Appendix 7.4
EMF and Migratory Fish

Waterside Ecology

Allt Easach hydropower scheme:

Potential interactions between electromagnetic fields (EMF) and migratory fish

Commissioned Report to Green Highland Renewables Limited

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1   Introduction

The proposed run of river hydroelectric scheme on the Allt Easach, on the west side of Loch Etive in Argyll, will require the installation of a sub-sea cable to export power. The cable will cross Loch Etive, a long, fjord-like, sea loch. It will traverse the loch between Rubha Bhar on the west side of the loch (NN 070 391) and the beach to the south of the River Kinglass estuary on the east side of the loch (NN 070 374).

Electric transmission cables are known to produce both electric and magnetic fields in the marine environments. Together, these fields are known as electromagnetic fields (EMFs). A wide variety of marine organisms are known to have the ability to detect EMFs. As a result, Scottish Natural Heritage (SNH) requested that the potential impact of EMFs on migratory (anadromous and catadromous) fish species should be included in the Environmental Impact Assessment Report (EIAR) for the Allt Easach hydropower scheme.

2   Aims and objectives

The aim of this report is to review current understanding of the interactions between EMFs and the migratory fish species likely to be present in Loch Etive.

Specific objectives are to:

- Identify the migratory fish species likely to be present in Loch Etive, which need to be considered as Important Ecological Features within the context of the EIAR.

- Present a summary of the predicted electric and magnetic fields around the proposed Loch Etive cable.

- Identify the potential interactions between each migratory fish species and cable-induced EMS in the context of the proposed Loch Etive cable.

- Where possible, consider the potential population effects, if any, of the proposed cable on anadromous and catadromous fish populations.

3   Migratory fish populations in Loch Etive

3.1   Species presence

The Loch Etive Integrated Coastal Zone Management (ICZM) Plan (Argyll and Bute District Council 2011) identifies ten rivers with catchment areas greater than 5 km^2 flowing into Loch Etive. The largest of these catchments are the River Awe (827 km^2), River Etive (161 km^2), River Kinglass (74 km²) and River Nant (46 km²). All of these sustain Atlantic salmon *Salmo salar* populations and the River Awe catchment in particular supports a valuable rod fishery (Argyll Fisheries Trust 2014). Smaller rivers such as the River Noe, River Liver, and River Esragan are likely primarily to be habitats for recruitment of sea trout *Salmo trutta.* Loch Etive itself traditionally supported net fisheries and some rod fishing for sea trout (Argyll Fisheries Trust 2009).

Data collated by Argyll Fisheries Trust (2009 & 2014a) demonstrate that wild salmon and sea trout numbers around Loch Etive have decreased substantially in recent decades. While it is accepted that factors operating in freshwater may have had some impact on recruitment, the Trust considers that marine survival between the smolt and adults stages is the chief factor impacting on adult abundance of salmon and sea trout populations. Any potential cable or EMF effects on these species should be considered within this context.

Of the ten rivers in the ICZM Plan, four (River Etive, River Kinglass, Allt Ghiusachan and Allt a' Bhiorain) are located inland of the proposed cable. As salmon are anadromous (i.e. spawning in

freshwater and feeding at sea as adults) all salmon smolts and returning adults from these rivers would have to pass over the proposed cable. As noted above, salmon are likely to be present only in the River Etive and River Kinglass. Sea trout are coastal in habit and fish from many rivers and streams, both within and outside of Loch Etive, might encounter the proposed cable as posts-smolts, finnock (immature fish in their first year at sea) or adults.

The European eel *Anguilla anguilla* is very widespread and despite recent declines still occurs in most UK watercourses that are accessible to it. Eels have remarkable powers of dispersal within freshwaters. Due to their ability to climb rough surfaces and, so long as they can stay moist, migrate overland (Moriarty 1978) eels may be found in waters where migratory salmonids are absent. Published distribution maps (Davies *et al.* 2004) show records of eels from most 10 km squares around Loch Etive. Waterside Ecology (2017a & b) found eels in both the Allt Easach and River Kinglass. The Loch Etive ICZM Plan lists European eel among UK BAP priority species using Loch Etive. Eels are catadromous i.e. they live in freshwaters as adults but migrate to sea to spawn.

Two migratory lamprey species, the river lamprey *Lampetra fluviatilis* and sea lamprey *Petromyzon marinus*, are present in Scottish rivers. Both species are anadromous. During a national survey of lampreys conducted on behalf of SNH, Watt & Ravenscroft (2005) recorded sea lampreys in the River Awe. No records of either sea or river lampreys were identified from other rivers flowing into Loch Etive in the data review conducted by Watt & Ravenscroft (ibid).

3.2 Conservation status

The Atlantic salmon is listed on Annexes IIa and Va of the EU Council Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora (known as the Habitats Directive). These apply only in freshwater (Davies *et al.* 2004). Atlantic salmon receive protection, particularly from over-exploitation, under the Bern Convention (Appendix 3). Salmon in Scotland receive further protection from Salmon and Freshwater Fisheries (Consolidation) (Scotland) Act 2003. This provides for a number of regulatory areas, including legal methods of fishing and offences, close times and protection of juvenile and spawning salmon. The Atlantic salmon is listed vulnerable on the IUCN red list.

Due to recent declines, eels are of increasing conservation interest and are protected by European (EC No 1100/2007) and Scottish (Freshwater Fish Conservation (Prohibition on Fishing for Eels) (Scotland) Regulations 2008) legislation. The latter makes it illegal to take eels without a license from the Scottish Government. European eels are listed as critically endangered on the IUCN Red List.

Both river lamprey and sea lamprey are listed on Annex IIa of the EU Habitats Directive. River lampreys also appear on Annex Va, which seeks to control exploitation.

Atlantic salmon, brown trout (including sea trout), European eel, river lamprey and sea lamprey are all listed as priority species on the UK and Scottish Biodiversity Action Plan lists.

4 Electromagnetic fields

4.1 Loch Etive cable specification

The proposed cable for the Loch Etive installation is a three-core 33 kV steel wire armoured cable. It would carry alternating current (AC) at a frequency of 50 Hz. Each of the three cores will have a metallic screen over the insulation (minimising the electric field around the cable) and the entire cable will be armoured in steel wire. The proposed cable has a maximum current of 50 A which equates to a loading 2.8 MW. The predicted output of the Allt Easach hydropower scheme is approximately 2 megawatts (MW) equating to an approximate current of 35 A.

4.2   Cable-induced electromagnetic fields in the aquatic environment

Reviews of sub-sea cable EMF are provided by CMACS (2003), Gill *et al*. (2005) and Normandeau Associates (2011). The following summary is based on these reviews.

An energised sub-sea cable will generate EMFs. These EMFs comprise three components – an electric field (E), a magnetic field (B) and an induced electric field (iE). Any or all of these components may interact with suitably sensitive marine species. The design and specification of cables, their capacity and load are all important in determining the nature and strength of associated EMF emissions. Most marine renewable energy infrastructure - mainly wind farms and in particular intra-array connections - uses AC three-core 33 kV cables, similar to that which would be installed at Loch Etive albeit at a higher rating. Research and modelling has therefore concentrated on this cable design.

Electric fields are generated whenever a sub-sea cable is energised. The strength of the electric field is related to the current, so that a cable carrying a higher current will generate a stronger electric field. However, in industry standard cables such as that proposed for Loch Etive the electric field is retained within the cable core so long as the conducting screens are effectively earthed.

A magnetic B field is created around a cable by the flow of current through the cable. In the case of an AC cable the B field emitted into the environment will not be static, but cyclical at 50 Hz. Due to the presence of three cores carrying current, the B fields from each core may interact causing the field outside the cable to rotate. This movement would induce an iE field in the surrounding water, which will not be eliminated by the shielding. The strength of the B field around a cable is linearly proportional to the current. Modelling at Kentish Flats (Gill *et al*. 2005) suggested that doubling the current load would double the strength of the resulting B field. An important feature of the B field is that its strength diminishes very rapidly with distance from the cable.

As noted above, movement of the B field may create an iE outside a cable. Similarly, an iE field will result from water movement or the movement of an organism through the B field and this will not be eliminated by shielding. The strength of the iE field will be proportional to the strength of the B field.

4.3   Predicted field strengths around Loch Etive Cable

Wilson (2017) provided the following comments and estimates for field strength based on published reviews (CMACS 2003; Meisner *et al* 2006) and empirical data from industry measurements.

The cable cores have a metallic screen covering the insulation to minimise the electric field around the cable. By earthing the metallic screens at one end of the cable it should be possible to eliminate any directly generated electric field on the outer surface of the cable. Electric fields may still exist outside the cable but these will be induced electric fields as a result of the magnetic field caused by current flowing in the cable. An estimate of the likely electric and magnetic fields present on the Loch Etive cable can be derived from the calculated and measured data contained within Table 8 from Meisner *et al*. (2006). The most appropriate comparison is with the AC (3 phase) cable operating at 33kV. The cable in Meisner's Table 8 has a maximum current of 50 A which equates to a loading of 2.8 MW. The maximum design loading for the Loch Etive cable is approximately 2 MW which equates to an approximate current of 35 A. As field strength is proportional to current, the electric and magnetic field strengths for the Loch Etive cable, measured directly above the cable are likely to be 35/50 = 0.7 or 70% of those figures stated in the table. These equate to:

- Electric field strength = 0 μVm^{-1}

- Magnetic field strength = 0.7 x 57 μT = 39.9 μT

- Induced electric field strength = 0.7 x 17.5 μVm^{-1} = 12.25 μVm^{-1}

The estimated field strength values given above are for EMF adjacent to the proposed cable. Based on the cable in Meisner *et al*. the predicted magnetic field strength at 2 m distance would be 14 μT reducing to 7 μT at 5 m from the cable. The iE field would be reduced proportionally.

5   Salmon and sea trout

5.1   Relevant aspects of biology and behaviour

5.1.1   Smolts and post-smolts

After spending between one and four years in freshwater juvenile salmon leave rivers to enter the sea as smolts. External triggers for downstream smolt migration are mainly water discharge and temperature (McCormick *et al*. 1998; Thorstad *et al*. 2011). Lunar phase may also be important, smolts preferring to migrate on darker nights. The timing of spring migration is thought to play an important role in determining marine survival, ensuring that smolts reach the sea when ocean conditions, including temperature and prey populations, are favourable. In Scottish rivers, the smolt migration period typically extends over a three to seven week period between April and June. Within this broad window, the majority of smolts may migrate within a relatively short one to two week period. Smolts often move downstream in groups or shoals, which may offer individuals some protection from predators. The smolt migration period, particularly when smolts enter estuaries, can be a time of high mortality (Kocik *et al*. 2009), with predation often the main mortality factor (Thorstad *et al*. 2012).

Smolt migration in sea trout is a broadly similar process to that in salmon and the pattern of spring migration with peaks determined by environmental cues is common across the two species (Aldvén *et al*. 2015). However, migration patterns of the two species during the first weeks at sea diverge.

On reaching the sea the movement of salmon smolts may be complex, some moving directly out to sea while others move in various directions. However, the overall vector of movement is always seaward and the migration is active, not passive. During the early migration down a Norwegian fjord Thorstad (2007) found that salmon smolts on average spent 5.6 days to cover the first 48 km, a rate of a little over 8 km per day. However, much faster rates of travel have been recorded elsewhere and individual variation in travel rate is generally large (Thorstad *et al*. 2011). During the marine migration available evidence suggests that salmon post-smolts usually swim close to the surface at depths of 1 to 3 m, but may make dives down to over 6 m (Davidsen *et al*. 2008; Thorstad *et al*. 2012).

In contrast to salmon, post-smolt sea trout may show no overall net movement in a seaward direction during their early weeks at sea (Thorstad *et al*. 2007). Johnstone *et al*. (1995) found that tagged post-smolts in Loch Ewe remained in the shallow littoral and sub-littoral zones within 1.5 km of the rivermouth for many days. More recently Middlemas *et al*. (2009) tagged sea trout post smolts in the Rivers Balgy and Shieldaig, both of which flow into Loch Torridon in Wester Ross. The fish tended to stay close to their natal rivers for the first 14 day after entering the sea. Around half the fish were lost to the study during this period, possibly to predators, although this is uncertain. Latterly, the trout moved more widely and towards the end of the study period (after approximately 40 days) the groups from both rivers converged into one of the loch basins. The post-smolts showed pronounced individual differences in habitat use. Post smolt sea trout generally uitilise the near-shore zone, foraging near the surface (Lyse *et al*. 1998; Flaten 2014).

5.1.2   Adults and kelts

The time spent by salmon at sea prior to returning to their natal river is variable. In most Scottish west coast rivers the bulk of fish are likely to return after a single winter at sea. These fish are termed grilse or one-sea winter salmon. Two and three-sea winter salmon may be present, but are generally less abundant than grilse. In the last ten to fifteen years telemetry has allowed the movements of salmon at sea to be studied. In general, these studies have shown that adult salmon are highly surface-oriented (Davidsen *et al*. 2013; Holm *et al*. 2006). Marine Scotland Science (MSS) have recently conducted studies into salmon swimming depth in relation to the expansion of the marine

renewable energy sector. These studies (Godfrey *et al.* 2014; Godfrey *et al.* 2015) confirmed that salmon tended to spend most of their time close to the surface. Of 117 salmon that provided reliable data, the median proportion of time spent in the top 5 m of the water column was 84% although there was considerable individual variation (8% to 99%). Although surface oriented, salmon were found to use the full range of available depths. It is important to note that the MSS studies relate largely to salmon in open sea and Pentland Firth. Based on a review of previous studies, Godfrey *et al.* (2015) suggest that adult salmon at sea may use a greater range of depths than salmon approaching their home river through fjordic environments, with the latter tending to remain in the upper 2 m of the water column. The MSS studies were carried out on maiden two and three-sea winter salmon, not grilse.

Salmon in the open sea travel quickly, at some 50 to 100 km per day relative to the ground. Migration speed slows in coastal areas, perhaps because they require time to identify their natal region and river. Indeed, salmon may not home directly to their natal river and some enter other rivers where they may remain resident for a variable period before dropping downstream to find their natal river (Stewart *et al.* 2006). On reaching the natal river salmon may wait around the estuarine reaches for many days or even weeks until conditions – usually increased discharge – are suitable for them to pass into freshwater (e.g. Solomon & Sambrook 2004).

Many salmon die after spawning. Those that do not will return to sea as kelts and some of these will regain condition and repeat spawn (Mills 1989). Kelts leaving rivers show variable use of water depth but, in common with other life stages, are largely surface oriented (Halttunen *et al.* 2009; Hedger *et al.* 2009). Halttunen *et al.* (ibid) found that salmon kelts moved rapidly through a fjord in Norway and stayed close to the surface, exhibiting a mean swimming depth of 2 m. Similarly, Hedger *et al.* (ibid) found that 49% of kelt locations in an embayment were within 1 m of the surface and 99% within 5 m.

Finnock (sea trout in their first summer at sea) and older adults are thought to be more coastal in habitat than are salmon. Netting studies in Argyll by Pemberton (1976) found that finnock were present in coastal embayments throughout May and June but then dispersed more widely, reappearing in catches in August. Many finnock will run into freshwaters in late summer and early autumn, where they may over-winter before returning again to sea. Studies have shown that adult sea trout may range long distances from their home rivers (Le Cren 1984; Nall 1930, Solomon 2006). While sea trout do not make the long, outward oceanic migrations associated with salmon, they do forage at distance from the coast as well as in shallow near-shore waters. In a study in northern Norway, both immature and maturing individuals were captured up to 5000 m offshore (Rikerdsen & Amundsen 2005) where their diet was dominated by small-sized herring *Clupea harengus*.

5.2   Electroreception, magnetoreception and migratory cues

There is a paucity of data on Atlantic salmon and sea trout response to EMF. Both species are known to have some ability to respond to EMFs but in many cases the response shown has been physiological or developmental rather than behavioural (Gill & Bartlett 2010). Due to the lack of data, Gill & Bartlett (ibid) suggest that discussion of Atlantic salmon response to EMF should consider data from other *Salmo* species. This would apply equally to sea trout.

Atlantic salmon possess magnetite particles in their lateral line sense organs (Moore *et al.* 1990). In some salmon species these particles have been shown to be arranged in chains and to be linked to neural connections. It is thought that this may allow them to use the earth's magnetic field to aid orientation during long distance migrations but this remains unproven. An ability to detect variances in the earth's geomagnetic field would potentially allow salmon to obtain positional (map) and directional (compass) cues from the inclination and intensity of the earth's magnetic field, since these vary regionally. Combined with other directional information, such as stellar cues, a magnetic sense would potentially assist migrating salmonids to identify particular coastal or oceanic regions. In effect, the unique magnetic signatures of an area might, in principle, be used to identify a natal region (Lohmann *et al.* 2008). Putman *et al.* (2014) found that drift of the magnetic field accounted for 23%

and 44% of variation in the migratory routes of sockeye salmon *Oncorhynchus nerki* and pink salmon *O. gorbuscha* respectively, suggesting that these cues may indeed be used by some *Salmo* spacies.

If salmonids do use magnetic cues for orientation or navigation it is likely that these cues are used at a large spatial scale (Lohmann *et al.* 2008; Putman *et al.* 2014). For salmon, this would be during the oceanic phase of outward and homeward migrations. There appear to be two phases of the return migration, the first phase involving relatively crude orientation from the feeding ground to the coast and second more precise stage once in coastal and estuarine waters leading salmon back to the natal river (Hansen *et al.* 1993). It is hypothesised (Lohmann *et al.* 2008) that if imprinting on magnetic cues during outward migration does take place, this may permit salmon to identify particular coastal regions during initial, long-distance phase of natal homing migrations. There is good evidence that the second phase of homing, once in the appropriate coastal region, is dependent largely on olfactory cues. The role of olfaction in identifying natal streams has been demonstrated for a range of pacific salmon (reviewed by Ueda 2014) and is strongly implicated in the homing of Atlantic salmon (Stabell 1984; Jonstone *et al.* 2012). Once salmon have reached sheltered fjords and sea lochs where chemical cues can extend a long way from natal streams olfaction may be the most important sense for homing and it is widely accepted that the last phase of the spawning migration is primarily governed by olfactory cues (Thorstad *et al.* 2011).

5.3   Empirical evidence of responses to EMF

Empirical data demonstrating an ability in salmonids to respond to EMFs are sparse. Nevertheless, it has been shown experimentally that sockeye salmon, which have magnetite in their nose area, can respond to DC magnetic fields (Walker *et al.* 1988; Putman *et al.* 2014). When rainbow trout *Oncorhynchus mykiss* larvae and fry were raised in a modified magnetic field their swimming orientation differed to that of fish reared in a natural geomagnetic field (Formicki *et al.* 2004). This suggests potential for the use of magnetic sensing for orientation or navigation. In experimental conditions, adult rainbow trout have also been shown to show a conditioned physiological response to shift in the intensity or inclination of a magnetic field (Hellinger & Hoffman 2009). As noted above, Putman *et al.* (2014) found that drift of the magnetic field was strongly implicated in explaining variation in migratory routes of sockeye and pink salmon. Physiological responses have been shown both for Atlantic salmon and brown trout (reviewed by Normandeau Associates 2011). Normandeau Associates (ibid) suggest sensory thresholds of 0.5 to 4.0 µT and 0.2 to 4.2 µT for Atlantic salmon and brown trout respectively. With the exception of the Formicki study, the data reviewed by Normandeau Associates related to physiological or developmental evidence of sensitivity. Taken together, published studies suggest that a number of salmonid species are likely to be able to detect and (potentially) respond to electromagnetic fields.

The ability of any organism to sense a stimulus does not necessarily mean it will respond behaviourally to that stimulus in any or all situations. The literature review by Gill and Bartlett (2010) concludes that the best available evidence is that Atlantic salmon normally experience background iE fields from the interaction of peak tidal movements with the geomagnetic field in the region of 8 to 25 μVm^{-1}. This is in the predicted range of the proposed Loch Etive cable. The geomagnetic field typically has a maximum field strength of around 50 µT, some 20% more than the maximum predicted around the Loch Etive cable. These data suggest that while salmon may be able to detect the EMFs around the cable (and this itself is uncertain) the maximum intensity of the iE and B fields would be in the same order of magnitude typically experienced in tidal habitats. Grant (2013) cites a study (Swedpower 2003) where transmitters generating twice the earth's magnetic field were attached to the heads of salmon and trout with no discernible effect on movement or behaviour.

If altered magnetic fields are detectable by Atlantic salmon they may be perceived as attractive, adverse, confusing or neutral stimuli. The response invoked, if any, might range from attraction to alarm or avoidance. Atlantic salmon response to EMF was recently tested empirically by MSS

(Armstrong *et al.* 2016). Experiments were conducted in an annular tank that provided a circular channel between concentric walls. The channel was divided into two halves each penetrated by openings through pairs of Helmoltz coils. Fish could pass from one side of the arena to the other by swimming through a coil pair. Two sizes of salmon were tested, large salmon of 62 to 85 cm and post-smolts of 24 to 41 cm. Large salmon were tested at a field intensity of 95 µT. Post-smolts were tested at 1.3, 11.4 and 95 µT. The numbers of fish passes through the coils and speed of approach and departure were measured when coils were activated and non-activated. The experiments found no evidence that willingness to pass through the coils, or speed of passage, were dependent on coil activation. No unusual behaviours or evidence of alarm or other response were observed during coil activation. The authors concluded that the main finding was that there was no identifiable behavioural response of Atlantic salmon to B fields up to an intensity of 95 µT. It should be noted that the salmon would also have experienced an iE field associated with the B field as they passed through each coil pair. The field strengths tested by MSS were of a similar magnitude to those predicted for the Etive cable.

6   European eels

6.1   *Relevant aspects of biology and behaviour*

It is generally thought that European eels are panmictic i.e. that they represent a single breeding population, although this has been challenged by some genetic studies suggesting there is population structuring related to geographic distance (Wirth & Bernachez 2001). However, there is no evidence that eels home accurately to a natal river and the population has been described as a genetic mosaic (Ragauskas *et al.* 2017) structured at a relatively large spatial scale.

Eels may live in freshwater for many years before migrating to sea. The outward migrating 'silver' eels move seaward in the autumn. Eels move downstream at night and generally during periods of elevated flow when large numbers may emigrate in a single flood event (Lowe 1955). The tendency of silver eels to migrate during floods has long been described by commercial fishermen and presumably is energetically advantageous, allowing the eels to be transported rapidly by strong currents. During the seaward migration and while still in streams eels switch from living on the riverbed to swimming in the water's upper layers (Tesch 2003).

On leaving the rivers their destination is the Sargasso Sea, in the north Atlantic, where all European eels spawn. On first leaving the river adult eel swimming depth during outward migration in coastal waters has been shown typically to be less than 0.5 m (Tesch 2003; Westerberg *et al.* 2007). However, once in the open ocean eels tagged in the west of Ireland were found to travel mainly at depths of over 100 m during the night, diving down to colder water at depths of 500 m during the day. Westerberg *et al.* (2014) found a similar pattern in eels migrating west from the Norwegian coast, with mean swimming depths of 283 m during the daytime and 123 m at night. On reaching the Sargasso sea, eels spawn and die.

Eel larvae journey back to Europe, probably by passive transport in the Gulf Stream and other currents (McCleave *et al.* 1998; Kettle & Haines 2006; Bonhommeau *et al.* 2009. The journey can be over 5000 km in length and its duration is uncertain, but may be up to two years (Kettle & Haines 2006; Bonhommeau *et al.* 2009). During the migration the larval eels gradually metamorphose into glass eels. Most glass eels arrive on the Scottish coast in late winter or spring (Maitland 2007). Tesch (2003) presents data suggesting that on reaching coastal waters glass eels make use of tidal currents for transport. Surface and deeper sampling at night with plankton nets in the Texel Current (Netherlands) showed that during the flood tide glass eels could be caught throughout the water column, but that on an ebb tide hardly any were present (Creutzberg 1961). During the day it was similarly the case that few glass eels were caught on ebb tides, while on daytime flood tides their distribution in the water column was restricted to the deeper layers. Similar data are presented by Gascuel (1986) from an estuarine environment in France. The data suggest that glass eels continue

to use tidal transport during their transition into a freshwater environment, preferentially moving at night.

6.2 Electroreception, magnetoreception and migratory cues

In the initial, freshwater phase of downstream migration eels appear to use the direction of stream flow as the orienting stimulus (Bruijs & Durif 2009), a phenomenon known as rheotaxis. Temperature, discharge and light intensity are all implicated in stimulating downstream migration (Tesch 2003). There is strong evidence that eels make route selection choices during this phase of migration based on those localities with highest discharge (Breteler *et al.* 2007; Jansen *et al.* 2007), effectively 'going with the flow'.

The SNH funded review by Gill & Bartlett (2011) presents data suggesting that European eels may be sensitive both to B fields and induced iE fields. Due to its long migrations the eel was among the first fish to be tested for magnetic orientation ability, the existence of which has been well documented since early experiments by Tesch (1974) demonstrating that silver (mature) eels would alter their orientation in response to magnetic fields in the same order of magnitude as the earth's geomagnetic field. Since then, it has become widely accepted that eels can respond to magnetic cues and recent experiments by Durif *et al.* (2013) suggest a) that eels have a magnetic compass and b) that they can use this to re-orient after their direction has been displaced. Such ability would clearly have biological advantages during in-river as well as the long outward migration. The latter must be accomplished partly or wholly by active, directional swimming.

In addition to the 'compass ability' described by Durif *et al.* (ibid) eels may also have access to a 'magnetic map', allowing them to detect geographic position as well as orientation. Naissbett-Jones *et al.* (2017) present evidence that by altering their swimming direction in response to the varying magnetic fields in different regions of the Atlantic, juvenile eels leaving the Sargasso increase their chances of finding the Gulf Stream and successfully returning towards Europe. Similarly adaptive direction preferences were shown by eels exposed to magnetic intensity and inclinations mimicking other parts of the migratory route. If juvenile eels do indeed possess such a magnetic map, it would equally be of use to outward migrating adult eels; but this has not yet been tested.

It is probable that the ability to detect and orient to magnetic fields is of most use to eels during the long distance part of their migration. However, the work of Durif, indicating that eels can register a direction to which they can subsequently return, may also be useful for in-river movements.

As noted above, once in the coastal environment eels respond to tidal cues to transport them landwards. Once near the coast, olfaction seems to play a part in locating river and streams. Eels have a particularly well developed olfactory sense and it has also been postulated that this may also assist their long distance migrations. However, experiments in which eels with blocked nasal cavities were transported from one coastal area to another indicated that their movements did not differ from control eels. Tesch (2003) concluded that olfaction is unlikely to be of use at sea for the location of distant goals. However, as in salmon it is likely to be used to orient towards freshwater once in the coastal environment (Tosi *et al.* 1990). Tosi *et al.* also found that naturally odorous waters were more attractive to the glass eels than odourless waters. Thus in the last stages of migration olfaction, as in salmon, may be very important to young eels. Unlike salmon however, eels are not intent on locating any particular river.

6.3 Empirical evidence of responses to EMF

There is now a substantial body of evidence that eels respond behaviourally to EMF. Evidence for response to B fields comes mainly from experimental arenas demonstrating that eels are able to sense fields equating in intensity to the earth's geomagnetic field. For instance, the recent work of Durif *et al.* (2013) demonstrating a magnetic compass sense used field strength of 50.3 to 51 µT with

an inclination of 73°, equating to ambient strength and inclination for their location. The work of Naissbett-Jones *et al.* (2017) suggests that eels also have the ability to detect and respond to changes in field intensity and inclination. In their tank experiments field intensity measured along magnetic north ranged from 36.2 to 49.7 µT while inclination varied from 55° to 66°; each combination of intensity and inclination simulating the geomagnetic properties of different areas in the Atlantic ocean. The variation in eel response (swimming direction) suggests the capability to detect relatively small shifts in magnetic field intensity and inclination.

If as seems probable detection of geomagnetic fields is of value to migrating eels, it is conceivable that anthropogenic EMF may result in behavioural responses. There is some evidence for this. Westerberg and Lagenfelt (2008) reported that adult eel swimming speed was reduced when crossing a 130 kV AC power cable traversing a straight in the Baltic Sea. The current in the cable at the time of the experiment varied from 140 to 300 A. The study, based on 60 tagged eels, measured time taken to traverse 4 km wide intervals, with the cable traversing the middle interval. Eel swimming speed through the interval with the cable was significantly lower than either to its north or south. The predicted delay in migration of less than 1 hour was considered unlikely to affect fitness in the context of migration of several thousand km. It was not conclusively demonstrated whether the delay was due to EMF or some other feature of the area around the cable, although the study did correct for current speed.

Potential effects on eel migration resulting from the presence of sub-sea power cables inspired Orpwood *et al.* (2015) to examine silver eel response to AC magnetic fields. The trials were conducted in a similar annular tank to that described above for Armstrong *et al.* (2015) study of salmon; both trials having been conducted by MSS. Eels were exposed to a field intensity of approximately 9.6 µT, reflecting the B field strength likely to be encountered in the vicinity of coastal power cables. Magnetic fields were generated using Helmoltz coils. The experiments found that eel passage frequency and speed through activated and inactivated coils did not differ significantly. No observations of startle or other behavioural responses were noted. However, the authors noted that many of the (wild caught) captive eels were largely inactive and that the experiment had low power to detect an effect due to the small number of active 'swimmers'.

7   Sea lampreys

7.1   Relevant aspects of biology and behaviour

Sea lampreys are anadromous, spawning in large freshwater rivers and migrating to sea to feed as pre-adults and adults. Adult sea lampreys migrate into freshwater to spawn during April and May (Maitland 2003). They aggregate to spawn and extrude their eggs into 'nests' excavated in the riverbed. Like other lamprey species, they die after spawning. After hatching the young lamprey larvae, known as ammocoetes, drift downstream with the current. They settle in nursery habitat consisting of fine, soft substrate in well oxygenated, slow flowing water. The ammocoetes are blind and spend several years in this muddy nursery habitat before metamorphosing.

Metamorphosis (or transformation) from larval to adult form takes many weeks. Transformation takes place in the late summer and autumn (Youson 1980; Hardisty 2006). The timing of emigration of the transformed sea lampreys is variable, ranging from late autumn until spring and there is some evidence that there may be both geographic variation and between-river differences in timing (Youson & Potter 1979; Kelly & King 2001; Maitland 2003; Hardisty 2006). Within any given river there appears to be a degree of synchrony in emigration and it generally though that movement is stimulated by periods of high discharge. Catches of migrating lampreys are mainly made at night, suggesting that movement is nocturnal (Potter 1980; Hardisty 2006).

After they have undergone full metamorphosis sea lamprey are parasitic. The marine feeding phase is thought to last from 18 to 28 months (Farmer 1980). Once at sea relatively little is known of the

behaviour and ecology of sea lampreys. Halliday (1991) collated records of sea lampreys from trawl data. He found that individuals of less than 39 cm were caught mainly in bottom trawls over the continental shelf. Larger animals (>56 cm) were caught in midwater trawls along the shelf edge and over the continental slope. Host species were diverse, ranging from herring to basking shark *Cetorhinus maximus*. Lamprey scars were also reported on several whale species and fast swimming pelagic fish including swordfish and blue finned tuna.

The return migration from pelagic feeding areas to the coast has not been studied in sea lamprey. Unusually for anadromous fishes, once at the coast sea lampreys do not home to their natal rivers (Bergstedt & Seelye 1995; Waldman *et al*. 2008).

7.2   *Electroreception, magnetoreception and migratory cues*

Sea lampreys possess ampullary organs on their heads and bodies. Bodznick and Preston (1983) showed that these are sensitive to weak, low-frequency electric fields. The response thresholds to uniform fields were found to be 1 to 10 μV.cm^{-1}. Maximum sensitivity with sinusoidal currents was to frequencies $\leq$1 Hz .   These physiological responses were identified by recording electroreceptor afferent fibre activity, not from changes in lamprey behaviour. How sea lampreys use these ampullary organs is uncertain but most aspects of their structure and show close parallels with those of non-teleost fish, which use them for prey-detection (Tricas & Carlston 2012). Hormonal feedback from electro-sensitive organs have also been implicated in reproductive behaviour as lampreys approach spawning (Chung-Davidson *et al*. 2008).

There is no evidence that sea lampreys possess an ability to detect B fields (Gill & Bartlett 2010). As such, there is no evidence that ability to detect EMF plays any role during migration from feeding areas to coasts and estuaries. The cues used by sea lampreys during their homeward migrations are not known.

Once at the coast stream-finding behaviour of adult sea lamprey has been subject to a substantial amount of research. To locate streams, sea lampreys appear to employ a three-phase odour-mediated strategy (Vrieze *et al* 2011). This involves an initial exploration along shorelines while searching both vertically and horizontally, followed by river-water-induced turning bringing the lampreys close to the rivermouth, which they then enter using rheotaxis. The olfactory cue used during this phase of migration is a bile acid released by lamprey larvae (Bjerselius *et al* 2000; Polkinghorne *et al*. 2001). In effect returning adult sea lampreys 'sniff out' rivers populated with juvenile lampreys. Thus while not homing to natal rivers like salmon, they do preferentially choose to ascend rivers where lamprey larvae are present. This presumably ensures the presence of suitable spawning and larval habitat in the chosen watercourse. The bile acid attractants seem not to be species specific (Fine *et al*. 2004) but are used as a common pheromone among several lamprey species. This is reasonable in ecological terms, since many lamprey species share similar habitat requirements.

7.3   *Empirical evidence of responses to EMF*

As noted above, there is no evidence that lampreys respond to magnetic B fields (Gill & Bartlett 2011).

A number of researchers have shown physiological responses to electric fields (reviewed by Normandeau Associates 2011). Chung-Davidson *et al*. (2008) examined the behavioural and neuroendocrine responses of adult sea lampreys to weak electric fields. Wild-caught adult sea lampreys, captured during the spawning migration, exhibited little active behaviour during exposure to weak electric fields and spent the most time attached to the wall of the testing arena near the cathode. This may suggest attraction. Hormonal responses of males and females differed and the authors suggested that electroreception may modulate the reproductive systems in adult male sea

lampreys. They also suggested that electrical stimuli mediate different behaviours from feeding-stage and spawning-stage sea lampreys.

Literature searches have revealed no direct tests of lamprey behavioural responses to cable induced EMFs or simulations of such fields.

8   Potential impacts on migratory fish species in Loch Etive

8.1   Salmon and sea trout

The proposed cable would come ashore approximately 500 m west of the mouth of the River Kinglass and would cross the full width of the Loch Etive, lying on the seabed. Given its placement, the cable would have the potential to interact with emigrating smolts, returning adults and emigrating kelts from two substantial rivers with salmon and sea trout populations - the rivers Kinglass and Etive. It is clear from the current review of published data that Atlantic salmon are likely to be able to detect magnetic fields and to respond to them physiologically. Whether they respond to them behaviourally is much less certain. If they do, it is most probable that magnetic fields are used for orientation during the oceanic phase of migration as has been demonstrated for sockeye and pink salmon. There is no evidence that magnetic cues are used as navigational cues by sea trout, although trout larvae and fry have been shown to have some response to B fields in experimental conditions.

Salmon or sea trout smolts leaving the River Kinglass are likely to do so mainly during periods of moderately elevated discharge and mainly at night. Moore *et al.* (1995) found that salmon smolts migrated seawards on an ebb tide travelling close to the surface and within the fastest moving section of the water column. Smolts moving through the River Dee estuary show similar behaviour, primarily moving within the main river channel (The River Dee 2016). These findings suggest that salmon smolts leaving the River Kinglass will follow, or be transported by, the river current and ebb tide into Loch Etive. They would not be expected to leave the main channel to move into the shallow near-shore areas at the periphery of the estuary where the cable comes ashore. Thus during their migration at the mouth of the river some degree of horizontal spatial separation from the cable would be predicted.

After departing the river salmon smolts are likely to move quite rapidly seawards by active directional swimming. Martin *et al.* (2009) showed that exposure to saline conditions is a key stimulus for inducing active seaward-oriented swimming. In a short estuary such as that of the River Kinglass, smolts will quickly encounter more saline waters and may be expected to move relatively rapidly away from the estuary. Throughout the fresh to saltwater transition smolts are largely surface oriented and vertical separation from the proposed cable would be predicted during smolt departure from the estuarine area.

Overall, the predicted movements and positional preference of salmon smolts suggest that they are unlikely to closely approach the proposed cable as they depart the River Kinglass. Their trajectory and swimming depth seem likely to separate them from the cable by at least several metres. The magnetic field generated around the proposed cable will occur within the context of the background geomagnetic field, which has an intensity of approximately 50 µT. The predicted maximum intensity of the magnetic field due to current in the proposed cable is 39.9 µT. This is the intensity adjacent to the cable covering. At a distance of 5 m from the cable the predicted field intensity would be reduced 5 µT and it will decline rapidly thereafter. While such fields may be detectable, there is no evidence that they are likely to elicit any adverse response from smolts. Indeed, the recent tank studies by Armstrong *et al.* (2015) showed no detectable response when salmon post-smolts were exposed to similar or greater field intensities. Given the predicted spatial separation between emigrating smolts and the proposed Loch Etive cable, it seems improbable that any avoidance or other adverse response would be elicited from smolts emigrating from the River Kinglass. This is equally true of

salmon smolts emigrating from the River Etive, which would also be expected to move actively seaward in the surface layers of the loch well above the cable.

A process of imprinting is thought to take place during smolt migration, allowing salmon to develop a sequentially learned route memory that they can reverse on their return as adults (McCormick *et al*. 1998). It has also been hypothesised (Lohmann *et al*. 2008) that imprinting on magnetic cues may take place during this period, although there is no direct evidence for this in Atlantic salmon or sea trout. Were magnetic imprinting to take place, Lohmann *et al*. (ibid.) consider that it would be at a large geographic scale – regional rather than local – allowing returning fish to arrive in the correct coastal region. Transitory exposure to a minor local magnetic anomaly such as the proposed cable seems unlikely to disturb any putative regional magnetic imprinting during outward migration.

Salmon returning to the River Etive or River Kinglass will, like smolts, have to pass the cable. Like smolts, their preferred position in the water column would mainly keep them vertically separated from the cable. During this stage of their migration olfaction is likely to be the main directional cue allowing them to find their natal river. Given its position, the olfactory cues for the River Etive and (in particular) the River Kinglass around the cable route will be concentrated and very easily detectable by salmon. There is therefore no reason to suppose that cable-induced EMFs would cause significant disorientation or confusion as to the location of the natal watercourse at this stage of migration.

Exposure times to cable-induced EMF for adult salmon returning to the River Kinglass might be longer than for emigrating smolts, as they may need to await suitable conditions to run upstream. During periods of low water, such fish might be in the vicinity of the cable for several days or weeks. It is clear that the EMF associated with the cable will be highly localised, but whether they might affect the spatial distribution of salmon in the estuary is unknown. The work of Armstrong *et al*. (2015) suggests that any behavioural response e.g. avoidance is improbable.

Sea trout smolts, unlike salmon, are not expected to swim directly out to sea on leaving the river and tracking studies suggest they may spend several days close to the rivermouth before dispersing. As for returning adult salmon, this behaviour may increase the likelihood and duration of potential interactions with magnetic or induced electric fields from the cable. It is not possible, based on available data or published studies, to predict whether such interactions are likely to elicit any behavioural response from sea trout. As EMF intensity decreases very rapidly with distance from the cable any shifts in distribution would be minor and perhaps unlikely to be of biological significance.

Sea trout post-smolts or adults foraging around the near-shore habitats of Loch Etive might encounter the cable and associated EMF at any time during their marine residency. It is not possible to predict whether such encounters might elicit any response. The tank studies of salmon perhaps suggest that any avoidance response is unlikely, but the confidence in this prediction is inevitably low due to the lack of empirical data on trout. Were sea trout to avoid the area immediately around the cable, some minor loss of foraging habitat might result.

8.2   European eels

Silver eels departing rivers in upper Loch Etive on their seaward migrations would have to pass the proposed cable as would returning glass eels and elvers. The occurrence of a magnetic sensing ability in eels is well established and data reviewed above strongly suggest that this sense is used for orientation and position-finding during migration. Furthermore, some empirical data have been collected suggesting that eels may respond to cable-induced EMFs.

During their transition from fresh to salt water silver eel behaviour changes and they switch from moving on the bottom of the river to moving in the water column. Emigration takes place at night. In order to facilitate downstream movement silver eels preferentially move on periods of high discharge and in the strongest currents. Therefore it is probable that emigrating eels will be carried some way out into Loch Etive before turning seaward. This would be predicted to result in some horizontal

separation from the shallowest parts of the proposed cable route. Such telemetry data as exist, mainly from the Baltic, suggest that on reaching the sea eels will initially swim mainly in the surface layers but move deeper during the daytime. Eels exiting the River Kinglass at night may therefore pass the cable route with several metres vertical separation. It is not possible to predict the swimming depth when nearing the cable of eels exiting other rivers in Loch Etive. This is likely to be variable and dependent on the state of tide (they will be expected to use passive tidal transport to assist seaward movement) and the time of day or night (they are likely to stay deeper in the daytime). As such, it is not possible to predict the likely proximity to the cable or the intensity of EMF that might be encountered by emigrating silver eels from River Etive or other watercourses in the upper loch.

Empirical data on eel passage over a high voltage cable are provided by Westerberg and Lagenfelt (2008). These data showed that tracked eels (n=60) successfully passed over an AC cable carrying a current of between 140 and 300 A in the Baltic Sea. Only two eels turned back and the authors concluded that this was a chance occurrence. Swimming speed over the cable was slower than in sectors north or south of it. The average delay was 40 minutes and this was considered biologically insignificant. The proposed Etive cable would carry a current of approximately 35 A. The EMF associated with this will be greatly less than that of the Baltic cable. Overall therefore, it seems likely that eels may detect and respond to the proposed Loch Etive cable, perhaps slowing as they pass it, but that they are unlikely to be deterred from seaward migration as a result of its presence. This is consistent with the recent tank studies by MSS demonstrating that eels would pass through energised Helmholtz coils (Orpood *et al.* 2015).

In proximity to rivers, migrating glass eels use olfactory cues to detect and move towards fresh water. These cues will be unaffected by the cable. Glass eels are expected to use tidal transport to help them move inland in Loch Etive, moving up into the water column on night-time flood tides. Tidal transport will also be used to assist entry to the River Kinglass and other streams around Loch Etive. No empirical data on glass eel response to sub-sea cable EMF have been identified. However, by moving into the water column to obtain tidal assistance the young eels will increase their vertical distance from the cable, reducing the EMF field intensity likely to be experienced as they do so. Given the migratory cues and transport migratory exhibited by glass eels, it might be suggested that low intensity EMF would be unlikely to impact on their successful migration. However, given the lack of empirical data, this is unproven.

8.3   Lampreys

An almost total lack of published information on lamprey behavioural responses to EMF makes it difficult to predict cable effects were recently transformed emigrant or returning adult sea lamprey to encounter the proposed cable. However, the likelihood of such encounters is probably low, as the closest known sea lamprey river is the Awe, which enters Loch Etive approximately 9 km to the seaward side of the cabling route. River lampreys have never been recorded around Loch Etive. Spot checks for lamprey larvae around Glenkinglass Lodge found none (Waterside Ecology 2017b). While the presence of lampreys and associated larval pheromone attraction cues in the lower River Kinglass cannot be entirely discounted, it is apparent from observation made during other surveys (Argyll Fisheries Trust 2014; Waterside Ecology 2017b) that the mobile, coarse sediments that characterise the river provide little suitable larval habitat.

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