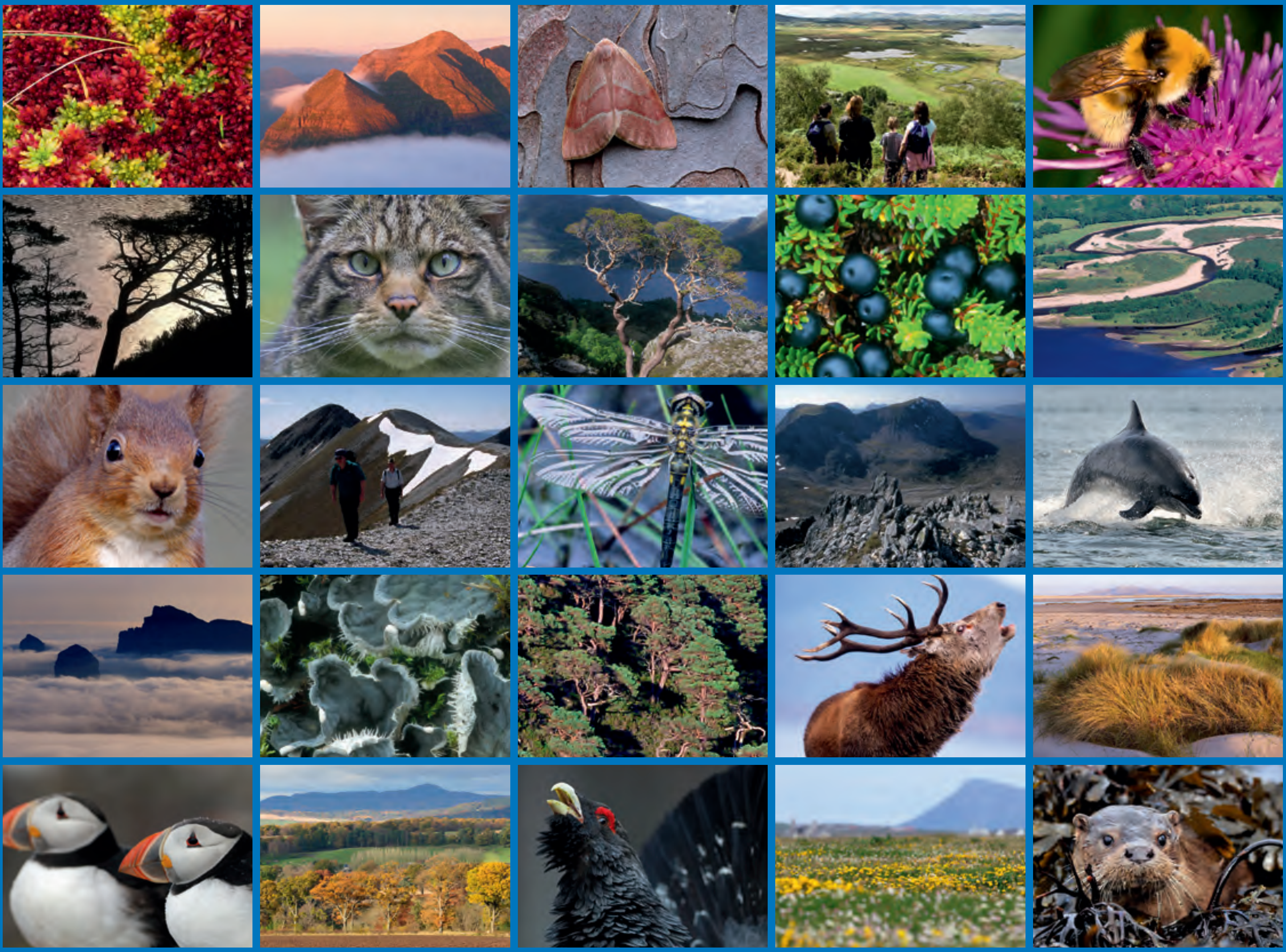
Scottish Natural Heritage
Commissioned Report No. 401

# Literature review on the potential effects of electromagnetic fields and subsea noise from marine renewable energy developments on Atlantic salmon, sea trout and European eel



# COMMISSIONED REPORT

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COMMISSIONED REPORT

# Summary

## Literature review on the potential effects of electromagnetic fields and subsea noise from marine renewable energy developments on Atlantic salmon, sea trout and European eel

**Commissioned Report No. 401 (iBids No. 10745)**
**Contractor: Cranfield University**
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### Background

This report reviews the current state of knowledge with regard to the potential for three fish species of conservation importance, namely Atlantic salmon (*Salmo salar*), sea trout (*Salmo trutta*) and European eel (*Anguilla anguilla*), to be affected by marine renewable energy developments (MRED). The focus is on marine wave and tidal power developments that will generate electricity offshore, which will then be transferred to land by subsea cable. During construction and operation, the marine renewable energy (MRE) devices are expected to cause a number of disturbances to the marine environment including electromagnetic fields (EMF) emissions and subsea sounds (generally referred to as 'noise').

Such disturbances were assessed to meet the following aims:

- To determine the current understanding of the effects of EMFs and noise associated with the installation and operation of MREDs, on the behaviour of three species: *S. salar*, *S. trutta* and *A. anguilla*.
- To determine the gaps in current knowledge and identify research requirements.

### Main findings

The availability and quality of the information on which to base the review was found to be limited with respect to all aspects of the fishes migratory behaviour and activity, both before and after MRE development; this makes it difficult to establish cause and effect.

The main findings were:

- *S. salar* and *A. anguilla* can use the earth's magnetic field for orientation and direction finding during migrations. *S. trutta* juveniles, and close relatives of *S. trutta,* respond to both the earth's magnetic field and artificial magnetic fields.
- Current knowledge suggests that EMFs from subsea cables and cabling orientation may interact with migrating eels (and possibly salmonids) if their migration or movement routes take them over the cables, particularly in shallow waters (<20m). The effect, if any, could be a relatively trivial temporary change in swimming

direction, or potentially a more serious avoidance response or delay to migration. Whether this will represent a biologically significant effect cannot yet be determined.

- *S. salar*, *S. trutta* and *A. anguilla* are likely to encounter EMF from subsea cables either during the adult movement phases of life or their early life stages during migration within shallow, coastal waters adjacent to the natal rivers.
- The subsea noise from MRE devices has not been suitably characterised to determine its acoustic properties and propagation through the coastal waters.
- MREDs that require pile driving during construction appear to be the most relevant to consider, in addition to the time scale over which pile driving is carried out, for the species under investigation.
- In the absence of a clear understanding of their response to subsea noise, the specific effects on *S. salar*, *S. trutta* and *A. anguilla* remain very difficult to determine for Scottish waters in relation to tidal and wave power.
- Based on the studies reviewed, it is suggested that fish that receive high intensity sound pressures (i.e. close proximity to the MRED construction) may be negatively impacted to some degree, whereas those at distances of 100s to 1000s of metres may exhibit behaviour responses, the impact of which is unknown and will be dependent on the received sound. During operation there may be more subtle behavioural effects that should be considered over the life time of the MRED. Whether these effects will represent biologically significant impacts cannot yet be determined.
- The current assumptions of limited effects are built on an incomplete understanding of how the three species move around their environment and interact with natural and anthropogenic EMF and subsea noise.
- A number of gaps in understanding exist, principally whether *S. salar*, *S. trutta* and *A. anguilla* respond to the EMF and/or the noise associated with MREDs in Scottish waters. A number of suggestions for specific studies are highlighted in the final section of the report.

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## Acknowledgements

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# 1 INTRODUCTION

This SNH commissioned report reviews current knowledge with regard to the potential for three fish species of conservation importance, namely Atlantic salmon (*Salmo salar*), sea trout (*Salmo trutta*) and European eel (*Anguilla anguilla*), to be affected by marine renewable energy developments (MRED). The review was undertaken to assist in the process of determining suitable locations for MREDs in Scottish waters. The focus is on marine wave and tidal power developments that will generate electricity offshore, to then be transferred to land by subsea cable. The surface and subsea marine renewable energy generation devices that are expected to be used, and their operation, will cause a number of disturbances to the marine environment, including EMF emissions and subsea sounds (generally referred to as 'noise').

The adoption of marine renewable energy (MRE) technology is currently increasing across the world. Offshore wind has led the way, but wave and tidal technologies are being extensively tested and will most likely be operational within the next few years. The understanding of the interactions between MREDs and the environment is poor, but interest is ever increasing (Gill, 2005). All MRE technologies have a common aim of harnessing renewable sources of energy and generating electricity, which is then transmitted to shore via a network of subsea cables. There are an increasing number of MRE devices and their associated subsea cables; however very few studies have considered the environmental impacts connected with their installation and operation.

Noise is generated within the surrounding sea and seabed during installation and operation of the energy devices, and electromagnetic fields (EMFs) are emitted when electricity is transported through the cable network. The basic assumption that marine ecologists have adopted is that reduced noise and smaller EMF emissions are desirable because logically their impact within the marine environment is likely to be smaller (Inger *et al.,* 2009). Unfortunately, the quality of the information on which to base this assessment remains poor with respect to all aspects of organism behaviour and activity, both before and after MRED installation; this makes it difficult to establish cause and effect (Boehlert & Gill, 2010).

Fish species are a major component of the environment in which MREDs are deployed. There are potentially both positive and negative impacts to the fish species from MRE. In the short term, the disturbance caused by construction of MREDs will lead to immediate habitat loss and degradation for many species (Gill, 2005). If such changes are similar to those seen for other human impacts in coastal waters then this may cause a depletion of a number of different species of, for example, some fish populations (Dulvy *et al*., 2003).

During operation, tidal and wave power units may add to an already noisy environment (Slabbekoorn *et al*., 2010) and have been suggested to present a greater collision risk for fish than wind power structures, because of their more mobile nature within the water column (Inger *et al.,* 2009). On the plus side, the development of MREDs could potentially have a beneficial effect for fish. Research at wind power installations in its early stages has shown that habitat creation associated with the wind farm structures increased abundance of fish surrounding the turbines (Wilhelmsson & Malm, 2008). This will potentially be of benefit for any species that are insensitive to or not affected by the EMFs which are generated, or that are not deterred by operational noise. Restricted commercial fishing in these areas will also contribute to a reduction in mortality factors within the fish population, thereby changing the ecological selective pressures, which in turn can result in shifts in species dominance and community composition (Dulvy *et al*., 2003).

Migration is an important life history aspect for a number of fish species that can be found in coastal waters. Some of these species, such as *A. anguilla*, are able to use cues from the Earth's geomagnetic field to orient and navigate. The main points of the life cycle that are considered to depend on geomagnetic orientation are during the prolonged migratory larval (leptocephalus) stage moving towards rivers, and the mature adult stage, moving from rivers into coastal and oceanic waters. However, spawning and migration of anguillid eels is poorly understood and remain challenging to monitor in open sea studies (Knights, 2003;Tsukamoto, 2009). The European eel has been placed on the IUCN red list as a critically endangered species and its population numbers are considered to be outside safe biological limits (IUCN, 2009). Decline in global *A. anguilla* populations has been attributed to the spread of EVEX (Eel Virus European X) which causes fatalities during long migratory swims (van Ginneken *et al.,* 2005). It is therefore important that anthropological factors in the marine environment, such as EMF emissions or noise from renewable energy production, do not further marginalise this species at key times in its life.

*S. salar* and *S. trutta* also undertake large scale migrations, but these are opposite to eels. The salmonids migrate downstream in rivers as juveniles, when they are known as smolts, and pass through the coastal environment on their way to productive marine feeding grounds, where they spend most of their adult life until returning to their natal rivers to spawn. It is during the migration times where the potential impacts from EMF and noise may occur. The smolt (sea going) stage will take many small fish into the coastal waters adjacent to the natal rivers to begin their migration, where they may encounter MREDs. As adults, the salmonids spend several weeks moving parallel to the coast, sometimes in relatively shallow depths, to find the right river. They also may spend time ‘hanging off’ the mouth of their natal river waiting for the right flow conditions, and to allow their physiological adaption to take place. *S. trutta* are also known to spend extended periods inhabiting coastal waters particularly during the early adult years. *S. salar* and *S. trutta* are both commercially and recreationally important species for the Scottish economy (Mills, 1989) and both have been identified by the UK Biodiversity Action Plan Priority Species List in 2007 (Joint Nature Conservation Committee, 2007).

## 1.1 Aims and objectives

The aims of this review were to:

- Determine current understanding of the effects of EMFs and noise, associated with the installation and operation of MRE devices on the migratory behaviour of three fish species: *S. salar*, *S. trutta* and *A. anguilla*.
- To determine the gaps in current knowledge and research requirements.

These aims have been met by addressing the following objectives:

- Assess the characteristics of the EMFs that are produced by the subsea cables and link the level of emission to species specific responses to EMF where possible (Section 4.1).
- Review the knowledge on the EMF sensitivity of *S. salar*, *S. trutta* and *A. anguilla* and its relation to the migratory behaviour of the fish (Section 4.2).
- Determine the degree to which each species relies on EMF sensitivity as opposed to other sensory stimuli during the migratory phase of life (Section 4.3).
- Review the available information on the noise output associated with MRE developments and link this to any sensitivity thresholds of the three fish species (Section 4.4).
- Determine, where possible, species specific responses to underwater noise and EMF associated with MREDs and how behaviour of the fish may be influenced (Section 4.5).

## 1.2 Context

By necessity much of the report refers to studies associated with offshore wind farms, as this is the most mature MRE technology. The available information for wave and tidal power is relatively scarce. Wind farms represent the nearest comparable technology and much of their interaction with the environment, particularly the EMF aspects, are similar.

### 1.2.1 *EMF - natural*

Within the marine environment, the Earth's geomagnetic field is the predominant EMF. Electric fields (E field) are also naturally emitted as a result of biochemical, physiological and/or neurological processes within an organism, known as bioelectric fields. Induced E fields can also occur as a result of the organism itself or oceanic waters interacting with the geomagnetic field.

Organisms that respond to magnetic fields can be categorised into two groups:

- Species that have a response based on magnetite or chemical mediated detection.
- Those that respond to an induced electric (iE) field.

Some species, such as *A. anguilla,* have significant magnetically sensitive material (called magnetite) within their skeletal structure (Berge, 1979). This mechanism of magnetic field detection occurs in a relatively large variety of organisms (such as birds, insects, turtles, fish and cetaceans; Kirshvink, 1997) and is commonly thought to be used for direction finding using the Earth's geomagnetic field.

Responses to iE fields are generally assumed to be a mode of navigation and may either be passive or active on the part of the animal. In active navigation the organism generates its own EMF to interact with the horizontal component of the Earth's magnetic field (Paulin, 1995; von der Emde, 1998). Passive detection is derived from the interaction of the tide or wind driven currents and the vertical component of the Earth's geomagnetic field.

### 1.2.2 *EMF - anthropogenic*

Anthropogenic sources of EMFs such as subsea cables are becoming increasingly common. EM-sensitive organisms in the marine environment can detect both localised polar and larger scale uniform EMFs; these are the predominant type of fields associated with subsea cables.

Electric fields are produced by electric charges. If the electric field moves, such as in the form of electrical current through a cable, then a magnetic field is produced. Magnetic fields can induce an electric field by electromagnetic induction. Hence the term electromagnetic field covers both the electric and magnetic fields. Within the electrical engineering profession and electricity industry, the standard nomenclature for an electromagnetic field is EMF, and this terminology is adopted throughout this report.

There are specific terms for the electric (E) and magnetic (B, or H[*]) components of an EMF. Figure 1 illustrates the main EMF emissions associated with an electricity cable. For context, Figure 1a highlights the emissions for a bare cable (i.e. with no shielding material), Fig 1b and 1c represent Direct Current (DC) and Alternating Current (AC) cables respectively. The E and B field are emitted into the environment and the emission will either be static in the case of a DC field (Figure 1b) or cyclical at 50Hz (cycles per second) for a UK AC electricity systems (Figure 1c).

In the context of wave and tidal MRE, there are some designs of devices that may emit EMF, such as those that use permanent magnet driven turbines. Hence the design of the device may need to be considered with regards to EMF. There is currently no information on EMF from wave or tidal devices. In this review, the view has been taken that any effects apparent will be similar to those associated with offshore wind subsea cable EMF, for which there has been limited research.

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[*] B fields refer to magnetic flux density which is measured in Tesla (or Gauss), whilst H fields describe the magnetic field strength in A/m, referenced to a particular point. The magnetic flux density is the product of the magnetic field strength (H) and the permeability of the medium in which the field is present (µ). Hence B and H are the same when the permeability is = 1. B field is generally used to describe the magnetic field generated within a medium/environment as it is more easily measured and takes account of the permeability of the medium.

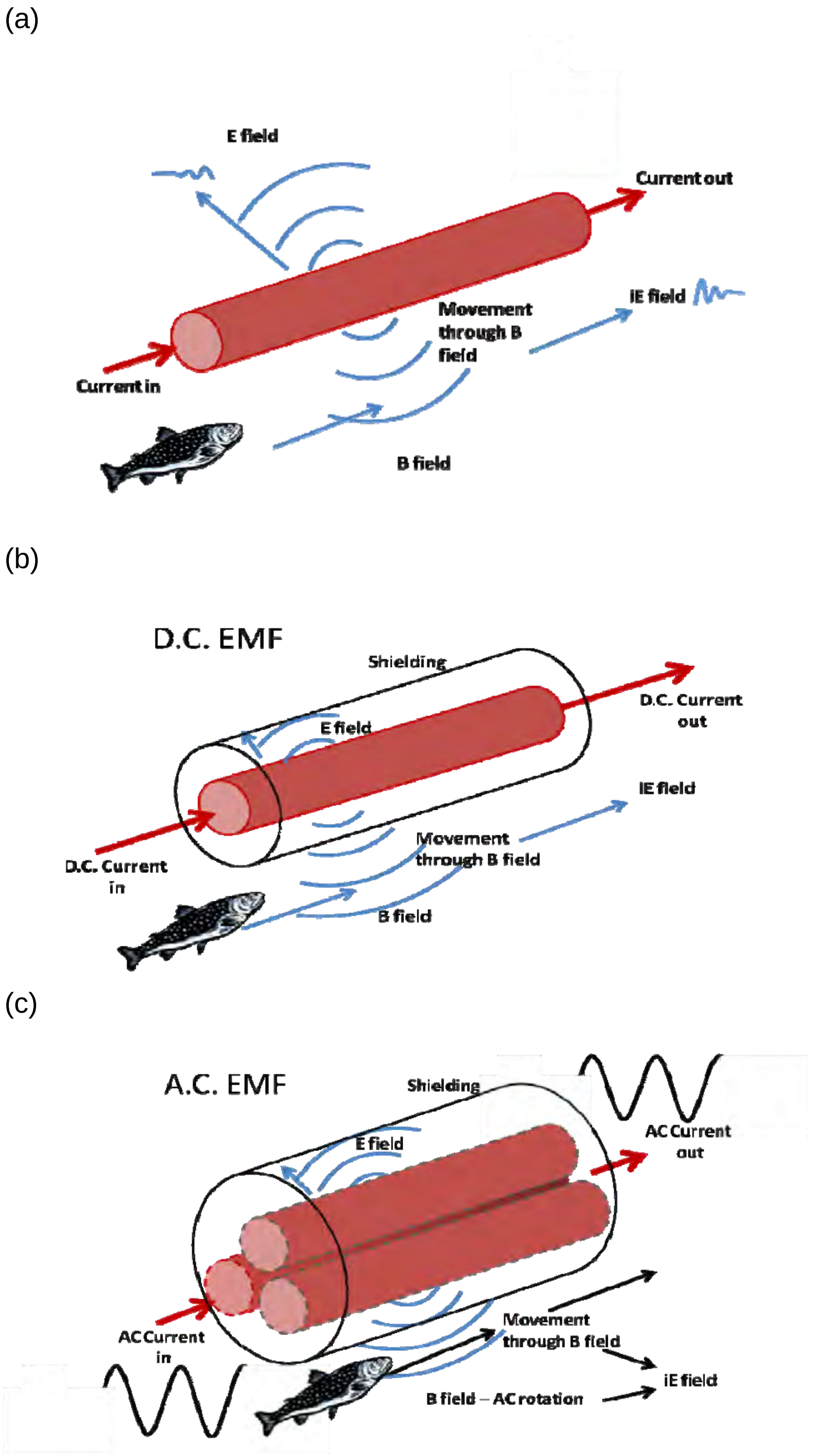

***Figure 1.*** *The electric and magnetic fields associated with a subsea cable. (a) A schematic diagram of the EMFs associated with an unshielded cable. For electric (E) and induced electric (iE) fields, wave magnitudes indicate relative sizes of EMF with distance from the cable. (b) an HVDC cable showing the shielding that contains the direct E field. The iE field is induced in the fish as it moves through the B field. iE fields are also induced by water moving through the B field. (c) an HVAC cable showing the three cores with the alternating current following a typical sine wave back and forth through each core. Similar to the DC cable iE fields are induced by the water and/or fish movement. Furthermore, the out of phase magnetic field emitted by each core causes a rotation in the magnetic emission which induces an iE field in the surrounding water.*

EMFs emitted from cables (and devices) can be altered by using shielding material. In industry standard High Voltage DC (HVDC) cables, the materials are sufficient to contain the directly emitted E field, but the B field cannot be fully shielded (Figure 1b). Where there is water (tidal) movement or the movement of an organism (e.g. swimming fish) through the B field, an induced electric field can also be generated; this separate electric field is referred to as an iE field (see Figure 1). This is not the only iE field that is associated with electricity production. In High Voltage AC (HVAC) cables, the B field produced rotates with the alternating movement of the electrical current through the three cores within the cable (Figure 1c). This magnetic rotation is not contained within the cable shielding, hence it is emitted into the adjacent sea water and induces an E field (Figure 1c). So for an AC cable, there is the directly emitted B field, similar to the DC cable and an induced E field associated with the electricity production. An organism swimming through and/or tidal movement will also induce other E fields, similar to the DC cable.

### 1.2.3 *Noise*

Marine waters are acoustically complex, with natural and human associated noise. Many fish species are acoustically sensitive, and use sound for orientation, finding food, communication and reproduction (Hastings & Popper, 2005; Slabbekoorn *et al*., 2010). Sound emissions will vary in terms of their peak levels and other physical properties. However, sounds can propagate over great distances under water, particularly low frequency sound waves.

The effects of anthropogenic noise on fish have received significantly less attention than the effects on marine mammals or birds (Thomsen *et al*., 2006; Slabbekoorn *et al*., 2010). In general, the research relating to sound induced effects on fish is scarce and focusses on the effects of pile driving and underwater explosions (OSPAR, 2009). Those studies that have been conducted are either based on laboratory type investigations or field based using caged fish at different distances from the sound source. These studies, some of which have used *S. trutta*, are regarded as restricted in their wider application and provide variable results that are difficult to extrapolate (Hastings & Popper, 2005). Each fish species has a specific hearing apparatus which leads to a variety of hearing sensitivities. Also, an MRE installation will expose the fish to device specific noise that needs to be characterised and then assessed with regards to the hearing capabilities of the fish species of interest.

Noise may propagate over many metres to several kilometres, depending on the physical properties of the emitted sound field and the environmental characteristics. The potential influences on fish will vary with the properties of the sound (such as loudness, rise time, frequency) received by the fish (Slabbekoorn *et al*., 2010). Hence, it is the received sound that will determine any response or effect on the fish, rather than the actual distance to the source. For simplicity, the relative effects that may occur to a receiving fish as a sound propagates away from the source are represented in Figure 2. The nearer the fish to the sound source, the more likely that an acute effect, such as mortality or injury to hearing apparatus will occur. Further away, more subtle effects may occur, shown by the fish responding behaviourally to the acoustic source, such as altering migration behaviour. Another effect, termed ‘masking’, may be apparent where the sound interferes in some way with normal acoustic-related behaviour, such as the reproductive acoustic behaviour seen in Gadoids (cod-fish). The consequences of these responses is not known, but could have wider effects on the population if sufficient individuals respond or if their sounds are masked (for a comprehensive and criticial review see OSPAR, 2009; Slabbekoorn *et al*., 2010).

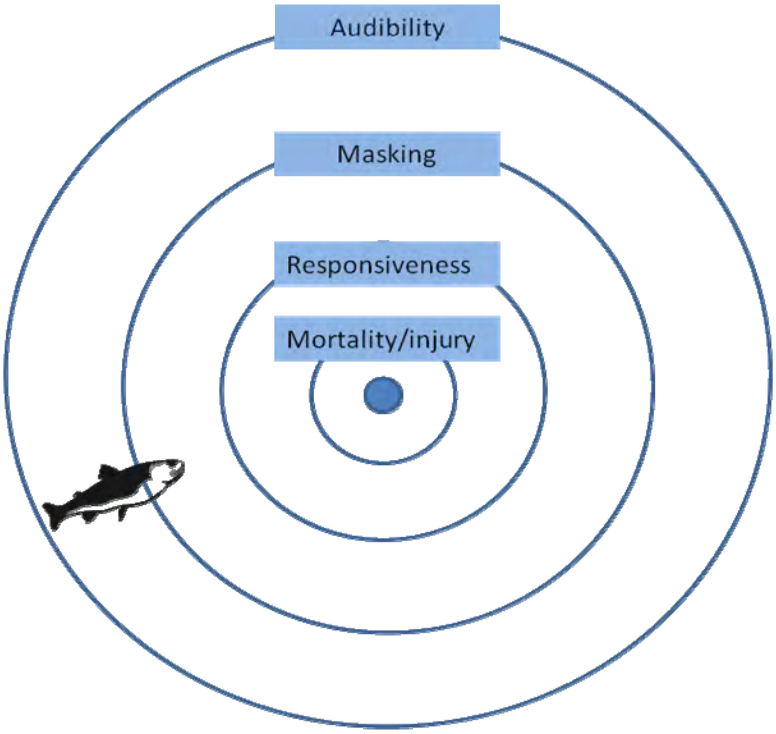

***Figure 2.*** *The theoretical zones of acoustic influence on fish. Sound source is at the centre. (Adapted from Thomsen et al., 2006).*

The construction phase of wind farm development is regarded as the noisiest (OSPAR, 2009), with operational noise being at a much lower intensity, albeit over a much longer period of time. Wave and tidal devices may require pile driving or installation of mooring systems, which can be the source of high intensity, short duration noises. Hence, in the absence of measured noise associated with wave and tidal devices, the sound generation and propagation is assumed to be similar to wind farms and therefore subject to comparable effects on fish. During operation, wave and tidal power devices are likely to produce a direct source of noise on the sea surface or under the sea, whereas operational wind farm noise from turbines is an indirect noise caused by the vibration of the main structure as the turbine blades turn or waves hit the turbine structure.

# 2 METHODS

## 2.1 Data sources and approach

To determine the current state of knowledge of the response of *S. salar*, *S. trutta* and *A. anguilla* to EMFs and noise, a comprehensive search of academic databases was conducted through Cranfield University library.

Primary sources consulted were:

- **Literature held by Cranfield University Library** – The library subscribes to a large variety of bibliographic and full text electronic resources for use by students and staff for teaching and research. These materials support our postgraduate courses and research in subject areas including Aquatic Environmental and Ecological Management, Environmental Impact Assessment and Offshore Technology and Engineering. The core of this collection consists of books, academic journals, reports and theses.

- **Electronically available literature** - The library also provides access to nearly 200 databases (many global) and 8500 electronic journal titles such as Scopus™ and Sciencedirect™. If resources are not directly available then the library has a quick and efficient interlibrary loan service from the British Library supplying books, journal articles and other material as required.

- **Subject specific database held by the Integrated Environmental Systems Institute** - IESI, at Cranfield University holds a large database on the subject of EMF in the marine environment, which contains relevant published material from a review that Cranfield University undertook in 2005 for the Crown Estate lead Collaborative Offshore Wind Research into the Environment group (COWRIE). Information relevant to EMFs (both electric and magnetic components) was extracted from this database for each of the three species with respect to their behaviour, electroreception (general, physiological and behavioural aspects) and magneto-reception (general, physiological and behavioural aspects) and other natural sources of EMF.

- **Subject specific database held by Cefas** - The potential effects of anthropogenic sources of underwater sound (often referred to as 'noise') is a current priority topic throughout Europe and Cefas has led a number of projects that provide the source of the most up to date understanding on responses of fisheries species to anthropogenic underwater sounds. Information was also derived from recent research funded by COWRIE of underwater pile-driving sound as well other Cefas experience, particularly relating to acoustic impacts on marine biota.

When considering the effects of subsea noise on fish, some recent reviews provided the most up to date and scientifically robust sources of information. The principal sources were:

- 2009 OSPAR (The Convention for the Protection of the Marine Environment of the North-East Atlantic) report titled 'Overview of the impacts of anthropogenic underwater sound in the marine environment'.
- Thomsen *et al.* (2006). Effects of offshore wind farm noise on marine mammals and fish, Biola, Hamburg, Germany on behalf of COWRIE Ltd.
- Popper, A.N. & Hastings, M.C. (2009). The effects of anthropogenic sources of sound on fishes. *Journal of Fish Biology,* **75**, 455-489.
- Slabbekoorn *et al*. (2010). A noisy spring: the impact of globally rising underwater sound levels on fish. *Trends in Ecology and Evolution,* **25**, 419-427.

Secondary sources:

- **Environmental Statements (ES) from Offshore Wind farms** – every commercial scale MRE development to date has had to go through the Environmental Impact Assessments (EIAs) process to meet the EU EIA Directive (85/33/EEC as amended by 97/11/EC). The ESs are available on request and a number were consulted and assessed previously by the team (see Gill *et al.* 2005) with supplementary updates from more recent EIAs for how EMF and noise aspects were dealt with.

## 2.2 Interpreting the data

The data sources were searched for information relating to *A. anguilla*, *S. salar* and *S. trutta*, and for other related species that are considered to be or have the potential to be sensitive to EMFs and subsea noise. Information linking wind farms and EMFs and noise was also considered and other emission sources (both artificial and natural). A number of data sources were from outside the UK; in these cases the information was interpreted in the context of UK coastal water species where appropriate.

# 3 RESULTS

## 3.1 EMF

Electric and magnetic field detection has evolved in a wide range of terrestrial, aerial and aquatic animals. For the majority of these species, EMF reception facilitates direction finding and spatial orientation (Kalmijn, 1984; Kalmijn, 1988; Kirschvink, 1997; Letovanec, 2001). In fish species, the detection of both electric and magnetic fields has been closely related to navigation during long distance migrations and the locating of spawning grounds (e.g. Griffin, 1982; Quinn, 1984; Arnold & Metcalf, 1989; Metcalfe *et al.,* 1993; Yano *et al.,* 1997; Akesson *et al.,* 2001). Migratory species, such as salmonids or anguillid eels, are likely to only utilise EMFs at specific stages of their life cycle, principally during migration. Furthermore, *S. trutta* inhabiting coastal waters theoretically could use EMF over extended periods. Some fish species that are regarded as EMF sensitive do not possess specialised receptors, but apparently are able to detect induced voltage gradients associated with water movement or geomagnetic emissions (see Table 1). The physiology of these sensory mechanisms for the detection of these EMFs is poorly understood, and is likely to vary on a species by species basis (Pals *et al.,* 1982). It is likely that the species listed in Table 1 will respond to EMF that are associated with peak tidal movements which can create fields in the range of 8-25 µv m$^{-1}$ (Barber & Longuet-Higgins, 1948; Pals *et al.,* 1982).

***Table 1.*** *Evidence based list of electromagnetic sensitive teleost fish species and their conservation status (according to the IUCN Red list) in Scottish and UK coastal waters. Superscript numbers show reference sources. E field = Electric Field; B field = Magnetic field.*

| Species | Common name | Conservation status | Frequency in Scottish and UK Waters | Evidence of response to E fields | Evidence of response to B fields |
|---|---|---|---|---|---|
| *Anguilla anguilla* | European eel | Critically Endangered | Common | ✓[1,2] | ✓[3,4] |
| *Salmo salar* | Atlantic salmon | Least Concern | Common | ✓[5,6] | ✓[5,6] |
| *Salmo trutta* | Sea trout | Least Concern | Occasional | | ✓[7] |
| *Pleuronectes platessa* | European plaice | Vulnerable | Common | ✓[8] | ✓[8] |
| *Thunnus albacares* | Yellowfin tuna | Least Concern | Occasional | | ✓[9-12] |
| *Lampetra fluviatilis* | European river lamprey | Near Threatened | Common | ✓[13,14] | |
| *Petromyzon marinus* | Sea lamprey | Least Concern | Occasional | ✓[15-17] | |

[1] Berge (1979); [2] Vriens & Bretschneider (1979); [3] Enger *et al.* (1976); [4] Westerberg (1999); [5] Moore *et al.* (1990); [6] Rommel & McCleave (1973); [7] Formicki *et al.* (2004) – *juvenile fish*; [8] Metcalfe *et al.* (1993); [9] Kobayashi & Kirschvink (1995); [10] Walker *et al.* (1984); [11] Walker (1984); [12] Yano *et al.* (1997); [13] Gill *et al.* (2005); [14] Akeov & Muraveiko (1984); [14] Bodznick & Northcutt (1981); [15] Bodznick & Preston (1983); [16] Bowen *et al.* (2003); [17] Chung-Davidson *et al.* (2004)

A total of seven EMF sensitive teleost fish species associated with Scottish and UK coastal waters have been identified (Table 1). The majority of studies describing EMF sensitivity are based on adult fish. Only juveniles of *S. trutta* have been investigated. Additionally, a range of elasmobranch species, which are highly sensitive to the magnitude of EMFs generated by offshore wind farms, are also known to be present in Scottish and UK waters (Gill & Taylor, 2001; Gill *et al.,* 2005).

The database search showed that a large number of references were available for the main subject search term 'Electromagnetic', over 100000 hits in the database (Figure 3). The vast majority of these references came from the engineering or physics disciplines. By combining the main search term with specific fish genera followed by offshore, it was evident that very little information has been published on the topics relevant to this review (Figure 3). In order to capture the largest number of sources, search parameters were set wide but limited to species and attributes that were deemed biologically comparable (e.g. taxonomically related species; freshwater and marine species hearing attributes).

A reasonable number of studies that have investigated electroreception in fish were found (239 references in Scopus; 507 in ScienceDirect; using search term "electroreception AND fish"). However, the main focus was on the elasmobranchs (sharks, skates and rays) and lampreys that have specialised electroreceptors. There has been some interest in eels and magnetic aspects of their migration, particularly in relation to orientation to the geomagnetic field. However, it was evident that there is a deficit of comprehensive and robust scientific literature available, specifically covering *S. salar*, *S. trutta* and *A. anguilla*, and relating to their response to anthropogenic generated EMFs and subsea noise. It is worth noting that the lack of knowledge was not just related to these species but many others too. A main reason put forward for this is that anthropogenic EMF and noise disturbances within the aquatic environment have only relatively recently become of interest (see Gill 2005; Slabbekoorn *et al*., 2010), and scientific understanding of the consequences to species individuals, populations and the whole ecosystem are only slowly being identified or addressed. No clear evidence was available on a species by species basis, which makes it very challenging to draw conclusions on biologically relevant impacts. Some laboratory based studies have suggested that EMF emissions in the environment will likely have no net effects on fish and invertebrate species (e.g. Bochert & Zettler, 2004), whereas others have shown a range of developmental and physiological responses for some marine invertebrates (e.g. Cameron *et al.,* 1985; Zimmerman *et al.,* 1990; Cameron *et al.,* 1993). Hence, definitive results are scarce. However, what does exist is sufficient to identify the main issues likely associated with EMF (see Sections 4.1 – 4.3).

For these reasons, this report took the approach of discussing *S. salar* and *S. trutta* and *A. anguilla* where possible, but also *Salmo* spp., *Anguilla* spp. in general and evolutionarily related species. The report also considered some other marine species which, while they are very distant relatives of the three species of interest, have either similar biochemical reception patterns or physiologically similar apparatus for the reception of EMFs and subsea noise. Interpreting these species responses to EMF and noise meant that a wider range of aspects for the three species of interest could be considered. This kind of approach is becoming recognised as a suitable way in which to assess interactions between humans and marine organisms in light of a poor information base (Slabbekoorn *et al*., 2010).

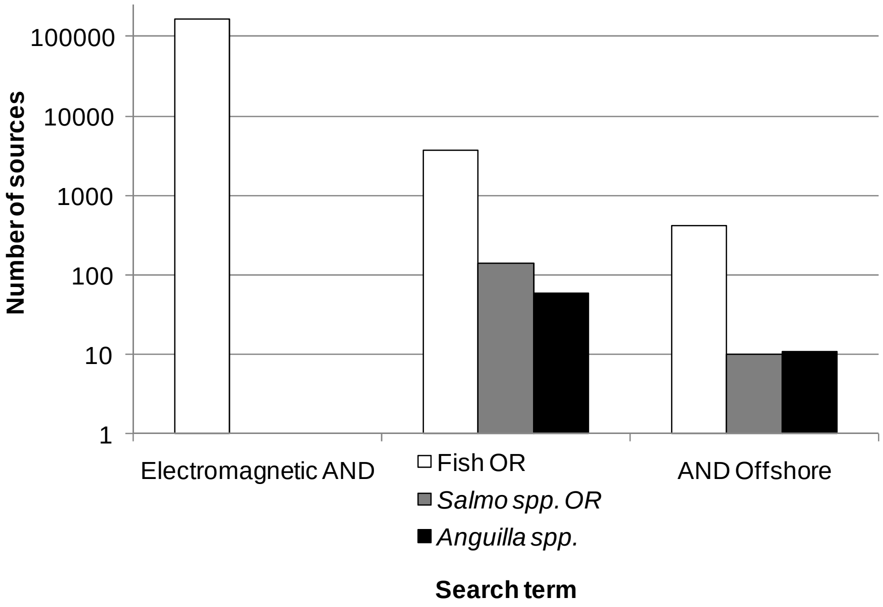

***Figure 3.*** *The number of peer-reviewed articles found through Sciencedirect database. X axis shows the main search terms used, with each term added to the previous column category to provide a subset of articles relevant to the fish species in relation to EMF and offshore. Y axis is a log scale.*

It is important to note that there are two potential reasons for the shortfall in scientific studies and other publications relating to this topic. The simplest assumption is that the research required to address the topics of interest for this report have not been carried out. The alternative to this could be that some pertinent research has been carried out, but either the results were inconclusive or the data showed nothing of interest, so the authors of these studies have not sought to publish the data. Where possible, these data have been identified through the research team's network of contacts and by accessing known reports. It is also important to consider that the observation of no detectable response is not the same as the EMFs (or noise) having no effect on the fish, and the discussion must be considered from within these constraints.

## 3.2 Noise

When considering the effect of underwater noise on fish species, it was evident that the diversity in hearing structures among fishes is extraordinary (Thomsen *et al.,* 2006; Slabbekoorn *et al*., 2010). The different acoustic apparatus result in different auditory capabilities across species. There are in principle two main categories of fish hearing:

- Species that have high sensitivity and are able to hear high frequency sound (up to 3 kHz and in some species even higher) owing to a link between the fish's swim bladder and specialised bones adjacent to the ear canals. These species, often previously referred to as hearing specialists, are sensitive to sound pressure.
- Species that have relatively poor sensitivity, hearing in the range of approximately 30 Hz to 1 kHz. These species hear primarily via a direct pathway of particle motion detected by the ear otoliths. They have previously been assigned as generalists.

It should be noted that these are rather broad categories and that there are many intermediate forms. Atlantic cod (*Gadus morhua*) for example can be considered a generalist as there are no specialised structures connecting the swim bladder with the inner ear. However, the species has a comparably good sensitivity to low frequency sounds and is sensitive to both particle motion and pressure (see Mueller-Blenkle *et al*., 2010).

It is further important to note that the categorisation into hearing specialist and generalist is independent of the taxonomic grouping being based entirely on a species‘ hearing capability (Popper & Hastings, 2009). The classification system is currently undergoing a revision (Popper, pers. comm.).

Salmonids have no specific connection between the swim bladder and the auditory apparatus. *S. salar* have been shown through physiological studies to respond to low frequency sounds (below 380 Hz), with best hearing (threshold 95 dB re 1 µPa) at 160 Hz. Hence, their ability to respond to sound pressure is regarded as relatively poor with a narrow frequency span, a limited ability to discriminate between sounds, and a low overall sensitivity (Hawkins and Johnstone, 1978). There is, however, evidence that juvenile *S. salar* smolts (as well as other salmonid species) are sensitive to very low frequency sound (ie. particle motion) avoiding localised high intensity sounds less than 10 Hz (Knudsen *et al*., 1994) in experimental and river settings. Something also demonstrated in other salmonids (Mueller *et al.,* 1998).

Little specific information relating to the acoustic ability of anguillid eels was found. As they do not appear to possess a specific link between the swim bladder and the ear (Popper & Fay, 1993), they could be regarded as hearing generalists (Nedwell *et al*., 2003). Similar to the salmonid smolts, migrating silver eels (the adult migratory form) have been shown to avoid localised, very low frequency sounds in a river (Sand *et al*., 2000).

# 4 DISCUSSION

The discussion section summarises the current understanding with regard to EMF and noise effects from MREDs on *A. anguilla*, *S. salar* and *S. trutta,* specifically looking at the information directly related to the migratory behaviour and ecology of the three species. For *S. salar* or *S. trutta,* available information was limited. There was more information relating to *A. anguilla*, principally through research on navigation in relation to geomagnetic fields. Where there was no species specific information, the best understanding for other species is explored, and potential effects are extrapolated.

## 4.1 EMF from subsea cables

All cables that carry electricity will emit EM radiation, which is generated as a result of the flow of electrical current in the cable (Figure 1). Industry standard cables are designed so that the direct E field is shielded; however the B field is not (see Section 1.2). The conductivity and permittivity of the cable shielding materials can be altered to reduce the B field (CMACS, 2003). However, whilst it is theoretically possible to contain the B field, the practical design and huge cost implications mean that it is not currently feasible. Furthermore, there is presently not sufficient evidence to require the cables to be redesigned. This is the main reason that further knowledge of the E and B fields and the responses by migratory fish is required.

### *4.1.1 The scale of electromagnetic emissions from subsea cables*

The design and specification of cables, their rated capacity, and associated substations are important in predicting the EMF emissions associated with offshore energy generation, and therefore their potential impact in the marine environment.

Recent reports and industry consultations indicate that increasingly there is widespread standardisation in cabling strategy across the wind farm industry (Gill *et al.,* 2005, and references within). Developers commonly select three-core, AC 33 kV cables for intra-array connections and 132 kV (or possibly 245kV) cables for grid connection to land. Physically larger cables are capable of carrying greater currents.

Research modelling EMFs from cables with contrasting conductor sizes and current loads at the Kentish Flats offshore wind farm site has been undertaken by the University of Liverpool (Table 2; Gill *et al*., 2005). The simulations indicated that a higher current within a cable means that the maximum size of the EMF in the sea and seabed is increased (Table 2), which has implications to the effects on EM-sensitive fish. A previous study modelled a single 132 kV AC, three-core subsea cable carrying 350 A in each conductor (CMACS, 2003).

Analysis methods were broadly similar between these studies but differences occurred relating to the conductivity constant used for seawater, and the environmental context of these two studies. This modelling approach is useful for making comparison of commonly specified subsea cables in MRE developments.

These models predicted that the B field on both the surface of a 33kV cable (i.e. within millimetres of the source) and the seabed directly above the cable was of the order of 40 $\mu$A m$^{-2}$ or 1.5 $\mu$T (Table 2). Assuming the seabed has a conductivity of 1 S m$^{-1}$ the resultant E field would have a likely strength of 40 $\mu$V m$^{-1}$. Furthermore, the E field in the seabed was modelled to dissipate rapidly to only 1 or 2 $\mu$V m$^{-1}$ within a distance of approximately 10 m from the cable. The maximum magnitude of the modelled B field at the interface between the seabed and seawater was approximately 10 $\mu$A m$^{-2}$ or 0.33 $\mu$T. This means that the maximum E field strength induced in the seawater would be *circa* 2.5 $\mu$V m$^{-1}$

(Table 2), assuming fully marine seawater (conductivity of 4 S m$^{-1}$). The modelling of 350 A, 132 kV three core cable buried at 1 m showed that the strength of the E field in the sea was 91 µV m$^{-1}$, indicating that there is a range for potential emissions from subsea cables and that these emissions are cable specific, as well as dependent on the conductivity of the seabed.

***Table 2.*** *EMF output parameters for industry standard cables buried 1.5 m in seabed.*

| Cable parameter | Cable A | Cable B |
|---|---|---|
| Conductor size (mm$^2$) | 500 | 185 |
| Maximum voltage (kV) | 33 | 33 |
| Maximum current (A) | 530 | 265 |
| Maximum B field in seabed (µT) | 1.5 | 0.9 |
| Maximum B field in sea (µT) | 0.03 | 0.02 |
| Maximum current density in seabed (µA m$^{-2}$) | 40 | 25 |
| Maximum current density in sea (µA m$^{-2}$) | 10 | 6 |
| Maximum iE field in seabed (µV m$^{-1}$) | 40 | 25 |
| Maximum iE field in sea(µV m$^{-1}$) | 2.5 | 1.5 |
| Estimated normal iE field in seabed (µV m$^{-1}$) | 20 | 12.5 |
| Estimated normal B field in sea (µT) | 0.015 | 0.01 |

The Kentish Flats modelling study also provided the first assessment of the B and iE fields from wind farm cables at their normal operating capacity, i.e. turbines generating energy at average wind speeds (Table 2; Gill *et al.,* 2005). A directly proportional linear relationship between current load and resultant B and iE fields was determined for both fields such that halving the current halves the size of the resultant fields. The predicted maximum iE field from both studies outlined above is within the magnitude and range (between 0.5 – 100 µV m$^{-1}$), which may be detectable and attractive to elasmobranchs and other fish species, possibly including *S. salar*, *S trutta* or *A. anguilla.* These emissions may have an effect on fish behaviour (see Section 4.2).

As the scale and extent of energy capture from MRE sources increases, the requirement for devices and offshore sub-stations incorporating switchgear and transformers is likely to also increase. This subsea infrastructure is required to convert the voltage of multiple renewable energy device cables into the voltage of the network of subsea cables to shore. Spatially, the result is likely to be an agglomeration of cables on the sea floor at offshore sub-stations with multiple cables over relatively short distances. The implications of this for the size of the EMF generated are unknown but there is the potential for the fields to interact. Normally, the magnitude of the EMF at any given point is inversely proportional to the distance from the power cable. However, when 50 Hz subsea cables are closely placed, the emission fields may cancel each other out to some extent (if 180° out of phase), or be combined constructively (in phase) in an additive fashion (Yi Huang, pers. comm.). This would result in larger emission fields in these areas, which could then create iE fields of several hundred µV m$^{-1}$ when cables come together at sub-stations. This, however, is an unknown and complex field of research.

## 4.2 The effect of subsea cables on movement and behaviour

There is little consolidation of knowledge on the effect of subsea cables relating directly to individual fish species. This is because the relationship has formerly not been recognised as a priority topic and there has been insufficient research conducted to address the gaps in our knowledge (Gill *et al.,* 2005; Öhman *et al.,* 2007; Inger *et al.,* 2009).

Most of the limited research that has been conducted has focussed on physiology based laboratory studies of responses to EMF. It has been demonstrated that EMF can elicit localised physiological response in all three species (Richardson *et al*., 1976; Vriens & Bretschneider, 1979; Hanson *et al.,* 1984; Formicki *et al.,* 1997, 2004). For example, when salmonid embryos and fry (*S. trutta* and *O. mykiss)* were raised in artificially modified magnetic fields, they exhibited significantly altered swimming orientations compared to those which had been reared in a natural magnetic field (Formicki *et al.,* 1997, 2004). The lateral line of *A. Anguilla* shows an electrophysiological response to changes in EMF (Vriens & Bretschneider, 1979; Hanson *et al.,* 1984). Activity of locomotor muscles in *S. salar* alters with exposure to low frequency electric and magnetic fields (Richardson *et al*., 1976). Other laboratory studies have shown that a range of fish species (including *A. anguilla* and *S. salar*) can be sensitive to the perceived changes in geomagnetic orientation similar to those that subsea cables can cause locally. This is thought to be particularly important in migratory species such as *S. salar* and *S. trutta,* which use passive geomagnetic location, and *A. anguilla* which uses active geomagnetic fields for navigation (Walker *et al*., 2002).

Whilst the applicability of these studies is limited it does strengthen the possibility that EMF emissions within the environment, including from subsea cables, may affect the detection mechanism of the fish via physiological and biochemical mediated mechanisms which could affect behaviour, including during movement in coastal waters and migration. However, this assumption of limited effects are built on an incomplete understanding of how these species orientate and navigate around their environment.

The lack of scientific understanding of the subject means that in an industrial context, salmonids and eels are frequently cited as not having any attributable or specific impact associated with them. However, this is a low confidence assessment. Furthermore, there is little discussion about the specific biology of salmonids and eels in relation to MRE (Gill *et al.,* 2005). Most industry Environmental Statement reports that were considered either exclude these considerations, or fail to comprehensively address them.

### *4.2.1 Electric field sensitivity and effects*

The best current understanding of the interaction between fish and the electric field component of the EMF comes from studies of elasmobranchs and their related species that are known to be electroreceptive. These fish possess ampullae of Lorenzini which consist of a series of pores on the surface of the skin, leading to canals approximately 1 mm in diameter and up to 200 mm long (Zakon, 1986; Adair *et al.,* 1998; von der Emde, 1998). These canals are filled with a conductive mucopolysaccharide jelly, which has a low resistance similar in magnitude to that of seawater (25 to 30 $\Omega$ cm$^{-1}$) (Murray, 1974; von der Emde, 1998). At the end of the canals are clusters of ampullae (alveoli with ampullary receptor cells situated on their walls), which enable elasmobranchs to detect very weak voltage gradients (down to 0.5 µV m$^{-1}$) in the environment around them (Kalmijn, 1971; Murray, 1974). On encounter with a polar E field, an elasmobranch can locate the emission based on differential voltage potential at the pores with reference to the internal potential of the body. In a uniform E field, the different length and orientation of the ampullae of Lorenzini canals allows an elasmobranch to compare voltage gradient change. A review of the cited behaviour thresholds for marine organisms to EMFs was recently carried out by Peters *et al.* (2007), who highlighted the wide range of sensitivities on a species by species basis.

Whilst not the primary species of interest to the present study, elasmobranchs and agnathans provide the best available evidence that there can be an interaction between fish and subsea cables. Of the range of E-sensitive fish, four are likely to be found in Scottish waters: dogfish (*Scyliorhinus canicula*), thornback ray (*Raja clavata*), river lamprey *(Lampetra fluviatilis)* and sea lamprey (*Petromyzon marinus*). From these, *S. canicula* has the widest behaviour threshold, up to 150 µV m$^{-1}$, and *P. marinus* represented the lower end of the spectrum at a behavioural response of 10 µV m$^{-1}$. All these values are within the range of emissions modelled or measured from cables associated with operational marine wind farms.

The only example found of the effect of EMF on a migrating fish was through observations of sturgeon (*Acipenser gueldenstaedtii*) moving away from high voltage (100 kV) overhead power cables (Poddubny, 1967). The fish swam slowly in proximity to the cables and accelerated when past them. Whilst these cables were not in the water, overhead cables are not well shielded. This means that the EMFs that they emit will have most probably entered the water where sections of cable crossed near to the surface. It was stated that the behavioural responses were a result of the effect of the EMF penetrating the shallow waters at this point in the lake (Poddubny, 1967).

The only documented example of an emission from a subsea cable having an effect on marine fish in the wild was a study by Marra (1989), who showed evidence of shark bites on submarine optical telecommunications cables. The cables were associated with two forms of induced electric fields: a 50 Hz E field of 6.3 µV $m^{-1}$ at 1 m which was caused by the power feed to the cable, and another of 1 µV $m^{-1}$ at 0.1 m resulting from the sharks crossing the B field emitted by the cable. Follow up laboratory behavioural tests, and trials carried out at sea, were inconclusive in determining cause and effect for this species.

A recent experimental study funded under the COWRIE programme showed that in semi-realistic circumstances benthic elasmobranchs are able to respond to the EMF emitted by subsea cables (Gill *et al*., 2009). This experimental study was the first of its kind in relation to any EM-sensitive species and MRE subsea cables. Whilst there were responses by the fish, they were variable and dependent on the individual fish and the species. There is much more that needs to be researched to determine the extent of the response by fish and importantly determining whether the response is biologically significant for the species populations and communities within the coastal ecosystem.

There is limited evidence that anguillid eels and salmonids are able to detect E fields, however this is a physiological assessment based on laboratory studies. The best available information (see Table 1) is that *S. salar*, *S trutta* or *A. anguilla* normally experience iE fields from peak tidal movements, in the range of 8 - 25 µV $m^{-1}$ (Pals *et al.,* 1982), which are within the range of emissions associated with subsea cable EMF. Extrapolating whether these species would detect E fields from subsea cables in the coastal environment is currently not possible without better data and a more detailed and quantitative analysis, which is outside the scope of this review.

### *4.2.2 Magnetic field sensitivity and effects*

Very low intensity magnetic fields have been associated with behavioural responses in a variety of animals, such as the homing ability in pigeons, sharks, bees and whales that is thought to be as a result of changes in magnetic fields which are at or below background geomagnetic levels (10 – 50 µT ; Walker *et al.,* 2002). Only a small number of studies have specifically looked at the effect of EMF on fish migration and movement.

*A. anguilla* has magnetic material in the skull and vertebral column (Hanson & Westerberg, 1986; Hanson *et al.,* 1984). Magnetic particles have been noted in the lateral line of the *S. salar* and *A. anguilla* (Moore *et al*., 1990; Moore & Riley, 2009). No specific studies on *S. trutta* were found. However, the most comprehensive study of the magnetic sense in any vertebrate to date showed that rainbow trout (*Oncorhynchus myskiss*) have a behavioural and electrophysiological response to magnetic fields based on magnetite-magnetoreceptor cells in the nose of the fish (Walker *et al*., 1997). The physiology of this detection method of EMFs is suggested to be similar in some species of Pacific salmon, e.g. chinook salmon (*Oncorhynchus tshawytscha*) and sockeye salmon (*Oncorhynchus nerka*) that have been shown to be able to respond to anthropogenic changes in both E and B fields (Mann *et al.,* 1988). It is this magnetic material that is likely to be affected by exposure to EMFs generated by subsea cables.

Exposure to B fields can have physiological effects on some fish. Brook trout (*Salvelinus fontinalis*) have been shown to have modified hormone levels as a result of prolonged exposure to a 0.62 mT magnetic field (Formicki *et al.,* 2004). Research has also indicated that in *S. trutta*, B fields cause alterations to their pulmonary circulation (Formicki, *et al.,* 1997). A study showed that *S. salar* showed no change of rhythmicity in locomotor activity when exposed to low frequency EMFs over a 10 day period. No conditioning or training behaviours were detected in movement cycles where magnetic fields were turned on or off (Richardson *et al.,* 1976). The same study also showed that the American eel (*A. rostrata*) demonstrated no physiological or behavioural responses to EMFs at ten times more than geomagnetic levels in controlled laboratory experiments (Richardson *et al.,* 1976).

Research with yellowfin tuna (*Thunnus albacores*) has shown that these fish are able to discriminate between different strength magnetic fields, thereby affecting their direction finding abilities (Walker *et al.,* 1984). Exposure to strong anthropogenic fields therefore may have an effect on the migratory patterns of these fish. However, the size and intensity of the magnetic field required to cause a significant effect on migration remains unclear. In the open sea, a related species to *S. salar* and *S. trutta*, chum salmon (*O. keta*) have been shown to have no detectable response to EMFs two orders of magnitude greater than the Earth's geomagnetic field (Yano *et al.,* 1997).

Branover *et al.,* (1971) demonstrated a strong direction finding component to the movement behaviour of *A. anguilla*, swimming and orienting themselves relative to magnetic north. These findings have been recently confirmed through an improved understanding of eel physiology (Moore & Riley, 2009). Research carried out in controlled condition swimming tunnels in laboratory conditions using *A. anguilla* has shown they can respond to changes in an EMF, over and above the ambient background levels (Tesch *et al.,* 1992).

Studies on *A. anguilla* in the Baltic Sea have highlighted some limited effects of subsea cables. The speed and timing of migration was shown to change in the short-term (tens of minutes) with exposure to AC electric subsea cables, even though overall direction remained unaffected (Öhman *et al.,* 2007; Westerberg & Langenfelt, 2008). Limited sea trials and field observations have also been carried out to investigate the potential for any change in the migratory patterns of *A. anguilla* in relation to offshore wind farms. The research principally carried out in Swedish waters showed no changes to the migratory behaviour of this species beyond 500 m from wind farm development sites (Westerberg, 1994; Westerberg & Begout-Anras, 2000; Öhman *et al.,* 2007). Within 500m of this cable system they reported that some deviation from the straight-line migratory course was detected, consistent with magnetic anomaly caused by the cable. Additionally, no significant effects to *A. anguilla* behaviour were observed when the turbines were either generating energy or not although experimental net catches were different (Westerberg, 1999; Westerberg *et al.,* 2007). It was not possible to determine if this was related to the EMF or acoustic disturbance associated with the operating turbines (Westerberg *et al.,* 2007). Therefore, this research suggests that any changes in behaviour of the eels may not necessarily be solely in response to the EMF component of the environmental impact of an offshore renewable installation.

Research in Sweden to determine the effect of the SwePol link[†] detected a magnetic field of 200 µT at a distance of 1 m from the cable, but did not show any effect on migration patterns of a range of fish species, including *A. anguilla* (Westerberg *et al.,* 2007; Westerberg & Langenfelt, 2008). This study also attempted to directly relate the activity of *S. salar* and *S. trutta* through tagging experiments with remotely operated magnetic devices attached to the

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[†] The SwePol link is a HVDC cable between Sweden and Poland

fish. However, no significant behavioural responses to these artificial magnetic fields were detected (Westerberg *et al.,* 2007; Westerberg & Langenfelt, 2008).

The Japanese eel (*A. japonica*) has similar magnetic sense organelles as *A. anguilla* and migrates thousands of kilometres through the open ocean to spawn in inland rivers. Research has shown that this species is significantly affected by small changes in magnetic fields (Nishi & Kawamura, 2005). The mechanism of this response remains unclear, but it is thought to take the same physiological form as other anguillid eels. The research showed that *A. japonica* can be conditioned to exhibit these responses during the glass eel stage of their life cycle (Nishi & Kawamura, 2005). This means that any prolonged exposure to magnetic fields (i.e. over months) during the early stages of their life-cycle may have an impact later on during their migratory behaviour as adults. This impact could include preventing them from being able to accurately locate their oceanic spawning or mating grounds. The cause of this effect is likely to be as a result of the magnetite particles in the lateral line becoming magnetised themselves, in the same way as a compass exposed to a B field over a prolonged period will result in systemic error in direction finding. Even if the eels develop in an area away from any anthropogenic EMF, the adults may still respond to EMFs if they pass through them on their migration to their mating and spawning grounds.

The mixed results from the few studies that have been reported suggest that the magnitude and intensity of the movement and behaviour effects from subsea cables, if apparent, will be closely linked to the proximity of the fish to the source of the EMF. EMFs are strongly attenuated and decrease as an inverse square of the distance from the cable (see Section 4.1 for further details). If there is going to be any effect on migration of *A. anguilla* or *Salmo* spp., it will most likely be dependent on the depth of the water and the proximity of natal rivers to MRE installations and the characteristics of the subsea cables.

However, there is currently no clear evidence as to what, if any, the overall effect of EMFs on migration and movement behaviour of *S. salar*, *S trutta* or *A. anguilla* from subsea cables is likely to be. Neither is there evidence on which to determine the effect of a small, local change in magnetic field in the context of the large scale migration of the fish or how this may impact the migratory routes of the fish. Based on the review undertaken, current knowledge suggests that EMFs from subsea cables and cabling orientation may interact with migratory eels (and perhaps salmonids) if their migration route takes them over the cables, particularly in shallow waters (<20m) where there is a greater probability of encounter with the high voltage cables coming to shore. What the effects will be is currently unknown but Figure 4 highlights the hypothesised effects which may occur if movement of the fish is affected. Figure 4a is the normal migration or movement with no subsea cable. Where a migration route is parallel to the EMF source (Figure 4b) there is likely to be no influence on direction of migration (Öhman *et al.,* 2007). Based on current understanding, there may be a limited effect on eel migratory routes for cables that are either at right (Figure 4c) or oblique (Figure 4d) angles to the migration route (Westerberg & Langenfelt, 2008). A lack of published research on the long term exposure of either *Salmo* spp. or *A. anguilla* to anthropogenic B fields in any stage of their lifecycle means that it is challenging to determine if this response is likely for Scottish waters. It is important to note that relatively few studies have described the migratory routes of anguillid eels, and those that do suggest that ocean currents may play as significant a role in migration as magnetic orientation (Fricke & Kaese, 1995; Knights, 2003; Tsukamoto, 2009).

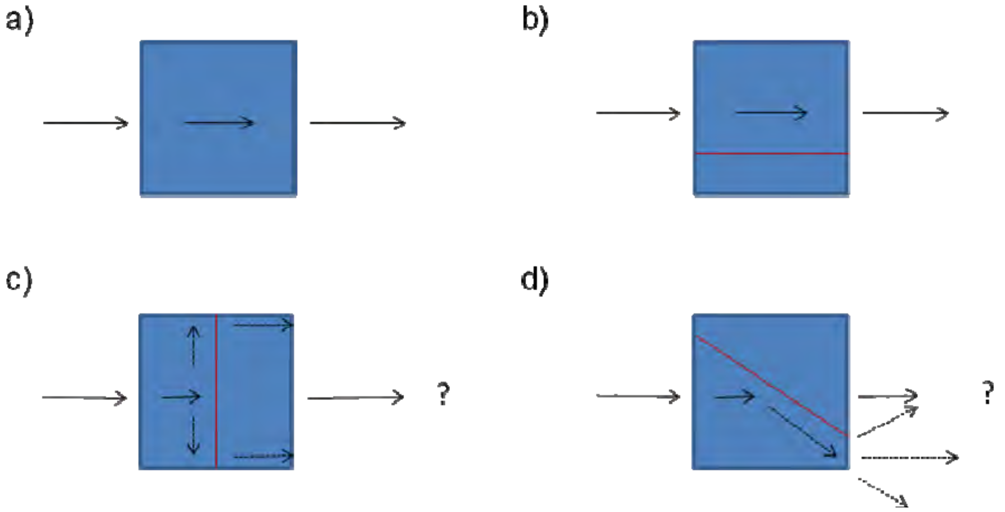

*Figure 4. Plan view diagrammatic representation of the potential effect of orientation of subsea cables relative to migration routes of fish species. Black arrows show migratory routes; Dashed lines show potential changes to migratory routes following exposure an EMF from the cable; Red line shows location of subsea cable for a) No subsea cable, b) Subsea cable parallel to migratory route, c) Subsea cable at 90° to migratory route, d) Subsea cable at an oblique angle to migratory route.*

***Summary***

Awareness of the size and scale of the impact of undersea disturbances, such as EMFs, on fish behaviour, and their ecology in general is increasing (Fristedt *et al.,* 2001). But as highlighted above, only limited species and spatial data on the effects of EMFs on fish are available. The few results come primarily from elasmobranchs. However, as elasmobranchs detect and respond to both E and B fields in a different way to salmonids and anguillids, no clear parallels can be drawn. For B fields, the evidence suggests that both of these fish Genera can respond to the level of emissions that would be associated with MRE EMF in Scottish waters. Whether there will be an effect and subsequent impact cannot be determined owing to lack of data. More research is required to understand the consequences of fish responses and whether there are any biologically relevant effects. Hence it is currently not possible to draw firm conclusions on whether there are any impacts on the three species considered in this review. In the future, it will be important to assess any response in terms of the likelihood of encounter, which will be a factor of how many MREDs are present and where in the coastal zone they are deployed in relation to the migratory and other movement routes of the fish.

### 4.3 Responses to EMF in relation to other stimuli

Species that have specialised EM-receptors have evolved in this way to naturally detect emissions from prey and potential predators, to facilitate inter and intra species interaction, or orientation and navigation. However, the EM-sense is only one of a suite of senses used by fish. For example a fish responding to E fields will do so primarily in close proximity (10’s of cm) to the E fields. Other senses, such as vision, hearing and smell are used over greater distances.

Because the range of detection mechanisms of EMFs and the ecological purpose for detection differs on a species by species basis, it is hard to generalise about the effects of disturbances in EMFs over the other orientation and predatory senses. Furthermore, the detection of a laboratory based response to a stimulus does not necessarily mean a change in behaviour in the sea. Experiments are normally conducted on single specimens rather than many individuals within a population and in unfamiliar surroundings for the fish. For example, light levels, water temperature, salinity and migratory swimming distance all effect the development of sexual maturity and therefore behavioural responses in *A. anguilla* (van Ginneken *et al.,* 2007). Species responses to stimuli and behaviour in general is controlled by complex interactions of environment, hormones and physiology, which are poorly understood at an individual and ocean scale (Dufour & Fontaine, 1985; Imbert *et al.,* 2008).

For both *S. salar* and *S. trutta,* migratory and sexual behaviour are pivotal in their life cycles, controlling population numbers and reproductive success (Adams, 1980). The behaviour of both of these fish species is largely controlled by the endocrine system within the fish, which controls and regulates hormone levels (Moyle & Cech, 2000). Sexual behaviour in fish is innate rather than learnt, with hormonal feedback loops within each fish being controlled by environmental and physiological cues (Jessop *et al.,* 2008). Consequently, temporary external stimuli such as EMFs may only have a transitory effect (Munakata & Kobayashi, 2010). But for fish that remain within the coastal waters, such as *S. trutta,* any effect may need to be considered further owing to longer periods of exposure to EMF. Research with *A. anguilla* has shown that locomotion behaviour is closely related to the physiological development stage of the eels and that this in turn is linked to the levels of the hormones thryroxine and triiodothyronine in the fish's blood (Imbert *et al.,* 2008; Sébert *et al.,* 2008). This dominance to movement behaviour by the endocrine system means that any transitory effects of either E or B fields on behaviour may not be strong enough to outweigh the dominance of whole organism biochemical changes and neuroanatomical control of the hormones within the fish, but this is currently unproven.

For most fish species the olfactory sense encodes important environmental information, enabling mating behaviour, food location, avoidance of predators and homing. This is the case for *S. salar*, *S trutta* and *A. anguilla*. Research in this area has been dominated by anthropogenic toxicity effects from chemical releases into the sea (e.g. Tierney *et al.,* 2010). However other species, such as sea lamprey (*Petromyzon marinus*), have been shown to use pheromones for the co-ordination of mating (Fine & Sorensen, 2008). Studies have shown that *A. anguilla* are sensitive to the chemical composition of mucus and conspecific bile as location finding information for breeding grounds (Huertas *et al.,* 2007). This kind of response to chemical cues is also important for reproductive success (Huertas *et al.,* 2006), and intraspecies interactions have also been hypothesised to be dominant over other environmental parameters in most fish species (Larsson, 2009). Further research is required to determine the extent of the dominance of these senses over the responses to EMFs for *S. salar*, *S trutta* or *A. anguilla*, which are expected to receive transient exposure to EMF. This exposure will depend on the scale and extent of the MRED with regards to the natal rivers and the length of time that the fish are within the vicinity.

During the planning and development phases of offshore wind farms in the UK, the Environmental Impact Assessments (EIAs) that were conducted all considered the impacts of subsea cables on *S. salar*, *S. trutta* and *A. anguilla,* but they did not focus on EMF[‡]. Where there was some consideration, for example in Liverpool Bay EIAs for North Hoyle and Burbo Banks wind farms, several existing buried cables were identified in the Dee estuary region which were considered to have no historical affects on eel or salmonid migrations. This, however, only takes into account the cables coming to shore and not the network within the wind farm. Salmonids and eels were also considered in the Robin Rigg, Solway Firth, Environmental Statement (Gill *et al.,* 2005), but no effect of magnetic fields was predicted as it was assumed that these species used olfaction rather than the Earth's

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[‡] The considerations of physical cable burial and resulting suspended sediment impacts were the points of focus.

magnetic field to navigate once they were inshore, close to their natal rivers. A key point is that there is relatively little information available on both subjects, and that much of the understanding is dominated by assumptions. Determining whether there is a dominance of one behavioural response over another or some alteration to resultant behaviour remains challenging without further laboratory and sea studies.

## 4.4 Sensitivity to subsea noise

The effects of the propagation of subsea noise from MRE installation and operation on marine organisms are also under-represented in peer reviewed literature. There are several commissioned studies available on the subject, but the greatest focus has been on the effects on marine mammals, rather than the effects on fish (Thomsen *et al.,* 2006). In the absence of a clear understanding of their response to subsea noise, the specific effects on *S. salar*, *S. trutta* and *A. anguilla* remain very difficult to determine for Scottish waters in relation to tidal and wave power.

Fish are able to detect and respond to a range of sea noise, and have been shown to use sound as a method of intra and inter species communication and for the perception of their environment (Fay & Popper, 1999; Webb *et al.,* 2008). Furthermore, a noise is likely to have a different effect on different species of fish because of species specific hearing abilities (Popper & Hastings, 2009). For example, salmonids, such as *S. salar* and *S. trutta*, are categorised as hearing generalists, capable of responding to received sound pressure wavelengths between 30 and 380 Hz[§] (Figure 5). However, current understanding of hearing in fish is based on studies of only approximately 0.3% of the total identified marine species (Popper *et al.,* 2003).

### *4.4.1 Transient noise effects*

The focus of most research relating to fish has been on noise and subsea wave propagation generated from pile driving (see Popper & Hastings, 2009); a commonly used technique in marine construction projects. The impact that the transient noise effects of construction are likely to have on *S. salar*, *S. trutta* or *A. anguilla* will be dependent on the construction techniques used for installation of either wave or tidal power units. A number of MRE designs have substantial foundations to support the turbine or generator and therefore will likely need to have pile driven foundations (e.g. Strangford Lough tidal turbine; Nedwell & Brooker, 2008) unless they are floating-type designs. It is widely acknowledged that different pile driving construction techniques result in different subsea noises. Regardless of the technique, the rapid release of energy when two objects are hit together results in a stress wave that travels through the water (Popper & Hastings*,* 2009).

Pile driving has been reported to result in deaths from several species related to *Salmo* spp. (Popper *et al.,* 2005; Popper & Hastings, 2009). Fish mortality of Shiner perch *(Cymatogaster aggregate)* in the USA was determined to be caused by exposure to the pile-driving sounds, within 50 m of the source. The cause of death in most of the fish was implied to be damage to the swim bladder. However, controlled trials using caged fish experiments produced inconclusive results (Caltrans, 2001 cited by Popper & Hastings, 2009). Research trials carried out with caged farmed *S. trutta* in Southampton Water investigated the effect of both pile driving and vibropiling (non percussive pile driving), where the source noise was between 193 and 201 dB re 1 μPa peak. The *S. trutta* were exposed to the sound source at a range of distances. The observations revealed no evidence that the fish reacted to impact piling at a distance of approximately 400 m (average received sound pressure level = 134 dB re 1μPa), nor to vibration piling at close ranges (<50 m; average received sound pressure level was not provided; Nedwell *et al.,* 2003; Nedwell & Howell, 2004). However, received

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[§] Normal range of human ear detection is approximately between 20 – 20000 Hz sound pressure levels were regarded as relatively low and the use of farmed fish may have raised the reaction threshold to noise disturbance (Hastings & Popper, 2005).

Some research has indicated that these kinds of noise may cause either temporary or permanent hearing loss to fish or shifts in their threshold response levels (TTS – Temporary Threshold Shift; PTS – Permanent Threshold Shift; Popper *et al.,* 2006). Even temporary loss or TTS in hearing could result in the fish being unable to respond to some environmental stimuli (Popper *et al.,* 2006).

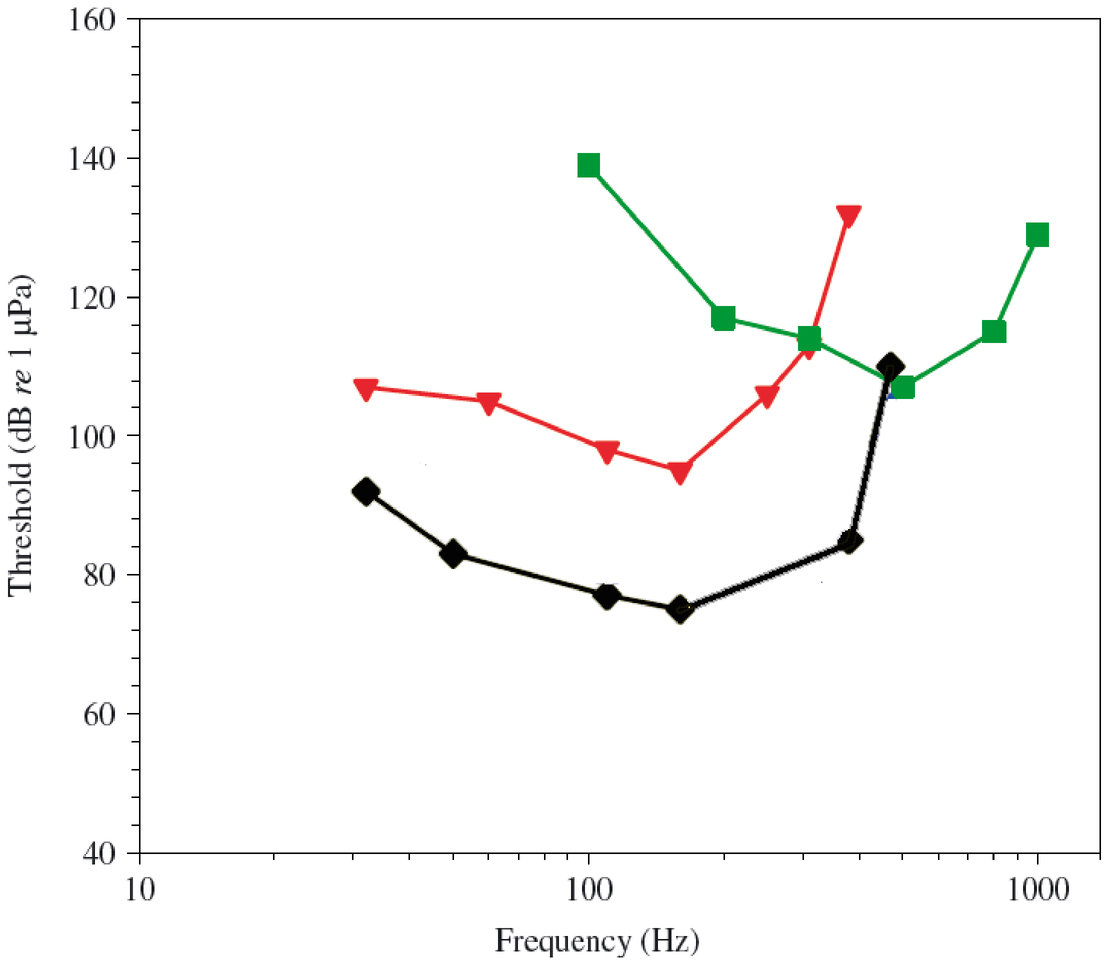

***Figure 5.*** *Hearing thresholds for three selected fish species. (▼) Atlantic salmon (Salmo salar); (♦) cod (Gadus morhua); (■) tuna (Euthynnus sp.). Redrawn from Popper and Hastings, 2009.*

### *4.4.2 Operational noise*

Operational noise in the sea from offshore wind farms has been reported to be in the region of 2 dB noisier than the surrounding sea environment (Nedwell *et al.,* 2007). Renewable energy generated by wave and tidal generators are likely to be noisier in the subsea environment than wind turbines, because the power generation unit is physically in the water and is reliant on the movement of the water to generate power. The potential for acoustic disturbance from tidal and wave devices has been identified previously in scoping studies on their environmental impact (RGU, 2002; OSPAR, 2005; BERR, 2007) and measurement of the acoustic emissions by the devices has been highlighted as a priority (BERR, 2007). However, the short and long-term effects on the behaviour of fish in response to this noise in the marine environment are hard to determine, as the levels of noise remain largely un-quantified. Furthermore, the received levels of sound by fish need to be considered in relation to the ambient levels. In the case of the only documented tidal stream location in the UK, these ambient levels have been measured be in the upper frequency band between approximately 200 Hz and 70 kHz if compared with levels of background noise at other coastal water locations (Nedwell & Brooker, 2008). In this study, it was suggested that this relatively high level of noise was due to the high tidal flow rates through the Strangford Narrows region.

Wahlberg & Westerberg (2005) estimated that *S. salar* and *Gadus morhua* (Atlantic cod) detect wind farm noise from a distance of 0.4 - 0.5 km and 7 - 13 km respectively and they speculate that the fish would change their swimming patterns to avoid the noise source. Research carried out for COWRIE suggested that, if noise levels do not exceed 90 dB and providing that fish are capable of moving out of the area, then they are unlikely to sustain permanent damage. The same research also implied that if operation noise was above 90 dB it would also act as a significant deterrent to fish entering that area of the sea (Nedwell *et al.,* 2007). However, the values proposed by Nedwell *et al.* (2007) are extrapolated from research undertaken on humans and are not validated by any empirical studies.

Field research has implied that noise from seismic surveys lead to a decline in the catch rate of haddock (*Melanogrammus aeglefinus*) and *G. morhua* for five days after the activity had ceased (Engås & Løkkeborg, 2002). It is likely that this was an effect of the fish leaving the area, a conclusion supported by other studies (Slotte *et al.,* 2004). It should be noted that these effects of seismic studies cannot be easily extrapolated to effects related to MREDs. It is provided here for completeness and to highlight how subsea noise in different forms can have effects on fish. However, our understanding of the effects are specific to the type of noise and the fish species.

### *4.4.3 Decommissioning noise*

The final phase of an MRE development life cycle is decommissioning. There is no current consensus on what the noises will be during this phase, but it is expected to be mainly linked with increased boat activity and marine cutting. Hence a similar set of responses as those associated with construction are currently predicted for the decommissioning.

## 4.5 Potential response of *S. salar*, *S. trutta* and *A. anguilla* to EMF and noise associated with MREDs

Despite some recent advances, there is a significant gap in the scientific knowledge concerning most fish species (including *A. anguilla*, *S. salar* and *S. trutta*) and the effects of EMF or noise (Yano *et al.,* 1997; Gill 2005; Thomsen *et al.,* 2006; Westerberg *et al.,* 2007; Westerberg & Langenfelt, 2008; Popper & Hastings, 2009). What is clear is that the impacts from EMFs and noise in the coastal environment are likely precipitated on the local behaviour of some (but probably not all) species of fish.

Fish species which use the earth's magnetic field for orientation and direction finding during migrations could be affected by MREDs, but whether this will represent a biologically significant effect cannot yet be determined. Increased offshore energy production will likely mean an increase in the number and density of subsea cables within the MRED area and more cables carrying the electricity to shore. For species such as *A. anguilla*, *S. salar*, and *S. trutta,* changes to cabling may mean an increased risk of encountering local anthropogenic B fields. Depending on the magnitude and persistence (in both space and time) of the magnetic fields, the impact could be a trivial temporary change in swimming direction, as seen with anguillid eels encountering a HVDC cable, or a more serious delay to the migration (see Figure 4). Species such as *S. salar* and *A. anguilla* may encounter EMF only during specific periods such as the reproductive season, early life stages in shallow water nurseries or migration.

Risks may exist when fish are in their early life stages, or on migratory routes which take them into shallow coastal waters. Salmonid fry (*S. trutta* and *O. mykiss)* raised in artificially modified magnetic fields exhibited altered swimming orientations compared to those which had been reared in a natural magnetic field (Formicki *et al.,* 1997, 2004). This distinction could be of importance for some marine species, as one of the ecosystem scale effects of the development of MRED has been the creation of niche and low predation habitats (Langhamer & Wilhelmsson, 2009; Snyder & Kaiser, 2009; Wolsink, 2010). The effects of EMFs, or the physical structure of subsea components of the MREDs themselves on available food sources, may have a significant impact on the activity and behaviour of these predatory fish species, and other parts of the trophic web (Hall *et al.,* 1994).

In terms of EMF, the observations of Poddubny (1967) with *Acipenser gueldenstaedtii* (Russian sturgeon), veering away from high voltage overhead lines crossing water; Gill *et al.,* (2009) showing some evidence of the benthic elasmobranchs responding to AC EM fields at emission intensities similar to those from offshore power cables; Meyer *et al.,* (2004) showing that elasmobranchs detect B fields in the range 25-100 µT against the ambient geomagnetic field of approximately 36 µT; Westerberg (1999) demonstrating that *A. anguilla* have some (limited) responses to magnetic emissions from high voltage cables all indicate the potential for responses that must be evaluated on a species by species basis.

Current research methods are not capable of determining the relative significance of the long, relatively narrow cable routes to shore compared to the network of cables within an offshore array. It is likely that the EMFs from multiple cables will be complex; those in the same orientation are expected to be additive, whereas those in the opposite orientation are likely to be subtractive, and those at different angles to each other will further complicate the situation.

If potential noise impacts are also considered, then the affected site might cover a substantial area, even for one MRED. However, this will depend on the characteristics of the noise source, the received level and the proximity of the fish to the stimuli. Similarly to the state of knowledge for EMF, the potential for responses from *A. anguilla*, *S. salar* and *S. trutta* to noise from MREDs must be evaluated on a species by species basis. For example, fish that use the coastal waters may be caused to move away from the source of the noise (or EMF), which perhaps would have potentially greater effect on the resident species (e.g. *S trutta*) than the transient migratory species. Such species based assessment combined with the best available understanding of other sources of environmental disturbance will provide significantly improved knowledge base.

As the density and frequency of Scottish coastal zone developments increases, it becomes increasingly important to consider the potential for cumulative impacts from these developments. Recent Government legislation in the form of the Marine (Scotland) Act 2010 will require assessments of cumulative impacts. It is insufficient to consider developments in isolation, because each MRE production centre in adjacent areas will have its own local environmental footprint. Noise propagation in the coastal waters over 10's of kilometres will mean that there is likely overlap and combination of the effects, resulting in a larger or different impact (refer to Section 4.4). Until the actual significance of existing anthropogenic sources of E and B fields and noise for each species of interest has been determined, it is only possible to make educated assumptions about these cumulative impacts.

Recent studies have shown that the specific latitude for spawning sites of *A. japonica* can change between months, and years, depending on oceanographic conditions. Further studies are required to determine the effect of this on recruitment and the overall fecundity of the species (Tsukamoto, 2009). Therefore *Anguilla* spp. and *A. anguilla* specifically, may be able to adapt their life history to avoid any potential negative impacts of MRE EMF and/or noise. However, this is currently speculation that requires further study.

Spatial planning for offshore wind farm developments will be important in minimising environmental impact and maintaining normal ecosystem processes and function (Punt *et al.,* 2009). Ecological models that have been developed on the impacts of MRED focus mainly on the effects on bird species (Tucker, 1996; Garthe & Hüppop, 2004). More recently, sophisticated GIS based models have been used to interpret the optimum location for positioning wind farms (Punt *et al.,* 2009). Punt *et al's* (2009) study concluded that by selecting areas with low antecedent, predatory bird activity, the net effect on the local fish populations is likely to be positive; however, this model fails to take into account the effect of EMF or subsea noise generated from MRE installations. Therefore the net effect on fish species that are sensitive to these impacts remains unclear, further data and a better understanding of the response of different species to EMF and noise would be required before more robust models could be developed.

# 5 CONCLUSIONS

## 5.1 Present state of knowledge

At present, the complex and challenging issues of the effects of EMF and noise on fish, in general, are avoided and a “best guess” approach appears to be taken (Punt *et al.,* 2009). Much more targeted research is required to determine underlying mechanisms and processes that determine any effects (Gill, 2005; Inger *et al.,* 2009; Boehlert & Gill, 2010; Slabbekoorn *et al*., 2010).

For *S. salar*, *S. trutta* and *A. anguilla*, this translates into the precautionary principle for conservation management, as there is little knowledge of how we may affect the species under threat. However, in the context of marine renewable energy this precautionary approach can be overly restrictive to an industry that has global benefit for controlling emissions to the atmosphere. With respect to EMF and noise, an adaptive management approach is perhaps more suitable. This will mean that as both research and practice provide a greater insight into the interactions between migratory fish and EMFs or subsea noise, guidance and decisions for conservation management can be reviewed and adapted.

Based on current knowledge, during MRED operation, *S. salar*, *S. trutta* or *A. anguilla* may respond to B or iE fields generated from subsea cables, either by short-term attraction or avoidance. If such behaviour occurs, then it may waste time and energy for the fish, and perhaps be a causal effect in delayed migration or alterations to movement and distribution. However, it is important to note that this review identified no clear evidence that either attraction or repulsion due to anthropogenic EMFs will have an effect on any of the fish species identified in this report, including *S. salar*, *S. trutta* or *A. anguilla*.

For noise, the construction phase appears to be the most critical time because of the acute effects. The type of construction, including the time-scale over which it is carried out, will play an important role in any impacts on the species under investigation. From this review, it would be suggested that fish that receive high intensity sound pressures (often in close proximity to the MRE) may be harmed to some degree, whereas those at distances of 100s to 1000s of metres may exhibit behaviour responses which will be dependent on the received sound.

During operation there will be noise produced and longer term, ecologically relevant effects should be considered (Slabbekoorn *et al*., 2010), particularly for species or life stages that may spend extended time in the MRED area (e.g. *S. trutta*).

## 5.2 Identified gaps in knowledge

The significance of anthropogenic electrical fields and noise associated with MRED in relation to *S. salar, S. trutta* and *A. anguilla* remain uncertain. If there are any effects, the most signficant impacts for *Salmo* spp. are likely to be either as smolts emerge into the sea or during the adult phase of life. In the case of eels, any effects are likely to be greatest during the larval/juvenile phase and the adult’s migratory phase.

In order to properly understand the effects of tidal or wave energy generation installations on *S. salar, S. trutta or A. anguilla,* it is important to determine the basic behavioural responses of each species. Identifying whether there are any effects such as attraction or avoidance (short or long term) of EMFs and noise in each species is critical. Such research should determine if the effects are similar for individuals within a species population (i.e. are there age, morphological stage or sex differences). It would also be important to determine any physical exclusion effects on fish, where the introduction of the submarine structures alone causes disturbance in each receptor species’ ecology.

If *S. salar, S. trutta and A. anguilla* coastal migration routes are within several kilometres of the shore then as more and more MREDs are installed they are likely to encounter either construction activities, an array of operating devices, a network of cables, and/or main cables to shore during their life. This may present a source of distraction to some of the migratory fish, causing them to deviate or slow down their migration. Potentially, and more problematically, this could present a barrier to migration owing to the cumulative effects of many developments (construction or operational noise) or multiple cables (some of higher voltage rating). This is similar to the current issues with migratory birds and offshore wind farms. The predictions are that some species will avoid the area of the wind farm or deviate from their main migratory route, thereby significantly increasing their energetic burden. The energy burden is expected to increase with the cumulative effect of multiple wind farms within a coastal area. This potential issue is currently speculation with regards to *A. anguilla*, *S. salar* and *S. trutta* but is an important consideration for future studies.

Another untested and perhaps more problematic situation for migratory fish is if they are unable to reach their natal rivers because of the location of these rivers near to extensive MREDs in coastal waters. Hence a clear understanding of how migratory fish species of conservation importance utilise the coastal zone and react to the construction and operational activities of MREDs is a fundamental requirement.

All these information gaps are of significance because the extent of understanding of anthropogenic EMF (both electric and magnetic fields) and subsea noise is pivotal to the sustainable development of MRED. It is therefore suggested that future research in relation to *S. salar*, *S. trutta* and *A. anguilla* should attempt to:

- Definitively determine whether these species will respond to the likely electric and magnetic field strengths associated with each MRE source and assess the potential significance of any effects for each of the critical life cycle stages identified. This could include studies of how exposure to EMF causes effects (e.g. physiological and biochemical stress resulting from EMF).
- Identify how each of the species interacts with the EMFs when free swimming and during the migration phases of their life cycles. This is likely to vary between species according to their habits, and needs to consider different life stages of each fish.
- Determine the threshold levels at which the three species detect and respond to the subsea noise during the construction and operation phases, separately using non-caged experiments from a range of different sound sources on the behaviour of each species of fish. This too could include studies of how exposure to noise causes effects (e.g. resulting physiological and biochemical stress; see Slabbekoorn *et al*., 2010).
- Specifically consider the cumulative impacts of adjacent developments, and determine the effects of constructive and destructive interference patterns and interactions between EMFs and noise from cables or marine renewable devices associated with whole developments.

Such future research is fundamental not only to tidal and wave power installations in Scotland, but anywhere in the world. Hence, the knowledge base could be significantly improved by coordinated effort to secure the necessary funds to undertake field and experimental based studies or such as semi-natural mesocosm studies similar to those recently completed within the COWRIE research programme for understanding effects of offshore wind farms generated EMF and noise on sensitive species (Gill *et al.,* 2009; Mueller-Blenkle *et al*., 2010).

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