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Equitable Testing and Evaluation of Marine Energy Extraction Devices in terms of Performance, Cost and Environmental Impact

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Uncertainties regarding environmental impacts.
A draft.

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Uncertainties regarding environmental impacts. A draft.

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Summary

In this report the main uncertainties regarding the potential effects of ocean energy schemes are presented considering the main components of the marine wild life and its interactions with the physico-chemical environmental alteration / disturbance provided by the deployment of ocean energy power devices. Future socio-economic uncertainties are also discussed considering the experiences of other offshore technologies.

CONTENTS

1 INTRODUCTION

Marine renewable energy is still at an early stage of development and therefore little data has been collected from monitoring that can aid our understanding of the potential environmental impacts of future developments. Much less is known about marine biota and ecosystems compared to terrestrial ecosystems and, for example, high energy tidal stream environments have been little studied, in part due to the limited access and cost of working in these areas. The limited data from practical examples make it difficult to predict the potential impacts and their magnitude, which are also likely to have site and technology specific components. The assessment of the potential environmental impacts of wave and tidal energy should be carried out to determine what is known and unknown and this information is useful to support the permitting process as well as to make responsible decisions to site facilities and to minimize environmental impacts.

Furthermore, partly due to the non-existence of operating farms the magnitude of environmental effects is far from being quantified, especially for the cumulative impacts of multiple devices. However, tools and methodologies based on field and laboratory experiments and modelling results are being developed to address impact uncertainties. For example, the risk of collision between marine animals (fish and marine mammals) and marine renewable energy generating devices has been addressed through the development and application of a mathematical modelling which simulates both the risk of encounter and the potential for animals to avoid encounter or to evade collision. Some other methodologies for impact assessment are thought to be adapted from the offshore wind technology.

Uncertainties regarding the socio-economic topic are also of concern particularly when space-use conflicts can exist. Experiences from wind offshore energy can help on the identification of the critical issues on space-use conflicts management and on pathways to gain public acceptance towards wave and tidal energy implementation.

In this report the main uncertainties regarding the potential effects of ocean energy schemes are presented considering the main components of the marine wild life and its interactions with the physico-chemical environmental alteration / disturbance provided by the deployment of ocean energy power devices (Figure 1). Future socio-economic uncertainties are also discussed considering the experiences of other offshore technologies.

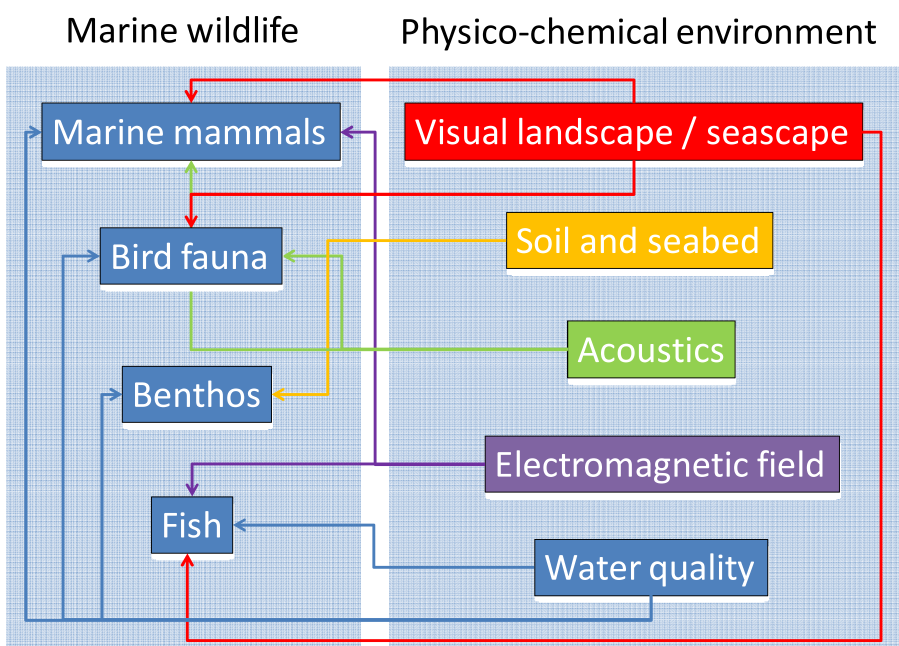

Figure 1 Components to consider in environmental impact analysis of ocean energy.

2 ALTERATION IN WATER CIRCULATION PATTERNS

2.1 CURRENTS AND WAVES

The potential impacts on currents and tides include changed mixing properties in the near field, modified sediment transport in the near and far-fields and the potential to reduce current power generation capability of the neighbouring area. Modification of wave-current interaction can result in wave-structure interactions (diffraction, reflection, breaking and sheltering) and current regime modifications (less than the wave-structure components). This type of alteration can change navigational conditions in the near-field, wave loads of adjacent structures and sediment transport under waves. At a far-field level, wave-climate modification could affect the recreational potential of nearby shorelines (e.g. surfing and swimming beaches), sediment transport along adjacent shorelines, possibly altering patterns and rates of shoreline erosion and deposition as well as the power generation capability from waves in the neighbouring area that was mentioned previously.

The effects of operating ocean energy devices on water circulation have not yet been measured. Thus some uncertainty is recognized in this field although model results suggest that reductions in water circulation patterns are probably small (Table 1). It is also accepted that the impacts on currents and waves are strongly dependant on technology and location of the projects with maximum effects closest to the installation and near the shoreline [1].

Table 1 Predicted wave height and current velocity reductions.

	Study site	Reduction values	Source
Waves	Wave Hub	1% in wave height	[2]
		3% (maximum decrease in wave height with a 90% energy transmitting wave farm)	[3]
	Wave Hub	3 to 13% reduction at the shoreline	[4]
	Wave Hub	3 to 6%	[5]
	-	3 to 15%	[1]
	Coastal California	3 to 13%	[6]
Currents	Wave Hub	1.5 to 2.0 m s^{-1} reduction in tidal currents and an increase of about 0.6 m s^{-1} elsewhere	[7]

The alteration of water circulation patterns can also be responsible for a number of indirect effects on aquatic flora and fauna such as richness and density of benthic and pelagic organisms due to e.g. changes in tidal range, sediment grain size or food availability. Although the occurrence of such effects it's a real possibility the extent or even the direction of change of such effects can be difficult to predict. For a small number of devices the changes are expected to be localized dissipating quickly with distance. However, it can be expected that the cumulative effects extend to a greater area if a large number of arrays are operating.

2.2 Sediment dynamics

As mentioned above disturbance on sediment dynamics can occur indirectly due to modifications on water circulation patterns promoted by device operation. Direct effects on sediment dynamics can occur during installation, e.g. during the attachment of the devices to the bottom through piling, anchors or cables, or during deployment e.g. if there are cables laying on the seabed and are not anchored to it. The effects which occurred during installation are usually temporary and their significance is proportional to the amount and type of bottom substrate disturbed.

During device operation, the alteration of sediment transport due to potential changes in current velocities or wave heights can have a role in erosion and sedimentation patterns increasing both scour and deposition on both local and far-field scales. Deposition of sediments is expected to cause shoaling and a shift to a finer sediment grain size on the lee side of wave energy arrays [1]. However, there are uncertainties related to the areal extent that can be deposited since it will depend on the local topography, sediment types and the characteristics of the currents and the projects [7]. At a far-field scale, there is a possibility for changes in beach sand erosion and deposition patterns. The wave climate was modelled in the Wave Hub connection [2] which would be located 20 km off the coast in water depths of 50-60 m. The predictions indicated that an array of wave energy converters would potentially affect the wave climate on the nearby coast by about a 1 to 2 cm decrease on wave heights. It is unknown whether these small changes in the average wave height would measurably alter sediment dynamics along the shore, considering the normal variations in waves due to wind and storms. Changes in scour and deposition can in turn alter the habitats for bottom-dwelling plants and animals (see topic 3).

3 Interference with benthic habitats

The installation and operation of ocean energy converters can directly displace bottom plants and animals or can alter their habitats through changes in water flows, structure of waves or substrate composition. During the installation process, disturbances in the bottom habitats will result from temporary anchoring of the construction vessels, digging and refilling the trenches of the power cables and installation of permanent anchors, pilings or other mooring systems. At this stage motile organisms will be displaced and sessile organisms destroyed in the areas affected by the activities referred. The increase of suspended sediments and sedimentation down-current from the construction area are expected to affect benthic organisms through smothering and decrease of light availability which can increase plant mortality and/or growth rate decrease of plant shoots (e.g. seagrasses and macroalgae).

When installation is completed, disturbed areas are supposed to re-colonize by the same organisms assuming that the substrate and habitats are restored to a similar state. Uncertainties from the indirect impacts of sediment transport, erosion and deposition changes can be stronger than direct effects (e.g. anchors and cable installation) and may be more extensive and long-lasting interferences with benthic habitats. These effects are difficult to predict but the analysis of model results can help to identify most sensitive areas.

4 ARTIFICIAL REEF EFFECTS

Due to fishing and navigation limitations or prohibitions, ocean energy parks are comparable to marine protected areas where enhancements in local fish species richness, size and biomass have been demonstrated [8] [9] [10]. The extensive and rapid colonization of ocean energy structures by macrobenthic communities has been also established, particularly on the device foundations installed in coastal sandy areas. The installation of artificial reefs on the seabed to mimic some characteristics of a natural reef has been introduced as a coastal management tool to e.g. enhance species biodiversity, increase fisheries yield and production, promote recreational diving and prevent trawling. When a hard substrate is added to a marine substrate great change can occur due to the introduction of a new kind of habitat that in turn can lead to new trophic opportunities and changes to local food web interactions. It is important to determine if this change is beneficial or not for the existing local conditions. However, although questions arise regarding the value of the introduction of artificial reefs in specific coastal areas, it is generally accepted that its success ultimately reflects the quality of prior planning and ongoing management. The solid structures placed on the seabed to support or as a part of, the offshore energy units should be regarded as artificial reefs and as such its design can play a critical role in species establishment.

There is some uncertainty regarding whether the local biomass enhancement is a result of mere aggregation from the surroundings or a true increase in biomass since it depends on species and on a number of environmental factors. In most cases, site specific input data only allows for general assumptions [11] [12].

Model results supported by field measurements around wind offshore foundations in Nysted, Denmark, suggest that they are particularly favourable for blue mussel growth in the western Baltic Sea and that the artificial reef function depends upon how the blue mussels interact with their local pelagic and benthic environment (grazing control and local depletion of phytoplankton and zooplankton above mussel beds [10]).

A comprehensive review of literature on the combination between wave power foundations and artificial reef technology is available [13]. In this work, wave power foundations design is discussed considering their potential role on sustainable coastal resource development. Results of this analysis show that a large complex structure such as a decommissioned ship is favourable for highest diversity of species. In terms of increasing population numbers, fishing industries that target bottom-dwelling fish would benefit most from low lying reefs such as assembled from concrete pipes while wave energy buoys tethered by hose pumps or hydraulic cylinders would imitate ships or Fish Aggregating Device (FAD) used in fisheries. The combination of the buoys and a benthic or larger reef structure would therefore create a type of "super reef" habitat, by combining multiple effective components for aggregating marine life [13].

First investigations on wave power devices were conducted in the test park of Lysekil, Sweeden, to analyse the colonisation of foundations by invertebrates and fish, as well as fouling assemblages on buoys. The influence of foundation surface orientation of on epibenthic colonisation was also examined and observations of the use by fish and crustaceans were carried out during three years. Results indicate a high degree of coverage on vertical surfaces dominated by blue mussels (*Mytilus edulis*) and a higher average abundance of crustaceans (mainly crabs *Cancer pagurus* and some lobsters *Homarus gammarus*) on foundations than in controls. In this study the biofouling on wave power equipment (buoys acting as point absorbers on the surface) was also examined and calculations indicate no significant effect in the energy absorption of a buoy [9].

5 WATER QUALITY INTERFERENCE

When addressing the chemical effects of the ocean energy devices, it is important to distinguish between spills as a source of chemical, low probability but high impact, versus continuous release of chemicals for example in fouling paints. Uncertainties of such effects on biological communities are concerned with the toxicity of the chemicals to the marine organisms and the probability of its passage through trophic levels (bioamplification). Furthermore, chemicals can move over a large area, depending on the site circulation pattern. Although this type of effects are, like others, strongly site-specific, information is needed on the toxic compounds to be used, potential amounts that could be released, responses of the biological receptors and the fate of contaminants.

In a scientific workshop conducted by the United States National Oceanic and Atmospheric Organization (NOAA) on the ecological effects of wave energy development in the Pacific Northwest [1], the potential chemical dissolved toxics from wave power devices were considered stressor factors on the natural physical and biological receptors (conducting to the results presented in Table 2. High impacts of such "pressure" (including some uncertainty regarding this classification due to information scarceness) have been identified for pelagic fish, forage fish and invertebrates and seabirds.

The rapid and heavy growth of marine fouling of wave energy devices is considered of particular concern since it has to be removed or avoided to prevent or reduce equipment corrosion and fatigue as well as to maintain efficiency of most types of devices. There are currently only three options to deal with marine fouling: use of antifouling coatings, *in situ* cleaning using high pressure jet spray by divers or remotely operated vehicles and removal of the device from the water surface for cleaning on site or onshore and reapplication of antifouling coatings. Antifouling coatings can reduce the frequency of maintenance by the slow release of a biocide at the surface. Most products have been developed for the shipping industry and rely on the movement of water to accomplish the self-polishing that exposes a new layer of the coating. Historically antifouling coatings used tri-butyl tin or copper as the biocide, which are very harmful compounds for several marine animals. Nowadays the use of tri-butyl tin compounds on coatings have been proposed to phase out and research have been carried out to develop less toxic antifouling coatings [7]. In the demonstrations buoys off Makah Bay, the results of the test of different types of antifouling coatings is expected to determine their effectiveness, as part of an agreement with the Olympic Coast National Marine Sanctuary [14].

Table 2 Stressor-specific effects table for chemical effects. Legend: L = low impact, M= medium impact, H = high impact, ? = some uncertainty associated with the estimate [1].

Activity (agent or stressor)		Ocean waves	Ocean currents	Benthic habitats	Plankton	Fouling Community	Pelagic fish	Forage fish and invertebrates	Demersal fish	Epibenthic macroinvertebrates	Benhic fauna	Seabirds	Pinnipeds	Cetaceans
Organics	Hydraulic fluids	L	L	L/M	L?	M?	H?	H	M	L/M	L/M	H	L	L
	Spills (fuel, oil)	L	L	L/M	L?	M?	H?	H	M	L/M	L/M	H	L?	L?
Metals	Sacrificial anodes (Zn^{++})	L	L	M	M?	M?	H?	H?	M?	M?	M	M?	L	L
Toxics	Tributyltin (Sn^{+++})	L	L	M	M?	M?/H	H?	H?	M?	M?	M	M?	L	L
	Antifouling coatings (Cu^{++})	L	L	M	M?	M?/H	H?	H?	M?	M?	M	M?	L	L

6 NOISE DISTURBANCE

6.1 NOISE DISTURBANCE ON MARINE MAMMALS

Construction and operation of large mechanical structures will inevitably produce sound that may disturb or even cause physical damage to wildlife in the vicinity. Physical/physiological effects may include hearing threshold shifts and auditory damage. For sensitive species such as marine mammals, effects may occur at short to moderate ranges. Behavioural responses, including fright, avoidance and changes in behaviour and vocalisation patterns have been observed in baleen whales, odontocetes and pinnipeds; in some cases at range of tens or hundreds of kilometres from loud industrial noises.

The biological significance of these effects has not been measured. However, where feeding, migration and social behaviour are affected, it is feasible that populations could be adversely effected. There may also be long-term consequences due to chronic exposure, and sound could affect marine mammals indirectly by changing the accessibility of their prey species.

There are important gaps in our knowledge. For example, the characteristics of the sound signature of these new and developing technologies are poorly known and how they propagate at different ranges and depths are poorly understood and there are insufficient data to identify appropriate propagation models for particular conditions. This could lead to orders of magnitude differences in predictions of the number of animals affected by sound sources.

While such large degrees of uncertainty continue, a precautionary approach to management and regulation should be pursued. This has direct financial and operational consequences that tend to make operations more expensive and or less efficient. Noise effects can be split into a number of categories briefly described below.

6.1.1 Physical damage

Ears, that have been adapted to be sensitive to sound, are also likely to be susceptible to being damaged by it. Exposure to noise of sufficiently high intensity causes a reduction in hearing sensitivity (an upward shift in the threshold). This can be a temporary threshold shift (TTS), with recovery after minutes or hours, or a permanent threshold shift (PTS) with no recovery. PTS may result from chronic exposure, and sounds that can cause TTS usually cause PTS if the subjects are exposed to them repeatedly and for long enough. However, very intense sounds can cause irreversible cellular damage and instantaneous PTS. At present we have little information on the levels of exposure to chronic noise pollution that are required to cause either TTS or PTS. Work is needed to estimate safe levels of exposure for different marine mammal species.

6.1.2 Auditory masking

Background noise will reduce an animal's ability to detect certain other sounds. Masking in humans and marine mammals has been reviewed [15]. Generally, noise will only mask a signal if it is sufficiently close to it in frequency, i.e. within that signal's 'masking band'. At low frequencies, masking bands are broad and have a constant bandwidth. At higher frequencies, bandwidths are narrower and their width scales with frequency. Marine mammals might be expected to be most susceptible to masking of low frequency sounds by low frequency turbine and construction noise. The effects of masking can be reduced when the noise and the signal come from different directions and the receiver is able to directionalise one or both. In effect, the signal to noise ratio is reduced in the direction from which the signal is coming. Directional hearing has not been investigated in marine mammals at the low frequencies where most industrial energy is centred.

It is not possible, given the current state of knowledge, to properly assess the potential for biologically significant masking by noise from construction and operation of marine generation systems.

6.1.3 Behavioural responses

Many studies have measured changes in behaviour in response to exposure to industrial noise sources, especially seismic noise. However, the behavioural responses are likely to be highly variable and site, device and species specific. To date we have no reliable ways of predicting behavioural responses. A range of factors may affect an animal's response to a particular sound including previous experience, its auditory sensitivity, its biological and social status and its behavioural state. By their nature, behavioural responses are likely to be unpredictable. Habituation occurs when an animal's response to a stimulus wanes with repeated exposure to predictable stimuli. The opposite process is sensitisation, when experience of a signal leads to an increased response. Neither of these aspects is well understood in marine mammals.

There have been no directed studies to investigate whether or not wet renewable construction or operation can lead to long-term disturbance and exclusion from habitat. However, there are examples where repeated seismic surveys do not appear to have caused animals to desert areas of preferred habitat, e.g. grey whales [16] bowheads [17]; and bottlenose dolphins [18] [19]. It is risky to extrapolate from these to other species and different sound sources.

6.1.4 Chronic Stress

The stress of having to remain within a habitat subject to a harmful or aversive signal could have damaging physiological and behavioural effects and leave animals vulnerable to disease. Such effects need to be studied. In mammals, stress is often associated with release of the hormones that may be associated with changes in behaviour, e.g. increased aggression, changes in respiration patterns or social behaviour and may lead to a reduction in the effectiveness of the immune system. Such effects have not been shown in marine mammals and will be difficult to demonstrate, but the potential for noise-induced stress to have effects on so many aspects of the health of individuals and populations makes it a matter of real concern.

Noise may indirectly impact cetacean and pinniped populations through its effects on prey abundance, behaviour and distribution. See below for effects on fish.

Three approaches can be used to assess the effects of noise on marine mammals:

1) Direct observations of marine mammals exposed to sounds in the field;
2) Extrapolation from work on marine mammals held in captivity or from better-studied animals;
3) Physical-psycho-physiological modelling of hearing mechanisms and processing;

Approaches 2 & 3 involve extrapolation from other species and have some scope for predicting the occurrence of trauma and threshold shift but are of limited vale in predicting disturbance reactions, which are likely to vary greatly, depending on species and context.

Behavioural responses to sound can be difficult to study. Observation from ships, aircraft and coastal vantage points have all been recommended as methods for assessing the likelihood of exposure and the responses of animals to them. Each has its own set of advantages and problems, but in many cases the relative effectiveness of different methods is poorly known.

For the more vocal species, acoustic monitoring can provide researchers with a variety of behavioural cues. Acoustic monitoring is usually combined with visual observations and the two approaches should be seen as complimentary. However, not all marine mammals are vocal, and the significance of changes in vocal behaviour can be hard to interpret. Further work is needed to determine the effectiveness of the monitoring, extend it to more species and investigate the meaning and significance of changes in acoustic signal output.

Telemetry techniques, particularly satellite linked tracking systems can provide large quantities of reliable data, including information on underwater behaviour, physiological responses and on the physical and acoustic environment. These methods allow animals to be tracked over extended periods and facilitate the collection of detailed behavioural, physiological and environmental data. Such methods need to be developed for a wider range of species and applied in a wider range of conditions.

6.2 NOISE DISTURBANCE ON FISH

Noise disturbance may occur in all phases of marine renewable energy devices construction / installation, operation and decommissioning. The construction phase is of particular concern if pile driving is required. The effects of pile driving operations on fish have received little attention [20] but ongoing work is being conducted by CEFAS and Cranfield University funded by COWRIE. Sound levels above 180 dB re to 1 µPa are considered to risk damage to or death of marine animals and that source levels during pile driving operations can be up to 202 dB re to 1 µPa, without bubble curtain mitigation [20]. Lethal noise levels are very uncertain. Early work that demonstrated that the rise and decay time is very important and that a combination of rapid rise and decay (~1 ms) and a sound pressure of ~229 dB re to 1 µPa are required to be lethal (see [21] for discussion). Thus it is unlikely that piling operations will cause mortalities directly.

There could, however, be physiological damage either temporary or permanent that could seriously affect subsequent survival. Sudden increases in pressure of more than 1*105 Pa (equivalent to 220 dB re to 1 µPa) can rupture the otic bulla membranes in the inner ears of herring [22], impairing their hearing and thus increasing vulnerability to predation. Similar results were reported for the Atlantic menhaden [23] indicating the likelihood of similar vulnerability of all clupeid fish. The experiences with herring [22] only used fish up to 17 cm long and found that the larger fish were more vulnerable to otic bulla rupture. Relatively large steps (0.5 ATA) in pressure change were used in these studies and, since the pressure pulse required to cause damage is close to sound pressures from pile driving it is clear that further research is required.

Even if physiological damage is unlikely to be caused by marine renewable energy devices construction, behaviour may be disturbed. Many species of fish use sound both for communication and for detecting prey and predators. A study on the effects of seismic air guns on fish behaviour [21] reported that, although gadoid fish responded to air gun blasts with C-start escape responses, their subsequent behaviour and distribution not affected. Their work did not include clupeid fish (e.g. herring) that are hearing specialists with a very low threshold and sensitivity extending into the ultrasonic [24] whose behaviour and distribution are more likely to be affected. Herring, for example are known to emit sounds by using their swimbladder to release streams of bubbles through their anal duct **Erro! A origem da referência não foi encontrada.**] that may have a role in communication. Temporary exclusion from a spawning ground or disturbance of behaviour during spawning would have serious consequences. Sound communication is an essential component of gadoid fish spawning behaviour, which has been extensively studied, commencing with [26]. It is not known if pile driving or other noise pollution would disturb this behaviour. The possible deleterious effects of transient sounds from interaction of fish with turbine blades are covered in Section 8, below.

7 ELECTROMAGNETIC FIELDS

7.1 WHAT ARE ELECTROMAGNETIC FIELDS AND WHY ARE THEY IMPORTANT?

To understand why electromagnetic fields (EMF) may be an important factor in assessing the environmental impacts of wave energy converters (WEC) we will first explain how they arise and define a standard nomenclature to be consistent throughout this report. The Electromagnetic field (EMF in upper case letters) is a broader term that includes the Electric Field (E Field), measured in µV/m, which is usually contained within the cable insulation and the magnetic (B- Field) measured in µTeslas which is detectable on the outside of the cable. In turn, the B-field can create an Induced Electrical Field (iE Field) when conductive animals move through it.

As the offshore renewable energies have been developing and maturing it became clear that the most practical way to transport the energy produced is to wire it to land through underwater cables. However cables are also expected to link devices between themselves and possibly a common hub, depending on the park design. Therefore a significant proportion of seabed in offshore parks is expected to have the presence of cables. The potential environmental impact derives from the fact that the earth geomagnetic field strength ranges from 20 to 75µT [27] and there is abundant evidence that some marine species have the ability to detect and some use EMF fields for orientation and detection of other animals (predator-prey interactions). Therefore the question is to what degree anthropogenic sources of EMF fields can affect marine organisms.

7.2 RESEARCH TO DATE

One very important aspect which must be considered when observing the results to date is the complexity and high costs implied in carrying out in-situ monitoring of sub-sea cables. Consequently the vast majority of the data available on this topic has been obtained through laboratory studies although some attempts have been made to create mesocosms and to obtain in-situ data. As methodologies improve and offshore monitoring experience amounts more field data is expected. For the purposes of this review it will be assumed that the cables used in the future WEC devices will have similar characteristics to those used in wind farms at present.

The offshore wind industry in the UK, which has been growing consistently, has been funding important environmental work through the Collaborative Offshore Wind Research Into The Environment (COWRIE) including a comprehensive study on EMF fields comprising of two reports. The first [28] is a broad literature review of existing information on the effects of EMF on marine fauna while the second [29] published in March of this year presents the results of a mesocosm study and in-situ EMF measurements at wind farms. Both these reports are freely available on-line for consultation and offer a very complete set of information.

The COWIE 1.5 report concluded that, with the information available, an interaction between electro-sensitive species and the EMF fields caused by offshore wind cables is likely to occur. However it also stated that although the organisms could possibly be affected from the cellular to the behavioural level, at this point, it is not possible to determine what kind of responses may be expected and in turn whether they may be positive or negative. The COWRIE 2.0 report, with the results of the mesocosm experiment found evidence that some benthic, elasmobranch fish species can respond to the presence of EMF that is of the type and intensity associated with sub-sea cables. However the responses registered were not predictable and appear to be species specific and perhaps individual specific.

There is a large amount of literature that documents the ability of marine organisms to detect and be affected by EMF. These species can be divided into two types. The main group which is known to be electroreceptive are the Chondrichthyes (the Elasmobranchii and their relatives the Holocephali). They include sharks, rays and skates. These species possess Ampullae of Lorenzini (AoL), which are special electroreceptors that enable the detection and location of very slight sources of E-fields, and are used especially in foraging [30].

The other species that are electrosensitive, do not posses specialized electroreceptors but can detect induced voltage gradients which can result from water movement and geomagnetic emissions. A list of species which have been found to be able to detect EMF fields can be found in the COWRIE 1.5 Report.

Therefore at this point it is known that the sub-sea cable emissions can be detected by the sensory organs of several marine organisms although very little can be predicted about what kind of interaction this may trigger. It is very hard, with current data, to estimate if there can be a species or an ecological impact from EMF.

7.3 EXISTING KNOWLEDGE GAPS

There are several unanswered questions regarding EMF impacts which need to be addressed in order to be able to understand the impacts that can arise. For example migration using magnetic field may be disturbed by EMFs but, since other cues are also used, EMFs from cables may only disturb migration routes on a small scale relative to the large migration distances over which magnetic field cues are used. It will be difficult to carry out laboratory experiments on an appropriate scale to establish a significant effect. Field tagging (acoustic tags for example) may be the way forward. The table below summarizes the main knowledge gaps that have been identified.

Table 3 Predicted wave height and current velocity reductions

Knowledge gaps	Source
EMF impacts on other species While there is some literature on the sensitivity of Elasmobranchs and some other species to EMF there is a general lack of information of many animal groups. Particular concern has been given to salmon, pinnipeds, cetaceans, seabirds, sturgeon, squid, baitfish, flatfish, rockfish, lingcod and plankton. Obtaining this background information will be crucial to identify the most susceptible species and therefore assess the suitability of a proposed site accordingly. It is also essential to devise monitoring plans that may have to be species specific. It is recognized that laboratory experiments are limited in assessing EMF effects on species migration. Field tagging of individuals (i.e. acousitc tags) can play an important role in improving our understanding on migrations in future in-situ monitoring.	[1]
EMF impacts at different life stages The information available regarding species responses is mostly based on experiments conducted with adult specimens. It is of particular importance to address the impacts that EMF may have on early life stages as individuals tend to be more vulnerable and many species move in-shore to breed.	[28]
Mitigation measures Although cable burial has been often presented as a possible mitigation measure, and is likely to help avoid the strongest B and iE fields owing to the physical barrier of the substratum, there is evidence to suggest that it is ineffective in 'dampening' the overall B field. Conversion of electricity to 60 Hertz synchronous AC and cable armoring are also expected to mitigate EMF. Faraday caging of the generation devices and sub-sea pods can also be considered.	[28] [1]
Cable properties and WEC park design The likely electric and magnetic field strengths associated with recent cable designs and the arrangement/design of WEC arrays and parks are unknown and can have a large influence on the overall EMF produced.	[28]

8 INTERFERENCE WITH MARINE ANIMAL MOVEMENTS

8.1 COLLISION AND STRIKE

8.1.1 *Defining the process of interaction and collision*

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 physical injury. A collision may, therefore, involve actual contact between the organism and device or the effects of the pressure field around the device. We will not consider the physical impacts of sound, which are dealt with in section 4, above. The marine vertebrates that we will consider are marine mammals (pinnipeds and cetaceans), seabirds and fish.

A better understanding of the problem and the uncertainties that require further research can be gained by considering and defining the processes that may lead to collisions. If a collision is to occur then there must be an encounter between an animal and part of a device. We define an encounter as an event when the trajectories of an animal and part of a device, in 3 dimensional space, are expected to occupy the same point in space and time. This, for example, does not equate to passage through the disc swept by the blades of a tidal stream turbine but to a collision course between an animal and a blade.

Animals will perceive the presence of a device as a result of visual and/or auditory cues. They may respond to these cues, either directly or as a result of a learnt response. 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. Avoidance will be on such a scale that the animal will be kept away from all parts of a device. By excluding themselves from the region of the device collisions do not occur; effectively reducing encounter rate to zero. If avoidance does not occur animals may evade collision at close range. Evasion is defined as the direct response to an attack or perceived attack. Fish, higher vertebrates and also many invertebrates perform escape responses to such sensory cues, often mediated neurologically as reflex responses, in order to evade capture by predators or, we assume, avoid collision with submerged objects. 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.

Taking offshore wind power as an example of the effects of ocean energy on marine birds, disturbance and collision are considered the most concerned issues since birds react to disturbance effects by avoiding the sites, although their less ability to avoid a site provides a higher collision risk. The permanent loss of habitat due to displacement (avoidance), barrier effects (e.g. fragmentation effects on units of the ecological habitat network such as breeding or feeding areas) and increased consumption of energy reserves during migration due to avoidance reactions, are other referred issues.

8.1.2 Estimating encounter rate

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 [31]. This model was modified and extended by [32] and applied to predation between medusae and fish that depend upon collision. In a strategic environmental assessment for the Scottish Government, this model was used to predict encounter rate between marine vertebrates and tidal stream turbine blades [33]. By combining the encounter model with prediction of routine swimming speed based on size it was predicted that encounter rate increases with animal size due to increased swimming activity. However, by also including densities predicted from a size-density spectrum, [33] it was shown that, as a proportion of a species population, encounter rate would increase with size of species (Figure 2).

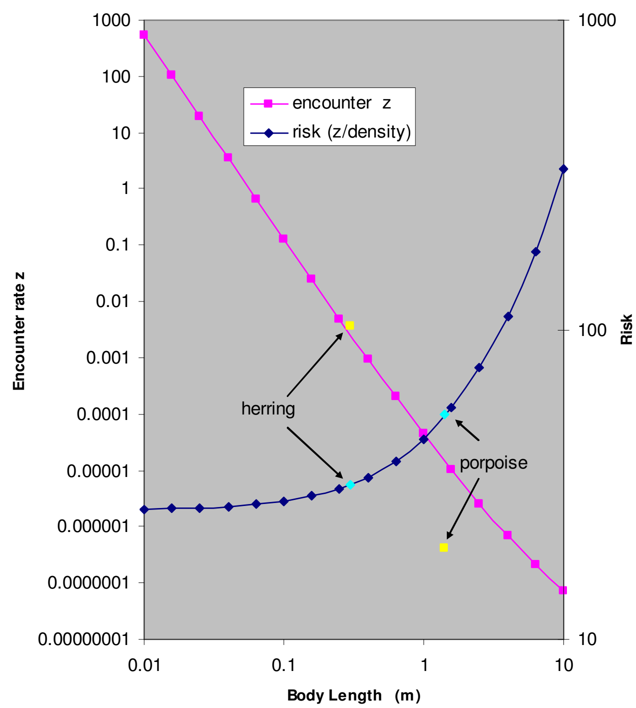

Figure 2 The theoretical effect of animal body length on encounter rate *z* dependant on expected size spectra and on relative risk to populations of animals independent of density (from [33]).

The predictions (at the population scale) made by [33] assumed random distribution of animals but in reality animal distribution is far from random, varying both spatially and temporally. For specific marine energy developments local distributions of species at risk will be required. Actual encounter rate will depend on spatial and temporal variation in behaviour within the locality.

8.1.2.1 Spatial and temporal variation in animal distribution and behaviour

Although certain species may be present in an area their interaction with marine energy generating devices will depend on their vertical and spatial distribution and how that varies on different temporal scales (diurnally, tidally and seasonally for example). To a large extent this is or should be a generic issue and not require detailed monitoring at proposed sites. The vertical distribution of fish species has been extensively studied, including diurnal vertical migration behaviour. Vertical movement of mammals and birds are less well known and need further research in order to be able to estimate potential encounter rates.

All marine animals have tidally synchronised behaviour driven by an internal tidal clock. This behaviour has been extensively studied in the intertidal environment and, relevant to tidal stream energy generation, for tidal stream migration [34]. Zooplankton and fish become concentrated at tidal fronts [35] and cetaceans and birds are known to be attracted to areas around tidal streams. How use of tidal streams varies with state of the tide as received little attention. One study of seabird tidal stream use [36] showed considerable variation between guilds (defined by feeding behaviour) and species in behaviour with state of the tide; some species feeding mainly at slack water others at peak flow. The water depths and spatial variation of flow velocity used were also found to vary by species.

The use of tidal streams by all marine vertebrates requires further research in order to fully understand and predict collision risk. Some work on pinniped behaviour that will help to clarify this is being done by SMRU as part of the monitoring of the MCT Strangford Loch demonstration project. Further studies of seabird, fish and cetacean behaviour in tidal environments are also required. Such studies would be of value in their own right as contributions to a neglected area of ecology.

There is anecdotal evidence that it is likely that fish may avoid the more intense tidal streams at peak flow either by moving into sheltered areas (bays), areas of lower velocity, moving close to the sea bed or exploiting back eddies. This is likely to affect the distribution and behaviour of fish predators (pinnipeds, cetaceans and birds) in tidal streams. We need to know how this type of behaviour varies between demersal and pelagic species. Further work is necessary to ascertain whether such responses are directly to velocity, to shear or to turbulence. Behaviour, therefore, may not be simply predicted from tidal stream velocity.

8.1.3 Avoidance and Evasion

Both avoidance and evasion depend on detection and an appropriate response. The sensory capabilities of marine animals and their behavioural responses to sensory cues have been reviewed [33].

8.1.3.1 Avoidance

On the scale that avoidance responses will occur, it is not likely that visual detection will play much role. The sounds emitted by devices may, however, be detected at an adequate distance for avoidance to be possible. The range at which devices may be detected will depend on intensity of noise that they emit, the background noise level and the auditory capabilities of the species of interest. A model for estimating the range, in terms of distance and time before encounter, at which marine mammals could perceive tidal stream turbines has been developed [37]. Detection range could be up to 1 km or less than 10 metres depending on background noise and the noise level from the device. Noise pollution from devices is considered in section 4, above but it is essential that a device emits an appropriate level of noise above the background for the location. Surveys of background noise level and device specific sound outputs in typical tidal streams will help to guide device design.

Although devices may be perceived by animals their behavioural responses are not known. Animals may be repelled by device noise but conversely they may be attracted. Field sound playback experiments are necessary in order to answer this question. If, however, animals are not repelled by the sounds they may still learn to associate characteristic sounds with devices and thus avoid subsequent encounters.

8.1.3.2 Evasion

The responses of fish to predator attack are well known [38] and provide a good basis for predicting evasive responses to marine energy devices. An evasion model based visual responses to looming objects has been developed by SAMS as a contribution to Equimar. This will be a useful tool to estimate the probability of evasion for fish but can only be applied with caution to mammals and birds whose behavioural responses underwater are less well known. A preliminary result from the model indicate that for fish the probability of evasion increases with fish size, as maximum swimming speed increases but is also critically dependent on blade thickness. Thin blades present a smaller looming target that will only exceed the animal’s looming threshold at too close a range allowing insufficient time for evasion. The relative velocity of the blade to the water is also critical. Below 6 m s^{-1} the probability of evasion is near to 1 but declines rapidly above that velocity. Blade tip velocity ratio (relative to stream velocity) is usually about 3.5. Risk of collision will increase rapidly at tidal stream velocities above 2 m s^{-1}. It is essential, therefore, that we obtain a better understanding of animal’s use of tidal stream environments above this velocity.

Visual responses depend on contrast between the looming object and the background. In order to maximise the probability of evasion it is essential that devices are have surfaces that are appropriately painted to maximise their visibility underwater with particular reference to the spectral composition of light at the depth of deployment, animal spectral sensitivities and their responses.

Visual cues are only available during the day in conditions of low turbidity but low frequency transient sound stimuli can also evoke evasive responses by animals (e.g. [39]) and enable evasion when visual cues are not available. The transient sounds that evoke such responses result from the pressure pulse as the bow wave of a predator approaches. Further interdisciplinary work is required to derive a model to predict evasion in response to the pressure field around moving parts of devices.

Intuitively, one expects that very small particles or organisms possessing less inertia will follow the stream-line flow around both fixed and moving parts of a device. They will have insufficient inertia to penetrate the boundary layer and collide. The question that remains is at what size and hydrodynamic scale (size and velocity of the blade for example) will animals have sufficient inertia to result in collision?

8.1.4 Near Misses, Pressure effects (cavitation) and shear stress

Although transient low frequency sounds (or pulses of pressure) may evoke evasive responses, they also have the potential to cause damage to animals. A rapid increase in pressure followed by a rapid decrease in pressure as a turbine blade passes close by will occur. There are three possible effects on animals.

The rapid decrease in pressure may draw gasses out of solution forming bubbles within tissues and body fluids; this is cavitation but occurring within an animal. Since device designers will seek to minimise cavitation, which will cause surface damage to turbine blades, this is not likely to be a serious problem but this opinion should be confirmed objectively by further research. Fish swim bladders would not be damaged by a rapid increase in pressure, causing volume reduction, but could still be damaged by rapid expansion during pressure reduction. Expansion of the swim bladder will be damped by elasticity in the wall and there will be variation in risk between species and body size. Further experimental work is necessary to resolve this question.

The second possible effect is on hearing. For many species of fish, hearing depends on particle displacement rather than pressure and they are unlikely to be harmed. Clupeid fish (herring, sardines, etc.) have gas filled structures, the otic bullae, within their labyrinth that transduces pressure to displacement. These delicate structures can be damaged by rapid changes in pressure [23], rendering these "hearing-specialists" much less sensitive to sound. Their subsequent behaviour and performance in evading predator attack will be impaired, leading to decreased survival.

Animals may also be damaged by shear stress close to moving parts. The effects of shear stress within hydro-electric Kaplan turbines have been studied using a combination of bioassay and computational fluid dynamics [40]. Shear stress may lead to mortality as a result of bruising and tearing of tissues or to scale loss. Susceptibility to sheer stress damage varies considerably between fish species. Those species vulnerable to scale loss (such as herring) may be the most vulnerable. These studies need to be extended to consider the effects shear stress around tidal stream turbine blades. CFD models should be the first step in this process since sheer stress is likely to be somewhat lower than in the more extreme environment of a Kaplan turbine where exit velocities can be over 20 m s^{-1}.

8.1.5 Monitoring

Encounter models combined with avoidance estimates are extensively used for assessing the risk of bird collision with onshore wind farms. For simplicity evasion is subsumed within the avoidance estimate which is estimated from the numbers of dead birds collected and the numbers seen flying in the area of the turbines. Avoidance estimates continue to be refined with values for individual species, season and weather conditions. The simple approach used with birds and onshore wind is not an option for tidal stream and wave energy devices.

Monitoring animal interactions with marine energy generating devices will be very difficult. We are unlikely to find the injured or killed animals, or to reliably attribute their injuries without, for example, intensively monitoring and conducting autopsies on marine mammal strandings near deployments. Direct surface observation from the shore, boats or device platforms is limited by available light and weather conditions and reveals nothing about behaviour under the water. Underwater video observation is limited in range by water clarity but may be of some value for observing interaction close to devices and, if encounters occur outside slack water, evasive responses. Sonar systems, including DIDSON, are being used but it can be difficult to distinguish inanimate objects from fish or marine mammals. Tagging seals can provide a lot of information on diving behaviour but only gives a location when the animal surfaces unless 3D movement logging tags are used. Ultrasonic tagging and tracking of fish may also be considered in order to assess habitat use in tidal stream environments and responses to the presence of turbines. By using all these monitoring methods and pooling data it will be possible to obtain a more complete picture of tidal stream habitat use and ultimately be able to obtain better estimates of encounter, avoidance and evasion. This will not be of any benefit to the development of this industry unless the data are freely available in the public domain.

8.2 INTERFERENCE WITH MARINE ANIMAL MIGRATIONS

Many marine organisms migrate on both long and short time scales and over distances of 10s to 1000s of kilometres. The term migrations is here be used to describe both local movement between foraging sites and haulout/rest areas which may occur on an hourly, daily or weekly temporal scale and larger scale migrations between remote breeding and feeding grounds which are usually on larger temporal and spatial scales.

Construction of large industrial scale generation systems could potentially disrupt the movement patterns of marine wildlife. In terms of the potential effects of offshore generation systems on such movements, the questions are essentially the same as those posed by the effects of sound. Any avoidance behaviour that requires or causes an animal to change its migration route may have a long term effect on that individual's fitness. If avoidance requires increased swimming or flying distances there will be direct energetic costs, if avoidance requires swimming or flying in less favourable conditions, e.g. greater predation risks, lower foraging opportunities, there may again be direct fitness costs for individuals. Considering offshore wind power possible loss or impairment of migrating orientation and disturbance at important migrating stopover-sites are additional effects indicated to affect bird fauna.

At present we have little information with which to quantify the likelihood of any developments causing changes in marine animal movement patterns. In addition we currently have little information with which to quantify the effects on individuals and even less with which to extrapolate to population scale consequences.

In order to provide informed estimates of the potential effects of developments on particular species we need to know:

- What are their movement patterns relative to development sites?
- How will they react to the presence of devices?
- What are the energetic consequences in terms of increased costs and/or reduced food intake?
- What are the survival consequences and/or effects on breeding performance of any changes in movement patterns?

These issues will require extensive studies using the same techniques described above for measuring the behavioural consequences of exposure to sound. Ecological modelling may be useful in order to estimate the effects of disturbance to migration at the individual and population level.

Figure 3 Killer whales, Tysfjord, Norway.

9 SOCIO-ECONOMIC ISSUES

9.1 PUBLIC OPINION, ACCEPTANCE AND PARTICIPATION

Opinion studies conducted in Europe and United States indicate that the public is generally supportive of developing alternative energy sources specifically onshore and offshore wind energy ([43], [44], [45] and [46]). A review on public acceptance of offshore wind energy in Denmark and United Kingdom indicates some fairly strong trends in public opinion which can be resumed in the following topics [7]:

1) The public is in favour of offshore wind energy also in the region where they reside;
2) Visual impacts appear to be the primary issue of public concern;
3) Offshore wind park development appears to gain public approval as the community is exposed to operational projects
4) Early local input to the planning process is critical to gain public acceptance.

Although there is uncertainty on the public support for wave power, it is reasonable to assume that similar conclusions would be obtained for wave and tidal energy installations. In general, public opinion depends on the awareness about environmental and socio-economic impacts. People tend to accept renewable energy due to environmental issues (reduction of pollution by producing clean energy) but questions arise about environmental impacts mainly those related with marine mammals, landscape / seascape changes and noise. The installation of ocean energy devices, particularly onshore, may create a “Not in my backyard effect” which means that while people generally accepts the concept of ocean energy, they prefer devices to operate far from their neighbourhoods.

From a socio-economic point of view wave energy farms may induce negative attitudes and create conflicts with other activities such as fishing (subsistence and commercial), recreational use (boating, surfing, diving etc), navigation, sand and gravel extraction etc. On the other hand ocean energy farms can induce favourable approval from the public as it represents an employment opportunity.

A comparison of the public acceptability within renewable energy has been carried out in 1995 to four technologies including tidal energy [49]. At that time, this study concluded that it was difficult to assess the impact of public concerns on tidal decisions because this is still a developing industry and there is little experience on environmental and social impacts and, consequently, a lack of public awareness on the subject [49]. Experiences from wind energy shows the importance of providing information and public dialogues avoiding technical descriptions that cannot be understand and further accepted by the local public. The main recommendation is dialogue instead of defence that implies an early public consultation and involvement in the project planning [48]. A more recent article on the public involvement in decision-making for marine resource use expands the discussion on the public participation characteristics in EIA of offshore projects [50]. This work recognize the need for more research on public participation, since it is limited, and raise several questions about the unique characteristics of public involvement in offshore projects, regarding the willingness or capacity of the public to take part in an EIA, which need to be addressed:

- Is the distance of the projects from shore related to the level of public interest?
- Are priorities placed on marine environmental impacts different from those on land?
- Are stakeholders familiar enough with the marine environment for them to contribute to the EIA process?

A framework for further analysis based on a review of empirical and theoretical research is provided in this study and the relevance of such framework and possible applications is explored. Finally public interest in marine environmental issues is significant and has increased, although the availability of independent information is limited as is shown in a survey made in a the UK's National Maritime Museum [51].

9.2 SPACE-USE CONFLICTS

The potential space-use conflicts common to all types of offshore alternative energy facilities include commercial fisheries, subsistence fishing, marine recreational activities such as boating, fishing, scuba diving and surfing, sand and gravel extraction, oil and gas infrastructure, navigation, aquaculture, proximity of designated conservation areas and other alternative energy facilities. Wave energy installations are thought to have several additional conflicts not specifically related with space conflicts: reduction of wave energy that could affect recreational surfing, a higher potential for an exclusive area around the installation and a potential interference with kelp harvesting [7].

Although some potential conflicts e.g. with navigation, oil and gas infrastructure, aquaculture, proximity of designated conservation areas and sand and gravel extraction, can be avoided during the site selection phase, other significant conflicts with commercial or subsistence fishing and recreational use cannot always be avoided since these activities occur in most marine coastal areas. Some various restrictions may be imposed to limit public access. For instances, although some wind parks have no restrictions on access, others have already imposed some rules for its construction and operation phases.

Restrictions to the public access around wave energy installations may be established not only because of the possible interference with the device performance but mainly for safety purposes because the devices can move according to waves and wind and have moving parts and mooring systems that could pose hazards to fishing, navigation and / or the public. The extension of such safety / exclusion zones is supposed to change according to the project characteristics. For example, during operations at the six-buoy demonstration project in Hawaii the recreational use (fishing, boating and diving) will not be restricted [48] but, around the Makah Bay demonstration project a fishing and navigation exclusion zone is planned which will affect the tribal crab and long-line commercial and recreational fishing [14]. In the Wave Hub project in United Kingdom there will be no exclusion zone along the cable route to shore because the plan is to ensure that fishermen are aware of the cable location and the risk of snagging, as well as using proper installation methods to reduce the potential for cable to span above irregularities in the seafloor [4]. Since no studies have been conducted on stakeholder's opinion on these rules, their impacts on stakeholder's reaction are uncertain.

Newly created habitat due to e.g. wave installations mooring systems could attract both commercial fisheries and recreational fishers and thereby potential conflicts can arise. An argument is often made on the benefits of no-take and no-trawl zones to fishery resources in the vicinity of the installation. This argument was used to offset the moderate negative impacts to fisheries at the Wave Hub project [4]. However, a lot of uncertainty exists regarding the efficiency of such benefit since it is not yet well studied (see above topic 4 on artificial reef effects).

The evaluation of catch data, vessel numbers and types, and temporal fishing patterns in the project area and its comparison with fishing loss due to the space occupation by ocean energy installations can help in the quantification of the potential impacts on fisheries. This approach is more difficult for recreational fishing because reporting requirements are voluntary [7].

The identification of sites with no use conflicts is difficult. Research on the impacts assessment of wave and tidal project occupation on other uses is needed in order to find the methodological approaches and if it is the case, discuss reasonable compensation measures.

10 CONCLUSIONS

The environmental and socio-economic effects of operating ocean energy devices are strongly dependant on the technology and location of the project. However, since wave and tidal energy technologies are still in development, the uncertainties regarding the most part of the potential impacts are still assumptions or predictions which need to be evaluated through monitoring. A lack in methodological approaches for environmental and socio-economic impacts evaluation of marine projects is also recognized because these projects have unique characteristics, different from the most well known types of land projects. A new approach for environmental analysis is needed for on and offshore energy projects particularly, wave and tidal energy projects and this can include a revision of methods and tools used for environmental impact analysis of land projects. A summary of the main uncertainties regarding environmental and social impacts is presented in Table 4.

Table 4 Summary of the uncertainties identified regarding environmental and social impacts of wave and tidal energy projects.

Issues	Uncertainties
Water circulation patterns	- Alteration on water circulation and sediment transport patterns: localized effects of a few number of devices versus cumulative effects of arrays of devices - Effects of sediment transport changes on shoreline - Effects on wave characteristics - Extent and direction of indirect effects on aquatic flora and fauna (richness and density)
Benthic habitats	- Extent of the effects of suspended sediments and sedimentation of sessile organisms during the installation process - Indirect impacts of sediment transport, erosion and deposition changes can be stronger than direct effects (e.g. anchors and cable installation) - Biological recovery of disturbed areas after installation process - Extent of the laying cable effects on benthic habitats
Artificial reef effects	- Effect of solid structures (and its design) placed on the seabed as promoters of biodiversity and abundance of marine organisms - The local biomass enhancement is a result of mere aggregation from the surroundings or a true increase in biomass? – Effects on fisheries
Water quality	- Effects of the chemicals toxicity used in the device equipment or spills during operation on biological communities - Effects of antifouling coatings of the equipment - Effects of antifouling removal operations
Noise disturbance	- Characteristics of the devices sound signature and propagation (ranges and depths) versus number of species affected by sound sources - Levels of exposure to chronic noise pollution that are required to cause either temporary TTS and PTS - Effects of masking noise - Biological significance of behavioural responses to sound sources - Indirect impacts of noise on prey accessibility - Effects of noise pollution (e.g. pile driving) on some fish species spawning behaviour
Electromagnetic fields	- Impacts on other species than elasmobranchs particularly salmon, pinnipeds, cetaceans, seabirds, sturgeon, squid, baitfish, flatfish, rockfish, lingcod and plankton - Impacts at different life cycle stages - Effects of some mitigation measures such as cable burial - Effects of recent cable design and arrangement / design of WEC arrays
Animal movements	- Patterns of tidal stream turbines perceive and dynamics of avoidance / evasion and collision of marine animals with the devices - Animal movement patterns relative to deployment sites - Reaction to the presence of devices - Energetic consequences in terms of increased costs and/or reduced food intake (if the animal avoid the site) - Survival consequences and/or effects on breeding performance of any changes in movement patterns
Socio-economic issues	- Willingness and capacity of the stakeholders to contribute to the EIA process - Benefits of ocean energy parks, as fishery protected areas, to fishery resources in the

		vicinity of the installations
	-	Methodological approaches to evaluate social impacts in order to discuss and approve reasonable compensation measures

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