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Electromagnetic fields and diadromous fish spawning migration: An urgent call for knowledge

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ABSTRACT

Diadromous fish species are characterised by spawning migrations between freshwater and marine environments, where they traverse through estuaries and close to coasts. This species group has declined substantially over the past decades due to anthropogenic effects such as habitat fragmentation and loss and overfishing. A rising potential threat to their population recovery is the increasing installation of subsea power cables (SPCs) which generate electromagnetic fields (EMF) as they transport energy from offshore wind farms to land. At least a part of the diadromous species are able to detect EMF, yet it is currently unknown whether EMF by SPCs affect their spawning migrations. With the increasing demand to offshore wind energy production and consequently the establishment of SPCs, the interaction between these SPCs and migrating diadromous fish species will rise in the near future. Consequently, there is an urgent need for knowledge on the impact of SPC-induced EMF on diadromous fish spawning migrations. Such knowledge can be obtained through a combination of lab and *in situ* experiments. International policy guidelines on the practicalities of deploying SPCs need to be established, taking into account the most up-to-date knowledge on the effect of SPC-induced EMF on diadromous fish spawning migrations.

1. Introduction

With a growing human population that is now over 8 billion people and our increasing dependence on technology, the need for energy is higher than ever. Renewable energy is essential for a sustainable use of our planet Earth and its ecosystems, as fossil fuel extraction, accompanied by the produced emission gases during combustion, have shown to negatively affect our climate (Crowley, 2000). One of the possible renewable energy sources is offshore wind production. There is a global increase in offshore wind demand, with Europe expecting to install a capacity of at least 193 GW by 2040 (ECA, 2023). To transport this offshore generated energy to land, the use of subsea power cables (SPCs) is required. When electricity is transported via SPCs, either via direct current (DC) cables or alternating current (AC) cables, electromagnetic fields (EMF) are generated. Current levels are expected to be in the range of <200 μT DC and 0–50 μT RMS AC, depending on burial depth and cable characteristics (Cresci et al., 2023; Hermans et al., 2024; Hutchison et al., 2020, 2024).

EMF consist of an electric field and a magnetic field. While the electric field is usually not emitted into the marine environment due to a shielding layer of the cables, the magnetic field is (Henkel et al., 2014). Where there is movement through a conductive medium (such as sea water), or the magnetic field rotates because of the alternating frequency of the transported current, an electric field is induced (Henkel et al., 2014). The intensity and extent of the total EMF at a certain location thus depends on the used power system (AC for cable transects <50 km or DC for cable transects >50 km (Öhman et al., 2007)) and the power that is transported through the cable. Other factors include cable characteristics, design and burial depths, environmental factors such as conductivity and water currents, and the Earth's magnetic field strength (roughly between 30 and 70 μT) (Nyqvist et al., 2020).

Research on the potential effects of EMF on magneto- and/or electrosensitive species has focused on various aspects, such as orientation (i.e. an animal's ability to identify where it is in relation to the

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environment) and navigation (i.e. the animal's ability for directed movement), behaviour, physiology, and (embryonic) development (Copping et al., 2021; Elvidge et al., 2022; Fey et al., 2019; Formicki et al., 2019; Klimley et al., 2021; Naisbett-Jones and Lohmann, 2022). The ability to sense EMF can stem from three different mechanisms: 1) induction-based magnetoreception, 2) magnetite-based magnetoreception, and 3) radical pair magnetoreception (Mouritsen, 2018; Nyqvist et al., 2020). Firstly, induction-based magnetoreception implies the movement of a (conductive) animal through the geomagnetic field. This induces currents in the electrosensory system, which can subsequently be used as a directional cue for navigation (Molteno and Kennedy, 2009), a navigation method presumably used by dolphins (Hüttner et al., 2023). Secondly, magnetite-based magnetoreception has been suggested for various animals, such as bats and birds (Cadiou and McNaughton, 2010; Holland et al., 2008). Chains of ferromagnetic particles like magnetite (Fe3O4) inside an organism align themselves when in a magnetic field (Kirschvink et al., 2001). Thirdly, the radical pair magnetoreception principle is based on the finding that magneto-sensory molecules interact with magnetic fields (W. Wiltschko and Wiltschko, 2005). The molecules are formed by photoexcitation of specific cryptochrome proteins in the retina (Hore and Mouritsen, 2016). This mechanism is believed to be active in magnetosensitive birds and some invertebrates (Lau et al., 2012; Mouritsen, 2018; Wiltschko and Wiltschko, 2019).

Sensitivity to electric and/or magnetic fields in aquatic animals has received attention as well, for example in the case of elasmobranchs (Molteno and Kennedy, 2009). However, one animal group for which the effect of SPC-induced EMF is largely unknown, are diadromous fish. Diadromous fish need to migrate between freshwater and the sea to complete their life cycle and many species are known to perform extensive migrations (>1000 km) such as eels and salmon (Righton et al., 2016; Rikardsen et al., 2021). All 24 diadromous species native to the northern Atlantic Ocean have declined in abundance by at least 90% since the end of the 19th century due to anthropogenic impacts such as climate change, overexploitation, habitat fragmentation and deterioration, introduction of non-native species and pollution (Limburg and Waldman, 2009). Diadromous fish comprise over 250 species (Myers, 1949) and provide important ecosystem services as a source of protein and the exchange fluxes of nutrients they generate between marine and freshwater environments (Drouineau et al., 2018; Limburg and Waldman, 2009; Wilcove & Wikelski, M., 2008). For instance, at the end of the 20th century, 75% of the inland landings in France were attributed to diadromous species (Boisneau and Mennesson-Boisneau, 2008). Yet, fisheries yields have been reduced or disappeared due to strong population declines.

While the impact of anthropogenic EMF on diadromous fish is still not clarified, there is evidence that some groups of fishes are receptive to EMF as several species showed behavioural reactions to magnetic stimuli in experiments (Gill et al., 2012; Naisbett-Jones and Lohmann, 2022). For instance, sockeye salmon (*Oncorhynchus nerka*) rely on geomagnetic imprinting to home into their natal river from their foraging areas at sea (Putman et al., 2013). In a laboratory setting, both Atlantic salmon (*Salmo salar*) and American eel (*Anguilla rostrata*) responded to electric and magnetic fields, similar to levels occurring in nature (Rommel and McCleave, 1973).

Many SPCs coming from offshore energy production reach land near estuaries and river inlets. These areas are intensively used by diadromous species for migration between the marine and freshwater environment. The resulting overlap between SPC locations and migratory routes could increase the exposure rate of diadromous fishes to SPC-related EMF. Since these cables can interact with the natural EMF, such as the geomagnetic field, they may affect diadromous species' orientation and navigation during their spawning migrations by attraction or avoidance behaviours. That could cause delays which disrupt ecological cues and lead to mismatches in migration patterns.

This article reviews the knowledge on the capacity of diadromous species to detect EMF and whether they use it for navigation between spawning and foraging areas. We review if EMF by SPCs may influence (migratory) behaviour and suggest research steps to provide reliable results for effective management measures. To do so, we focus on the diadromous species of five families of the Actinopterygii (i.e., Acipenseridae, Alosidae, Anguillidae, Gasterosteidae and Salmonidae) and one order of the Hyperoartia (i.e., Petromyzontiformes) that occur in Europe, where renewable offshore energy development, and thus the potential impact of anthropogenic EMF, is growing.

2. Capacity to detect and use electromagnetic fields in diadromous species

Research on the ability to perceive magnetic and electric fields, as well as the sensitivity level and potential effects of anthropogenic EMF varies greatly per species group. Historically this has been governed by the importance of a species in fisheries or (nature) policy. Below we provide an overview of diadromous species groups and the status of knowledge.

2.1. Acipenseridae

The family of the sturgeons (Acipenseridae) consists of four genera and 25 species which occur in North America and Eurasia (Litvak, 2010). They are valued around the world for their precious roe, but they are at risk of extinction, making them the most threatened group of animals on the IUCN Red List of Threatened Species. Of all 25 species of the Acipenseridae family, one is extinct in the wild, 17 are listed as critically endangered (and decreasing), three are endangered and four are vulnerable (IUCN, 2024). All sturgeon species spawn in freshwater, with 15 exhibiting anadromy (i.e. growing phase at sea but spawning in freshwater). The species that is currently most relevant to the North Sea is the European sturgeon (*Acipenser sturio*), with a last spawning population in the River Gironde in France. However, the relict population in France reproduces infrequently (last observed in 1984, 1988 and 1994; IUCN, 2024). The species is strictly protected under a number of international and European agreements (e.g. Convention on the International Trade in Endangered Species (CITES), Bern Convention, Bonn Convention, European Habitats Directive) as well as under national legislation in most countries of its historic range (IUCN, 2024). Though currently no relict populations are found, historic evidence supports the hypothesis that also the Atlantic sturgeon (*Acipenser oxyrinchus*) was thriving in Europe up until (at least) the 17th century (Desse-Berset and Williot, 2011; Elvira et al., 2015; Nikulina and Schmölcke, 2016; Thieren et al., 2016). An introduction programme for this species has been started in Poland with the species being reintroduced in the Oder and Vistula river basins since 2006 and 2007, respectively (Elvira et al., 2015). Hence, beside the European sturgeon, also the Atlantic sturgeon should be considered in the North Sea and near the European coastlines with regards to potential effects of EMF.

Although the biology and ecology of several of the sturgeon species are well studied, research on their use of the Earth's EMF for migration, and the potential impact of human induced EMF is rare. Physiologic research on the lateral line system showed that the Acipenseridae can display both magneto- and electro-reception (Gibbs and Northcutt, 2004; Tricas and Carlson, 2012). To date, only five publications address studies on the potential use and impact of human induced EMF: three on the green sturgeon (*Acipenser medirostris*) (Klimley et al., 2017; Poletto, 2014; Wyman et al., 2023), one on the Atlantic sturgeon (McIntyre, 2017) and one on the pallid sturgeon (*Scaphirhynchus albus*) (Bevelhimer et al., 2015). The overall conclusion was that if the sturgeons can avoid EMF at a distance of 1 m, there should be little effect on their natural behaviour (Bevelhimer et al., 2013; Klimley et al., 2017; McIntyre, 2017). Klimley et al. (2017) did not find evidence of a trans-California-bay DC cable impacting the in- and outbound migration of green sturgeon into the San Francisco Estuary. Moreover, they found that the bridges crossing the bay, such as the Golden Gate Bridge, had a larger effect on the Earth's magnetic field than the DC cable. Though the bridges' effect exceeded those of the cable by an order of a magnitude more, the migrating sturgeons were not affected by it and passed the bridges without big delays or substantial effects on migration behaviour. A more detailed analysis of the behaviour of the green sturgeons in the San Fransisco Bay suggested a subtle relationship between the energization of the DC cables and the non-energized state, but without significant influence on the migration behaviour in and out of the estuary (Klimley et al., 2017; Wyman et al., 2023). Also, McIntyre (2017) did not find evidence that Atlantic sturgeons in a laboratory setting were influenced by human induced EMF. The authors quantified behavioural changes through time spent in the area, number of passes through the field and swimming speeds. In conclusion, these studies suggest that although sturgeons seem to be able to sense EMF by physiological evidence in their lateral line, they probably react to it in a subtle way, rather than their spawning migrations to be affected by it. However all studies suggest that more research is required to develop a better understanding of potential impacts.

2.2. *Alosidae*

The Alosidae or shads are pelagic fish related to herrings within the order of the Clupeiformes. The family consists of four genera, of which the genus *Alosa* contains various anadromous species occurring in the northern Atlantic region, extending into the Mediterranean, Baltic, Black and Caspian Seas. Their upstream spawning migrations were once huge, leading to lucrative fisheries with substantial economic importance (Mansueti and Kolb, 1953). Despite their economic importance and abundance in terms of geographical distribution and upstream migrants, less research effort has been made to the migration behaviour of shads compared to salmonids and eels, for example.

Alosidae are highly sensitive to handling and stress, which makes it challenging to study their movement behaviour (Breine et al., 2017). This is likely the reason why no publication was found on the sensitivity of shads to EMF, neither of natural nor of anthropogenic origin. However, Dunlop et al. (2015) studied the fish species community near an SPC in Lake Ontario (Canada). Alewife (*Alosa pseudoharengus*) was the most abundant pelagic species being caught, assuming it to be not negatively affected by the SPC. Research on the larvae of a non-anadromous, but highly migratory related species, Atlantic herring (*Clupea harengus*), did not find evidence that this species has magnetic sensitivity either (Cresci et al., 2020). Yet diffuse, microscopic iron-rich particles have been found in herring, although it is uncertain whether these are used for magnetoreception (Hanson and Westerberg, 1987). Especially because the same levels of these particles were found in non-migratory teleosts. Hence, there is a need for knowledge on whether or not shads are sensitive to EMF and can be impacted by SPCs.

2.3. *Anguillidae*

Freshwater eels from the single genus *Anguilla* within the Anguillidae occur on all continents apart from Antarctica. These species undertake impressive migrations from their growing areas in coastal and freshwater habitats to their oceanic spawning locations (i.e. catadromy). The distances differ between the 19 species and subspecies, and can range from a few hundred kilometres to about 9000 km for the European eel (*Anguilla anguilla*) (Arai, 2016). Eels adopt a pelagic lifestyle during their migration, which contrasts their benthic lifestyle in the growing phase on the continent. How eels navigate has been a research topic for a long time, which continues until this day. It has been hypothesised that European eels use the Earth's geomagnetic field to navigate to the spawning grounds as they follow a specific isoline of geomagnetic intensity, imprinted during their colonisation stage (Durif et al., 2022).

Studies have shown that eels are sensitive to both electric and magnetic fields. Eels responded to electric fields perpendicular to their body, but not in parallel. Since the electric fields in the marine environment established through the geomagnetic field are perpendicular to the water current direction, eels could use geoelectric currents for orientation during their large-scale migrations (McCleave and Power, 1978; Rommel and McCleave, 1972, Rommel and McCleave, 1973; Zimmerman and McCleave, 1975). Eels can also detect magnetic fields (Naisbett-Jones et al., 2017; Tesch, 1974; Tesch et al., 1992; Zimmerman and McCleave, 1975) and it is suggested that they use a magnetic compass for orientation through the Earth's magnetic field (Cresci et al., 2017; Durif et al., 2013; Nishi et al., 2004). While the physiological adaptation to detect magnetic fields is unknown, eels have magnetic material associated with the lateral line system, potentially being biogenic magnetite (Moore and Riley, 2009). Magnetic particles associated with their bones have also been observed, but it was concluded that its composition and distribution in the eel's body was not sufficient for magnetic sensitivity (Hanson et al., 1984; Hanson and Westerberg, 1987).

Given the sensitivity of eels to EMF it can be hypothesised that these fish respond to EMF induced by SPCs. Indeed, Westerberg & Lagenfelt (2008) analysed the migration speed of tagged migrating eels in the Baltic over a 130 kV AC SPC moving through arrays of detection stations. While they observed a significantly slower speed near the vicinity of the SPC, they concluded that this delay was likely not affecting their >7000 km long migration. Another field study conducted by Hutchison et al. (2018) also found a sensitive reaction of migratory eels to a DC SPC. The study indicated that eels moved faster towards the SPC when passing its vicinity. However, they also concluded that the SPC was not substantially affecting the eels' migration progression and hence was not acting as a migration barrier. These field studies prove that SPCs can have an effect on migratory diadromous fish and therefore requests more impact-related research. However, other aspects of the SPCs may actually be attractive to eels. It is known that they hide in substrate (Steendam et al., 2020) and Dunlop et al. (2016) found high densities of American eels in the scouring protection of SPCs in Lake Ontario (Canada).

2.4. *Gasterosteidae*

The family Gasterosteidae represents the sticklebacks, a diverse family of both marine and freshwater fish spread over five genera. One particular species has an anadromous life cycle, the three-spined stickleback (*Gasterosteus aculeatus*). Research on stickleback covers disciplines such as ecotoxicology, genetics, physiology, ecology and evolution (Hendry et al., 2013). However, the three-spined stickleback is mostly subject to migration history studies trying to identify the migration behaviour in terms of anadromy versus residency (freshwater or estuarine) in different morphological forms (Arai et al., 2020). The species moreover is a popular organism to investigate genetic processes (Seymour et al., 2013). To date, no publication could be found on EMF sensitivity of sticklebacks. Even publications on the movement and migration behaviour of the anadromous morphological form are rare (Laskowski et al., 2015). This may be because this species is neither on a protected list such as the Habitat Directive nor is it threatened according to the IUCN. However, its small size, short life cycle and the fact that it can be easily bred in captivity may make it a useful model organism to perform laboratory experiments on anthropogenic EMF.

2.5. *Salmonidae*

The Salmonidae are widely distributed among the northern hemisphere and consist of 11 genera with numerous (facultative) anadromous species. The Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*) and various Pacific salmonids from the *Oncorhynchus* genus such as sockeye salmon (*Oncorhynchus nerka*) are probably the most famous for their long-distance anadromous spawning migrations. Due to their economic importance as commercial fisheries products, as trophy game fish, and because of their significant decline by human impacts (Criddle and Shimizu, 2014; Kurlansky, 2020; Shaw and Muir, 1987), a lot of research has been conducted on their migration behaviour and orientation mechanisms (e.g. Kovach et al., 2015; Thorstad et al., 2008).

Like eels, also salmonids are sensitive to electric fields perpendicular to their body (Rommel and McCleave, 1973). More attention went to the detection of magnetic fields: numerous studies illustrated that salmonids can detect magnetic fields at levels which occur naturally. Salmonids contain magnetite allowing them to detect magnetic fields (Kirschvink et al., 1985; Mann et al., 1988; Naisbett-Jones et al., 2020). Laboratory studies conducting "magnetic displacement" studies revealed that salmon can rely on a magnetic map for their oceanic migration (e.g. Minkoff et al., 2020; Putman et al., 2020; Putman et al., 2014a,b) and that even non-anadromous populations of Atlantic salmon have such a mechanism, indicating that the trait may be ancestral and therefore common among various salmonids (Scanlan et al., 2018). Sensitivity to the Earth's magnetic field has also been investigated in the ocean. Azumaya et al. (2016) attached data loggers with magnetic sensors to chum salmon (*Oncorhynchus keta*) and found that the homing migration routes correlated with the isoline of the magnetic intensity. In addition, sockeye salmon take different oceanic routes during their spawning migration to the outlet of the river where they were born, depending on the intensity and inclination of the Earth's magnetic field (Putman et al., 2013). Even more, it has been suggested that juvenile salmonids inherit the magnetic map from their parents to locate foraging grounds at sea: the smolts could be able to identify their geographic location by combining the magnetic intensity and inclination of the Earth's magnetic field (Putman et al., 2014b).

The only study to our knowledge that investigated the impact of EMF generated by SPC on salmon migration, showed mixed effects in the San Francisco Bay (USA) (Wyman et al., 2018): at some cables salmon smolts were attracted, while they seemed to avoid others. The study concluded that there was no strong effect of the SPC on smolt migration and that SPCs did not act as barriers, but that more detailed and long-term research on the effect of EMF from SPC is needed.

2.6. Petromyzontiformes

The order of the Petromyzontiformes consists of only one family, Petromyzontidae, containing almost 40 lamprey species (Maitland and Campbell, 1992). Lampreys are characterised by round boneless jaws with rows of rasping teeth, and their long eel-like cartilage bodies (Potter and Hardisty, 1971). Most Petromyzontiformes, including the sea lamprey (*Petromyzon marinus*) and river lamprey (*Lampetra fluviatilis*), are anadromous species. Adults migrate to coastal areas for a parasitic lifestyle on marine vertebrates after spending several years as larvae inhabiting (sandy) mud in freshwater regions as filter feeders.

Lampreys have electroreceptors (Ronan, 1988) and are sensitive to electric fields (Bodznick and Preston, 1983; Chung-Davidson et al., 2004). Although it is still uncertain how lampreys use their electroreceptors, it is suggested that these receptors are used for prey-detection because of close structural similarity to electroreceptors in sharks and rays (Tricas and Carlson, 2012). Another potential electrosensory function might include predator detection and avoidance (Wilkens and Hofmann, 2005) and detection of conspecifics over short distances, believed to play a role in reproduction (Chung-Davidson et al., 2008).

In the adult stage, sea lampreys seem more sensitive to electric fields than in the larval stage. When exposed to electric fields between 25 μV/cm and 1 mV/cm in a laboratory setup, adult lampreys stopped moving (twitching as well as swimming) (Chung-Davidson et al., 2008). Above and below these values, the lampreys did move, and when the electric field was switched off, movement stopped almost instantly (Chung-Davidson et al., 2008). The 25 μV/cm - 1 mV/cm range corresponds to the action potential sea lampreys emit themselves, measured on the skin (Chung-Davidson et al., 2008). This suggests the electroreceptive system could play a role in mate choice, sexual behaviour and/or retaining lampreys in the nest (Chung-Davidson et al., 2008). Adult, parasitic-stage lampreys did not show any behavioural response when exposed to these field strengths, suggesting the electroreceptive system of lampreys may serve different purposes throughout the lifecycle (Chung-Davidson et al., 2008). According to Chung-Davidson et al. (2008) there might also be a difference between males and females, because when exposed to weak electric fields, hormonal responses of males and females differed. To our knowledge, there is no species-specific research to other Petromyzontiformes, besides the sea lamprey. There is furthermore no evidence that lampreys have the ability to detect magnetic fields, and there is no *in situ* research into this species group. Hence, conducting studies to obtain knowledge on potential effects of SPC-related EMF on this species group is recommended.

3. Covering the knowledge gaps

To gain a better understanding on how fish use EMF for navigation and orientation, and whether or not their migration is affected by anthropogenic EMF, both lab and *in situ* experiments are necessary (Klimley et al., 2021). Both approaches have their pros and cons, such as the level of control for the testing variables (i.e. lab experiments) versus real-life examples with natural environmental interactions (i.e. *in situ* experiments). In Fig. 1 we provide a flow chart with the different steps to cover the knowledge gaps.

3.1. Lab experiments

In laboratory settings, sensitivity to EMF can be studied in a fully controlled environment, trying to distinguish the effects of EMF from other environmental or anthropogenic impacts like water currents, temperature, anthropogenic noise or heat emissions from cables. Electromagnets, Helmholtz coils or cables can be used to generate DC or AC EMF and expose fish to *in situ* relevant EMF strengths. Laboratory experiments can target effects of EMF exposure that are difficult or costly to demonstrate *in situ*, i.e. physiological effects occurring during development or (subtle) behavioural effects such as reduced swimming speed or small scale movement. Additionally, lab experiments allow for controlling EMF exposure levels and consequently the development of a dose-response relationship, while *in situ* the EMF can fluctuate substantially. Further, mesocosm experiments form a bridge between laboratory experiments and field experiments as they allow for controlled parameters in an environmental setting (i.e. environmental interactions) (Gill et al., 2009; Hutchison et al., 2020). Mesocosm experiments ensure prolonged and repeated exposure to anthropogenic EMF which is challenging to ensure in *in situ* studies. It allows for a higher degree of repeatability, allows habituation studies, and it increases the possibilities of end-points due to the possibility to (easily) retrieve the animals.

In the following sections different parameters are discussed that facilitate a good laboratory experimental set-up for research on the impact of SPC-generated EMF.

3.1.1. Exposure levels

In a traditional ecotoxicological approach, it is attempted to form a dose-response relationship between a stressor and ecologically significant endpoint (Calabrese, 2005; Ritz, 2010). While this provides insight into the possible effects of EMF, due to the rapid expansion of offshore wind farms and the associated SPCs, it is advised to use *in situ* relevant exposure levels. For example, Fey et al. (2019) exposed rainbow trout (*Oncorhynchus mykiss*) to 10 mT DC and 1 mT AC 50 Hz, and found an increased yolk-sac absorption rate. It is uncertain if this change in yolk-sac absorption would also have been found with realistic exposure levels which limits the use of this study for i.e. environmental impact assessments. Cresci et al. (2023) conducted EMF larval impact studies with Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) to DC EMF (22–156 μT) in a raceway. The experiment showed that the swimming behaviour was reduced, and due to the use of *in situ*

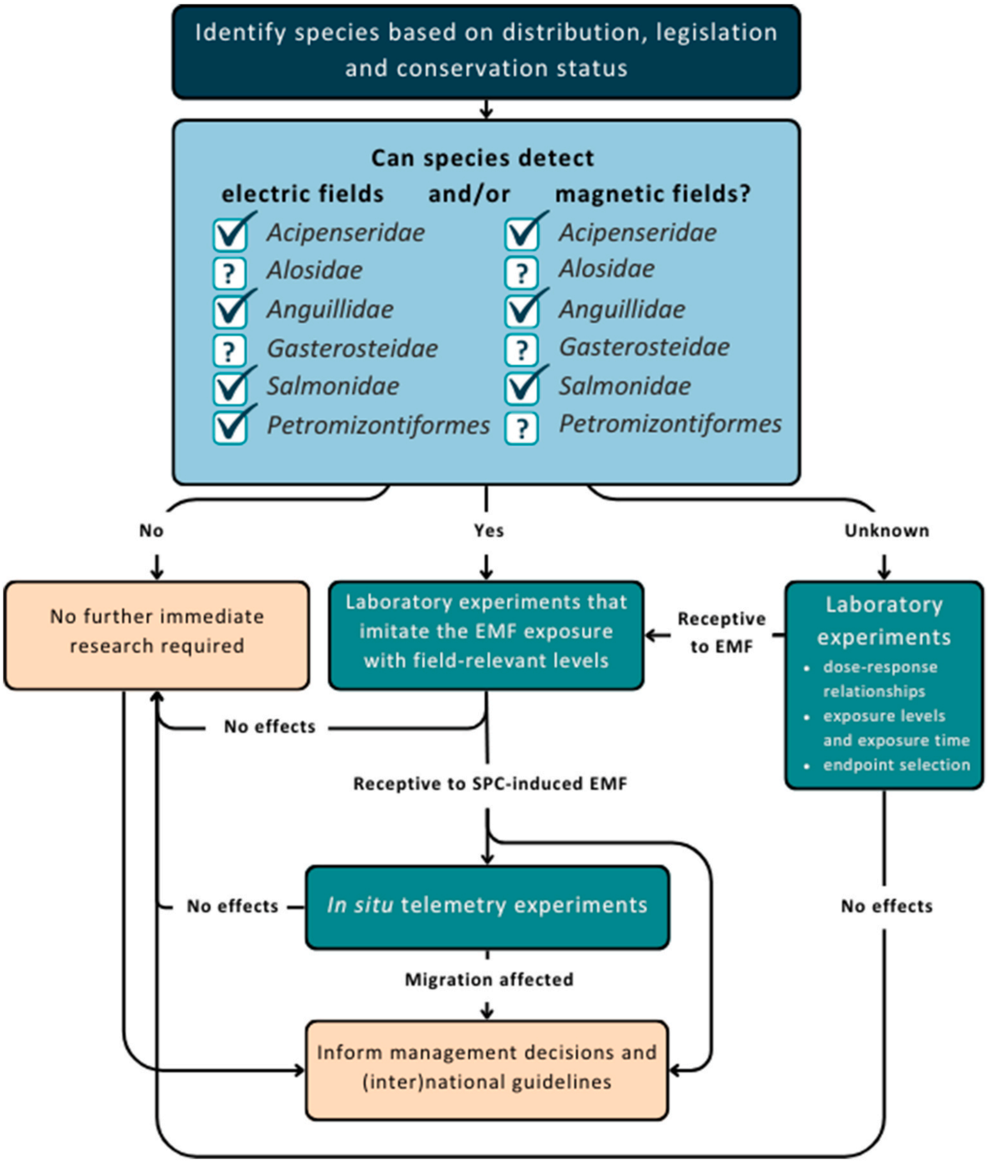

Fig. 1. A flow chart with the current state of knowledge on which diadromous species groups in Europe can detect electric and magnetic fields (blue), how to cover the remaining knowledge gaps (green) and the subsequent implementation of knowledge in management and guidelines (orange).

relevant exposure levels, this result may be representative for a real-world situation.

Not only the EMF level, but also the frequency distribution and inclination (or 'shape' of the field) should be considered (Naisbett-Jones and Lohmann, 2022). For example, Bevelhimer et al. (2013) explored the effects of AC and DC EMF on several freshwater fish using a ceramic (ferrite) bar magnet, and found altered swimming behaviours for lake sturgeon (*Acipenser fulvescens*). Although this study indicated magnetoreception of the species, it is challenging to draw conclusions to *in situ* application as EMF from SPCs are shaped differently.

EMF-generating processes are complex; there is a connection between magnetic fields and electric fields, and some magnetosensitive species are also electrosensitive. It is therefore preferred not to limit research to either one of these components of EMF, but report on both magnetic and electric field values as for example in Paoletti et al. (2023). Furthermore, there are many possible sources of electric and magnetic fields originating from the infrastructure (e.g. electrical devices, lighting, generators, steel elements) which should be minimised, for example by using Mu metal plating (reducing magnetic fields) or aluminium sheeting (reducing electric fields), reported and taken into account in the analysis.

3.1.2. *Exposure time*

When designing a behavioural laboratory study the likely exposure time and the likelihood of repeated exposure should be considered per life stage of a specific species. Specifically, the time that a fish is exposed to the EMF from SPCs will depend on their swimming characteristics (e.g. slow vs fast and benthic vs pelagic) and potential residence or waiting behaviour, which in turn are determined by the species' biology and life stage. Yet, this requires information on the movement behaviour of the studied species. Such information may not always be known but can be obtained through electronic tracking or simple observation methods such as fishing (Verhelst et al., 2023). However, if there is no *in situ* knowledge available on the potential exposure time, lab experiments should perform tests on a range of exposure times, recording effects of those times.

3.1.3. *Endpoint selection*

Given the early stage and exploratory nature of EMF research for diadromous fish, investigations should include a wide range of potential physical and behavioural endpoints. These endpoints are dependent on life stage and could include yolk-sac absorption rate, residual yolk upon hatching, biometrics (weight, size and size ratios) and development time (per phase) for larval research. For the juvenile/adult life stage, species dependent behavioural parameters that are indicative for stress such as (changes in) locomotion patterns, a startle response at EMF onset, proximity to EMF source, swimming depth, crossing behaviour, foraging behaviour, resting time and position and ventilation/respiration could be measured. Fey et al. (2019) studied many parameters in the rainbow trout which revealed no significant effect in terms of larval mortality, hatching time, larval growth, and time of larvae swim-up from the redd, but also one parameter was significant i.e. yolk-sac absorption rate. Conversely, a follow-up study by Jakubowska et al. (2021) on the same species and with the same exposure levels but looking at different parameters showed detection and attraction of EMF, with no visible signs of stress (i.e. increased oxygen consumption). These studies emphasize the importance of careful endpoint selection to cover a broad range of potential effects, whilst balancing animal welfare, available resources, analysis complexity, and the research objectives.

3.1.4. *Limitations of laboratory experiments*

It is important to respect the limitations of laboratory research. The captive environment (in terms of scale and abiotic conditions) can affect fish behaviour and with that the experimental results (Johnsson and Näslund, 2018). It is therefore important to pay attention to appropriate control treatments (Yager et al., 1969), so the experimental group, being subducted to EMF in the lab, can be validated against a control group which should be considered to show a behaviour not influenced by the EMF. An example of the possible difference between lab and *in situ* studies is a laboratory study exposing European eels to magnetic field strengths (AC) in the order of magnitude of 10 μT (Orpwood, 2015). Although with low statistical power, this did not lead to measurable changes in behaviour (Orpwood, 2015). Research on the same species by Westerberg and Lagenfelt (2008), where tagged eels were crossing a 130 kV SPC, showed reduced swimming speed around the SPC. In addition, when lab experiments show attraction or orientation towards or from a certain magnetic or electric stimulus (Formicki et al., 2021), this might not occur *in situ*. The results could be due to habituation, for example. Moreover, in the wild, many other sensory inputs are present (registered through vision, hearing or smell).

3.2. *In situ experiments*

Electronic tracking technologies are arguably the best technique to gain detailed spatio-temporal information on fish movements (Verhelst et al., 2023). Especially in the marine environment acoustic telemetry has proven to be valuable (Hussey et al., 2015): transmitters emit acoustic signals with a specific ID that can be detected by a network of submersed acoustic hydrophones, also called receivers. Indeed, the handful of published field studies that investigated the potential impact of EMF by SPCs on diadromous fish relied on this technique (Westerberg and Lagenfelt, 2008; Wyman et al., 2018). Notably, the impact of SPCs on passing fish could also be related to prevailing environmental conditions and location characteristics like hydromorphology instead of the anthropogenic EMF (Wyman et al., 2018). Hence, in future *in situ* studies the environment needs to be measured and mapped well, so it can be taken into account in the analysis.

In acoustic telemetry *in situ* studies, the set-up of the receivers is key to address the provisioned research questions. In narrow straits, one possible set-up is to have different arrays perpendicular to the SPCs. This allows to identify migration routes and compare migration speeds between compartments with and without SPCs, which enables to estimate SPC impacts as done by Westerberg and Lagenfelt (2008). Next to arrays, another approach is to deploy a grid of receivers over an SPC which enables researchers to calculate fish positions with regular time intervals and highly detailed spatial positions (within metres) (e.g. van der Knaap et al., 2021). In contrast to arrays, a grid allows for a more detailed investigation of fish behaviour near the SPC such as hesitant, attractive or repelling behaviour (Hutchison et al., 2021). However, due to safety and environmental characteristics (e.g. bottom topography, shipping and fishing) it is not always feasible to deploy receivers in the required grid.

Acoustic telemetry is ever improving, with transmitters nowadays also able to acoustically transmit environmental and biological parameters from integrated sensors in the transmitter together with the ID, such as depth and acceleration of the animal at the time of transmission. Such extra parameters can provide additional insights on how fish react to the presence of EMF generated by the SPCs. For instance, depth sensors allow to identify whether the fish moves close to the bottom and hence closer to the SPC-induced EMF. Sensors become particularly useful when applied within the aforementioned high-resolution grids as the swimming depth and acceleration data can be related at high spatio-temporal resolution to the SPCs. This could for instance illustrate if the fish adjust their depth in relation to the EMF or even calculate the fish's movement in 3D (Hutchison et al., 2021).

Additionally, integrating magnetometers (that measure magnetic field strength) in acoustic transmitters would be highly valuable in the context of EMF impact research. Sensors with a magnetometer allow for analyses on how fish use the Earth's magnetic field for orientation and navigation, and to which extent fish are subjected to anthropogenic EMF. In combination with high-resolution grids, it could even be validated if the EMF detected at certain distances from the SPCs are in accordance with other *in situ* measurements and models. While such sensors are only now being developed and tested in acoustic telemetry with currently no published results, there have been archival data storage tags (DSTs) on the market for a few years that can measure magnetic fields. Azumaya et al. (2016) applied such DSTs to study if Pacific salmon use the magnetic intensity and inclination during their migration from oceanic feeding grounds to rivers for spawning. These sensors can log and store information at a high temporal resolution (i.e. minutes to even seconds, depending on the memory size and battery life of the tag). Although the estimation of migration routes via DSTs is possible, this process requires geolocation modelling which generally has a spatial resolution too low to relate migration behaviour to SPCs at a specific site (e.g. Verhelst et al., 2022). However, combining acoustic telemetry with DSTs can relate the measured magnetic values to the fishes' position by the acoustic transmitter. To improve tagging handling and to reduce animal stress, combining both acoustic and archival telemetry in one tag can be a relevant development and should be supported (Goossens et al., 2023).

While potential impacts of anthropogenic infrastructure are often investigated when they are established, significant results can be obtained by applying the BAG (before, after and gradient) framework (Methratta, 2020): The migration behaviour of diadromous fish is analysed before and after the installation and activation of SPCs, along a gradient with increasing distance from those SPCs. When it is not feasible to study sites before SPC installation, opportunities could exist by using available data from international tracking databases (e.g. the European Tracking Network and Ocean Tracking Network databases (Abecasis et al., 2018; Iverson et al., 2019)). Over the last decade, efforts to establish international, collaborative networks have increased, allowing researchers to upload and share their telemetry data. This data sharing enables researchers to track animals on a geographical scale beyond the specific study areas (Abecasis et al., 2018). The emerging collaborative approach naturally leads to long-term datasets of various species. Having true replicates across a wide spatial/temporal scale allows to perform meta-analyses applying the BAG approach on diadromous species when SPCs are deployed in the future.

3.3. *Setting priorities*

While we argue that both lab and *in situ* experiments are necessary to cover the existing knowledge gaps, it can be helpful to set priorities on where to start first. If there is no knowledge on whether or not diadromous fish are receptive to electric and magnetic fields (i.e. Alosidae, Gasterosteidae and partly Petromyzontiformes) lab experiments need to be conducted first as they can target EMF effects very specifically in a controlled environment (Fig. 1). Next, if species are receptive to electric and magnetic fields (i.e. Acipenseridae, Anguillidae and Salmonidae) lab analyses that imitate the EMF exposure at an *in situ* SPC site can be conducted. Finally, *in situ* experiments can be applied, preferably applying the aforementioned BAG approach.

Next to experiment types, species can be prioritised as well. In a particular area with SPC deployment the diadromous species migrating through the area need to be identified. However, although not all species occur at the same place at the same time, the wide geographic distribution and/or migration distances of many diadromous species need to be considered, such as European eel and Atlantic salmon (Rikardsen et al., 2021; Verhelst et al., 2022). Consequently, it is likely that various species cross a certain SPC at a specific location at a certain time.

4. Policy measures

EU member states are legally bound to prevent impacts of energy production in marine ecosystems through Descriptor 11 of the Marine Strategy Framework Directive (MSFD). Adopted in 2009, it requires all EU member states to reach ‘Good Environmental Status’ of their waters. Good Environmental Status implies using marine resources (such as offshore energy) in a sustainable way, while maintaining clean, healthy, productive, and resilient marine ecosystems. Until now, research efforts regarding marine renewable energy in line with Descriptor 11 of the MSFD have focused on determining the impacts of underwater noise on marine life (e.g. through pile driving (Kok et al., 2021)).

In addition, the Habitats Directive has put measures in place to conserve Europe’s wild flora and fauna with the overall objective to maintain and restore specific habitats and species (including several diadromous fish species) to thrive over the long-term. To comply with Descriptor 11 of the MSFD and the Habitats Directive, impact assessments of artificial EMF from SPCs need to be carried out and adequate policy and management measures need to be developed. Overall, the lack of empirical knowledge on the exposure to anthropogenic EMF and the risks of EMF towards sensitive marine life (such as diadromous fish) hinder the large-scale development and implementation of effective policy measures (Hermans et al., 2024).

Efforts to gather information and develop policy measures on a number of anthropogenic stressors of the marine environment were undertaken by the Ocean Energy Systems (OES) initiative, an intergovernmental collaboration between countries operating under the framework of the International Energy Agency (IEA) (Melikoglu, 2018). This initiative developed a management tool for Tidal and Wave Energy (https://tethys.pnnl.gov/management-measures). The management tool categorises mitigation measures into receptors and stressors and lists Marine Renewable Energy projects that adopt these measures. For the stressor ‘EMF’ and the receptor ‘Fish’, mitigation measures specifically addressing migratory fish include 1) burying the SPCs deeper (>1 m), 2) using AC instead of DC cables, 3) installing cables that are equipped with an insulating layer (made of e.g. XLPE, also known as Cross-linked polyethylene), and 4) bundling cables together to reduce EMF vectors (Federal Energy Regulatory Commission, 2020). Additional suggestions by researchers have been made, such as not employing sea electrodes when using DC cables, which would prevent locally high EMF values and chemical pollution (Brignone et al., 2023; Taormina et al., 2018).

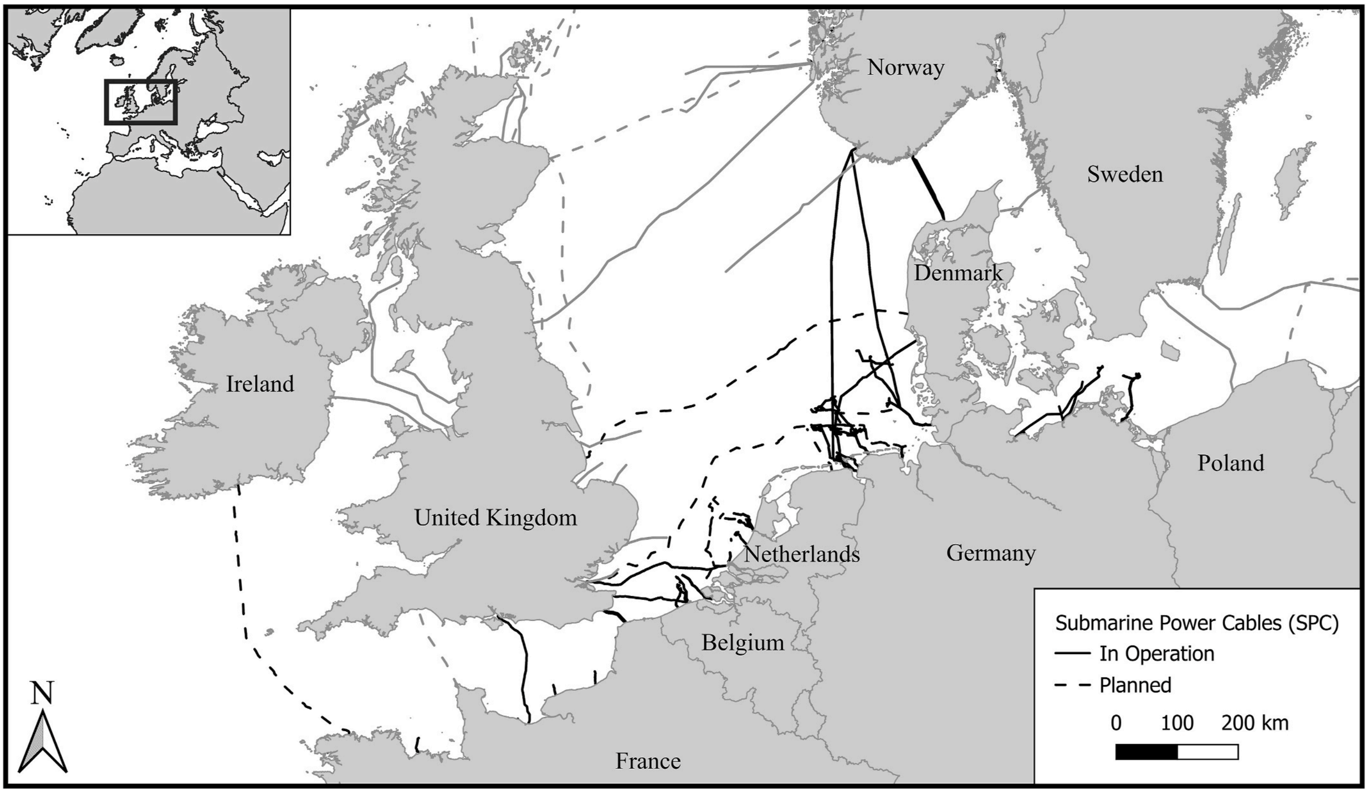

Fig. 2. Overview map of Subsea Power Cables (SPCs) in the Channel, North Sea and southern Baltic Sea. Solid lines represent operational SPCs, while dashed lines are planned SPCs. Black lines show SPCs where geospatial information could be acquired via databases such as EMODnet Human Activities. Grey lines indicate cable trajectories traced from openly accessible map services (KIS-orca, https://kis-orca.org/map/and 4COffshore, https://www.4coffshore.com/windfarms/). SPCs inside offshore wind farms are not included. The authors do neither claim completeness nor accuracy of this map.

5. Adequate impact assessments of anthropogenic EMF

The number of active SPCs, for example in large areas of the Northeast Atlantic, is already substantial and will increase in the future (Fig. 2). As the SPCs transport electricity from offshore areas to land, they traverse coasts, estuaries and river deltas, and are consequently intersecting with the migration routes of diadromous species. The interaction between this species group and the SPCs is therefore likely to increase in the future.

To allow for adequate impact assessments three aspects are crucial. First, data and metadata on SPCs need to follow the FAIR principles: findable, accessible, interoperable and reproducible (Wilkinson et al., 2016). This not only entails the scientific data, but also information on the cable positions, technical specifications, insulation and shielding, whether they transport AC or DC currents, and when they are active. Currently, SPC position data are managed in various ways, with some companies or institutions making them freely available through databases and web feature services, while others require payment. Still others are very hard to find or not accessible at all. Bringing all these data together in a centralised data repository would allow for an easier use of the data within the FAIR principles. Although probably not all data can be (openly) available, better agreements on data resolution and time delay in data access are needed. A central data portal where stakeholders/data users can access the necessary information should become available for scientific purposes. The European Marine Observation and Data Network (EMODnet), for example, is an ingestion portal based on the FAIR principles that facilitates data managers to ingest their marine datasets which can be further used for scientific and societal applications.

Second, migration tracks from animal tracking data also need to be stored on data repositories such as the European and Ocean Tracking Network data systems (Abecasis et al., 2018; Iverson et al., 2019). This allows the tracking of animals over a wider range than the study area and hence taking into account a more realistic migration range. Consequently, more accurate conclusions can be taken on, for example, migration speeds and forthcoming potential delays due to EMF. In addition, storing and sharing data can result in reusing data, preventing duplicate studies and/or reducing the number of tagged animals. This is in compliance with the three 'R' principles in European animal welfare, i.e. reduction, replacement and refinement (in this particular case the former) (Lloyd et al., 2008).

Third, digital infrastructure is crucial to combine data on SPCs and animal positions for analysis and impact assessment. This is essentially what the Digital Twin of the Ocean (DTO) is designed to do: the DTO brings together various data types to create a digital copy of the real world that allows the simulation of 'what if' scenarios, advancing ocean knowledge, informing evidence based policy and offering a range of societal applications (Tzachor et al., 2023). Within the preliminary development of the DTO, relevant policy use cases are elaborated, such as the impact of the construction of wind farms on the marine environment. Although the impact of SPC-induced EMF as a use case has not yet been considered, it could, or even should be in the near future.

6. Conclusion

There are numerous uncertainties regarding the impact of anthropogenic EMF on diadromous fish migration, partly because their navigation and orientation mechanisms are not well understood. Based on the current knowledge it is therefore not possible to determine if anthropogenic EMF have an impact on this species group, let alone to take adequate management measures. With the expansion of offshore energy production and associated SPCs, there is an urgent need to gain insight in the effects of anthropogenic EMF on diadromous species migration behaviour. These knowledge gaps need to be addressed by both lab and *in situ* experiments. The obtained knowledge will need to be integrated into management measures to contribute to effective policy, and translated into international guidelines since the SPCs can cross jurisdictional boundaries, as do the migratory diadromous fish.

CRediT authorship contribution statement

Pieterjan Verhelst: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Formal analysis, Conceptualization. **Ine Pauwels:** Writing – review & editing, Writing – original draft. **Lotte Pohl:** Writing – review & editing, Visualization. **Jan Reubens:** Writing – review & editing. **Britte Schilt:** Writing – review & editing, Writing – original draft, Visualization. **Annemiek Hermans:** Writing – review & editing, Writing – original draft, Visualization, Supervision.

Code availability

Not applicable.

Ethical approval

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Consent for publication

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Data availability

No data was used for the research described in the article.

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