual densities.

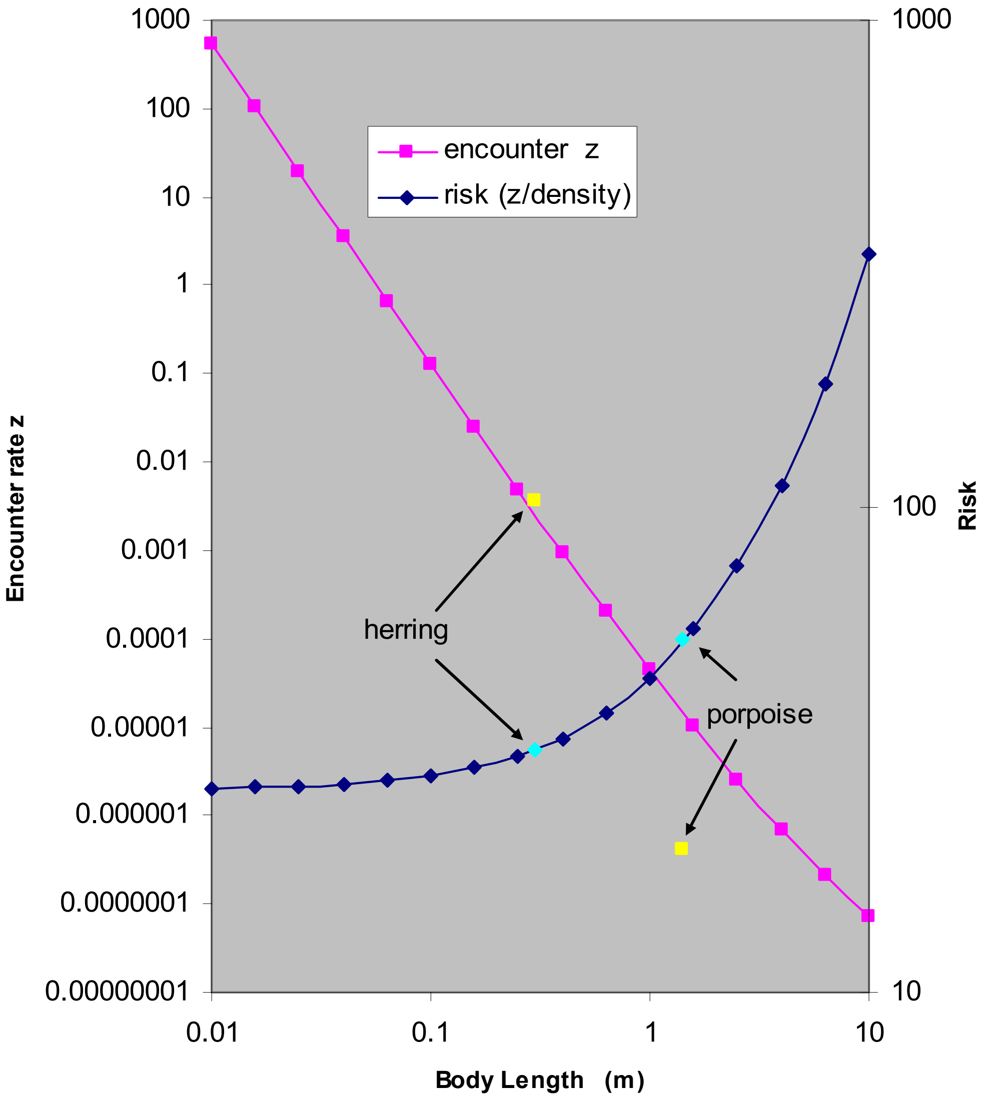


Figure 5: The theoretical effect of animal body length on encounter rate dependant on expected size spectra and on relative risk to populations of animals independent of density

Using mean animal density to predict encounter risk is perhaps misleading and as we did for the herring should consider encounters as a proportion of the population. For the purpose of our model the simplest approach is to divide encounter rate z by density per unit volume; in effect remove animal density from the encounter model. We are considering relative encounter risk versus body size (Figure 5).

The model predicts that larger animals are at much greater risk of encounter with turbine blades than smaller animals. The scale effect will be greater than this, however. The smallest animals with lower inertia will tend to follow flow streamlines around the blades more closely thereby reducing or eliminating encounter risk.

6. Location and collision risks

6.1. Depth

6.1.1 Marine Mammals

All marine mammal species found on around the coasts of Scotland are capable of diving to all likely operating depths of marine renewable devices (<200 m). Our extent of knowledge on the vertical distribution of different marine mammal species differs markedly, with most information known about the seals, then porpoises then the other cetaceans. Most species divide the majority of their time between foraging at depth and breathing at the surface. Species, such as the seals that forage at or near the bottom will therefore spend least time in the open water column while pelagic feeders, such as white-beaked dolphins, will spend the majority of their time in the water column. The collision risk for marine mammals will therefore depend on the species of concern, the depth of the device and its relative position within the water column.

6.1.2 Fish

Depth of occurrence differs between species but also varies with time of day, season and stage of development within species. However, in danger of stating the obvious, demersal fish will be at greater risk from devices that are founded on the sea bed and have moving parts in close proximity to the sea bed such as some proposed vertical axis turbines. Pelagic fish that migrate diurnally will also be at risk during the day when they are near the bottom. Devices on or near the surface will pose a particular risk to pelagic fish at night when they are near the surface. Vertical axis turbines mounted at the surface will present some increased risk for these species; non-clupeiod fish with less sensitive and sophisticated mechanoreception (see section 7.2) will be at the greatest risk.

Horizontal axis turbines are typically deployed in mid water. If there is an adequate depth both below and above the turbine the risks to both pelagic and demersal fish will be considerably reduced. Pleagic fish will only encounter the blades during the brief vertical migrations; upwards before dusk and downwards after dawn.

6.1.3 Birds

Collision risk will depend on the extent to which species will be distributed through the water column (Table 12). Thus, diving species will be at greater risk of collision than surface feeding species. Empirical data exist on the depth usage of a range of species: European shags, northern gannets, northern fulmars, common guillemots, razorbills and Atlantic puffins (Wanless *et al.* 1988; Harris *et al.* 1990; Wanless *et al.* 1991; Garthe *et al.* 2000; Garthe & Furness 2001; Daunt *et al.* 2003; Daunt *et al.* 2005; Daunt *et al.* 2006b). In general, depth distribution depends on maximum foraging depth, with shallow divers spending most time near the sea surface and progressively less time at depth, whereas deep divers, which are principally benthic feeders, showing a bimodal depth distribution with peaks of time spent at the sea surface and at deep depths and less time spent at intermediate depths. Collision risk with depth is likely to reflect how time is allocated to different depths in relation to the location in the water column of the development.

The data collected on depth usage by marine birds is exclusively on breeding birds in summer. These findings should not be extrapolated to other times of the year. For example, cormorants in polar regions make shallower dives on average in winter than in summer (Grémillet *et al.* 2005b).

Furthermore, nothing is known about the depth usage of juvenile birds, which tend to have lower foraging proficiency so may forage more extensively at night than adults to compensate.

Only anecdotal evidence of depth usage by the other species are available (Cramp & Simmons 1977; 1983), although categorisation into divers and surface feeder is reliable, with the possible exception of manx shearwater whose maximum foraging depths are completely unknown.

Table 12: provides an estimate of risk of collision with depth.

Species group	Depth usage	Risk at depth	Knowledge gaps
Divers	Usually <20m; but capable of deeper	Greatest risk at shallowest and deepest depths	No data on precise depth usage
Grebes	Usually <20m; but capable of deeper	Greatest risk at shallowest and deepest depths	No data on precise depth usage
Fulmar	<5m	Declining risk with depth	No data on precise depth usage of juveniles and in all ages outside breeding season
Shearwaters	Unknown; probably <20m	Unknown	No data on precise depth usage
Storm-petrels	<5m	Declining risk with depth	No data on precise depth usage
Gannet	Generally <10m, max 30m	Declining risk with depth	No data on precise depth usage of juveniles and in all ages outside breeding season
Cormorants	Usually <40m; but capable of deeper	Greatest risk at shallowest and deepest depths	No data on precise depth usage of juveniles and in all ages outside breeding season
Phalarope	<5m	Declining risk with depth	No data on precise depth usage
Sea ducks	Usually <20m; but capable of deeper	Greatest risk at shallowest and deepest depths	No data on precise depth usage
Skuas	<5m	Declining risk with depth	No data on precise depth usage
Gulls	<5m	Declining risk with depth	No data on precise depth usage
Terns	<5m	Declining risk with depth	No data on precise depth usage
Auks	Usually <60m; but capable of deeper	Greatest risk at shallowest and deepest depths	No data on precise depth usage of juveniles and in all ages outside breeding season

6.2. Time of day

6.2.1 Marine Mammals

All marine mammal species in Scottish waters occur at sea throughout the diel cycle. Like birds, pinnipeds have the capacity to haul-out (i.e. exit the marine environment) but both seal species forage in bouts lasting several days and have haul-out regimes influenced by weather and by site availability tidally (Grellier et al. 1996). Thus they can be assumed to be at risk of collision with devices at sea throughout the diel cycle. Little is known about cetacean behaviour at night but their distribution is likely to be similar day and night. The largest impacts of time of day on collision risks are likely to concern the abilities of animals to detect devices in darkness and any influences of diel changes in prey availability or behaviour on whether marine mammals forage in areas of risk.

While they have other senses, both pinnipeds and cetaceans use vision for navigation and prey capture and so it is logical to infer that collision risks will be increased during periods of low light intensity. However as light does not travel well through water and water clarity off Scotland is usually in the realms of tens of metres or less, oscillations in light intensity will influence the evasion abilities of animals rather than their avoidance abilities (see definitions in section 8).

Diel influences on foraging are likely to occur in two ways. 1) Changes in prey distribution with light regimes (see section 6.2.2) will influence the foraging behaviour of marine mammals and hence their abundance or transit through areas of concern. 2) Marine mammals and their prey have different sensory abilities with fish relying on vision for mid-range predator detection and marine mammals using vision, hearing and mechano-reception. Thus the relative predator-prey dynamic between these species varies between night and day and with it the foraging behaviour of marine mammals. These foraging relationships are likely to be species and area specific and therefore outside the realms of this overview report but require consideration at the EIA level.

6.2.2 Fish

Variation in risk of exposure due to diurnal vertical migration with time of day has already been discussed above. From the available studies, although there is some variation observed the pattern is not enough to suggest a greater risk of exposure at any specific time of day. Evasion ability (see definition in section 8) will however vary with time of day according to the visual sensory information available.

6.2.3 Birds

Collision risk will depend on diurnal rhythms of feeding and in particular the proportion of foraging taking place at night. Diurnal rhythms have only been recorded precisely in a few species using animal borne instrumentation. The data are based almost exclusively on adults during the breeding season. The exception is adult European shags, whose diurnal patterns are known year-round. Adult European shags only feed during daylight throughout the year. A proportion of foraging time of northern gannets, northern fulmars, black-legged kittiwakes, common guillemots and razorbills occurs at night in summer (Garthe *et al.* 2000;

Garthe & Furness 2001; Daunt *et al.* 2002; Daunt *et al.* 2006a; Daunt *et al.* 2006b). These species are therefore more at risk of collisions at night than European shags. Night-time foraging tends to occur close to dusk and dawn and feeding is avoided during the darkest 1-2 hours.

However, this finding should not be extrapolated to other times of the year when day length is shorter and foraging conditions poorer overall. For example, cormorants in polar regions do a considerable proportion of daily foraging at night, in complete darkness, presumably via tactile methods (Grémillet *et al.* 2005a).

Furthermore, nothing is known about the diurnal foraging patterns of juvenile birds, which tend to have lower foraging proficiency so may forage more extensively at night than adults to compensate.

Precise data on diurnal rhythms of foraging of the remaining species are lacking, but anecdotal evidence suggests that they are principally diurnal feeders (Cramp & Simmons 1977; 1983). However, the extent of night-time feeding is poorly understood throughout the year, and the behaviour of juveniles is unknown.

Table 13 provides an estimate of risk of collision with respect to time of day, based on the extent to which foraging at night occurs, and on foraging mode.

Table 13: Collision risk and time of day

Species group	Diurnal rhythm	Risk during night	Knowledge gaps
Divers	Largely diurnal	Probably low	No data on extent of foraging at night
Grebes	Largely diurnal	Probably low	No data on extent of foraging at night
Fulmar	Largely diurnal; some foraging at night	Moderate	No data on extent of foraging at night
Shearwaters	Largely diurnal	Probably low	No data on extent of foraging at night
Storm-petrels	Largely diurnal	Probably low	No data on extent of foraging at night
Gannet	Largely diurnal; some foraging at night	Moderate	No data on extent of foraging at night outside breeding season and in juveniles
Cormorants	Diurnal	Probably low	No foraging at night by adults; juveniles unknown
Phalarope	Largely diurnal	Probably low	No data on extent of foraging at night
Sea ducks	Largely diurnal	Probably low	No data on extent of foraging at night
Skuas	Largely diurnal	Probably low	No data on extent of foraging at night
Gulls	Largely diurnal; some foraging at night	Probably low	No data on extent of foraging at night outside breeding season and in juveniles
Terns	Largely diurnal; some foraging at night	Probably low	No data on extent of foraging at night outside breeding season and in juveniles
Auks	Largely diurnal; some foraging at night	Moderate	No data on extent of foraging at night outside breeding season and in juveniles

6.3. Season

6.3.1 Marine Mammals

Marine mammal abundance and behaviour varies seasonally in Scottish waters. Some species such as the baleen whales and warm water dolphins (especially common and striped) typically increase in abundance in Scottish waters in summer and autumn. Most other species are resident and show only local changes in distribution. Of these, the most notable are the breeding and moulting seasons for harbour and grey seals with the abundance of seals at sea declines during these times. Because of the different breeding regimes of these two species, the change is more marked in grey than harbour seals.

Marine mammals are seasonal breeders and it is likely that the limited swimming abilities and the naivety of calves / pups will put them at greater risk of collisions with renewable devices. Information on cetacean calf production is limited but generally positively correlated with water temperature (i.e. occurs in summer). Harbour seal pups enter the water in early summer and grey seal pups in late autumn.

6.3.2 Fish

There are two important issues here. Variation in day length, which during the winter with longer and darker nights restricts visually mediated behaviour leaving non-clupeoid fish at enhanced risk (see section 7 below). Distribution also varies seasonally with movements between spawning, feeding and overwintering grounds. Many species move inshore during the summer.

6.3.3 Birds

The seasonal patterns of foraging ecology of most species are very poorly understood, in particular ecology outside the breeding season. Marine birds are under greater foraging constraints in winter due to depressed food abundance, increased daily energy requirements, higher frequency of extreme weather events and shortened day length. Visibility during the day is also lower in winter. However, a number of groups are not present in the UK in winter (see section 3.3). The risk at different times of the season is extremely hard to assess but should reflect these two points. A tentative risk rating is given in relation to time of season in Table 14.

Table 14: Collision risk and season

Species group	Risk with season	Knowledge gaps
Divers	Greater in winter because abundance higher	Lack of data on year-round foraging ecology
Grebes	Greater in winter because abundance higher	Lack of data on year-round foraging ecology
Fulmar	Greater in winter because environment more severe	Lack of data on year-round foraging ecology
Manx shearwaters	No risk in winter because not present in the UK	Lack of data on year-round foraging ecology
Storm-petrels	No risk in winter because not present in the UK	Lack of data on year-round foraging ecology
Gannet	Lower in winter because less abundant	Lack of data on year-round foraging ecology
Cormorants	Greater in winter because	

Species group	Risk with season	Knowledge gaps
	environment more severe	
Red-necked phalarope	No Risk in winter because not present in the UK	Lack of data on year-round foraging ecology
Sea ducks	Greater in winter because abundance higher	Lack of data on year-round foraging ecology
Skuas	No risk in winter because not present in the UK	Lack of data on year-round foraging ecology
Gulls	Lower in winter for some species that are absent	Lack of data on year-round foraging ecology
Terns	No risk in winter because not present in the UK	Lack of data on year-round foraging ecology
Auks	Lower in winter for puffins that are largely absent; greater for little auks which are winter visitors; greater for common guillemots, razorbills and black guillemots because environment more severe	Lack of data on year-round foraging ecology

6.4. Water quality

6.4.1 Marine Mammals

The primary feature of water quality relevant to collision risks is turbidity. Evasion at close range is likely to be mediated for many marine mammal species by the visual cues provided by submerged devices. In other words, low turbidity (high visibility) environments are likely to give marine mammals more warning of an impending collision risk and allow them more options for escape. As well as vision, odontocete cetaceans use echolocation to navigate and while this sense is not significantly reduced by suspended matter in the water it is likely to be disrupted by air bubbles in the water column. Therefore the “visibility” in acoustic terms of marine renewable devices is likely to be reduced in areas where tidal mixing or surface waves are sufficient to entrain air bubbles into the water column.

6.4.2 Fish

Turbidity is the main issue here. Recent work by the Ecology department at SAMS in collaboration with colleagues in a European Union funded project *ETHOFISH* has demonstrated that many fish exhibit a preference for moderate turbidity and for example forage more effectively in turbid conditions (Meager and Batty, 2007 and also other papers in preparation). Our general conclusion is that small animals prefer turbidity as a refuge from predators but can still see their own prey at closer range. Large predators will not be able to function effectively in these conditions but turbines will continue to operate; this may lead to an increase in risk of collision.

If turbines are deployed in regions of moderate to high turbidity or if they increase turbidity not only will they increase the risk of collision due to their reduced visibility but also due to turbid waters being actively selected by many fish species. Larger visually feeding predators will perform less well in turbid conditions but turbine blades will of course not be affected.

6.4.3 Birds

The most relevant water quality issue to collision risk is the impact of renewable schemes on turbidity. Vision can be affected by small levels of turbidity (Strod *et al.* 2004). However, no data exist on collision risk in relation to turbidity. Diving species will be more at risk of collision in turbid waters than surface feeding species, and nighttime feeders more at risk than diurnal foragers. Table 15 reflects this with, for example, cormorants (exclusively diurnal divers) having a lower risk rating than diving groups that forage at night.

Table 15: Collision risk and turbidity

Species group	Risk from increased turbidity	Knowledge gaps
Divers	Moderate	No empirical data available
Grebes	Moderate	No empirical data available
Fulmar	Low	No empirical data available
Shearwaters	Low	No empirical data available
Storm-petrels	Low	No empirical data available
Gannet	Low/moderate	No empirical data available
Cormorants	Low/moderate	No empirical data available
Red-necked phalarope	Low	No empirical data available
Sea ducks	Moderate	No empirical data available
Skuas	Low	No empirical data available
Gulls	Low	No empirical data available
Auks	Moderate	No empirical data available

6.5. Flow characteristics

6.5.1 Marine Mammals

Many marine mammals (particularly harbour porpoises and bottlenose dolphins) are attracted to areas of high flow to forage. This may be because of higher prey density but also because of the energetic advantages set up by local discontinuities of flow rates. Renewable devices within these tidal streams may create greater discontinuities or disrupt existing ones. The greatest consideration in terms of collisions, however, is the reduction in manoeuvring options that result from moving within a tidal stream.

6.5.2 Fish

Fish are known to often accumulate by structures in regions of high water velocity and hold station swimming against the flow. This behaviour is typical of both marine and freshwater fish. This behaviour is to some extent an attempt to find regions of reduced water velocity (a velocity refuge) and therefore reduce energy expenditure. Fish will therefore accumulate around the supporting structures of marine renewable devices unless they are driven away by the noise and visual cues generated by moving parts. Accumulation very close to these structures could increase the risk of collisions with moving parts.

6.5.3 Birds

Most species are attracted to areas of high flow because of good foraging opportunities (Daunt *et al.* 2006b). Risk of collision will be increased if renewable schemes alter the flow characteristics, especially if such changes create new foraging opportunities for marine birds, since this may impact on the manoeuvrability and underwater swimming agility of the birds. Flow effects are likely to increase collision risk in particular in poor light conditions. However, no empirical data exist. Risk will be higher among diving than surface feeding species (Table 16). However, overall risk associated with change in flow characteristics is likely to be linked to the extent to which birds feed at night.

Table 16: Collision risk and flow characteristics

Species group	Impact of altering flow characteristics	Knowledge gaps
Divers	Moderate	No empirical data available
Grebes	Moderate	No empirical data available
Fulmar	Low	No empirical data available
Shearwaters	Low/moderate	No empirical data available
Storm-petrels	Low	No empirical data available
Gannet	Low/moderate	No empirical data available
Cormorants	Low/moderate	No empirical data available
Red-necked phalarope	Low	No empirical data available
Sea ducks	Moderate	No empirical data available
Skuas	Low	No empirical data available
Gulls	Low	No empirical data available
Terns	Low	No empirical data available
Auks	Moderate	No empirical data available

6.6. Proximity to other devices

Throughout section 6.6, we refer to the placement of the devices as in parallel or as in series. Figure 6 below illustrates the alignment of the devices.

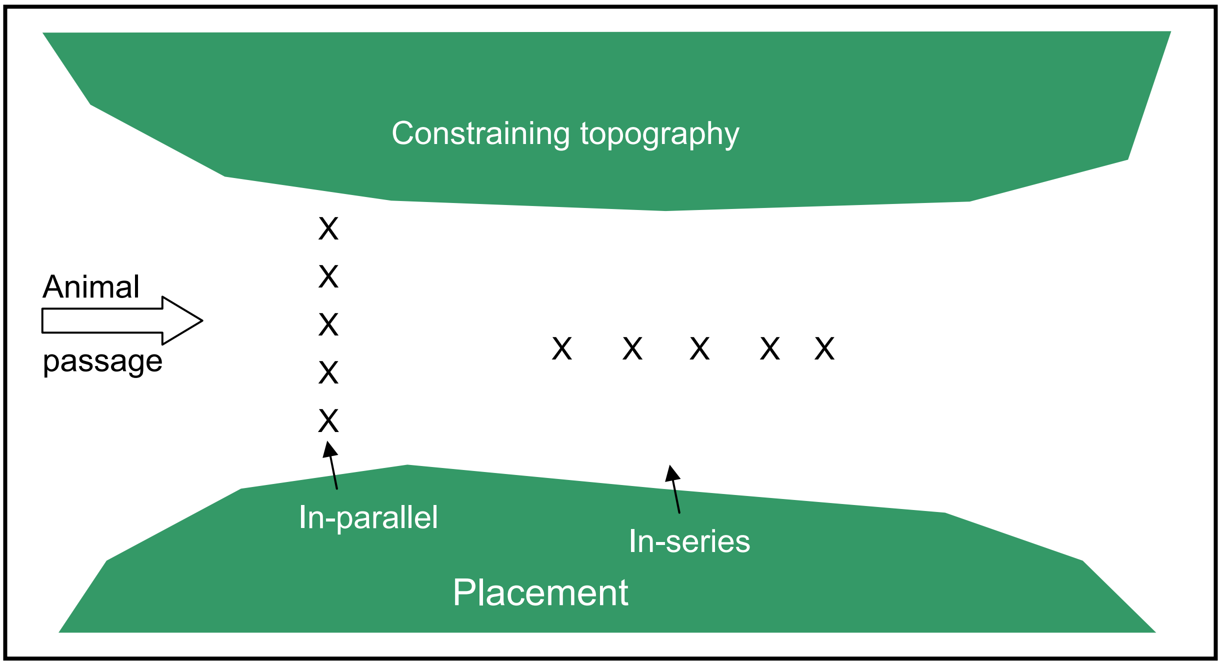


Figure. 6. Potential configurations of tidal or wave devices (X) in an area of constrained topography. Real configurations are likely to be more complex but will have components of these two spatial elements

The placement of several devices in proximity will complicate marine vertebrate collision risks in several ways. When the animals are at long range, they will provide a larger target and set of cues for animals to avoid (1) but also produce a larger combined area that will need to be avoided (2). At close animal-device range, multiple devices will produce a more complex and potentially confusing set of cues for approaching animals (3) and increase the number of collision risks (4) with some potential configurations creating traps (5) or ricochet affects (6) - where the avoidance/evasion tactics used to escape one device will guide an animal into the danger area of another.

In summary, multiple devises will produce greater cues at long range and have potential to reduce the number of animals getting into proximity. But once at close range they will present a more complex super-device to avoid with associated elevated collision risks.

The exact configuration of devices relative to one another is likely to make a considerable difference to their additive effects. In homogenous environments, simple proximity will be the primary issue but in areas constrained by topography or polarised by tidal flow, relative orientation will also be important.

6.6.1 Marine Mammals

6.6.1.1 In-parallel placement

In constrained areas, parallel placement (see Figure 6) will represent a linear barrier across a potential corridor. This it will reduce the possibilities for all animals passing through the area to avoid the devices and as a result increase the need for evasion tactics.

6.6.1.2 In-series placement

Unlike in-parallel placement, in-series placement for transiting animals will represent a similar target to avoid to that of a single device but should avoidance fail the collision risk and need for evasion by individual animals will be increased by the number of devices in the series.

6.6.2 Fish

6.6.2.1 In-parallel placement

Suitable gaps to allow avoidance and passage of fish between devices may be required. It is difficult to predict how large this spacing should be. Further research of fish behaviour and /or monitoring of prototype deployments will be required. We will need to know the extent of the area around a device from which fish may be excluded. Alternatively, if fish do not exhibit an avoidance response, large spaces between devices will reduce the number of fish encounters and, for schools of fish, should be larger than a school so that repeated encounters of fish on the edge of schools are avoided. Parallel arrays of sea bed mounted turbines with ducting structures between them (see Blue Energy Turbines, Appendix 2) may represent an enhanced impediment to passage.

6.6.2.2 In-series placement

Risk of collision will depend on the layout. An in line series may reduce risk if an encounter with the first device results in fish swimming away normal to the flow and thus avoiding subsequent devices. We cannot predict how likely such behaviour would be; further research is required. If turbines are deployed in 2 dimensional arrays, there may be a risk of fish (particularly pelagic schooling species) being trapped between devices or within the array reducing foraging activity and thus feeding.

6.6.3 Birds

Collision risk is likely to depend on the distance and orientation of devices, since these parameters will affect the extent to which marine birds can perceive and/or avoid the devices.

Device spacing will be important. Increasing spacing will increase the overall area of the scheme for a given number of devices, thereby potentially increasing the potential foraging area avoided by birds. However, it may also have a positive impact on collision risk if it increases overall visibility and increases options for safe avoidance by providing larger refuges between devices.

With respect to collision risk underwater, precise foraging methods of marine birds will be critical in determining risk. However, they are poorly understood. Dives last from a few seconds to a few minutes but the structure of search paths is largely unquantified. Avoidance behaviour and the impact of turbine-induced turbulence on trajectory are also poorly understood. Two main designs of array orientation are considered

6.6.3.1 In-parallel placement

Parallel orientation is preferable if marine birds avoid obstacles by changing heading as opposed to, for example, changing heading briefly before reversing direction to revert to the original path, which may put them at greater collision risk if devices are in parallel. Parallel orientation may also be more problematic if turbulence caused by moving parts draws birds into the slipstream directly behind the device.

6.6.3.2 In-series placement

If tidal turbulence draw birds into the slipstream, series placement may be preferable for reducing collision risk. In addition, if birds avoid turbines by a brief heading change followed by a reversal, series placement is also likely to be advantageous, providing there is sufficient spacing between devices to carry out the manoeuvre. However, series placement may increase collision risk if birds change overall heading on detection of a device, if by doing so they increase the likelihood of approaching an adjacent device.

To fully understand the relative risk of parallel and series placements, avoidance behaviour underwater and turbulence effects must be studied in detail.

If several rows of devices placed in series are being considered, collision risk will depend on whether each series is in line or staggered. Once again, the relative risk will depend on avoidance behaviour and impact of such an orientation of devices on turbulence.

To understand the risk of flying birds colliding with above-surface structures, we can draw on what has been learnt from wind farms. Device spacing and orientation is important in enabling birds to fly between devices or circumnavigate the entire scheme (see section 2.3.2).

The relationship between number of devices and collision risk may be complex and non-linear. A decline in rate of increase in risk with increasing number of devices may be expected if rate of detectability increases. For example, a scheme comprising 11 devices may not be 10% more visible than a scheme comprising 10 devices to a marine bird. In contrast, an increase in rate of risk may be expected if avoidance behaviour or turbulence diverts marine birds from one device into close proximity with another. This latter scenario will depend on device spacing, but it is possible that, for example, two devices may be more than twice as likely to result in a collision than one device. To quantify the shape of the relationship between number of devices, device spacing, device orientation and collision risk requires empirical data and modelling.

These issues are likely to be more pertinent to diving than surface feeding species. Thus, the overall collision risk assessment in Table 9 can be used to summarise relevance of these issues to the different marine bird groups, with the exception of the northern gannet whose relevance to the above section is likely to lie between diving species and surface feeding species.

6.7. Topography

6.7.1 Marine Mammals

6.7.1.1 Open Waters

Device placement in homogeneous environments provide animals with the most options for avoidance and will therefore, with all else being equal, incur the lowest collision risks. The impacts of devices on marine mammal habitat exclusion are likely to be localized to the area of placement.

6.7.1.2 Sounds

There are many areas between land masses used by marine mammals off the coast of Scotland. Because these constrictions join water masses they are often used by marine mammals as transit corridors and because they similarly used by fish their bottleneck properties are attractive to marine mammals for foraging. Many of these areas therefore have higher marine mammal densities than others (e.g. Hastie et al. 2004). If placement in these areas leads to avoidance then such installations may have significant impacts on the downstream area use as well as potentially lost foraging opportunities. However, because of the transit and foraging value of such areas, animals may be particularly resistant to avoidance and therefore place themselves at higher collision risk.

6.7.1.3 Sea loch entrances

Interactions between marine mammals and devices placed at the mouths of sea lochs are likely to be similar to those for sounds but because sea lochs are blind ended they will only impact local rather than transiting species.

6.7.2 Fish

6.7.2.1 Open Waters

Deployment of devices in the open sea will present the least risk unless the spacing between devices increases the risk of encounter (see above). However, water depth at the point of deployment will be critical turbines need to be far enough off the bottom to reduce interaction with benthic fish.

6.7.2.2 Sounds

Deployment within sounds increases risk of encounter and subsequent collisions. Deployments of single devices, provided the sound is considerably wider than the turbine or wave generating device would not be of high risk but multiple deployments are likely to present a much greater risk per device – greater than the sum of the parts.

6.7.2.3 Sea loch entrances

Locating turbines in sea loch entrances could prevent passage through the entrance into or out of a sea loch and therefore exclude fish from a loch or cause thier retention within the loch. Although it is unlikely that complete exclusion or retention will result, a reduction in numbers passing through could have a significant effect on the diversity of sea loch communities. The shallow sills at sea loch entrances limit the possibility of mitigation by allowing a space above and bellow a turbine for free passage of fish. Alternatively if fish do not exhibit an avoidance reaction to the turbines there will be an increased risk of collision during passage through these areas. Salmon and other anadromous species would be at greatest risk during their spawning migrations.

6.7.3 Birds

6.7.3.1 Open Waters

The above concerns are likely to be of general relevance to schemes placed in open waters, which will potentially be equally visible from all directions (device orientation notwithstanding) both above and below the water surface to marine birds. However, marine birds do not fly evenly and in all directions across open water, and are aggregated in relation to oceanographic conditions and prey availability (Daunt, et al, 2006b). Thus, detailed data on the use made of the area by birds, including travelling and underwater foraging trajectories, are required.

6.7.3.2 Sounds

The device distance and orientation are likely to be particularly important where topography restricts options for bird avoidance behaviours e.g. sounds and channels. This is true both for birds in flight and underwater. In such cases, detailed data are required on how birds use the area. Sounds are used for both activities by marine birds (Daunt 2006c). For birds in flight, in the majority of cases, heading will be longitudinal to the sound, so a parallel design is likely to be preferable to a series design for schemes that protrude above the sea surface. It is less clear which design is likely to increase collision risk among underwater foraging birds. The rationale is set out in Section 6.6.3, although that section was written on the understanding that no topographic restriction was present. That section concluded that it is not clear whether parallel or series placement incurs a lower risk to birds underwater. However, all other things being equal, devices placed in series are more likely to impact on marine birds in sounds and channels since topography will be more likely to restrict options with such a design, especially in cases where the scheme spans the width of the sound or channel.

6.7.3.3 Sea loch entrances

As above, a detailed understanding of how birds used sea loch entrances for travelling and foraging is required. Sea loch entrances may in many cases be regions of high tidal currents, so are likely to be important areas for foraging (Daunt 2006c). The relative risk of parallel and series placement is unclear for foraging birds, but as with sounds (section 6.7.2) the added component of topography may result in a greater risk associated with a series placement, in particular if it spans the width of the sea loch entrance.

These issues are likely to be more pertinent to diving than surface feeding species Thus, the overall collision risk assessment in Table 9 can be used to summarise relevance of these issues to the different marine bird groups, with the exception of the northern gannet whose relevance to the above section is likely to lie between diving species and surface feeding species.

7. Underwater cues for marine species

7.1. Sight

7.1.1 Marine Mammal

All Scottish marine mammals use vision to navigate in their environment, avoid obstacles and forage. However, unlike many birds, marine mammals forage throughout the diel cycle and in very turbid waters and therefore they are able to function as predators in very low light levels including at night. Vision is a primary sense for seals, whose large eyes face forward giving them binocular vision. Cetacean eyes are placed on the sides of the head and so give a more panoramic view. The visual fields do overlap but binocular vision has not yet been demonstrated. Colour vision in cetaceans and pinnipeds is limited and skewed to the blue-green region of the spectrum. The underwater coloration of marine renewable devices may therefore appear different (more or less obvious) for these species than to ourselves. Table 17 details the impact of reduction in visibility.

Table 17. Impact of reduction in visibility

Species group	Impact of reduction in visibility	Knowledge gaps
Seals	High	
Porpoise	Medium	Low light level vision capabilities
Delphinids	Medium	Low light level vision capabilities
Large odontocetes	Medium	
Mysticetes	Medium	Low light level vision capabilities

7.1.2 Fish

Visual acuity and sensitivity varies between species depending on the behavioural requirements of a species habitat and behaviour. Regardless of the role of vision infeeding behaviour, most species have adequate visual acuity to detect predator attacks as long as light permits. The spectral sensitivity of fish varies with the depth that they occupy. Most fish occupying the relatively shallow waters where marine renewable generating devices will be deployed have spectral sensitivities extending from 400 to 650 Nm and teleost fish have cones in their retinae providing colour vision for teleost fishes (Bone et al. 1995). The book edited by Douglas and Djamgoz (1990) provides many reviews and sources of data on fish vision. Figure 7, taken from this book, shows the spectral sensitivity of the visual pigments of a typical coastal marine species.

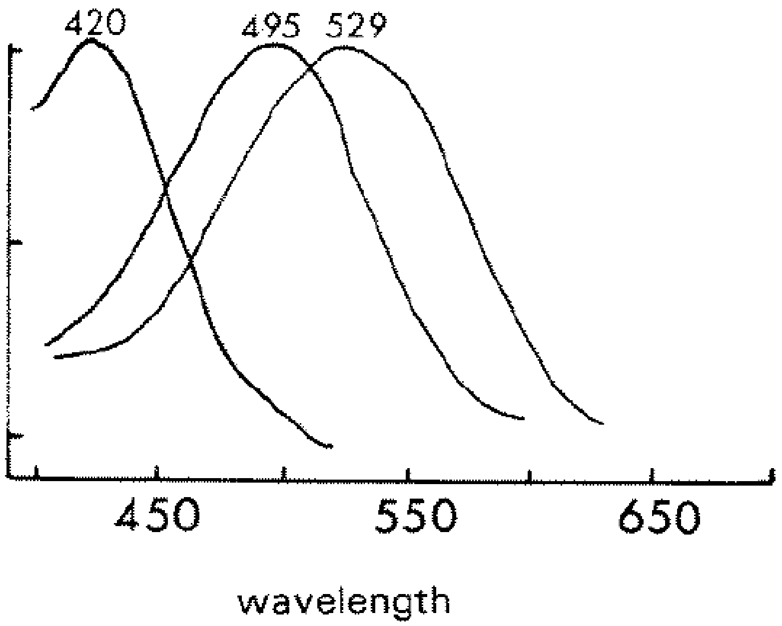


Figure 7: Spectral sensitivity of typical teleost visual pigments.

7.1.3 Birds

All marine birds use sight to obtain prey, and have adaptations for amphibious foraging (Martin 1998; 1999; Martin & Prince 2001). Most species are predators of fast-moving prey and have binocular vision (the main exception among the species described here being the marine ducks, which typically forage on more sessile prey such as bivalve molluscs). However, very little empirical data exist on the importance of visibility, but it is likely to depend on the type of prey and the extent to which birds can switch to tactile foraging (see section 7.6). Table 18 summarises the likely impact on birds if visibility is affected by marine renewable schemes.

Table 18: Impact of reduction of visibility

Species group	**Impact of reduction in visibility**	**Knowledge gaps**
Divers	Very high	No empirical data available
Grebes	Very high	No empirical data available
Fulmar	Very high	No empirical data available
Shearwaters	Very high	No empirical data available
Storm-petrels	Very high	No empirical data available
Gannet	Very high	No empirical data available
Cormorants	Very high	No empirical data available
Red-necked phalarope	Very high	No empirical data available
Sea ducks	Very high	No empirical data available
Skuas	Very high	No empirical data available
Gulls	Very high	No empirical data available
Terns	Very high	No empirical data available
Auks	Very high	No empirical data available

7.2. Sound

7.2.1 Marine Mammals

Marine mammals are known to have acute hearing capabilities. These senses are both passive, meaning that they listen to sounds already in the environment and active, meaning that they produce their own sounds and interpret the returning echoes. Toothed cetaceans are known to use both passive and active listening when navigating and foraging. The peak energy in echolocation signals are typically at high frequencies giving these animals good fine scale discrimination abilities. However, unlike vision the information derived from echolocation is limited by the update frequency of the sound pulses and hence their perception of objects has a stroboscopic nature. It is unknown how echolocating animals will therefore perceive a rotating objects such as turbines. In addition, update rates are limited by the travel time of sound. Detection of distant objects requires use of a longer inter-pulse interval than close objects and small odontocetes are known to attempt to minimize their inter-pulse intervals when foraging. A consequence of this is that their active echolocation is continuously tuned to the distance of interest but with the sacrifice of being able to detect more distant objects. Thus while these animals may be capable of detecting distant objects they may be effectively blind to them when foraging on nearby prey. Although there has been much discussion of the capabilities of seals and mysticetes to echolocate, it seems that their use of sound to locate objects in the water column is primarily passive. The hearing sensitivities of these species groups differ significantly with the toothed cetaceans (porpoises, delphinids and large odontocetes) being predominantly high frequency specialists; mysticetes thought to be low frequency specialists and seals to hear a broad range of frequencies in between. Table 19 details current knowledge gaps.

Table 19: Marine mammal species groups use of sound knowledge gaps.

Species group	Magnitude of impacts	Knowledge gaps
Seals	High	Abilities to detect renewable device acoustic signatures
Porpoise	Medium	Perception of rotating objects using echolocation
Delphinids	Medium	Perception of rotating objects using echolocation
Large odontocetes	Medium	Perception of rotating objects using echolocation. Hearing abilities
Mysticetes	Medium	Hearing abilities

7.2.2 Fish

Fish mechanoreception is very sophisticated and involves both the labyrinth (inner ear) and the lateral line system; for reviews see Blaxter (1987) and Bone et al. (1995). This acousticolateralis system has been most extensively studied in the herring (Denton and Blaxter, 1976, Denton et al, 1979) and further extended by work on many other species. Audiograms have been produced for many species of fish. Figure 8 summarises the general frequency and sensitivity ranges of audiograms for three classes of fish: the clupeoids (herring, sardine, sprat, anchovy etc.), the ostariophysi and non-ostariophysian fish. The clupeids and ostariophysi are most sensitive and can hear a wider range of frequencies than non-ostariophysian fish. The enhanced sensitivity of clupeoid fish to very low frequencies is particularly important for their ability to detect sounds emitted by moving underwater devices and to avoid them (Blaxter and Batty, 1985). It should be noted that the superorder Ostariophysi includes the majority of the worlds freshwater fish species but with very few living in the marine environment.

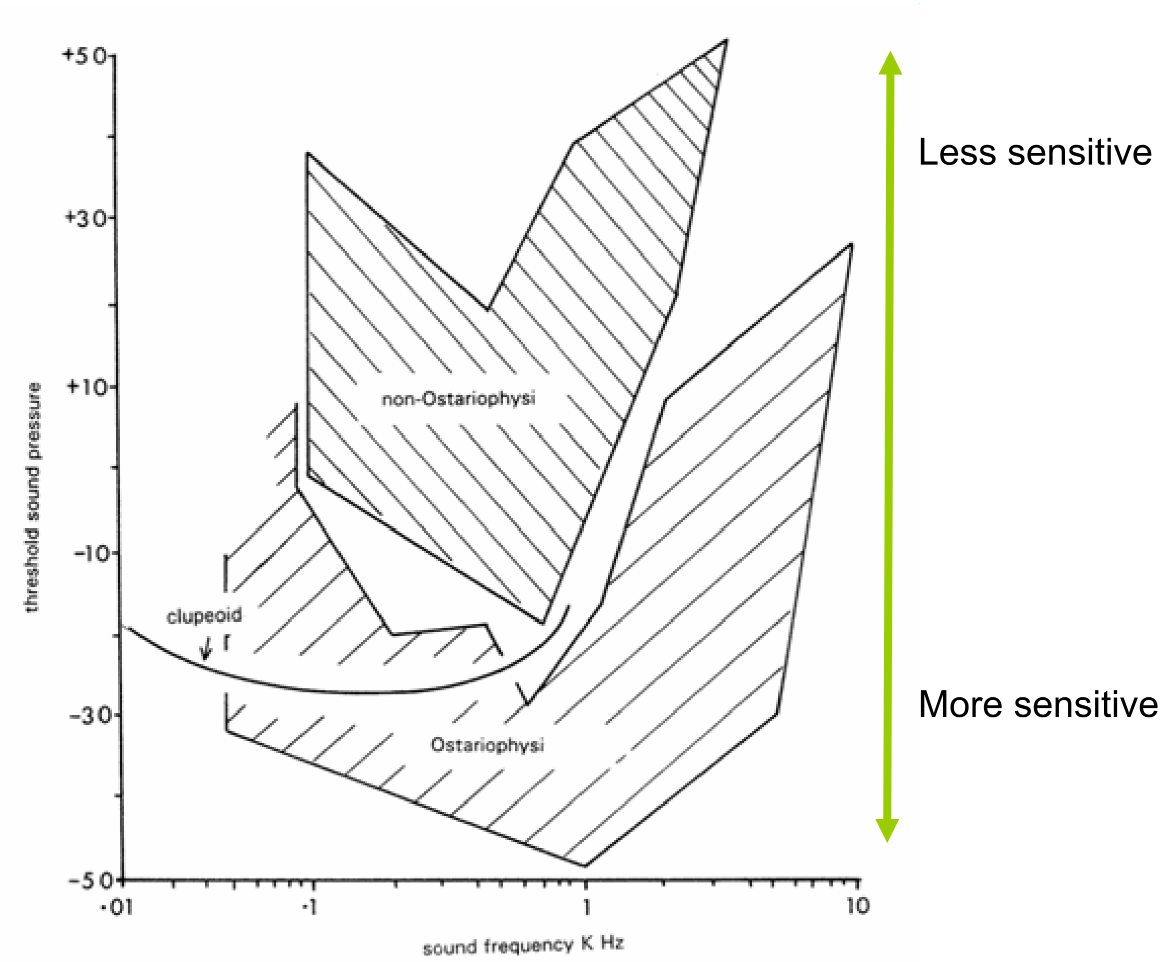


Figure 8: A comparison of the audiograms of different groups of fish (from Blaxter and Hunter 1982).

7.2.3 Birds

It is evident from the behaviour of birds on land that they have acute hearing. However, little is known about the importance of hearing underwater and whether noise can disorientate birds or adversely affect their foraging success. Generally, diving species are likely to be more adversely affected than surface feeding birds (see Table 20).

Table 20: Impact of noise

Species group	Effect of noise on foraging	Knowledge gaps
Divers	Moderate	No empirical data available
Grebes	Moderate	No empirical data available
Fulmar	Low	No empirical data available
Shearwaters	Low	No empirical data available
Storm-petrels	Low	No empirical data available
Gannet	High	No empirical data available
Cormorants	Moderate	No empirical data available
Red-necked phalarope	Low	No empirical data available
Sea ducks	Moderate	No empirical data available
Skuas	Low	No empirical data available
Gulls	Low	No empirical data available
Terns	Low	No empirical data available
Auks	Moderate	No empirical data available

7.3. Mechano-reception

7.3.1 Marine Mammals

Because of logistical difficulties in measuring the stimuli that might be used by marine mammals for mechano-reception, little is known about this sense. Our best information concerns seals, which have been shown to use their vibrissae to sense small-scale hydrodynamic vibrations and flow vortices in the water column. They are thought to use this sense to track the wake of prey organisms swimming through the water column. Its use for navigation or detecting larger objects is unknown. The existence of a similar sense in cetaceans is unknown.

7.4. Electro-magnetism

7.4.1 Marine Mammals

Little is known about the abilities of marine mammals to detect or use an electromagnetic sense. The organ(s) used to receive these signals need not be large or at any obvious location in the body so searches for such organs have not been successful. There is equivocal evidence that mass stranding sites are linked with particular geomagnetic features but the definitive use of this sense has yet to be established.

7.5. Tactile foraging

Several species of marine bird use tactile methods of finding immobile prey during day light (e.g bivalve molluscs, sheltering fish). Furthermore, several studies have expressed perplexity at the low light levels at which marine birds may forage in at night (Martin & Prince 2001; Grémillet *et al.* 2005a). It is likely that marine birds switch to tactile foraging strategies, for example by scanning the water column or sea floor with their bills until they make contact with prey (Grémillet *et al.* 2005a). Such a strategy may be particularly effective in winter when sea temperatures are lower and fish less mobile. If marine birds are foraging at night using tactile methods i.e. where visual acuity is very low they may be particularly susceptible to collision from wave or tidal schemes. Table 21 summarises the importance of tactile foraging and, by inference, the potential risk to species that may use an area with high turbidity or at night because they are not using vision to find prey, and are therefore at greater risk of collisions.

Table 21: Importance of tactile foraging

Species group	Importance of tactile foraging	Knowledge gaps
Divers	Moderate	No empirical data available
Grebes	Moderate	No empirical data available
Fulmar	Low	No empirical data available
Shearwaters	Low	No empirical data available
Storm-petrels	Low	No empirical data available
Gannet	Low	No empirical data available
Cormorants	Moderate	No empirical data available
Red-necked phalarope	Low	No empirical data available
Sea ducks	High	
Skuas	Low	No empirical data available
Gulls	Low	No empirical data available
Terns	Low	No empirical data available
Auks	Low/moderate	No empirical data available

7.6. Chemoreception

7.6.1 Marine Mammals

Olfaction in marine mammals is severely restricted in comparison to species groups such as fish. In seals it is used to detect con-specifics and predators in air on haul-outs but nothing is known about its use underwater. There is no firm evidence that cetaceans use this sense to navigate or orientate underwater.

7.6.2 Fish

Fish use chemoreception extensively for locating prey and for prey searching behaviour. They are able to detect and move up concentration gradients; this behaviour develops early in life during the larval phase (Dempsey,1978). Some benthic and/or nocturnal species rely heavily on olfaction for foraging, sole being a good example (Batty and Hoyt, 1995; Harvey et al, 1992). The use of olfactory information would appear to be integrated with the use of superficial neuromasts (Harvey, 1996). Many species use gustation to detect prey. Cod and other gadoid fish, for example, use superficial taste buds on the barbel and paired fins (Harvey and Batty, 1998). Olfactory signals are also used for commutation within fish shoals. Alarm substances have been extensively studied.

7.6.3 Birds

Northern fulmars, being members of the Procellariformes bird family, use olfactory cues to locate food over large distances (Nevitt 1999; Nevitt *et al.* 2006). It is believed that olfactory cues are sensed principally through air, but olfactory cues underwater may also be used.

8. Responses and escape options

Responses by animals to sensory cues may be on variety of scales but responses can be placed into either of two categories depending upon the perceived threat; avoidance or evasion. In general, avoidance occurs on a larger scale relative to the size of the responding animal. In the context of predator/prey interactions, avoidance responses are intended to reduce encounters by avoiding contact with the predator. For interaction with marine renewable generating devices the response would be to avoid the area close to the device. By excluding themselves from the region of the device collisions do not occur. In contrast to avoidance responses, evasion is defined as the direct response to an attack or perceived attack. Fish and also many invertebrates perform escape responses to such sensory cues, often mediated neurologically as reflex responses. In the context of marine renewable energy devices such responses would occur during a close encounter with a moving part such as a turbine blade and lead to a bout of maximum speed swimming away from the stimulus direction.

8.1. Marine Mammals

Being highly mobile underwater, marine mammals have the capacity to both avoid and evade marine renewable devices. This is as long as they have the ability to detect the objects, perceive them as a threat and then take appropriate action at long or short range. However there are several factors that compromise this ideal scenario.

1) **Detection failure**: The broad acoustic, visual and hydrographic signatures of marine renewable devices are at present poorly understood. Other than the visual appearance of devices, the need for efficient energy conversion will encourage the development of devices that produce as little extraneous energy signatures as possible. This is in direct contrast to any warning stimuli required by the animals at risk. There is therefore a key conflict between the stimulus output from the devices and perceptual acuity of the animals at risk. The distances that animals perceive, and hence can take avoiding/evasive action will therefore depend on this ratio. Environmental circumstances such as darkness, turbid water, background noise from rough weather or ship noise may all impact perception distances and hence escape options.

2) **Diving constraints**: Marine mammals are accomplished divers and typically dive close to aerobic dive limitations. This means that animals do not have unlimited time and manoeuvrability underwater and may have few options other than upwards at the end of a dive. In addition to this, buoyancy varies among marine mammals from negative to neutral to positively buoyant. Irrepressible positive buoyancy is a particular problem for whales such as right whales when surfacing from depth and therefore constrains manoeuvring options.

3) **Attraction**: It is quite possible that marine renewable devices will not be perceived as a threat but instead attract marine mammals as a result of devices acting as Fish Aggregating Devices or artificial reefs. It is also

possible that species such as seals and small delphinids will be attracted to renewable devices should they injure or disorientate their prey.

4) **Confusion**: We do not yet know how marine mammals will respond to perceiving a marine renewable device, especially one with moving parts. It is quite possible that they will simply swim around it but it is also possible that they will respond in an inappropriate way. This is particularly likely for devices with gaps that move relative to the animal's trajectory such as ducted turbines. Alternatively, in arrays, an escape response from one device may put the animal into a collision path with another – the so-called Ricochet effect.

5) **Distraction**: Marine mammals undertake a variety of activities underwater from simple transits, social interactions to complex foraging tactics. It is likely that during some of these occasions the animals' awareness of objects in the water column will be compromised. A particular example is the range detection problem encountered by echolocating cetaceans. When acoustically locked onto prey they reduce the interpulse intervals of their echolocation clicks such that they become acoustically blind to objects at greater distance than their intended prey. Therefore cetaceans feeding around submerged devices run an enhanced risk of close encounters without active acoustic detection.

6) **Illogical behaviour**: It is commonly believed that marine mammals have a high capacity for intelligent behaviour and as such would act logically when faced with a threat. However, there are many examples where this is not the case. The reticence of dolphins to leap the head line of tuna nets (see section 2) is a prime and ecologically significant example.

8.2. Fish

8.2.1 Avoidance

Rather than avoidance some species of both demersal and pelagic fish may be attracted to structures where prey are more plentiful or that provide a degree of cover (shelter from predators) but the sound and visual disturbance of moving parts may cause some species to avoid the area around a device. It is particularly difficult to predict exactly how any species may behave. The hearing and visual capabilities of many species are well documented (see above) but the sounds that a particular device emit and resulting fish behaviour are more difficult to predict.

Work on herring behaviour (Blaxter and Batty, 1985) has demonstrated that, on a small scale this species, and by implication many others, can in the absence of light react to the low frequency sounds emitted by moving underwater objects. These experiments, however, demonstrated that these responses depended on the interaction of sound pressure (detected by the labyrinth) and displacement (detected by neuromasts in lateral line system). Information on range and direction are provided by this integrated sensory system but only in the "near field" (Figure 9) where displacement is significant signal. The extent of the near field varies with frequency, extending much further at lower frequencies; to 50 metres at 5 Hz, one of the frequencies used by Blaxter and Batty (1985) in their experiments. It is clear, therefore, that low frequency sounds have the potential to initiate avoidance behaviour.

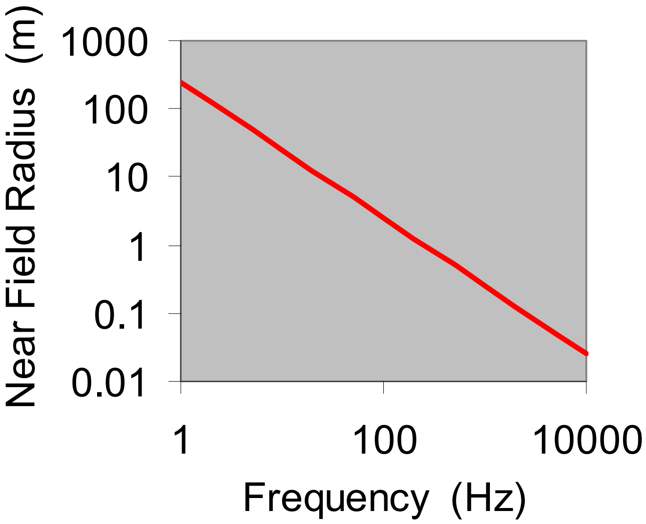


Figure 9: The effect of sound frequency on the extent of the "near field" within which information of range and direction can be inferred from the relationship between sound pressure and displacement.

8.2.2 Evasion

Fish are able to evade threatened collisions or attacks by making startle responses. These responses are often called C-start responses because the response begins with a contraction of all muscle on one side of a fishes body leading to a sharp turn followed by a bout of swimming at maximum speed. The role of C-start responses in predator-prey interaction has been extensively studied in a wide range of species of fish (for reviews see Domenici and Blake, 1997; Batty and Domenici, 2000). This behaviour, however, is not exclusive to predator evasion and will be the means by which fish can evade collisions during a close encounter with moving parts of marine renewable devices. The typical C-start behaviour can be initiated by mechanical (sound) stimuli, by looming visual images or by touch. Transient stimuli rather than a continuous stimulus evoke these responses. Such stimuli are likely to be provided by turbine rotor blades. For herring, escape behaviour is mediated by transient sound stimuli by not by continuous sounds (Blaxter, et al, 1981). Responses to sound stimuli are evoked, following detection of sound in the labyrinth, by a reflex response. There is a direct connection between the inner ear and the Mauthner cells in the reticulospinal system in the brain stem. Mauthner cell firing can be gated, suppressing responses during some locomotor manoeuvres or due to repeated stimulation; the physiological mechanism underlying habituation.

For fish, vision can also be involved in their predator evasion behaviour. Visually looming objects trigger escape behaviour in many, if not all species. This behaviour has been extensively studied, for example by Dill (1974). Behavioural experiments on herring (Batty, 1989) demonstrated that fish respond to primarily to edges moving horizontally and much less to edges moving in the vertical direction. A finding confirmed by electrophysiological studies on fish retinae (Galand and Liège, 1975) and in other behaviour experiments which demonstrated a greater response rate to attacks by laterally compressed predators (Webb, 1982), the shape of most piscine predators. Fish are therefore likely to respond to the visual stimuli provded by turbine rotor blades. Horizontal axis turbines will, however, present a particular problem for fish (and probably mammals too) in that they only present a good looming image for part of their circular trajectory.

Escape responses of schools are coordinated following simple rules (Domenici and Batty, 1993, 1997). In general all fish will move in the same direction which is appropriate for escape from predator attacks but with turbine blades, although fish nearest to the blade at the initiation of response will move away others may be carried directly into the path of the blade thus turning the usual advantage of schooling in predator prey interaction into a disadvantage when compared with the performance of solitary fish.

It is essential that the sound and visual stimuli that are produced by turbine blades are studied and considered in the light of what is known about fish escape behaviour. It may be necessary to make some modifications in order to ensure that fish have the appropriate cues to ensure that escape responses are triggered.

All C-start escape responses, regardless of the sensory stimulus that evokes them, depend for their success on the latency of the response – the time between stimulus presentation and the onset of escape swimming – and maximum burst swimming performance. The latter is predictable. Batty and Blaxter 1992), using data from their experiments on larval fish and other data from adult fish (Wardle, 1975) were able to derive a simple model for prediction of tail beat frequency and hence maximum swimming speed from fish length and ambient temperature. This knowledge, together with turbine blade movement parameters, could be used to predict the probability of collision evasion during encounters between fish and marine renewable devices. The study of killer whale predation on fish (reported in section 2.2.4) is a good example of the use of such predictions to understand the killer whale feeding mechanism; the same approach can be used with fish rotor blade collision evasion.

8.3. Birds

Marine birds have means of escaping moving or stationary hazards. The response of marine birds to a wave or tidal scheme will depend on whether it is detected above or below the surface and how close to the object is before the animal detects.

Above the surface: If schemes are visible from above the surface birds in flight will probably operate broadly similar avoidance tactics to those employed when encountering offshore wind farms i.e. by taking alternative flight routes and avoiding obstructions to a greater degree at night (Desholm & Kahlert 2005).

Below the surface: Similar avoidance tactics are likely to be employed by diving birds when they detect a stationary or moving object as flying birds when detecting a wind turbine. More drastic avoidance behaviours are likely to be required if an object is only detected very late, especially if the bird is in the path of a turbine blade. Birds have a moderately fast burst speed which, although considerably slower than the speed of the outer edge of blades (Fraenkel 2006), would enable escape under many situations where the bird manages to move out of the path of the blades.

9. Ecological implications (feeding, breeding, migration, population status)

9.1. Disturbance / avoidance

9.1.1 Marine mammals

There is a high potential that marine mammals will avoid marine renewable devices. The magnitude of these reactions will depend on the species and any sensory output from the devices. Species like harbour porpoises tend to be wary of novel installations where as seals may be positively attracted. It is likely therefore that the more timid species or those individuals that have had previous negative interactions with devices will show the strongest avoidance reactions. This behavioural response is likely to have little ecological impact unless it constitutes habitat exclusion whereby animals are driven from key areas for their foraging, breeding, transits or resting. The geographic placement of renewable devices is therefore key to habitat exclusion issues.

There has been much research work on disturbance impacts on marine mammals. Many human activities are known to change pinniped and cetacean behaviour on the short term but longer term impacts are generally less well understood. Of the most critical impacts of disturbance, the energetic penalties of repeatedly swimming around a disturbing object and habitat exclusion appear to be most relevant to disturbance and avoidance. Another consequence, that has been little studied, is the increased risk of attack from predators in disturbance situations.

9.1.2 Fish

It is possible that avoidance reactions will exclude fish from a larger area than necessary to avoid collisions. Such behaviour will protect some smaller prey species from predation and therefore alter community structure locally. Larger animals are more likely to be excluded and therefore smaller animals will be provided with a refuge. This effect could, depending on the type of device, the numbers and pattern of deployment provide a refuge to fish from marine mammal and bird predation. Generally, the smaller the species the greater the advantage; see exploitation below

9.1.3 Birds

Evidence from offshore wind farms is that they cause a proportion of individuals and species to avoid the area (Garthe & Huppop 2004; Desholm & Kahlert 2005). It is possible that the same would be the case with tidal and wave schemes, in particular because they are likely to overlap with favoured foraging areas of many species of marine bird (Daunt *et al.* 2006b).

The extent to which wave and tidal schemes could have an indirect impact on marine birds is likely to depend on the size and number of schemes, the sensitivity of these habitats to those schemes, and the importance of these areas as foraging habitat for the bird species in question. There may be immediate impacts on foraging, or more far-reaching consequences for bird populations. The latter will depend on the time of year. For example, altering habitats during the breeding season may impact on adult and offspring survival, whereas impacts outside the breeding season are more likely to affect over-wintering survival of immature and adults birds.

9.2. Injury

9.2.1 Marine mammals

Collisions between marine mammals and devices are likely to have a variety of outcomes. Acute effects will range from minor injuries such as abrasions through to temporary or permanent debilitation (internal injuries, surface wounds or damage to delicate organs such as eyes or mandibles) to more significant injuries (major cuts, amputations or internal trauma). Depending on severity and bodily location these injuries may result in recoverable injury, long-term debilitation, delayed or instant mortality. Clearly, debilitation or deaths are significant concerns but their manifestation may vary considerably. Marine mammals that die rapidly after a collision event are likely to strand or appear in the vicinity of the devices and therefore there is a possibility of linking the injuries to the cause. However animals that sustain severe injuries that are not instantly fatal may travel considerable distances before succumbing or die of complications (infection, starvation etc) rather than the original collision. These types of injuries are likely to be more common than those causing instant mortality but ironically will be more challenging to detect.

Of most obvious concern are impacts from turbine blades or downward strikes from floating structures in heavy seas. Marine mammals are relatively robust to potential strikes as they have a thick sub-dermal layer of blubber that would potentially defend their vital organs from the worst of any blows. However the coverage of this tissue is not even and the head is particularly vulnerable. Furthermore evidence from ship-strikes suggests that for impacts with large objects, a blubber layer is insufficient.

It is not known what forces are required to fatally injure marine mammals but road traffic research may provide some useful information that, with care, could be applied. Studies of seals killed by blows from killer whales and also the fatal strikes on harbour porpoises by bottlenose dolphins could be also informative (Ross and Wilson, 1996). In terms of minor collisions, seal epidermis is considerably more resistant to abrasion than that of cetaceans.

9.2.2 Fish

Collisions with objects moving with velocities greater than 8 $m.s^{-1}$ stun fish, as shown during work on killer whale feeding. Turbine tip velocities of 12.5 $m.s^{-1}$ (Fraenkel 2006) and with velocities greater than 8 $m.s^{-1}$ for half the radius of a turbine will result in any collisions being fatal.

Demersal species of fish are resistant to abrasion injuries and are therefore at little risk from abrasion against fixed structures. Pelagic species, for example mackerel and herring do not normally encounter structures. Abrasion injuries cause scales to lost resulting in osmotic stress and in many cases ultimately death. Devices with ducting particularly venturi devices present a risk of abrasion injuries to pelagic fish.

9.2.3 Birds

Collisions may result in death. Alternatively, catastrophic injury could take place. Marine birds extend appendages (wings, feet or both) underwater to propel their body or steer. These appendages are likely to be the most vulnerable part of the body to potential injury. A bad injury or break to an appendage that is critical to forging would obviously have a serious impact on the bird.

The extent to which disturbance, avoidance and injury will impact on population size and migration are not possible to assess without empirical data on injury and death rates as a result of tidal and wave schemes in relation to age and time of year.

9.3. Exploitation

9.3.1 Marine mammals

It is highly likely that marine mammals will exploit marine renewable devices for their own ends. Seals are likely to haul-out on surface structures and seals and small delphinids are likely to exploit the fish aggregating tendencies of structures for foraging opportunities. Furthermore if such devices kill or injure fish or squid then seals and delphinids are likely to scavenge around these installations. While potentially being a positive outcome for these species, being attracted to devices may put them at higher collision risk.

9.3.2 Fish

Structures, moorings and foundations will essentially be artificial reefs and will be colonised. SAMS work on artificial reefs will provide good background information on the likely succession of colonising organisms. However, these reefs will only function naturally if the moving parts are sufficiently above the fixed colonised structure. The moving parts may exclude larger predators and therefore lead to a different community structure from other artificial reefs. In effect they may be artificial reefs with built in large predator exclusion properties.

10. Potential for mitigation

Table 22 outlines a series of potential mitigation measures to reduce the probability and severity of collisions. The applicability of the measures we have suggested will depend heavily on the device design, location and species at risk.

Mitigation measures that have potential to increase the options for avoidance are desirable as they will reduce the number of close encounters between device and animal. However they also have to be considered in relation to their potential for habitat exclusion. For example, loud underwater acoustic alarms may give marine mammals or fish good warning of renewable devices but if too loud they may banish the animals from valuable habitat.

Table 22: Potential mitigation measures. Dark shading signifies relevance to species groups.

Aim	**Mitigation**	**Comments**	**Species group**		
			Marine mammals	**Fish**	**Birds**
Reduce encounter risk	Location of device relative to the bathymetry	Ensure space is left around the device	■	■	■
	Device design choice	Scale of device appropriate for area and species present. Certain devices designs may be easier to detect than others.	■	■	■
	Location choice	To avoid priority areas *e.g.* significant spawning, migration or feeding grounds.	■	■	■
	Closed seasons	To protect areas at vulnerable seasons *e.g.* seal pup first foraging trips.	■	■	■
Raise device(s) conspicuousness	Device visibility	Blade colour or lighting (but may act as an attractant). Visual acuity of target species needs consideration.	■	■	■
	Addition of acoustic deterrents / warning devices (eg pingers/seal scarrers)	Would have to be balanced so as not to exclude animals from important habitats, and directed at the relevant hearing abilities.	■	■	
Protect against close encounter	Protective netting or grids	May be collision hazards themselves.	■		■
Protect against entrapment	Reduction of vertical traps for air breathing species	Diving birds and mammals may have limited abilities to escape from inverted concave structures once entered.	■		■
Soften collision	Shock absorption on structures of concern	e.g. faired padding on rotor leading edge	■	■	■
	Reduction of sharp edges	Particularly in areas likely to receive a glancing blow or be used for hauling out.	■		

11. Knowledge gaps and further research

The knowledge gaps have been set out in Table 23. For marine birds there is an almost complete lack of empirical data on collision risk from wave and tidal schemes. Therefore, our assessments are based on our knowledge of the ecology of the birds, which in many cases is incomplete, especially outside the breeding season and in younger age classes. We are also learning lessons from other developments, in particular offshore wind farms. However, there are large differences between wind, tidal and wave schemes, and the risk of collision will differ accordingly. Modelling collision risk provides one assessment method, but parameterisation will prove difficult. There is thus an imperative need to quantify the likelihood of collision empirically.

In comparison, the behaviour and responses of fishes to potential disturbance and collision is relatively well understood. Information on risks to marine mammals is intermediate between fish and birds. However, the complexity of their behaviour makes predicting responses to new marine technologies particularly challenging. Seals are generally better understood than cetaceans.

Table 23: Relevant knowledge gaps

Distribution and abundance			
	Aspect	**Known**	**Unknown**
Seals	Distribution	• Good data on haul-out distribution • Some data and predictive models of at-sea distribution	Fine-scale at-sea distribution over most areas.
	Abundance & population trends	Comparatively good data from breeding counts	
Cetaceans	Distribution	• Species present • Broad brush distribution • High-resolution information in some areas	Fine-scale distribution in most areas Winter distribution Seasonal movements
	Abundance	Up to date estimate for the most abundant species	Data limited to July 2005 Population trends of any species

Fish	Distribution	Large scale distribution well known for commercially important species	Small scale distribution not adequately known
	Abundance	Well known for commercially important species	Need more detailed information on local populations. Must also understand mechanisms controlling population size on the small scale
Birds	Distribution	Well know on the large scale	Small scale distribution may not be adequately known in area of a proposed deployment
	Abundance		Need greater understanding of fine scale population variation, including mechanisms controlling population size, but local abundance must be placed in broader population context
Sensory Capability and use in Feeding and Predator Evasion			
	Aspect	**Known**	**Unknown**
Seals and cetaceans		Capacity of key senses in seals and small cetaceans	Mysticete (baleen whale) hearing unknown How all species use their senses to detect and catch prey Whether outputs from devices will mask biologically relevant cues How much warning information devices will produce. Esp. how moving structures (eg turbines) will be perceived by echolocating species
Fish		Use of all senses in feeding and predator evasion well understood in some species	Further work needed on a wider range of species
Birds		Use of vision, chemosensory and tactile cues well known Use of sound in air	Effects of turbidity on use of vision and switching to dependence on other senses not known. Tactile foraging suspected in some situations but poorly understood Importance of sound underwater
Behaviour			
Seals and cetaceans	Responses to devices	Info available on responses to analogous structures	Reaction distances to devices Precise responses on detection of

		Manoeuvring abilities	devices (attraction/avoidance/evasion etc)
	Affinity for tidal streams	Areas of high tidal flow favoured by many species	Why these areas are so favoured 3 dimensional use of these areas
Fish	Reactions to sound stimuli	Understood on the small, laboratory scale for some species	Need more studies on appropriate scales and on more species Reaction distance/sound pressure relationship not been studied Habituation possible but needs further controlled laboratory experiments
	Disruption of behaviour by sound pollution		Not yet extensively studied
Birds	Responses to underwater sound		Not been studied. Birds have acute hearing but no known how important it is in foraging
	Use of areas of high wave and tidal activity		Detailed understanding on the importance of these regions to different species, and age classes, sexes and populations within thosespecies
	Flow characteristics		Little understanding of the impact of changes in flow characteristics on interactions between seabirds and their prey
Encounter rates (results from model Section 5) – note: Model constructed to consider the magnitude of potential interactions between marine species and a commercial scale development of 100 tidal turbines. It calculates the number of times animals moving within the Scottish west-coast environment will enter the vicinity of turbine blades over a period of a year. It does **not** estimate the number of collisions.			
	Aspect	**Known**	**Unknown**
Marine mammals	Harbour porpoises	Population size, depth range, body size and average swimming speed	Population distribution relative to device placement – especially areas of strong tidal flow. Depth distribution in Scottish waters and proportion of time moving vertically within the water column Responses once submerged devices are detected Implications of social and foraging behaviour on avoidance/evasion
	Other species	Equivalent information available for several other species, especially seals and minke whales.	Information gaps as above.

		Information on vertical distribution best for seals.	
Fish	Herring	Population size, depth range, body size and swimming speed	Population distribution relative to device placement – especially in areas of strong tidal flow. Fish response behaviour once submerged devices are detected Implications of schooling behaviour on avoidance/evasion
	Other species	Potential to run for those fish species where sufficient data are available	Particular relevance to large species (eg basking sharks) but vertical / horizontal distribution and population size poorly known.
Birds	Model not run		Information on proportion of population within the water column and progress through it too limited to run the model. Information on vertical distribution, hotspots and swimming behaviour within the water column required. Behaviour once submerged devices are detected
Range of potential responses (avoidance/evasion, summary of Section 8)			
	Aspect	**Known**	**Unknown**
Seals & cetaceans	Detection	Perception underwater cues generally known for seals and small cetaceans	Sensory abilities of large whales Impact of environmental circumstances (eg darkness, turbid water, background noise) on perception distances and hence escape options
	Evasion	Swimming/turning abilities generally known	Behavioural & locomotory responses of animals once devices detected
	Diving constraints	Diving performance for many species Proportion of time at different depths for some species.	Surfacing options when animals at or past their aerobic diving limits. Impacts of buoyancy constraints on vertical manoeuvring options.
	Attraction	Attraction likely for seals and small cetaceans	How foraging compromises abilities to perceive and avoid underwater structures
	Confusion		Interactions between multiple devices on avoidance/evasion options

	Distraction	Collisions with nets suggests Confusion / Distraction occurs	Severity of sensory abilities (esp echolocation) being compromised by other activities (foraging, social interaction etc)
	Illogical behaviour	Examples from fisheries interactions	How marine mammals will perceive then respond to novel structures in the marine environment
Fish	Detection	Respond to visual, acoustic and flow stimuli. Respond more readily to horizontal loom than vertical loom	Sensory stimuli produced by marine renewables be studied WRT known fish escape behaviour. Modifications to devices be considered to ensure that fish have appropriate cues to trigger appropriate escape behaviour.
	Evasion	C-starts primary means of close range evasion. Evoked more readily by transitory stimuli	Close-range escape capabilities limited by size and species. Consideration of device specific movement velocities to determine species at risk. Potential for ricochet effects in devices with multiple moving parts.
	Schooling	Responses of individuals linked to those of others in school	Appropriate escape responses to predators may be less so for marine renewables. IE fish responding on one side of a school may force the other side into danger. Device design needs to consider.
Birds	Detection	Some data on above surface detection abilities of birds in flight	No empirical data underwater
	Evasion	Some data on above surface evasion behaviour of birds in flight	No empirical data underwater
	Diving constraints	empirical data available in several species;	Behaviour outside the breeding season and in younger age classes poorly understood
	Confusion		No empirical data
	Distraction		No empirical data
	Illogical behaviour		No empirical data
Potential effects of collision risks (summary of Section 9)			
	Aspect	**Known**	**Unknown**
Seals & cetaceans	Disturbance / avoidance	Avoidance likely in several species	Implications for habitat exclusion. Long-term impacts of short-term behavioural responses.

	Injury	Range of outcomes – minor injuries, temporary or permanent debilitation, death. Instant death less likely than other injuries but easier to detect and attribute to cause.	Magnitude of collisions required to cause significant injuries. Relative vulnerabilities of different parts of the body in different species. Post-mortem signs in/on carcases following injury. Signature of any non-lethal signs in living animals following collisions.
	Exploitation	Seals and small delphinids likely to exploit any increased foraging opportunities around devices.	Potential benefit foraging opportunities against cost of higher collision risk.
Fish	Disturbance / avoidance	Avoidance of surrounding area probable, esp by large species Potential implications for community structure for species not excluded	Potential for avoidance behaviour. Impacts of any habitat exclusion on community structure .
	Injury	Pelagic species particularly vulnerable injury from physical contact	Magnitude of collision needed to cause significant injury Venturi devices and compression-decrompression issues for fish with swim-bladders.
	Exploitation	Artificial reefs widely exploited by fish	Implications for alteration in community structure.
Birds	Disturbance / avoidance	Avoidance likely in several species Time of year important	Implications for habitat exclusion, especially in favoured habitats. Long-term impacts of short-term behavioural responses
	Injury	Appendages associated with locomotion (wings / legs) particularly vulnerable	Magnitude of collision needed to cause significant injury Potential collision rates in bird populations.

11.1. Suggested further research

11.1.1 Understanding interactions

Interactions between marine renewable devices and marine vertebrates are likely to be complex and modulated by multiple factors in concert. To gain an understanding of these interactions and formulate effective mitigation it is important that we can disentangle critical factors from those that are not. This will require a mixture of approaches. The following are examples:

- **Escape options modelling:** desk-based modelling of avoidance options given the sensory and mobility of the different species and the upstream sensory cues put out by marine renewable devices.

- **Sensory capabilities**: Information on the sensory capabilities varies substantially between the different marine vertebrate groups, with fish being best understood and mysticete (baleen) whales the least. However, to understand at what distance these species will perceive marine renewable devices and hence what avoidance responses they are capable of, better information on senses is required. Incorporating data from ongoing studies of Auditory Brainstem Responses have potential to improve our understanding of the hearing capabilities of particularly the large species. Animal-borne dataloggers have potential to investigate response distances and tactics of live animals at sea .

- **Trauma studies (1):** veterinary / pathological studies of the magnitude of collisions required to inflict physical injuries. Several approaches could be used. 1) The study of natural physical injuries in wild marine vertebrates. For example, marine mammals are frequently beach cast as a result of fatal physical trauma (ship strikes and violent attack by bottlenose dolphins are UK examples). Reconstructing the magnitude of the events required to produce the fatalities would provide a context upon which to gage how robust marine mammals are in comparison to collisions strikes from renewables devices. 2) Comparison with road collision studies with terrestrial wildlife.

- **Trauma studies (2)**: It is advisable that upon implementation of high collision risk installations at sea, a monitoring programme be initiated to record collision occurrence. Part of such a study would likely be pathological follow up studies of any beach-cast animals in the area (particularly large fish, birds and marine mammals). For such studies to be conclusive, accurate information is required on the key pathological signs of renewable strikes left on carcases. Consideration therefore needs to be given to the adaptation of existing post-mortem protocols such that collision signs can be reliably detected.

- **Group response studies**: Of the fish, pelagic species in particular form highly cohesive schools. Because the movements of each individual are not independent, the behaviour of fish schools to collisions is part way between that of a single independent fish and a less manoeuvrable super-organism the size of the entire school. To understand the extent to which this schooling behaviour will compromise the escape capacities of schooling fish experimental trials in large flume tanks will be necessary.

- **Device specific collision risk comparisons**: Because of the considerable variation in device designs and methods of operation (see Section 4 & Appendix 2), it is likely that collision risks will vary significantly between these devices. The understanding of what features lead to collisions will be valuable in ranking different designs. However a more direct and an initial stage of comparison could be an investigation of strike rates with passive objects in a flume situation.

- **Prototype at-sea experiments**: Many of the issues associated with collision risks are scale dependant. For example, a porpoise might be able to evade a three meter turbine but have insufficient response time to dodge a 12 m diameter device. Therefore a full understanding the collision risks of large scale commercial devices may not be answerable using laboratory scale experiments, particularly when animal behaviour is a key parameter. Therefore, there is potentially a significant role to be gained from monitoring biological interactions with prototypes operating at sea. The use of video cameras, sonar equipment and surface observers are all potential ways of looking at interactions as they occur but to produce a generic, rather than device specific, understanding ancillary information should also be considered, including the potential cues given out by the devices (sound, visibility, vibrations etc) and any environmental factors mediating the interactions such as turbidity, prey abundance, bubbles in the water column and so on.

- **Behaviour Response Studies:** an alternative (or compliment) to the prototype studies described above would be to replace the physical presence of the devices with the cues alone and investigate avoidance responses. The use of playbacks of turbine noise to look at deviations in movement paths of marine mammals is an example.

Monitoring collisions

11.1.2.1 Marine Mammals

Determining the impact of marine renewable device proliferation in Scottish waters on local marine mammal populations requires investigation at a variety of scales. At the most **direct** are the interactions between individual animals and individual devices (collisions, use of devices to forage around, haul-out on etc). At an **intermediate** scale (devices or arrays of devices) may alter the patterns of habitat use or movements of individuals. Finally at the **ultimate** and ecologically most important scale, marine renewable devices may work to alter the survival or reproductive rates of impacted populations and therefore lead to changes in total population size and viability.

Establishing cause and effect in marine systems in notoriously difficult and in the case of marine renewables, effects at the direct and intermediate scales (described above) will be the easiest to establish. Determining whether devices have ultimate impacts will be particularly challenging, firstly because determining these rates with appropriate degrees of precision is often difficult for mobile marine mammal populations and secondly because many factors already impact these rates from climate to prey stocks to other human impacts. So unless marine renewable devices have high levels of impact then separating out population level impacts from these devices as opposed to other variables will be a significant challenge. However, measures of population size remain an important context within which to view any of the other interactions. For example, one fatal collision a year may be insignificant for a large and growing marine mammal population but the same collision rate could be much more serious for an already small or declining population. Therefore measures of population size, reproductive output and survival remain significant and valid monitoring goals.

An initial stage to any monitoring programme is to establish what exactly needs to be monitored. At its simplest this is the marine mammal species (including any age / gender bias) that use the areas likely to be impacted prior to development of the sites. Marine systems in temperate latitudes are variable both seasonally but also from one year to another so not only would the use of the area need to be monitored for a year prior to development but also an indication of inter-annual trends needs to be established. Ideally this would involve multiple years of monitoring but failing this, the year of study needs to be historically grounded to determine whether it is representative.

11.1.2.2 Fish

Local and large scale effects will need to be separated; both local resident populations and transient individuals and schools will be affected. It will, however, be difficult to collect detailed information given the considerable variation in behaviour and distribution of fish both daily and seasonally. The most simple approach would be to sample fish in the area of a proposed site both before and after construction by using traps or fishing techniques or diver surveys. Further information could be obtained using acoustic surveys. Multiple frequency devices can now be used to identify likely species and could and fixed acoustic devices could provide detailed information on temporal variation in distribution and behaviour.

Resident populations could be studied using acoustic tracking methods (Glass et al, 1992; Johnstone et al, 1991; Smith et al, 1993; Sarno et al, 1994). Such studies would provide evidence of attraction and/or exclusion from the area surrounding a device.

Underwater video imaging could have a role in observing behaviour on a small scale close to devices and to observe species attracted to structures. Static underwater video has been used successfully to observe invertebrate and fish behaviour on serpulid reefs in Loch Creran (Poloczanska et al 2004) providing detailed information on diurnal movements and behaviour.

11.1.2.3 Birds

The ultimate aim is to establish the impact of collisions on population size of local marine birds. This is a challenging because establishing impacts on population size takes many years for long-lived species such as marine birds.

Therefore, the first main aim is to establish the importance of a proposed area for development to the birds' ecology prior to installation taking place. This is achieved by surveying the area and control areas adjacent to it using a number of available technologies that fall into four main categories:

- surveys: ship-borne or aerial line transect surveys. The former is expensive, slow and comprehensive; the latter is cheaper, covers a wider area but is less comprehensive.
- shore-based counts
- radar: this technology has been used recently to establish distributions of birds at sea
- animal-borne instrumentation: by attaching data loggers or transmitters to breeding animals, precise location and activity can be recorded. The disadvantage over surveys is the small sample sizes.

Second, to understand the impact of energy schemes on population size, the demography of local marine birds must also be surveyed. Population size is the simplest currency to measure, but tells you little about the underlying mechanisms. It is preferable to also establish whether variation in population size is driven by adult survival, breeding success, emigration or immigration. To do so, these must be monitored in a range of colonies, so that movements between them can be assessed. Demographic studies are time-consuming and results in long-lived species only become apparent after several years.

Once installation has been completed, the programme of assessing marine bird distributions in relation to the development and control sites, and assessment of demographic parameters and population size at local colonies, should continue. Surveys such as this will establish the potential positive or negative impacts the scheme will have indirectly on the birds, by altering their foraging conditions and potentially their population size

11.2. Monitoring summary

The specifics of a programme to assess and mitigate impacts will depend greatly on the nature of the location, species involved and devices employed. However a monitoring programme sufficient to assess long-term ecological impacts should include as a minimum those factors outlined in Table 24:

Table 24: Suggested Monitoring and Methods

Phase	**Monitoring requirements**

Pre-installation	❖ Composition and abundance of species using area (literature & field studies). Focusing on:
	  ➢ Assessment of total population size for impact assessment (see 8.3 above)
	  ➢ Tidal, diel and seasonal abundance in site.
	❖ Patterns of animal movement in site (esp. sites in sounds, sea loch entrances and estuarine mouths)
	❖ Background measurement of ambient underwater noise

Installation	Depend heavily on the device type and seabed attachment but at a minimum will require consideration of seasonal issues, contaminants, noise pollution (engines, pile driving, explosives), seabed disturbance, impacts on prey and visual disturbance (esp seal haul-outs).

Operation	❖ Assessment of how animals interact with device(s)
	❖ Re-evaluation of tidal, diel and seasonal use of site.
	❖ Re-evaluation of species abundance and patterns of animal movement in and around site
	  ➢ Fish, Mammals and Birds (while underwater)
	    ▪ Fixed multibeam multiple frequency sonar could be used
	    ▪ For small scale interaction, video imaging may be useful
	    ▪ Passive acceleration detection of collision events and magnitude (interpreted as size of animal)
	    ▪ animal-borne instrumentation
	  ➢ Birds in air and on water
	    ▪ ship-borne or aerial line transect surveys and shore-based counts
	    ▪ radar to establish distributions of birds at sea
	    ▪ animal-borne instrumentation
	❖ Monitoring of community structure on static parts (foundations, moorings etc.)
	❖ Measurement of underwater noise around device

Post-operation	as Installation

12. Literature cited

Batty, R.S. (1989). Escape Responses of Herring Larvae to Visual-Stimuli. *Journal of the Marine Biological Association of the United Kingdom* **69**, 647-654

Batty, R. S. and Blaxter, J. H. S. (1992). The Effect of Temperature on the Burst Swimming Performance of Fish Larvae. *Journal Of Experimental Biology* **170**, 187-201.

Batty, R. S. and Domenici, P. (2000). Predator-prey relationships in fish and other aquatic vertebrates: kinematics and behaviour. *In: Biomechanics in Animal Behaviour. ed. P. Domenici and R.W. Blake.: pp. 237-257. Oxford: BIOS.*

Bailey, K. M. and Batty, R. S. (1983). A laboratory study of predation by Aurelia aurita on larval herring (Clupea harengus): experimental observations compared with. *Marine Biology* **72***, 295-301.*

Batty, R. S., and. Hoyt, R.D. (1995). The role of sense organs in the feeding behaviour of juvenile sole and plaice. *Journal of Fish Biology,* **47***, 931-939.*

Band, W., Madders, M. and Whitfield, D. P. (2005) Developing field and analytical methods to assess avian collision risk at wind farms. In *Birds and wind power.* (ed. M. De Lucas, G. Janss & M. Ferrer). Barcelona: Lynx Editions.

Blaxter, J. H. S. (1985). The herring: A successful species? *Canadian Journal of Fisheries and Aqatic Sciences* **42**, 21-30.

Blaxter J.H.S., Batty R.S. (1985) Herring Behaviour in the dark: Responses to stationary and continuously vibrating obstacles. *Journal of the Marine Biological Association UK* **65**:1031-1049

Blaxter, J. H. S., Gray, J.A.B. and Denton, E.J. (1981). Sound and startle responses in herring shoals. *J.mar.biol.Ass.U.K. (1981) 61, 851-869*.

Blaxter, J. H. S. and Hunter, J. R. (1982). The biology of the clupeoid fishes. *Advances in Marine Biology* **20**, 1-223.

Breen M. DJ, O'Neill F.G., Jones W., and Haigh M. (2004) Swimming endurence of haddock (*Melanogrammus aeglefinus* L.) at prolonged and sustained swimming speeds, and its role in their capture by towed fishing gears. *ICES Journal of Marine Science* **61**:1071-1079

Bone, Q., Marshall, N. B. and Blaxter, J. H. S. (1995). Biology of fishes. GLASGOW (UK): BLACKIE & SON LTD.

Chamberlain, D. E., Rehfisch, M. R., Fox, A. D., Desholm, M. and Anthony, S. J. (2006) The effect of avoidance rates on bird mortality predictions made by wind turbine collision risk models. *Ibis* **148**, 198-202.

Craik, C. (2004) Record breeding success of terns in West Scotland. *Seabird Group Newsletter* **98**, 6-7.

Cramp, S. and Simmons, L. (1977) *Birds of the Western Palearctic*. Oxford: Oxford University Press.

Cramp, S. and Simmons, L. (1983) *Birds of the Western Palearctic*. Oxford: Oxford University Press.

Cox T.M., Read A.J., Swanner D., Urian K., Waples D. (2003) Behavioral responses of bottlenose dolphins, *Tursiops truncatus* to gillnets and acoustic alarms. *Biological Conservation* **115**:203-212

Daunt, F., Benvenuti, S., Harris, M. P., Dall'Antonia, L., Elston, D. A. and Wanless, S. (2002) Foraging strategies of the black-legged kittiwake Rissa tridactyla at a North Sea colony: evidence for a maximum foraging range. *Marine Ecology Progress Series* **245**, 239-247.

Daunt, F., Peters, G., Scott, B., Grémillet, D. and Wanless, S. (2003) Rapid-response recorders reveal interplay between marine physics and seabird behaviour. *Marine Ecology Progress Series* **255**, 283-288.

Daunt, F., Camphuysen, C. J., Humphreys, E. M., Hamer, K. C., Wanless, S. and Skov, H. (2005) Local/daily scale hydrography, prey and seabird interactions. In *Understanding marine foodweb processes: an ecosystem approach to sustainable sandeel fisheries in the North Sea* (ed. C. J. Camphuysen), pp. 163-192. Texel: Royal Netherlands Institute for Sea Research.

Daunt, F., Afanasyev, V., Silk, J. R. D. and Wanless, S. (2006a) Extrinsic and intrinsic determinants of winter foraging and breeding phenology in a temperate seabird. *Behavioral Ecology and Sociobiology* **59**, 381-388.

Daunt, F., Wanless, S., Peters, G., Benvenuti, S., Sharples, J., Grémillet, D. & Scott, B. (2006b) Impacts of oceanography on the foraging dynamics of seabirds in the North Sea. In *Top predators in marine ecosystems: their role in monitoring and management.* (ed. I. L. Boyd, S. Wanless & C. J. Camphuysen), pp. 177-190: Cambridge University Press

.

Daunt, F. (2006c) Marine birds of the north and west of Scotland and the Northern and Western Isles. Report to METOC. CEH Banchory, Hill of Brathens, Banchory AB31 4BW

David L. (2006) Risks of collision for fin whales in the north-western Mediterranean Sea in Summer. *Fins*, p 16-18

De Lucas, M., Janss, G. and Ferrer, M. (ed.) (2005) *Birds and wind power*. Barcelona: Lynx Editions.

Dempsey, C. H. (1978). Chemical stimuli as a factor in feeding and intraspecific behaviour of herring larvae. *J. mar. biol. Ass. U.K.* **58***, 739-747.*

Desholm, M. and Kahlert, J. (2005) Avian collision risk at an offshore wind farm. *Biology Letters* **1**, 296-298.

Dempster T, and Taquet M (2004) Fish aggregation device (FAD) research: gaps in current knowledge and future directions for ecological studies. *Reviews in fish biology and fisheries* **14**:21-42

Desholm, M., Fox, A. D., Beasley, P. D. L. and Kahlert, J. (2006) Remote techniques for counting and estimating the number of bird-wind turbine collisions at sea: a review. *Ibis* **148**, 76-89.

Denton, E. J., Gray, J.A.B. and Blaxter, J.H.S. (1979). The mechanics of the clupeid acoustico lateralis system: frequency responses. *J.mar.biol.Ass.U.K.(1979) 59, 27-47*.

Denton, E. J. and Blaxter, J.H.S. (1976). The mechanical relationships between the clupeid swimbladder, inner ear and lateral line. *J.mar.biol.Ass.U.K.(1976) 56, 787-807*.

Dolman S., Williams-Grey V., Asmutis-Silvia R., and Isaac S. (2006) *Vessel collisions and cetaceans: What happens when they don't miss the boat,* WDCS science report

Drewitt, A. L. & Langston, R. H. W. (2006) Assessing the impacts of wind farms on birds. *Ibis* **148**, 29-42.

Domenici, P., and Batty, R.S. (1994). Escape manoeuvres of schooling Clupea harengus. *Journal of Fish Biology,* **45** *(supplA), 97-110.*

Domenici, P. and Batty, R. S. (1997). Escape behaviour of solitary herring (Clupea harengus) and comparisons with schooling individuals. *Marine Biology* **128**, 29-38.

Domenici, P., Batty, R. S. and Simila, T. (2000). Spacing of wild schooling herring while encircled by killer whales. *Journal Of Fish Biology* **57**, 831-836.

Domenici P., Batty R.S., Simila T., and Ogam E. (2000) Killler Whales (Orcinus orca) feeding on schooling herring (Clupea Harengus) using underwater tail-slaps: Kinematic analyses of field observations. *The Journal of Experimental Biology.* **203**, pp283-294

Domenici, P., Blake, R.W. (1997). The kinematics and performance of fish fast-start swimming. *Journal of Experimental Biology, 200, 1165- 1178.*

Domenici P., (2001)The scaling of locomotor performance in predator-prey encounters: from fish to killer whales. *Comparative Biochemistry and Physiology Part A,* **131**, pp169-182

Domenici, P., Ferrari, R., Steffensen, J. and Batty, R.S. (2002). The effect of progressive hypoxia on school structure and dynamics in Atlantic herring Clupea harengus. *Proc. Roy. Soc. Ser. B* ***269**, 2103-2111.*

Fraenkel, P. L. 2006 Tidal current energy technologies. *Ibis* **148**, 145-151.

Freon P, and Dagorn L (2000) Review of fish associative behaviour: toward a generalisation of the meeting point hypothesis. *Reviews in Fish Biology and Fisheries* **10**:183-207

Fox, A. D., Desholm, M., Kahlert, J., Kjaer Christensen, T. and Krag Petersen, I. B. (2006) Information needs to support environmental impact assessment of the effects of European marine offshore wind farms on birds. *Ibis* **148**, 129-144.

Galand, G. and Liege, B. (1975). Responses visuelles unitaires chez la truite. In *Vision in fishes: new approaches in research.*, (ed. M. A. Ali), pp. 127-135. New York and London: Plenum

Garthe, S., Benvenuti, S. and Montevecchi, W. A. (2000) Pursuit plunging by northern gannets *Sula bassana* feeding on capelin *Mallotus villosus*. *Proc. R. Soc. Lond. Ser. B-Biol. Sci.* **267**, 1717-1722.

Garthe, S. and Furness, R. W. (2001) Frequent shallow diving by a Northern Fulmar feeding at Shetland. *Waterbirds* **24**, 287-289.

Garthe, S. and Huppop, O. (2004) Scaling possible adverse effects of marine wind farms on seabirds: developing and applying a vulnerability index. *Journal of Applied Ecology* **41**, 724-734.

Gerritsen, J. and Strickler, J. R. (1977). Encounter Probabilities and Community Structure in Zooplankton: a Mathematical Model. *J. Fish. Res. Board Can.* **34**, 73-82.

Greenwood, J. J. D. (2005) Wind, fire and water: renewable energy and birds. A report on the BOU's annual conference held at the university of Leicester, 1-3 April 2005. *Ibis* **147**, 865-867.

Grellier K, Thompson PM, Corpe HM (1996) The effect of weather conditions on harbour seal (Phoca vitulina) haulout behaviour in the Moray Firth, northeast Scotland. *Canadian Journal of Zoology*, **74**:1806-1811

Grémillet, D., Kuntz, G., Gilbert, C., Woakes, A. J., Butler, P. J. and Le Maho, Y. (2005)a Cormorants dive through the polar night. *Biology Letters* **1**, 469-471.

Grémillet, D., Kuntz, G., Woakes, A. J., Gilbert, C., Robin, J. P., Le Maho, Y. and Butler, P. J. (2005)b Year-round recordings of behavioural and physiological parameters reveal the survival strategy of a poorly insulated diving endotherm during the Arctic winter. *Journal Of Experimental Biology* **208**, 4231-4241.

Glass, C. W., Johnstone, A. D. F., Smith, G. W. and Mojsiewicz, W. R. (1992). The movements of saithe (*Pollachius virens* L.) in the vicinity of an underwater reef. In *Wildlife Telemetry: Remote Monitoring and Tracking of Animals.*, eds. I. G. Priede and S. M. Swift), pp. 329-341. Chichester: Ellis Horwood

Goodson A.D., **and Sturtivant C.R.,** (1996) Sonar characteristics of the harbour porpoise (*Phocoena phocoena*): source levels and spectrum. ICES Journal of Marine Science **53**:465-472

Hamer, K. C., Phillips, R. A., Wanless, S., Harris, M. P. and Wood, A. G. (2000) Foraging ranges, diets and feeding locations of gannets *Morus bassanus* in the North Sea: evidence from satellite telemetry. *Marine Ecology Progress Series* **200**, 257-264.

Harris, M. P., Towll, H., Russell, A. F. and Wnaless, S. (1990) Maximum dive depths attained by auks feeding young on the Isle of May, Scotland. *Scottish Birds* **16**, 25-28.

Harvey, R. (1996). The olfactory epithelium in plaice (Pleuronectes platessa) and sole (Solea solea), two flatfishes with contrasting feeding behaviour. *J. Mar. Biol. Assoc. U.K., 76, 127-139.*

Harvey, R., Blaxter, J. H. S. and Hoyt, R, D. (1992). Development of Superficial and Lateral Line Neuromasts in Larvae and Juveniles of Plaice (*Pleuronectes Platessa*) and Sole (*Solea Solea*). *J, Mar, Biol, Ass, U.K, Vol 72, Pp. 651-668*.

Harvey, R. and Batty, R. S. (1998). Cutaneous taste buds in cod. *Journal of Fish Biology* **53**, 138-149.

Hastie GH, Wilson B, Wilson LJ, Parsons KM, Thompson PM (2004) Functional mechanisms underlying cetacean distribution patterns: hotspots for bottlenose dolphins are linked to foraging. *Marine Biology* **144**:397-403

Hastie, G. D. and Wilson, B. (2006) Marine Mammals of the north and west of Scotland and the Northern and Western Isles. Report to METOC. Scottish Association for Marine Science, Oban, Scotland, PA37 1QA.

Helvey M, and Dorn PB (1987) Selective Removal of Reef Fish Associated with an Offshore Cooling-Water Intake Structure. *The Journal of Applied Ecology* **24**:1-12

ICES. (2006). Report of the Planning Group on Herring Surveys (PGHERS), 24-27 January. 2006, Rostock, Germany, pp. 239 pp.

IWC (2006) 58th Annual Meeting of the International Whaling Commission. Ship strikes working group. First Progress report to the conservation committee. Report No. IWC/58/CC3

Jamieson A.J. RGO, Bagley P.M., Partridge J.C., and Priede I.G (2006) Illumination of trawl gear by mechanically stimulated bioluminescence. *Fisheries Research* In press.

Johnstone, A. D. F., Glass, C. W., Mojsiewicz, W. R. and Smith, G. W. (1991). The movements of saithe (*Pollachius virens* (L.)) revealed by acoustic tracking. *Prog. Underwater Sci.* **16**, 61-73.

Kraus, Read, Solow, Baldwin, Spradlin., (1997) Acoustic alarms reduce porpoise mortality. *Nature.* **388**: 525

Laist D.W., Knowlton A.R., Mead J.G., Collet A.S., Podesta M., (2001) Collisions between ships and whales. *Marine Mammal Science* **17**:35-75

Maes J, Turnpenny AWH, Lambert DR, Nedwell JR, Parmentier A, Ollevier F (2004) Field evaluation of a sound system to reduce estuarine fish intake rates at a power plant cooling water inlet. *Journal of Fish Biology* **64**:938-946

Martin, G. R. (1998) Eye structure and amphibious foraging in albatrosses. *Proceedings Of The Royal Society Of London Series B-Biological Sciences* **265**, 665-671.

Martin, G. R. (1999) Eye structure and foraging in King Penguins Aptenodytes patagonicus. *Ibis* **141**, 444-450.

Martin, G. R. and Prince, P. A. (2001) Visual fields and foraging in procellariiform seabirds: Sensory aspects of dietary segregation. *Brain Behavior And Evolution* **57**, 33-38.

Meager, J.J. and Batty, R.S. (2007) Effects of turbidity on the spontaneous and prey-searching activity of juvenile Atlantic cod (*Gadus morhua*). *Phil. Trans. R. Soc. Lond*., B (In Press)

Nevitt, G. (1999) Olfactory foraging in Antarctic seabirds: a species-specific attraction to krill odors. *Marine Ecology-Progress Series* **177**, 235-241.

Nevitt, G. A., Bergstrom, D. M. and Bonadonna, F. (2006) The potential role of ammonia as a signal molecule for procellarifform seabirds. *Marine Ecology-Progress Series* **315**, 271-277.

Notarbartolo-di-Sciara G, Zanardelli M, Jahoda M, Panigada S, Airoldi S (2003) The fin whale Balaenoptera physalus (L. 1758) in the Mediterranean Sea. *Mammal Review* **33**:105-150

Otani. S., Naito. Y., Kato. A., and Kawamura. A. (2000) Diving behaviour and swimming speed of a free ranging harbor porpoise, *Phocoena phocoena. Marine Mammal Science.* **16** (4), 811-814

Oxley, R. (2006) An overview of marine renewables in the UK: a synopsis of Michael Hay's presentation. *Ibis* **148**, 203-205

Pace D.S. MA, and Mussi B. (2006) Vessels and dolphins: scars that tell stories *Fins,* p 19-20

Panigada S., Pesante G., Zanardelli M., Capoulade F., Gannier A., Weinrich M.T. (2006) Mediterranean fin whales at risk from fatal ship strikes. *Marine Pollution Bulletin* **52**:1287-1298

Platt, T. and Denham, K. (1977). Organization in the pelagic ecosystem. *Helgol. Wiss. Meeresunters.* **30**.

Platt, T. and Denham, K. (1978). The structure of pelagic ecosystems. *Rapp. p-v. Reun. Cons. Int. Explor. Mer.* **173**.

Poloczanska, E. S., Hughes, D. J. and Burrows, M. T. (2004). Underwater television observations of Serpula vermicularis (L.) reefs and associated mobile fauna in Loch Creran, Scotland. *Estuarine, Coastal and Shelf Science* **61**, 425-435.

Read A.J., Drinker P., Northridge S. (2006) Bycatch of marine mammals in U.S. and global fisheries. Report to IWC SC/55/BC 20:163

Richardson, W. J. Bird migration and wind turbines: migration timing, flight behaviour and collision risk. In *National Avian - wind power planning meeting III*: nationalwind.org.

Russell B.A. KA, and Zoodsman B (2001) Recommended Measures to Reduce Ship Strikes of North Atlantic Right Whales IFAW

Ryer C.H., and Olla B.L., (2000) Avoidance of an approaching net by juvenile walleye pollock *Theragra chalcogramma* in the laboratory: the influence of light intensity. *Fisheries Research* **45**:195-199

Sarno, B., Glass, C. W. and Smith, G. W. (1994). Differences in Diet and Behavior of Sympatric Saithe and Pollack in a Scottish Sea Loch. *Journal Of Fish Biology* **45**, 1-11.

Smales, I. (2006) Wind farm collision risk for birds: cumulative risks for threatened and migratory species. Melbourne: Biosis Research Pty Ltd.

Smith, G. W., Glass, C. W., Johnstone, A. D. F. and Mojsiewicz, W. R. (1993). Diurnal Patterns in the Spatial Relationships between Saithe, Pollachius-Virens, Schooling in the Wild. *Journal Of Fish Biology* **43**, 315-325.

Sonny D, Knudsen FR, Enger PS, Kvernstuen T, and Sand O (2006) Reactions of cyprinids to infrasound in a lake and at the cooling water inlet of a nuclear power plant. *Journal of Fish Biology* **69**:735-748

Strod, T. A., Z., Izhaki, I. & Katzir, G. (2004) Cormorants keep the power: visual resolution in a pursuit-diving bird under amphibious and turbid conditions. *Current Biology* **14**, R376-R377.

Walsh S.J. and Godo O.R., (2003) Quantitative analysis of fish reaction to towed fishing gears-What responses are important? *Fisheries Research* **63**:289-292

Wanless, S., Morris, J. A. and Harris, M. P. (1988) Diving behavior of guillemot *Uria aalge*, puffin *Fratercula arctica* and Rrazorbill *Alca torda* as shown by radio telemetry. *J. Zool.* **216**, 73-81.

Wanless, S., Burger, A. E. and Harris, M. P. (1991) Diving depths of shags *Phalacrocorax aristotelis* breeding on the Isle of May. *Ibis* **133**, 37-42.

Wanless, S., Monaghan, P., Uttley, J. D., Walton, P. and Morris, J. A. (1992) A radio-tracking study of kittiwakes (*Rissa tridactyla*) foraging under suboptimal conditions. In *Wildlife Telemetry* (ed. I. Priede & S. Swift), pp. 580-590. New York: Ellis Horwood.

Ward-Geiger LI, Silber GK, Baumstark RD, Pulfer TL (2005) Characterization of ship traffic in right whale critical habitat. *Coastal Management* **33**:263-278

Wardle, C. S. (1977). Effects of size on the swimming speeds of fish. *In: T.J. Pedley (ed.): Scale effects in animal locomotion. Academic Press, London.*

Wardle CS (1986) Fish behaviour and fishing gear. In: Pitcher T.J. (ed) The behaviour of Teleost fishes. Croom Helm Ltd, London, UK, p 463-495

Watanuki, Y., Takahashi, A., Daunt, F., Wanless, S., Harris, M., Sato, K. and Naito, Y. (2005) Regulation of stroke and glide in a foot-propelled avian diver. *Journal Of Experimental Biology* **208**, 2207-2216.

Watanuki, Y., Wanless, S., Harris, M., Lovvorn, J. R., Miyazaki, M., Tanaka, H. and Sato, K. (2006) Swim speeds and stroke patterns in wing-propelled divers: a comparison among alcids and a penguin. *Journal Of Experimental Biology* **209**, 1217-1230.

Webb, P. W. (1982). Avoidance responses of fathead minnow to strikes by four teleost predators. *J. Comp. Physiol. 147, 371-378.*

Westgate. A.J., Read. A., Berggren. P., Koopman. H.N., and Gaskin D.E (1995) Diving behaviour of harbour porpoises, *Phocoena phocoena*. *Canadian Journal of Aquatic Science.* **52**, 1064-1073.

Wilson, B. (2005) Cetaceans of the Scottish western seaboard. Report 2 to METOC. Scottish Association for Marine Science, Oban, Scotland, PA37 1QA.

Zollett E.A., Rosenberg A.A. (2005) A Review of Cetacean Bycatch in Trawl Fisheries, University of New Hampshire. Literature Review prepared for the Northeast Fisheries Science Centre. USA.

Appendix 1:

English and Latin names, species group and status in Birds Directive of all species included in this report

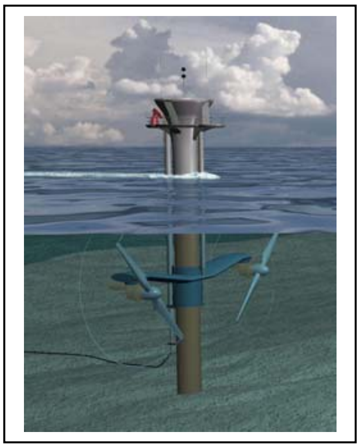
	Species	**Species group**	**Status**
1	Red-throated diver *Gavia stellata*	Diver	Annex I
2	Black-throated diver *Gavia arctica*	Diver	Annex I
3	Great northern diver *Gavia immer*	Diver	Annex I
4	Great crested grebe *Podiceps cristatus*	Grebe	Migratory
5	Red-necked grebe *Podiceps grisena*	Grebe	Migratory
6	Slavonian grebe *Podiceps auritus*	Grebe	Annex I
7	Black-necked grebe *Podiceps nigricollis*	Grebe	Migratory
8	Northern fulmar *Fulmarus glacialis*	Fulmar	Migratory
9	Cory's shearwater *Calonectris diomedea*	Shearwater	Annex I
10	Great shearwater *Puffinus gravis*	Shearwater	Migratory
11	Sooty shearwater *Puffinus griseus*	Shearwater	Migratory
12	Manx shearwater *Puffinus puffinus*	Shearwater	Migratory
13	Balearic shearwater *Puffinus mauretanicus*	Shearwater	Annex I
14	European storm-petrel *Hydrobates pelagicus*	Storm-petrel	Annex I
15	Leach's storm-petrel *Oceanodroma leucorhoa*	Storm-petrel	Annex I
16	Northern gannet *Morus bassanus*	Gannet	Migratory
17	Great cormorant *Phalacrocorax carbo*	Cormorant	Migratory
18	European shag *Phalacrocorax aristotelis*	Cormorant	Migratory
19	Greater scaup *Aythya marila*	Sea duck	Migratory
20	Common eider *Somateria mollissima*	Sea duck	Migratory
21	Long-tailed duck *Clangula hyemalis*	Sea duck	Migratory
22	Black scoter *Melanitta nigra*	Sea duck	Migratory
23	Surf scoter *Melanitta perspicillata*	Sea duck	Migratory
24	Velvet scoter *Melanitta fusca*	Sea duck	Migratory
25	Common goldeneye *Bucephala clangula*	Sea duck	Migratory
26	Red-breasted merganser *Mergus serrator*	Sea duck	Migratory
27	Goosander *Mergus merganser*	Sea duck	Migratory
28	Red-necked phalarope *Phalaropus lobatus*	Phalarope	Annex I
29	Pomarine skua *Stercorarius pomarinus*	Skua	Migratory
30	Arctic skua *Stercorarius parasiticus*	Skua	Migratory
31	Long-tailed skua *Stercorarius longicaudus*	Skua	Migratory
32	Great skua *Catharacta skua*	Skua	Migratory
33	Mediterranean gull *Larus melanocephalus*	Gull	Annex I
34	Little gull *Larus minutus*	Gull	Migratory
35	Sabine's gull *Larus sabini*	Gull	Migratory
36	Black-headed gull *Larus ridibundus*	Gull	Migratory
37	Common gull *Larus canus*	Gull	Migratory
38	Lesser black-backed gull *Larus fuscus*	Gull	Migratory
39	Herring gull *Larus argentatus*	Gull	Migratory
40	Iceland gull *Larus glaucoides*	Gull	Migratory
41	Glaucous gull *Larus hyperboreus*	Gull	Migratory
42	Great black-backed gull *Larus marinus*	Gull	Migratory
43	Black-legged kittiwake *Rissa tridactyla*	Gull	Migratory
44	Sandwich tern *Sterna sandvicensis*	Tern	Annex I
45	Roseate tern *Sterna dougallii*	Tern	Annex I
46	Common tern *Sterna hirundo*	Tern	Annex I
47	Arctic tern *Sterna paradisaea*	Tern	Annex I
48	Little tern *Sterna albifrons*	Tern	Annex I
49	Black guillemot *Cepphus Grylle*	Auk	
50	Common guillemot *Uria aalge*	Auk	Migratory
51	Razorbill *Alca torda*	Auk	Migratory
52	Little auk *Alle alle*	Auk	Migratory
53	Atlantic puffin *Fratercula arctica*	Auk	Migratory

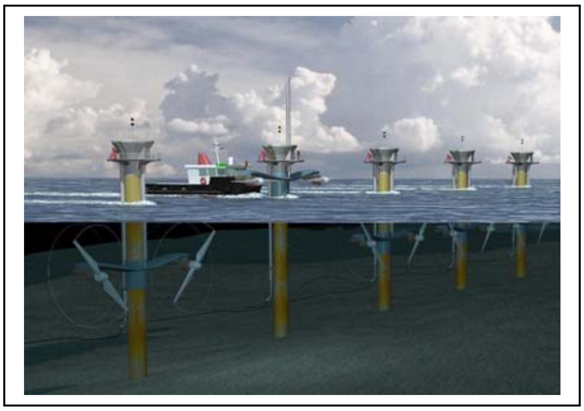
Appendix 2:

This appendix outlines the variety of marine renewable devices that we used as background when considering potential collision risks.

SEAGEN – Marine Current Turbines

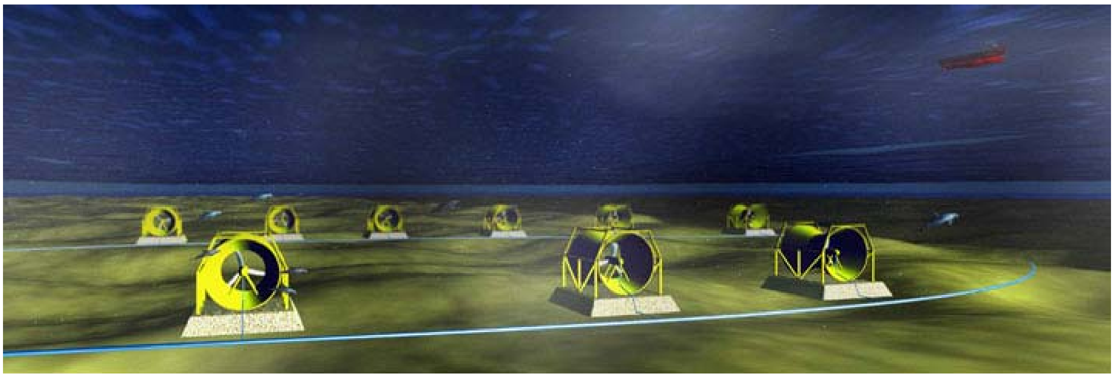
Type	Tidal horizontal axis turbine Operational mean spring peak velocity 2.25-2.5 ms^{-1} (4-5 knots)
Dimensions	Rotor diameter 15-20m Monopole 3m diameter
Water depth	20m (min) to 30m (max)
Distance from shore	Inshore waters where sufficient tidal current.
Method of attachment to sea bed	Monopole
Function principles	Marine current turbines work like submerged windmills. Seagen have twin axial flow rotors ach driving a generator via a gearbox
Development status	First generation device was tested in Devon from 2003 (Seaflow), Seagen is due to be installed in Strangford Lough in Jan 2007. Following the UK Governments Energy review and the publication of the Welsh Affairs select committee report (July 20th 2006) MCT has announced plans to investigate the potential for a commercial tidal energy farm off the Anglesey coastline, 7 units]
Intended array size	Expect to install commercially in batches of 10-20 machines, initially although company state that many sites investigated could accommodate hundreds of devices.
Developer contact details	Marine Current Turbines Ltd The Court The Green Stoke Gifford Bristol BS34 8PD www.marineturbines.com





Lunar Energy

Type	Tidal - horizontal axis turbine Operational tidal flow 6 knots
Dimensions	Inlet diameter 21m Overall length 27m Turbine 16m diameter
Water depth	Minimum 35m
Distance from shore	?
Method of attachment to sea bed	Large concrete plinth acts as an anchor
Function principles	The duct captures a large area of the tidal stream and accelerates the flow through a narrowing channel into the turbine. The ducted rotor is bi-directional and the turbine blades are symmetrical Modular unit allows for maintenance
Development status	Developmental – full size prototype, they were aiming for full size testing by 2006
Intended array size	Not stated, but see image below.
Developer contact details	Lunar Energy Limited Parkgate House, Hesslewood Country Office Park Ferriby Road, Hessle, East Yorkshire, HU13 0QF, UK tel/fax: +44 (0)1482 648964 http://www.lunarenergy.co.uk/contact.htm



Rochester Venturi

Type	Tidal venturi
Dimensions	?
Water depth	10-60m
Distance from shore	Tidal streams, fjords, inshore sites
Method of attachment to sea bed	(website does not mention)
Function principles	Rochester Venturi (RV) is a pressure amplifier governed by Bernoulli's Theorem. It uses shapers placed into a primary (tidal or river) flow to accelerate the flow and generate a reduction in pressure at the point where that flow is most constricted. The reduction in pressure can then be used in order to pull water or air from another location into the primary flow. It is this secondary flow that allows generation of electrical power. To avoid the need for water turbines, HydroVenturi has developed air injection technology where air is used as the secondary flow medium.
Development status	Scale test installed in marine environment since June 2002
Intended array size	(website does not mention)
Developer contact details	HydroVenturi Ltd, Incubator Unit, Bessemer Building (RSM) Level 1 London SW7 2BP, United Kingdom Phone: 44 (0) 207 594 3503 www.hydroventuri.com

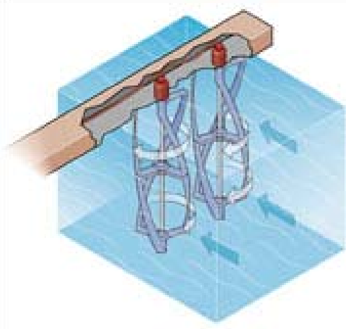
Hammerfest strom – Blue concept

Type	Tidal horizontal axis turbine
Dimensions	Blades are 15-16m long
Water depth	~50m
Distance from shore	?
Method of attachment to sea bed	Lowered onto the seabed, weights attached to the footings.
Function principles	Underwater mills The turbine is a propeller driven by the current. This converts the energy of the current into rotational energy of the shaft. The power is optimised by adjusting the angle between the propeller blades and the current. The gearbox converts the low rotational speed of the turbine shaft to the desired higher speed of the generator shaft. The generator converts its shaft energy to electric energy that is transmitted to the shore via a cable on the sea bed. The blades can alter their pitch so that energy can be extracted in both directions.
Development status	Pilot project – Kvalsundet, mean current speed at location is $1.8ms^{-1}$. The max depth is approx 50m. Installation commenced on 25th September 2003 and generates power to the national grid.
Intended array size	In Pilot power plant 20 water mills
Developer contact details	HAMMERFEST STRØM AS Address: Strandgt. 1, 9613 Hammerfest Tel.: + 47 78 41 71 03 www.e-tidevannsenergi.com

Gorlov Turbine

Type	Vertical axis turbine
Dimensions	?
Water depth	?
Distance from shore	?
Method of attachment to sea bed	None – floating.
Function principles	Rotates at twice the velocity of the water. Self starting with water flow speeds of 2ft/s. Rotates in the same direction, independent of flow direction. Modular can be assembled vertically, horizontally.
Development status	Was developed in1994. Project proposed for Uldolmok Strait in Korea. (strong current up to 12 knots(6m/s)) The plan is to install 6 twin-turbines in a vertical, side-by-side arrangement. Demonstration project at Vinlhaven Island Maine. On March 19, 2002, the Korean Ocean Research and Development Institute lowered the first Gorlov turbine into the Uldolmok Strait, a tidal channel that runs between the western coast of the Korea Peninsula and Jindo Island. Last autumn, South Korea commenced the second phase of the project, when it installed a 15-foot turbine in the strait. [http://www.nrdc.org/onearth/05spr/gorlov3.asp]
Intended array size	
Developer contact details	GCK Technology Inc. SOLEDAD PLAZA WEST 425 SOLEDAD STREET, SUITE 600 SAN ANTONIO, TEXAS 78205 Dr. Alexander M. Gorlov Vice President & Chief Technology Officer gorlov@gcktechnology.com Mary Ables-Miller Director of Public Relations miller@gcktechnology.com Telephone: (210) 226-0920

GORLOV HELICAL TURBINE



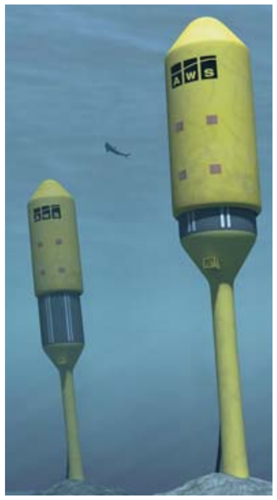
The design of Gorlov's helical turbine means that it will continue to rotate regardless of the direction of the current.

Wave dragon

Type	Overtopping/Terminator
Dimensions	Can be constructed at different sizes due to wave regime and / or power output. Approx – 300x200x20 with wave reflector 120-190m
Water depth	>20m
Distance from shore	2-3 miles
Method of attachment to sea bed	Mooring blocks and chains
Function principles	Arms channel waves, meet steep ramp and then into reservoir – floating hydroelectric dam -
Development status	Pre commercial demonstrator in Wales.
Intended array size	Not known but 9 units are required to produce 100MW power station compared to 100s from other technologies.
Developer contact details	Wave Dragon ApS Blegdamsvej 4 DK-2200 Copenhagen N Denmark Phone: + 45 3537 0211 / +45 - 35 37 02 11 Fax: +45 3537 4537 email: info@wavedragon.net http://www.wavedragon.net/

Archimedes Wave Swing

Type	Point absorber
Dimensions	12m diameter, stroke distance 12m.
Water depth	80-90m depth (AWS will be at least 3m below surface)
Distance from shore	?
Method of attachment to sea bed	Monopole
Function principles	AWS is a large air-filled cylinder which is submerged beneath the waves. As a wave crest approaches, the water pressure on the top of the cylinder increases and the upper part or 'floater' compresses the air within the cylinder to balance the pressures. The reverse happens as the wave trough passes and the cylinder expands. The relative movement between the floater and the fixed lower part or 'basement' is converted directly to electricity by means of an linear generator
Development status	Pilot plant off coast of Portugal (2005). Next stage is to develop full scale prototype, a pre commercial demonstrator unit by 2007 and install by 2008 with commercial sites post 2008.
Intended array size	Several tens of units, Area 3 nautical mile by 2 cables
Developer contact details	AWS Ocean Energy Ltd Redshank House Alness Point Business Park Alness Ross-shire IV17 0UP Scotland Tel: +44 (0) 1349 88 44 22 www.awsocean.com

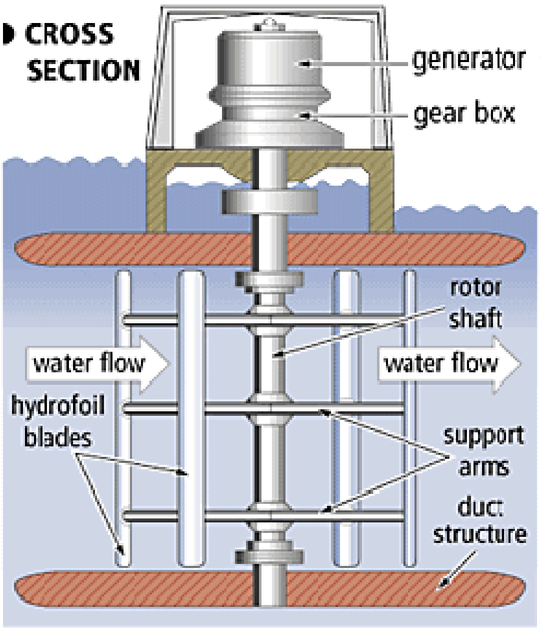


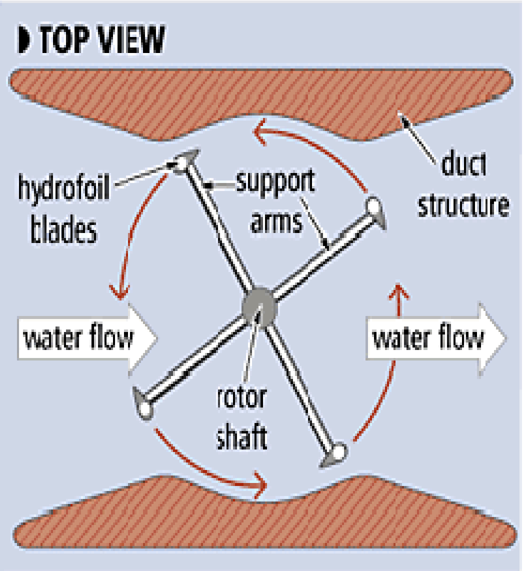
Pelamis

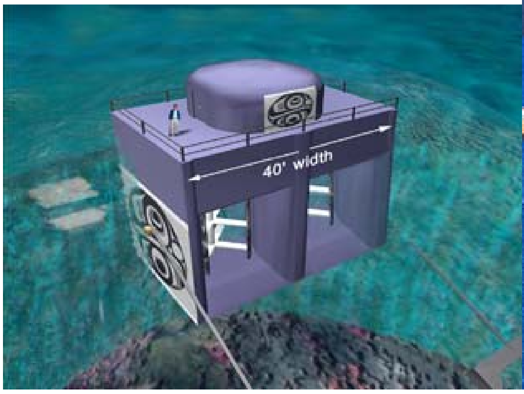
Type	Attenuator
Dimensions	120m long, 3.5m diameter
Water depth	50-60m depth
Distance from shore	5-10km from shore
Method of attachment to sea bed	Moorings
Function principles	Pelamis is a semi-submerged, articulated structure composed of cylindrical sections linked by hinged joints. The wave-induced motion of these joints is resisted by hydraulic rams, which pump high-pressure oil through hydraulic motors via smoothing accumulators. The hydraulic motors drive electrical generators to produce electricity. Power from all the joints is fed down a single umbilical cable to a junction on the sea bed. Several devices can be connected together and linked to shore through a single seabed cable.
Development status	Pre commercial /commercial. Model testing from 1998. Full scale prototype tested EMEC 2004. March 2006, 3 units shipped to Portugal for installation 5km off N. Portugal coast. OPD have letter of intent to supply a further 28 units subject to satisfactory performance.
Intended array size	Aiming for wave farms. Could occupy an area similar to wind farms *i.e.* 10km^2, 1km^2 = 40 devices.
Developer contact details	104 Commercial St, Edinburgh EH6 6NF, Scotland, UK. Telephone: +44 (0) 131 554 8444 www.oceanpd.com

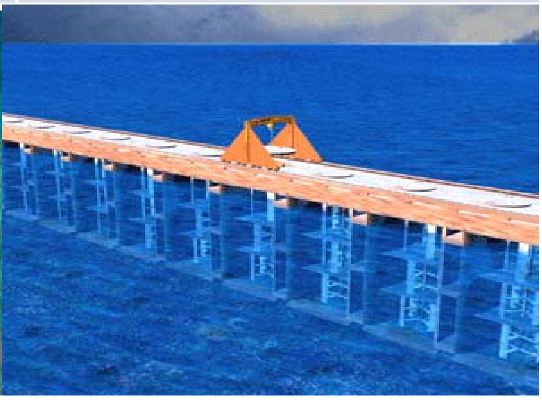
Blue Energy

Type	Vertical axis tidal turbine
Dimensions	Variable, from micro unit that can be place in riverine flows designed for remote domestic users, to the mega tidal power fence which could be many km long and in water depths up to 70m.
Water depth	
Distance from shore	
Method of attachment to sea bed	Concrete caisson anchor. (smaller units can be floating instead of anchored)
Function principles	Four fixed hydrofoil blades of the Blue Energy Ocean Turbine are connected to a rotor that drives an integrated gearbox and electrical generator assembly. The turbine is mounted in a durable concrete marine caisson which anchors the unit to the ocean floor, directs flow through the turbine further concentrating the resource supporting the coupler, gearbox, and generator above it. These sit above the surface of the water and are readily accessible for maintenance and repair. The hydrofoil blades employ a hydrodynamic lift principal that causes the turbine foils to move proportionately faster than the speed of the surrounding water.
Development status	Early prototypes tested between 1981-1985, (Blue Energy's predecessor, Nova Energy Ltd). Now Blue Energy Canada Inc is working with the University of British Columbia to further prototype research. Proposing a pre commercial demonstration project in BC using floating units and also proposing the development of a 4km long tidal fence in the Philippines.
Intended array size	
Developer contact details	Box 29068, 1950 West Broadway Vancouver, BC, V6J 1Z0 Phone: 1-604-682-2583 General Information: inform@bluenergy.com Blue Energy President and CEO Martin Burger: mjb@bluenergy.com www.bluenergy.com


CROSS SECTION
generator
gear box
rotor shaft
water flow
water flow
hydrofoil blades
support arms
duct structure

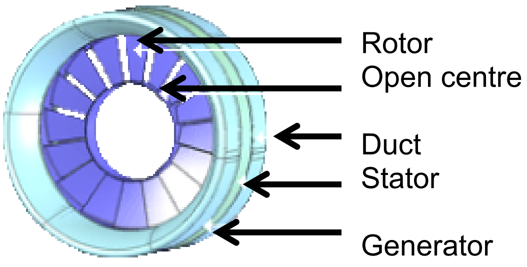

TOP VIEW
hydrofoil blades
support arms
duct structure
water flow
water flow
rotor shaft


40' width



Openhydro

Type	Tidal turbine
Dimensions	6m individual turbine (Demonstration unit)
Water depth	
Distance from shore	
Method of attachment to sea bed	Gravity base
Function principles	“The Open-Centre Turbine, with just one moving part and no seals, is a self-contained rotor with a solid state permanent magnet generator encapsulated within the outer rim, minimising maintenance requirements. The large open centre provides a safe passage for marine life and the turbine's clean hydrodynamic lines ensure that fish will not become entangled. The blade tips are retained within the outer housing which clearly defines the moving component and the turbine is designed to generate energy at a slow rotational speed.” “OpenHydro turbines are deployed at depth and out of sight. The design avoids the needs for oils, greases or other lubricating fluids.” [www.openhydro.com]
Development status	Will test at EMEC tidal site in Orkney (2006) This turbine will be installed between a twin monopile structure enabling the unit to be raised and lowered for demonstration purposes. The company intends that all future installations will be deployed on the seabed where no part of the structure will be visible from the surface or interfere with navigation channels.
Intended array size	
Developer contact details	66 Fitzwilliam Square Dublin 2 Ireland http://www.openhydro.com/contact.html



Underwater Electric Kite

Type	Horizontal axis turbine, ducted turbine design Tidal current 4-8 knots
Dimensions	Site specific, (*e.g.* 10ft diameter) units will be custom designed for each site.
Water depth	
Distance from shore	
Method of attachment to sea bed	Single cable anchor
Function principles	UEK unit tethered to seabed. Is positively buoyant. Depth controlled by computer. Able to swing laterally to stay in core of current.
Development status	1984 – winner of the Rolex prize 2000 – demonstrator project in Ontario 2005 – UEK company formed in Switzerland to develop devices in Europe. A device installed in the Rhone river at Geneva. Plans for pilot unit in Delaware Indian River
Intended array size	12 units or more
Developer contact details	P.O. Box 3124 Annapolis, MD 21403 USA Telephone: 410.267.6507 http://uekus.com/contact.html

Statkraft

Type	Horizontal axis turbine
Dimensions	
Water depth	
Distance from shore	
Method of attachment to sea bed	Floating steel structure, conventional anchor system.
Function principles	Underwater turbines
Development status	Statkraft 3rd largest power supplier in the Nordic region. Designing tidal power since 2001 with Hydra Tidal Energy Technology AS. Design completed in 2005. Building full scale demonstration project and would like to install either at EMEC or at Kvalstundet Strait near Tromso, Norway.
Intended array size	N/K
Developer contact details	PO Box 200, Lilleaker NO-0216 Oslo Tel: +47 24 06 70 00 Fax: +47 24 06 70 01 Street address: Lilleakerveien 6, Lilleaker http://www.statkraft.com/pro/about_statkraft/contact_us/index.asp

TidEL

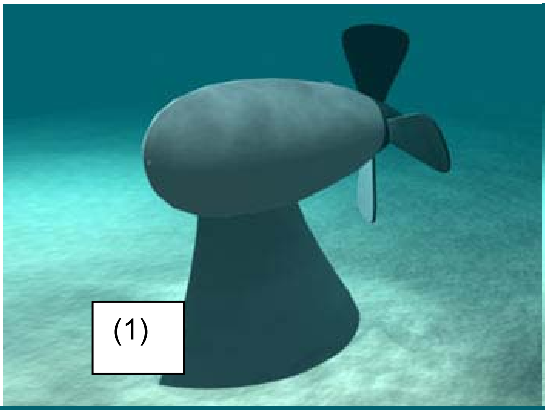
Type	Horizontal axis turbine.
Dimensions	
Water depth	“reasonable coastal water depth” Ideally 5 knots peak velocity tidal flow
Distance from shore	
Method of attachment to sea bed	Tethered by a series of mooring chains
Function principles	Floating, moored to seabed, generator free to move in line with direction of current flow. Pair of contra rotating turbines on a single crossbeam.
Development status	1:10 scale unit tested at New and Renewable Energy Centre (NaREC) in Blyth in 2004. 2005, DTI funding to develop demonstrator unit to be tested at EMEC SMD was established in 1971. Design and manufacture tractors and subsea equipment *e.g.* cabling, ROVs
Intended array size	30-100 units
Developer contact details	Michael Jones, Ralph Manchester SMD Hydrovision Wincomblee Road Newcastle upon Tyne NE6 3QS 0191 234222 www.smdhydrovision.com/

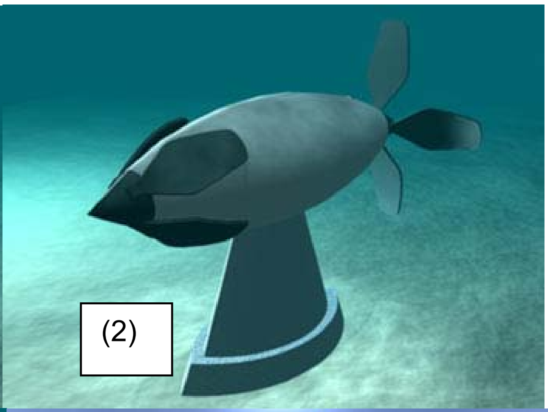
Verdant Power – Kinetic Hydropower System KHPS

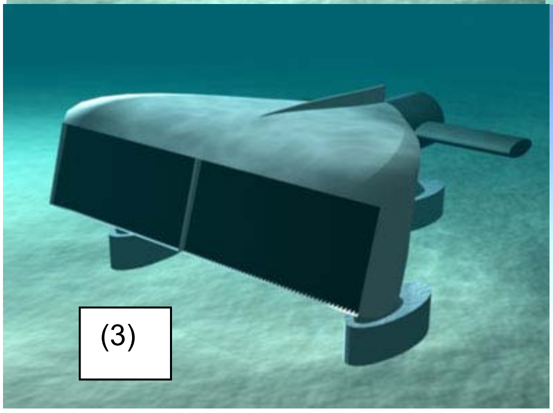
Type	Horizontal axis tidal turbine
Dimensions	5m diameter blade
Water depth	At least 6m
Distance from shore	
Method of attachment to sea bed	Anchored to water bottoms, either by pylons, concrete bases, or other site specific anchoring devices
Function principles	~4 knot current, 3 blade rotor design. Turning speed~30rpm. “Self-cleaning screen for horizontally deflecting debris and fish away from turbine blades (also designing screenless, debris immune, and more fish-friendly turbine)”
Development status	Began designing and testing ~ 1998. System was first demonstrated in 2000. Company have approval to install 6 devices in New York (off the coast of Roosevelt Island) 18 month test programme began June 2006. If successful planned farm size will be ~300 units by 2010. Also looking at projects in Ontario and with EMEC.
Intended array size	300 units
Developer contact details	Verdant Power, LLC 4640 13th Street, North Arlington, VA 22207 Phone: (703) 528-6445 http://www.verdantpower.com/contact/information.html

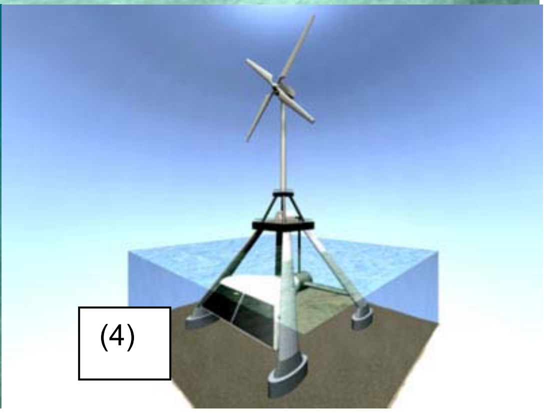
Kinetic Energy Systems

Type	Horizontal axis turbines
Dimensions	Bowsprit(1) and tidal generator(2) – 10m turbine diameter Hydrokinetic Generator (3) – 15m turbine Offshore energy platform (4)
Water depth	From shallow river and coastal, no max depth given
Distance from shore	
Method of attachment to sea bed	Various -Pedestal on seabed, attached to ships (Bowsprit) docks and bridges, or tethered by anchor
Function principles	Tidal turbines
Development status	Prototype stage. Patents applied for.
Intended array size	N/K
Developer contact details	Kinetic Energy Systems, Inc. 10846 SW 67th Terrace Ocala, FL 34476 (352) 875-5972 Mobile www.kineticenergysystems.com


(1)


(2)


(3)


(4)