



# Bellrock Offshore Wind Farm

## Wind Farm Development Area

**Appendix 8.1: Electromagnetic Fields Assessment Report  
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# Electromagnetic Fields Assessment

## Bellrock Offshore Wind farm - Wind Farm Development Area

**BELLROCK OFFSHORE WIND FARM LIMITED**

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# 1 Introduction

Bellrock Offshore Wind Farm Limited (the Applicant) requested that Arcadis Netherlands provide a study on electromagnetic fields (EMF) for the Bellrock Offshore Wind Farm's Wind Farm Development Area (Bellrock WFDA) and the effects on marine life to support the Bellrock WFDA Environmental Impact Assessment Report (Bellrock WFDA EIA Report). This study provides information to support the assessments of fish, shellfish and benthic communities for both the WFDA alone and cumulatively with other plans and projects.

The Bellrock Offshore Wind Farm will be located in the North Sea, 120 km east of Stonehaven in Aberdeenshire and will have up to the 132 wind turbine generators (WTGs). The Bellrock WFDA is the boundary within which the wind farm infrastructure will be constructed, operated and maintained, and decommissioned. The wind farm infrastructure located within WFDA comprises WTGs, floating substructures, station keeping systems and associated scour protection; inter-array cables (IACs) and associated cable protection; and subsea cable hub(s). Some infrastructure associated with the Bellrock Offshore Transmission Development Area (OfTDA), such as offshore substation (OfSSs), interconnector cables and sections of the offshore export cables, will also be located within the WFDA boundary but will be subject to a separate OfTDA EIA Report and Marine License.

The focus of this report is the IACs which will link the WTGs to each other and/or to the subsea cable hub(s) and/or the OfSS(s). The IACs will have sections which are dynamic (i.e. moving in the water column) or static (i.e. on or buried under the seabed). It is typical for WTGs to be connected together via strings or loops of IACs, depending on the selected electrical design. As the offshore export cables will be consented separately, they do not form part of this EMF-study, however, are considered in Section 5 from a cumulative EMF perspective.

## 1.1 Reading Guide

This report is structured to provide a comprehensive overview of the subject matter, progressing logically through key areas of research, analysis, and conclusions. Chapter 2 provides an overview of electric and magnetic fields, explaining foundational concepts such as differences between AC and DC, magnetic fields, and both electric and induced electric fields. Chapter 3, the Literature Study, reviews existing knowledge relevant to the topic, including a legal framework overview in the United Kingdom (UK), international guidelines, and UK-specific laws and policy. It also explores the impacts of EMF on marine life, with details on various organisms and EMF thresholds. Chapter 4 delves into electromagnetic field modeling, covering theoretical model development, assumptions, parameter values, and results like lateral profiles of magnetic fields relevant to different species. In Chapter 5, the report evaluates cumulative EMF impacts and discusses potential mitigation measures for the Bellrock Project, including monitoring strategies. The report concludes with Chapter 6, summarising findings and key insights, followed by Chapter 7, in which the references are listed. In appendix A the lateral profiles of the induced voltages are found.

## 2 Overview of Electric and Magnetic Fields

When an electric field and a magnetic field are coupled, it is referred to as an EMF (RIVM, 2020). An electric field (E Field) arises due to a difference between the voltage in a cable and its surroundings. It is the effect of attraction or repulsion of one electrical charge by another. A magnetic field (B Field) is created when current flows through cables such as IACs. An induced electric field (iE Field) is an E field created outside the cable by the B field in combination with movement through this B field. Figure 1 provides an overview of the different fields.

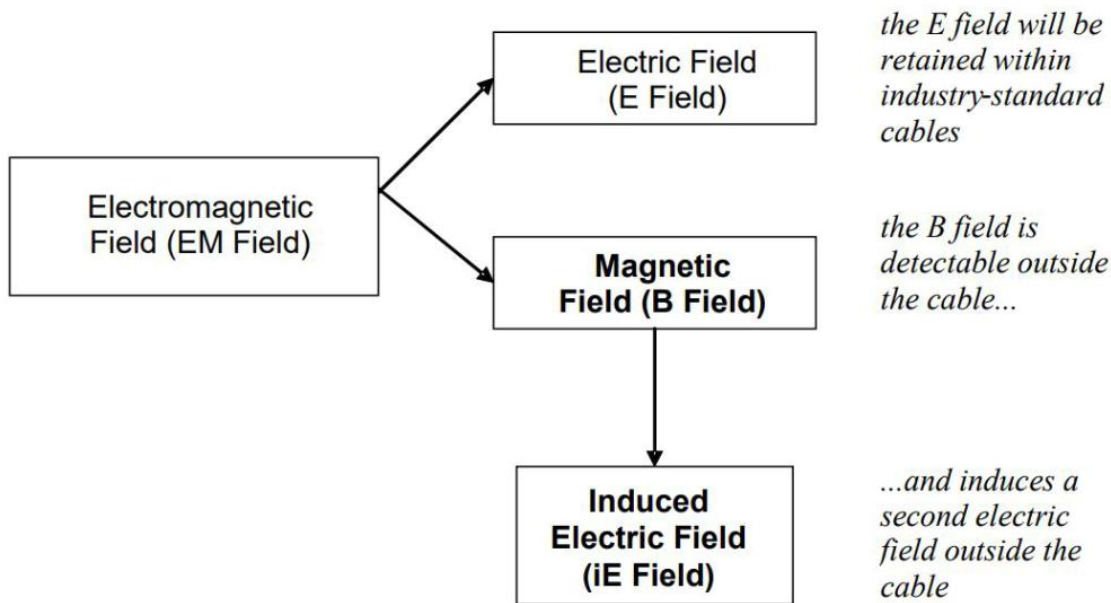


Figure 1: Overview of different types of fields, from Gill et al. (2009).

### 2.1 AC and DC Current Types

Alternating Current (AC) and Direct Current (DC) are different current types, both of which can be used in offshore wind farms. For power transmission between WTGs, AC is preferred because it is naturally generated, easily transformed for efficiency, cost-effective, and compatible with existing infrastructure. AC periodically changes its direction, flowing back and forth in a sinusoidal pattern (i.e., alternating flow), making it highly efficient for short- to medium-distance power transmission. DC flows in a single, constant direction, which makes it ideal for applications in High-Voltage Direct Current (HVDC) systems for specialised applications like underground cables, as it experiences lower energy losses compared to AC. Within the Bellrock WFDA, only AC IACs are proposed to be used for transmitting electricity between the WTGs themselves and then to the OfSSs. Due to the different nature of these currents compared to DC, the magnetic field is different as well, see Chapter 2.2.

## **2.2 Magnetic Fields**

The constant fluctuation of magnetic fields produced by AC creates time-varying magnetic fields that can induce electric currents (known as eddy currents) in nearby conductive materials. In contrast, DC magnetic fields are static and unchanging, as they are produced by a steady current flowing in one direction. AC magnetic fields are also more complex in behaviour, as their frequency and amplitude influence their interactions with materials and nearby systems.

At the time of writing, no published studies have been conducted on 1100 A 50 Hz cable systems. However, both magnetic and induced electric fields have been modelled in Chapter 4 by the specifications of the Bellrock WFDA cables.

## **2.3 Electric Fields (E Field) and Induced Electric Fields (iE Field)**

The electric fields of subsea cable systems on the seabed are not detectable in the marine environment because they are shielded by the insulation around the cable (Rijkswaterstaat, 2016). However, movement within the magnetic field of a cable (due to water currents or swimming organisms) can generate an iE field (Rijkswaterstaat, 2016). An iE Field occurs when an organism moves through a magnetic field as opposed to parallel to the field. Perpendicular movement generates a maximum iE Field (Snoek et al., 2016).

## 3 Literature Study

### 3.1 Legal Framework: Legislation in the UK

This report supports the Bellrock WFDA EIA Report and is therefore relevant to marine life only. In the UK, the regulation of EMFs is governed by a combination of international guidelines, European-derived laws (retained after Brexit), and domestic legislation. These include both EMF relevant to people and marine life. For completeness, an overview of the most relevant legal and regulatory instruments relevant to people and marine life are presented.

#### 3.1.1 International Guidelines Adopted in the UK

The UK often uses international standards as the basis for regulating exposure to EMFs. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) has established scientifically based guidelines that limit human exposure to EMFs. These recommendations are widely adopted in the UK and form the foundation for exposure limits for the general public and workers (ICNIRP, 2010). The World Health Organization's (WHO) recommendations on EMFs are also referenced to guide risk assessments and ensure public safety.

#### 3.1.2 UK Legislation and Policy

##### Health and Safety Regulations:

The Control of Electromagnetic Fields at Work Regulations 2016 (CEMFAW) implement Directive 2013/35/EU in the UK and set minimum requirements for protecting workers from risks associated with exposure to EMFs (Control of Electromagnetic Fields at Work Regulations, 2016).

- Employers are required to:
  - Assess exposure to EMFs in the workplace.
  - Take necessary steps to reduce exposure if it exceeds action levels or limit values.
  - Provide information and training to employees who may be exposed to EMFs.

##### Environmental Protection:

Environmental protection is covered by several legislative acts:

- 1) The Marine and Coastal Access Act 2009 which regulates activities that may impact the marine environment, including the installation of submarine cables for offshore wind farms (OWFs) or other purposes. Developers must assess the potential ecological impacts of EMFs as part of the marine licensing process (UK Public General Acts, 2009).
- 2) The Wildlife and Countryside Act 1981, which aims to protect biodiversity and habitats. EMFs generated by infrastructure such as submarine cables must not adversely affect protected species or habitats (UK Public General Acts, 1981).
- 3) The Environment Act 2021 focuses on environmental protection and biodiversity enhancement. It requires environmental considerations for projects that may have ecological impacts, including EMFs (UK Public General Acts, 2021).
- 4) The Conservation of Offshore Marine Habitats and Species Regulations 2017 are designed to protect marine habitats and species. While they focus on conservation and habitat protection, they do not specifically address EMFs (UK Statutory Instruments, 2017b).
- 5) The Conservation of Habitats and Species Regulations 2017 aim to protect habitats and species, particularly those within the European Union's Natura 2000 network. They require impact assessments for various activities, although they do not specifically address EMFs (UK Statutory Instruments, 2017a).
- 6) The Marine (Scotland) Act 2010 provides a framework for marine management and conservation in Scottish waters. While it focuses on sustainable management and protection of the marine environment, it does not specifically address EMFs (Acts of the Scottish Parliament, 2010).

##### Planning and Infrastructure:

Planning and infrastructure are regulated by the following legislative acts:

- 1) The Electricity Act 1989 governs the generation, transmission, and distribution of electricity, including the regulation of high-voltage transmission cables that may emit EMFs (UK Public General Acts, 1989).

- 2) The Marine Works (Environmental Impact Assessment) Regulations 2007 require an EIA for marine construction projects that could significantly affect the environment, ensuring potential impacts—including those related to submarine cables—are properly assessed during marine licensing (UK Statutory Instruments, 2007).
- 3) The Electricity Works (Environmental Impact Assessment) (Scotland) Regulations 2017 mandate EIAs for electricity-related infrastructure projects in Scotland to evaluate environmental effects before consent is granted (Scottish Statutory Instruments, 2017).

### **National Policy Statement for Renewable Energy Infrastructure (EN-3):**

National Policy Statement EN-3 for renewable energy infrastructure provides the primary basis for decisions by the Infrastructure Planning Commission (IPC) on applications it receives for nationally significant renewable energy infrastructure (Department for Energy Security & Net Zero, 2024). The key provision in Paragraph 2.8 states for fish:

- 2.8.245 EMF in the water column during operation, is in the form of electric and magnetic fields, which are reduced by use of armoured cables for inter-array and export cables.
- 2.8.246 Burial of the cable increases the physical distance between the maximum EMF intensity and sensitive species. However, what constitutes sufficient depth to reduce impact may depend on the geology of the seabed.
- 2.8.247 It is unknown whether exposure to multiple cables and larger capacity cables may have a cumulative impact on sensitive species. It is therefore important to monitor EMF emissions which may provide the evidence to inform future EIAs.
- 2.8.248 In the case of floating wind, the cables may hang freely in the water and thus potentially require alternative monitoring and mitigation.
- 2.8.249 Construction of specific elements can also be timed to reduce impacts on spawning or migration. Underwater noise mitigation can also be used to prevent injury and death of fish species.

### **Public Health:**

Public Health Act 1936 and Health Protection (EMF Public Exposure) Guidance:

- Public health authorities in the UK rely on ICNIRP guidelines to set exposure limits for the general public. Governmental agencies, such as Public Health England (now part of the UK Health Security Agency), provide guidance and monitor public EMF exposure levels (UK Public General Acts, 1936).

## **3.1.3 Regulatory Agencies and Oversight**

UK Health Security Agency (UKHSA):

- Provides guidance on the risks associated with EMFs and ensures public health standards are met. In Scotland, public health implementation is overseen by Public Health Scotland, which may use UKHSA guidance as a reference.

Office of Communications (Ofcom):

- Regulates EMFs from telecommunications equipment, including 5G networks, to ensure compliance with ICNIRP guidelines.

Marine Directorate:

- Oversees marine licensing and ensures that the impact of EMFs from submarine cables is considered and mitigated in Scottish waters.

Scottish Environment Protection Agency (SEPA):

- Regulates environmental compliance for infrastructure projects in Scotland. Ensures that infrastructure projects comply with environmental regulations, including those related to EMFs.

## **3.1.4 Conclusion**

The UK's legal framework for EMFs is comprehensive, balancing public health, environmental protection, and infrastructure development. It relies on international guidelines (i.e. ICNIRP) and includes domestic regulations such as the Control of Electromagnetic Fields at Work Regulations 2016, the Marine and Coastal Access Act 2009, and the Wildlife and Countryside Act 1981 (as amended in Scotland). Developers are required to assess and mitigate the potential effects of EMFs on workers, the public, and ecosystems as part of project planning and approval processes.

According to CEMFAW, frequencies ranging from 0 to 1 Hz have a health effect exposure limit value of 8T magnetic flux density ( $B_0$ ). Health effect exposure limit values for frequencies between 1 Hz and 3 kHz are not expressed in T but instead internal electric field strength (E). The health exposure limit value for employers relevant for this project is according to the CEMFAW 1.1  $Vm^{-1}$ . In Table 1 are the project relevant levels for public and occupational exposure.

Table 1: Reference levels for public and occupational exposure to time varying electric and magnetic fields (unperturbed rms values) with  $f$  in Hz (ICNIRP, 2010).

	Frequency range	E field strength E (kV m <sup>-1</sup> )	Magnetic field strength H (A m <sup>-1</sup> )	Magnetic flux density B (T)
<b>Public</b>	25 Hz–50 Hz	5	$1.6 \times 10^2$	$2 \times 10^{-4}$
<b>Occupational</b>	25 Hz–300 Hz	$5 \times 10^2/f$	$8 \times 10^2$	$1 \times 10^{-3}$

## 3.2 Literature Review on EMF Impacts on Marine Life

### 3.2.1 Effects on Marine Organisms

E fields, iE fields, and B fields all occur around active power cables. Different organisms experience varying effects. The following sections provide information per organismal group, combining the results of the different field-types.

Four main effects of EMFs on fish have been identified (Snoek et al., 2016):

- Effects on behavioural responses and movements (attraction or avoidance);
- Changes in navigational and migratory behaviour;
- Changes in predator-prey interactions, as well as prey distribution; and
- Effects on physiological, embryonic, and cellular development.

For other organisms, most effects of EMFs can be categorised into one of these categories. Numerous studies have investigated the impact of EMFs on different organismal groups, and a brief overview of recent findings for each group is provided below. This literature study primarily focuses on AC magnetic fields due to their distinct characteristics, which make results from DC magnetic fields non-comparable. These differences are discussed in Chapter 2.

#### 3.2.1.1 Benthic Communities

Research on the Baltic clam (*Limecola balthica*) and common ragworm (*Hediste diversicolor*) found significant genotoxic and cytotoxic activity of EMF at 50 Hz 1,000  $\mu\text{T}$  in a 12 day laboratory study (Stankevičiūtė et al., 2019). Shrimp are possibly attracted to magnetic fields around offshore wind farms, however further studies were suggested to look into the magnitude and explanation of this behaviour (Gill et al., 2014). Common periwinkles (*Littorina littorea*), common starfish (*Asterias rubens*), edible sea urchins (*Echinus esculentus*), and velvet swimming crabs (*Necora puber*) showed no physiological response in their "righting reflex" (reorienting after being turned over) when exposed to EMFs of 500  $\mu\text{T}$  (Chapman et al., 2023). Additionally, velvet swimming crabs exhibited no behavioural changes when exposed to EMFs of 70-300  $\mu\text{T}$  (Albert et al., 2023).

Young European lobsters (*Homarus gammarus*) showed no changes in shelter-seeking behaviour after 7 days of exposure to 200  $\mu\text{T}$  (Taormina et al., 2020). For American lobsters (*Homarus americanus*), spatial behaviour was measured after exposure to an EMF (maximum 14  $\mu\text{T}$  above the Earth's magnetic field of 51.3  $\mu\text{T}$ ) from a DC power cable (330 MV, 1,175 Amps) (Hutchison et al., 2018). Lobsters placed in enclosures over buried power cables exhibited statistically significant but subtle spatial behavioural changes. Compared to the control group, they stayed closer to the seabed and made more frequent 180-degree turns. However, the study concluded that the cables did not serve as a barrier for lobster movement.

Laboratory studies with the brown crab (*Cancer pagurus*) demonstrated a preference for shelters with higher magnetic field strengths, with crabs maintaining homeostasis even when exposed to a magnetic DC field of 2,800  $\mu\text{T}$  (Scott et al., 2018). Further research exposing crabs to 250, 500, and 1000  $\mu\text{T}$  revealed that higher EMF levels (500 and 1000  $\mu\text{T}$ ) disrupted normal metabolic rhythms and immune responses, while 250  $\mu\text{T}$  had no significant effect. These behavioural trials also showed attraction to high EMF-exposed shelters, and the findings suggest a threshold effect at 250  $\mu\text{T}$  (Scott et al., 2021). Freshwater crayfish are known to exhibit attraction to DC electric fields with current densities of 0.4  $\mu\text{A}/\text{cm}^2$  (Snoek et al., 2016). The American mud crab (*Rhithropanopeus harrisi*) was exposed to both DC and AC fields (2,800  $\mu\text{T}$ ) in an 8-day set-up, and showed no difference in respiration, excretion and osmoregulation. The mud crabs showed a clear attraction to AC, no significant effect on movement endpoints but were more socially interactive. There was no clear attraction to DC but a significant decrease in movement endpoints was observed, the crabs were less socially interactive in DC compared to AC (Jakubowska-Lehrmann et al., 2025).

#### 3.2.1.2 Benthic and Demersal Fish

Fish are sensitive to strong magnetic fields. For instance, Atlantic halibut (*Hippoglossus hippoglossus*) exhibited reduced growth and development after exposure to a 3,000  $\mu\text{T}$  DC field in laboratory conditions (Gill, 2015). In a long-term survival and fitness experiment with young flounders (*Plathichthys flesus*) no difference were found with the control group after seven weeks of exposure to a magnetic DC field of 3,700  $\mu\text{T}$  (Bochert & Zettler, 2004).

Little is known about the importance of magnetism for orientation and navigation in fish. Fish that navigate through the use of magnetic material in their bodies are potentially influenced by magnetic fields. One such fish is the European

eel (*Anguilla anguilla*). However, they appear to be unaffected by magnetic fields (Otremba et al., 2019). In addition, other research suggests that, despite eels swimming more slowly when crossing a DC cable, the cable did not act as a permanent barrier (Westerberg & Lagenfelt, 2008). The Atlantic sturgeon, like elasmobranchs (described below), has Lorenzini's ampullae in its body, electroreceptors that enable it to detect (induced) E fields in the water (Jørgensen, 1980). However, no information is currently available on the effects of EMFs on Atlantic sturgeon. These receptors are also present in sea lampreys (*Petromyzon marinus*) (Snoek et al., 2016). Sea lampreys showed increased active behaviours within a range of cathodal fields (– 0.1 to - 30.0  $\mu\text{V}/\text{cm}$ ). When the field intensity was increased beyond 30  $\mu\text{V}/\text{cm}$ , all movements were reduced to below baseline (Chung-Davidson et al., 2004). Recent research has also shown that juvenile lumpfish (*Cyclopterus lumpus*) do not experience barriers caused by buried submarine cables (Durif et al., 2023).

### 3.2.1.3 Pelagic Fish

An experiment with Atlantic salmon (*Salmo salar*) showed no behavioural changes. In the experiment, fish crossed a magnetic field to swim from one side of a region to the other. No changes in behaviour or the number of fish crossing were observed after the generation of a magnetic DC field of up to 95  $\mu\text{T}$  (Armstrong et al., 2015). Atlantic Salmon are sensitive to weak electric and magnetic fields (S. Rommel & J. D. McCleave, 2011), with the lowest threshold 0,06  $\mu\text{V}/\text{cm}$  at  $0.15 \times 10^{-2} \mu\text{A}/\text{cm}^2$  and  $0.9 \times 10^{-4} \text{pW}/\text{cm}^3$ .

### 3.2.1.4 Embryonic and Larval Stages

For teleosts, no effects of magnetic fields were found on embryonic or larval mortality, growth, or hatching success of eggs in Atlantic halibut, California halibut (*Paralichthys californicus*), northern pike (*Esox lucius*), or rainbow trout. For Atlantic halibut, California halibut, and rainbow trout, the electromagnetic field strengths ranged between 0.1 and 3 mT (Woodruff et al., 2012). For northern pike, a strength of 10 mT was used (Fey, Greszkiewicz, et al., 2019). The study by Fey, Jakubowska, et al. (2019) repeated the 10 mT strength for rainbow trout and also investigated AC 50 Hz 1 mT. However, the aforementioned magnetic field strengths did lead to a reduced hatching time and increased yolk sac absorption in northern pike. Increased yolk sac absorption was also observed in rainbow trout (Fey, Greszkiewicz, et al., 2019; Fey, Jakubowska, et al., 2019).

Fish larvae may also experience effects from EMFs, depending on the species. For example, research shows that larvae of the Atlantic haddock (*Melanogrammus aeglefinus*) swim more slowly in a magnetic DC field of 50–150  $\mu\text{T}$ , which may make them more vulnerable to predators (Cresci, Durif, et al., 2022). However, for sandeel (*Ammodytes marinus*) larvae, no effects were found in a similar experiment (Cresci, Perrichon, et al., 2022). Thus, the effects are likely species-specific.

For crustacea, a study assessed the effects of exposure to a magnetic DC field of 2.8 mT throughout embryonic development in European lobster and brown crab. Larvae exposed to EMF were significantly smaller and showed higher rates of deformities, although mortality rates were not increased. The findings indicate that static EMF at values relevant to those found near HVDC submarine cables can disrupt early development and larval fitness in these commercially important crustaceans (Harsanyi et al., 2022).

### 3.2.1.5 Elasmobranchs

Elasmobranchs, such as the common smoothhound (*Mustelus mustelus*), common stingray (*Dasyatis pastinaca*), thornback ray (*Raja clavata*), blue shark (*Prionace glauca*), and spurdog (*Squalus acanthias*), are known to detect E fields (Öhman et al., 2007). All elasmobranchs possess Lorenzini's ampullae, which allow them to detect E fields (Snoek et al., 2016). Several studies have confirmed that sharks and rays share similar sensitivities to E fields. For example, thornback rays exhibited cardiac and gill responses when exposed to a field of 5 Hz at an electric field strength of 0.01  $\mu\text{V}/\text{cm}$  (volts per centimetre, the strength of an electric field per meter) (Fisher & Slater, 2010).

Additionally, an experiment by Gill et al. (2009) showed that some thornback rays swam more frequently when a cable carrying 130 kV AC power was active. However, these responses were individual-specific, meaning no definitive conclusions can be made about the overall effects of E fields on these species. It is likely that sharks are sensitive to E fields, and the iE fields generated by the cable systems are likely detectable by these species.

There is also evidence that elasmobranchs can detect EMFs. For example, little skates (*Leucoraja erinacea*) released in an enclosure over a buried DC power cable exhibited significant behavioural changes compared to a control area without a power cable (Hutchison et al., 2018). The skates spent more time in zones within the enclosure where the

EMF was higher than 52.6  $\mu\text{T}$ , swam more slowly, and stayed closer to the seabed. According to the researchers, this indicated exploratory/foraging behaviour. Importantly, the cables did not act as barriers for the skates to cross.

Evidence of potential effects was also found in a recent study comparing literature on current and future magnetic fields in the North Sea and their effects on elasmobranchs. This study suggested possible effects on development and navigation but emphasized that further research is needed (Hermans et al., 2024).

Furthermore, it is known that the lesser-spotted dogfish (*Scyliorhinus canicula*) can distinguish between artificial and natural direct electrical currents (Newton et al., 2019). A recent study involving 15.0  $\mu\text{T}$  AC and 19.6  $\mu\text{T}$  DC experiments on lesser-spotted dogfish found no evidence of attraction, avoidance, startle responses, or changes in shelter use or cable crossings. However, a 25% reduction in swimming and overall activity was observed. As the sharks covered the same distances, this indicated an increased swimming speed when the animals were active (Hermans et al., 2025).

Basking sharks (*Cetorhinus maximus*) have ampullary pores over the head which proposes that both the spacing and orientation of electrosensory pores enables basking sharks to use passive electroreception to track zooplankton (Kempster & Collin, 2011). Shark and ray species have been observed biting cables (Newton et al., 2019). Though unlikely to occur in the North Sea when cables are buried deep enough, for dynamic cables coming from WTGs this might pose a problem to cable integrity.

## 4 Electromagnetic Field Modelling

This chapter investigates the magnetic fields that emanate from an armoured 3-phase single core (trefoil arrangement) high voltage submarine cable used to connect the WTGs within the Bellrock WFDA. The induced voltage that marine life may experience when moving through the magnetic field within the WFDA has been modelled for four species: the common ray, the brown crab, the Atlantic salmon and the basking shark, all with given sizes and speeds. The magnetic field and induced voltage calculations have been carried out for seven separation distances between organism and the armoured 3-phase single core (trefoil arrangement) high voltage submarine cable, ranging from 0.2 to 20 m.

### 4.1 Theory, Model and Assumptions

Assumed is a 3-phase single core (trefoil arrangement) high voltage submarine AC cable,  $f = 50$  Hz (Table 2). It produces a magnetic field  $B$  [ $\mu$ T] through which an organism moves. The magnetic field is calculated at the position of the organism, which is taken at its centre. This is done for a dense range of values of 5 to 30 m on both sides of the cable, to create a profile and to ensure to capture the maximum value (which may be off-centre with respect to the 3-phase single core (trefoil arrangement) high voltage submarine cable). The maximum value of the magnetic field is given in Table 3.

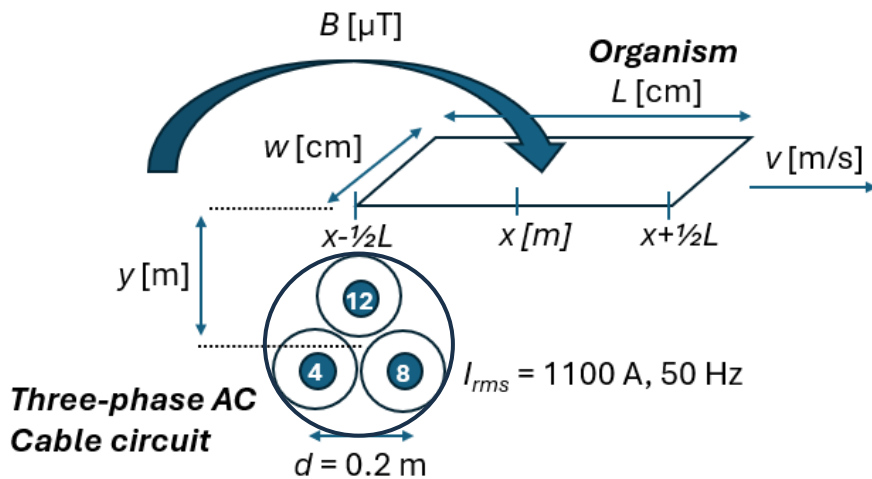


Figure 2: Assumed configuration of 3-phase trefoil armoured cable and moving organism.

In Figure 2, “4”, “8” and “12” denote the phase numbers (clock numbers) of the live, current carrying conductors of the trefoil AC three-phase cable circuit. The phases are in a bundle arranged according to an equilateral triangle of side length  $d$ . The effective phase current is derived from a given power of 120 MVA and a root mean square (rms) line voltage (phase-to-phase voltage) of 66 kV, leading to a rms phase current of 1100 A (rounded up). An increase in voltage will result in an increase in the magnetic field  $B$  [ $\mu$ T].

The organism swims in a direction perpendicular to the cable at a vertical separation of  $y$  at a speed  $v$ . It is modelled as a (possibly open) loop of length  $L$  and width  $w$ .

It is assumed that the centre of the trefoil cable arrangement is at coordinates  $(x,y) = (0,0)$ . The centres of the current carrying phase conductors are then at the following coordinates:

$$\begin{aligned}(x_{12}, y_{12}) &= (0, d/\sqrt{3}) \\(x_4, y_4) &= (-d/2, -d/(2\sqrt{3})) \\(x_8, y_8) &= (d/2, -d/(2\sqrt{3}))\end{aligned}$$

The  $x$ - and  $y$ -components of the magnetic field  $B$  at the position of the organism  $x$  are given by:

$$B_x(x, t) = \frac{\mu_0 I_0}{2\pi} \sum_{k=12,4,8} \frac{y - y_i}{(x - x_k)^2 + (y - y_k)^2} \cos\left(\omega t + \frac{k\pi}{6}\right)$$

$$B_y(x, t) = -\frac{\mu_0 I_0}{2\pi} \sum_{k=12,4,8} \frac{x - x_i}{(x - x_k)^2 + (y - y_k)^2} \cos\left(\omega t + \frac{k\pi}{6}\right)$$

Here, the infinite-line-approximation is used for the magnetic field. The iterator  $k$  visits the three separate phases and takes the values of their clock numbers (12, 4, 8). The coordinates  $(x_k, y_k)$  are specified above. The currents through the phases are of the form  $I_k = I_0 \cos(\omega t + \phi_k)$ , where it is assumed that all phases are balanced, which is to say that all phases carry the same current amplitude<sup>a</sup>  $I_0$ ; hence this can be taken outside the summation symbol.  $\phi_k = k\pi/6$  are the phase shifts in radians.  $\omega = 2\pi f$  is the angular frequency [rad/s] with  $f$  the frequency [Hz]. Finally,  $\mu_0$  is the permeability of free space<sup>b</sup>, with a value of  $1.256637061 \times 10^{-6}$  m kg / (A<sup>2</sup> s<sup>2</sup>)<sup>c</sup>, a fundamental constant of nature.

The total *rms*-magnetic field  $B_{rms}$  is calculated as:

$$B_{rms} = \sqrt{\frac{1}{2} B_x^2(x) + \frac{1}{2} B_y^2(x)}$$

Where  $B_x(x)$  and  $B_y(x)$  are the amplitudes of the time-dependent components  $(B_x(x,t), B_y(x,t))$  of the magnetic field.

The organism moves with a speed  $v$  [m/s] through the magnetic field, transversal to the cable. The induced voltage  $V_{ind}$  [mV] is then a result from two effects: 1) The intrinsic time-variance of the magnetic field with 50 Hz, and 2) the movement of the organism through regions of different magnetic field strength.

The induced voltage  $V_{ind}$  is given by Lenz' law<sup>d</sup>:

$$V_{ind} = -\frac{d\Phi}{dt}$$

Here,  $\Phi$  is the magnetic flux that permeates the organism. Note that Lenz' law involves a *total* derivative. The flux not only depends *explicitly* on the time (via the magnetic field and ultimately, via the time-varying current), but also *implicitly* via the time-dependent coordinate:  $\Phi = \Phi(x(t), t)$ , so that the total derivative becomes:

$$V_{ind}(x, t) = -\frac{\partial\Phi(x, t)}{\partial t} - \frac{\partial\Phi(x, t)}{\partial x} \frac{\partial x(t)}{\partial t}$$

Here,  $\partial x/\partial t = v$  is just the velocity of the organism, so that we have:

$$V_{ind}(x, t) = -\frac{\partial\Phi(x, t)}{\partial t} - v \frac{\partial\Phi(x, t)}{\partial x}$$

This expression reflects the two different contributions to the induced voltage.

Meanwhile, the flux  $\Phi$  is defined as:

$$\Phi(x, t) = \int_A \vec{B}(x, t) \cdot d\vec{A}$$

<sup>a</sup> Also known as *vacuum magnetic permeability*.

<sup>b</sup> This used to be *by definition exactly*  $4\pi \times 10^{-7}$  m kg / (A<sup>2</sup> s<sup>2</sup>) until in 2019 the standard SI units were redefined.

<sup>c</sup> Which can in turn be derived from Faraday's law from the Maxwell-equations.

Where  $A$  is the surface area with which the organism captures the magnetic field lines, defined by  $A = wL$ , where it must be understood that the magnetic field is constant over the width  $w$  of the organism, but varies over its length  $L$ .

The magnetic field and the surface are *vector* quantities. In case of the surface area, the vector points in the direction of the *surface normal*. The dot product states that only the component of the magnetic field in the direction of the surface normal, that is perpendicular to the plane, contributes. Given that the organism moves horizontally in the chosen coordinate system, this means that from the magnetic field vector  $\mathbf{B} = (B_x, B_y)$  only  $B_y(x, t)$  needs to be considered. The flux is thus calculated by:

$$\Phi(x, t) = w \int_{x-\frac{1}{2}L}^{x+\frac{1}{2}L} B_y(x', t) dx'$$

Care has been taken to distinguish the integration variable  $x'$  (primed) from the coordinate  $x$  of the organism (taken at its centre). The width  $w$  of the organism can be taken outside the integral.

Starting with the velocity term (the second term) of the induced voltage, and applying the fundamental theorem of calculus to the above expression for the flux, we obtain:

$$v \frac{\partial \Phi(x, t)}{\partial x} = vw \left( B_y(x + \frac{1}{2}L, t) - B_y(x - \frac{1}{2}L, t) \right)$$

After filling in the expressions for the flux and the magnetic field in the total expression for  $V_{ind}$ , then working out time-derivatives and integrals and rearranging, the following expression is produced.

Ultimately, the effective (rms) value of this expression is taken, for each  $x$ -value in a dense range. Of these, the maximum value is tabulated in Table 3.

$$\begin{aligned} V_{ind}(x, t) = & -\frac{\mu_0 I_0 w}{2\pi} \left\{ \frac{\omega}{2} \left[ \sin(\omega t) \log \left( 1 + \frac{2xL}{(x - \frac{1}{2}L)^2 + \left(y - \frac{d}{\sqrt{3}}\right)^2} \right) + \sin\left(\omega t + \frac{2}{3}\pi\right) \log \left( 1 + \frac{(2x + d)L}{(x - \frac{1}{2}L)^2 + \left(y + \frac{d}{2\sqrt{3}}\right)^2} \right) \right. \right. \\ & \left. \left. + \sin\left(\omega t + \frac{4}{3}\pi\right) \log \left( 1 + \frac{(2x - d)L}{(x - \frac{1}{2}L)^2 + \left(y + \frac{d}{2\sqrt{3}}\right)^2} \right) \right] \right. \\ & - v \left[ \left( \frac{x + \frac{1}{2}L}{(x + \frac{1}{2}L)^2 + \left(y - \frac{d}{\sqrt{3}}\right)^2} - \frac{x - \frac{1}{2}L}{(x - \frac{1}{2}L)^2 + \left(y - \frac{d}{\sqrt{3}}\right)^2} \right) \cos(\omega t) \right. \\ & + \left( \frac{(x + \frac{1}{2}d + \frac{1}{2}L)}{(x + \frac{1}{2}d + \frac{1}{2}L)^2 + \left(y + \frac{d}{2\sqrt{3}}\right)^2} - \frac{(x + \frac{1}{2}d - \frac{1}{2}L)}{(x + \frac{1}{2}d - \frac{1}{2}L)^2 + \left(y + \frac{d}{2\sqrt{3}}\right)^2} \right) \cos\left(\omega t + \frac{2}{3}\pi\right) \\ & \left. \left. + \left( \frac{(x - \frac{1}{2}d + \frac{1}{2}L)}{(x - \frac{1}{2}d + \frac{1}{2}L)^2 + \left(y + \frac{d}{2\sqrt{3}}\right)^2} - \frac{(x - \frac{1}{2}d - \frac{1}{2}L)}{(x - \frac{1}{2}d - \frac{1}{2}L)^2 + \left(y + \frac{d}{2\sqrt{3}}\right)^2} \right) \cos\left(\omega t + \frac{4}{3}\pi\right) \right] \right\} \end{aligned}$$

## Parameter Values

Table 2: Quantities and values.

Quantity	Symbol	Value
<b>RMS current</b>	$I_{rms} = I_0/\sqrt{2}$	1100 A, 50 Hz (based on $P = 120$ MVA, $V_{ph2ph} = 66$ kV)
<b>Phase configuration</b>	$D$	Trefoil, distance between phases 20 cm

## 4.2 Results

The  $B$ -field strengths range between 1,926  $\mu\text{T}$  at 0.2 m to 0.13 at 20 m from the submarine cable this is the same for all species. For induced electric field, the results range from 162 mV for the common ray as the highest electrical field 0.2 m from the centre to the submarine cable, to 8.7 mV for the brown crab (Table 3).

Figure 3 through Figure 7, provides lateral profiles of the induced voltage at  $y = 0.2$  m for each species, offering additional context for their potential exposure to E fields.

Table 3: Magnetic fields and induced voltages without mitigation.

Species	Length of species [cm]	Width of species [cm]	Speed of species [m/s]	Distance to centre cable bundle [m]	$B$ [ $\mu\text{T}$ ]	$V_{ind}$ [mV]
Common ray	285	200	1.5	0.2	1,926	163
				0.5	224	53
				1	54	24
				3	6.0	6.0
				5	2.16	2.5
				10	0.54	0.66
				20	0.13	0.17
				30	0.060	0.075
				40	0.034	0.042
				50	0.022	0.027
Brown crab	10	25	0.5	0.2	1,926	8.7
				0.5	224	1.1
				1	54	0.27
				3	6.0	0.032
				5	2.16	0.012
				10	0.54	<0.01
				20	0.13	<0.01
				30	0.060	<0.01
				40	0.034	<0.01
				50	0.022	<0.01
Atlantic salmon	100	11.5	1.5	0.2	1,926	9.3
				0.5	224	2.8
				1	54	1.0
				3	6.0	0.14
				5	2.16	0.053
				10	0.54	0.014
				20	0.13	<0.01
				30	0.060	<0.01
				40	0.034	<0.01
				50	0.022	<0.01
Basking shark	1200	150	1.5	0.2	1,926	110
				0.5	224	39
				1	54	19
				3	6.0	6.0
				5	2.16	3.6
				10	0.54	1.6
				20	0.13	0.49
				30	0.060	0.23
				40	0.034	0.13
				50	0.022	0.085

## Lateral Profiles Magnetic Field (Same for all Species)

Below are the lateral profiles for the magnetic field at the cable centre. With a lateral position of 0 meters, the organism is swimming directly above the cable, the lateral position represents the distance at which the animal swims perpendicular to the cable at the same height ( $y$ ). Figure 3 to Figure 7 illustrate these profiles.

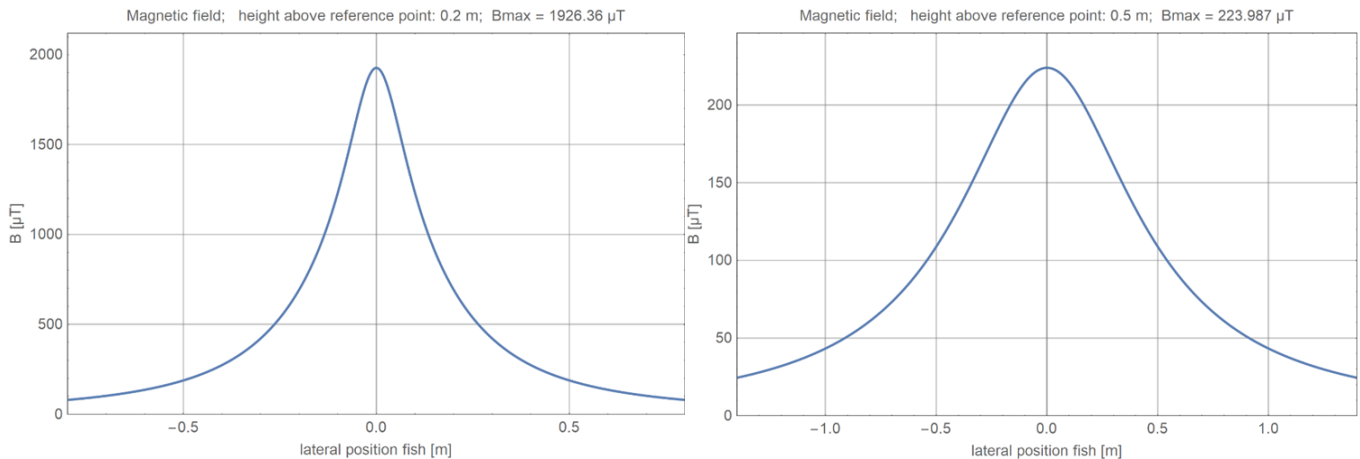


Figure 3: Magnetic field lateral profile, with the modelled strength of the magnetic field on the y-axis and the distance from the cable as the lateral position on the x-axis. The vertical distance at which the organism is moving above the cable is depicted as:  $y = 0.2$  m (left) and  $y = 0.5$  m (right).

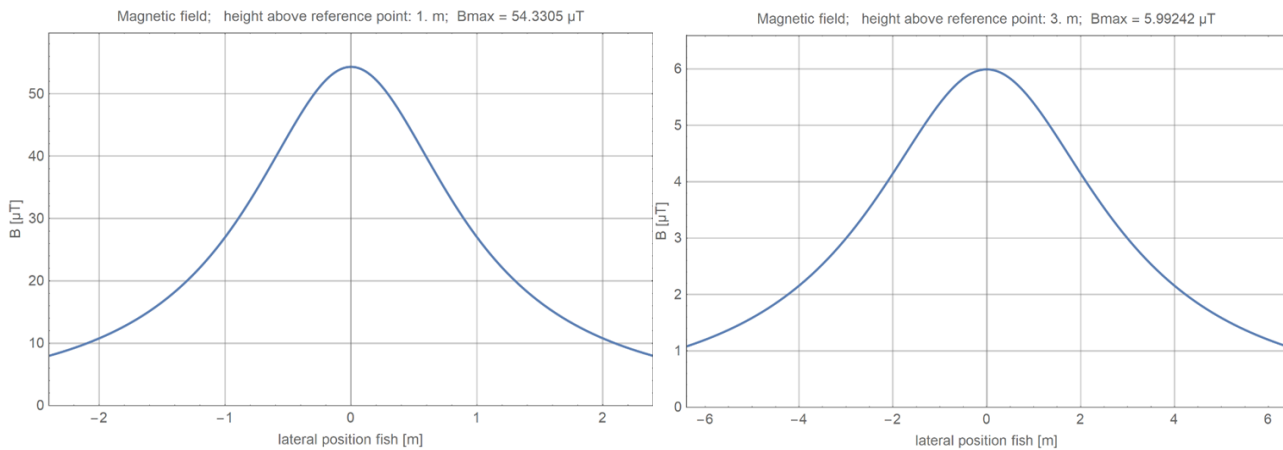


Figure 4: Magnetic field lateral profile, with the modelled strength of the magnetic field on the y-axis and the distance from the cable as the lateral position on the x-axis. The vertical distance at which the organism is moving above the cable is depicted as:  $y = 1$  m (left) and  $y = 3$  m (right).

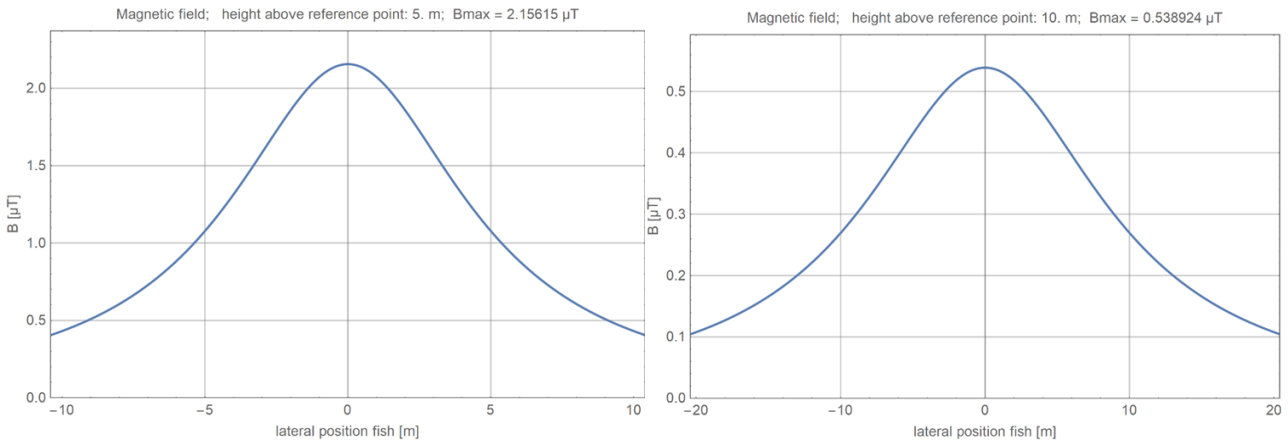


Figure 5: Magnetic field lateral profile, with the modelled strength of the magnetic field on the y-axis and the distance from the cable as the lateral position on the x-axis. The vertical distance at which the organism is moving above the cable is depicted as:  $y = 5$  m (left) and  $y = 10$  m (right).

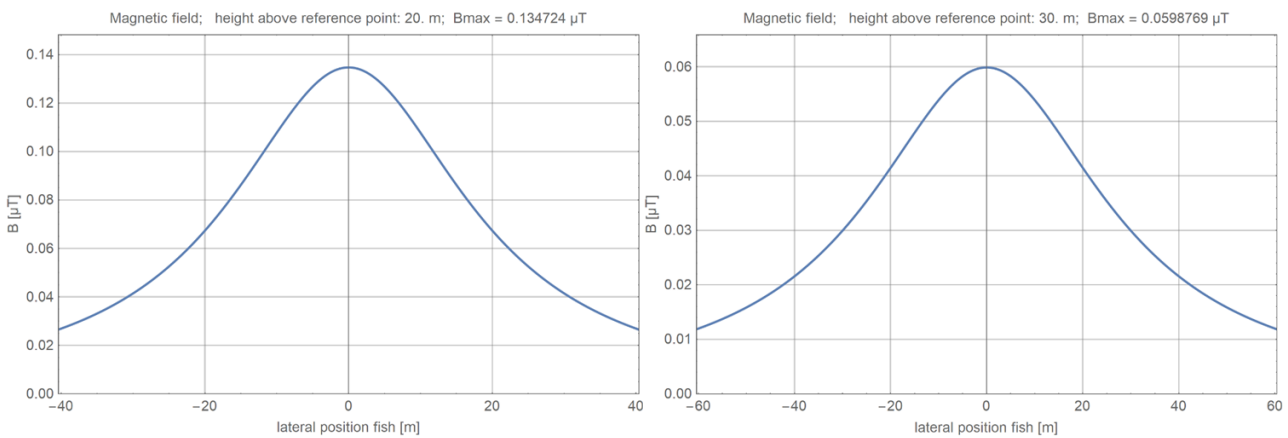


Figure 6: Magnetic field lateral profile, with the modelled strength of the magnetic field on the y-axis and the distance from the cable as the lateral position on the x-axis. The vertical distance at which the organism is moving above the cable is depicted as:  $y = 20$  m (left) and  $y = 30$  m (right).

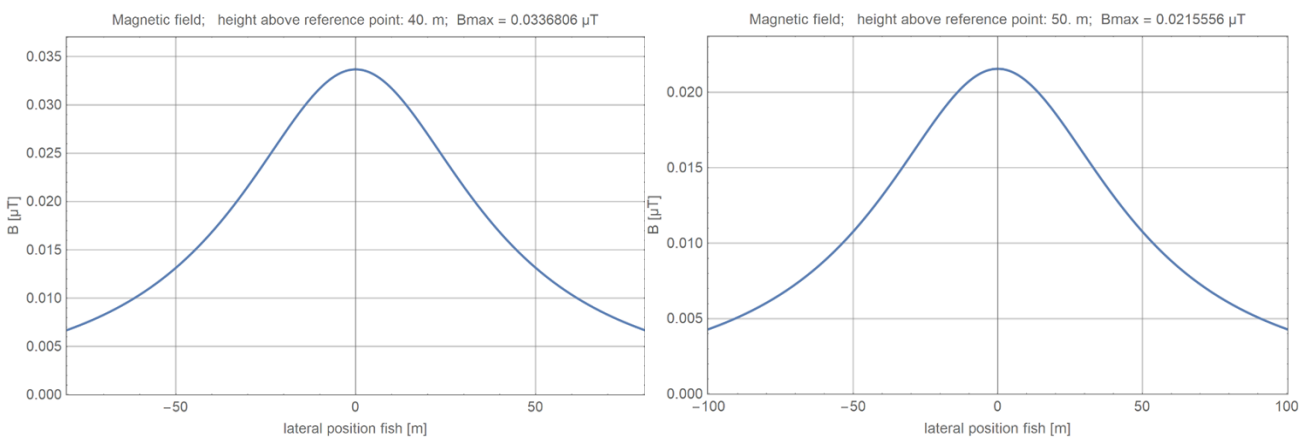


Figure 7: Magnetic field lateral profile, with the modelled strength of the magnetic field on the y-axis and the distance from the cable as the lateral position on the x-axis. The vertical distance at which the organism is moving above the cable is depicted as:  $y = 40$  m (left) and  $y = 50$  m (right).

## 5 Cumulative Assessment

### 5.1 Overview

The cumulative assessment in the Bellrock WFDA EIA Report evaluates the potential impacts of EMFs arising from the combined electrical infrastructure associated with various sources, both within and outside of the Bellrock WFDA.

Part of the Bellrock OfTDA overlaps with the whole of the WFDA. It is expected that the IACs within the WFDA may interact with the interconnector cables and part of the offshore export cables within the Bellrock OfTDA. It is expected that the remaining part of the offshore export cables located outside of the WFDA, as well as operational cables from other nearby projects, may also interact with the IACs within the WFDA. The cumulative assessment determines whether the overlapping EMFs from the Bellrock WFDA (IACs) and OfTDA (interconnectors and part of the export cables), and operational cables from other nearby projects could affect fish, shellfish and benthic communities.

The IACs within the WFDA are AC, while the offshore export cables within the OfTDA are under consideration for either DC or AC, making it uncertain if they will cancel each other out. When multiple EMF sources, such as different cable circuits, are present, they can interact, adding to or subtracting from the total field, provided they operate at the same frequency (which could result in a cancellation of the field, if the subtraction is large enough). However, AC (50 Hz) and DC (0 Hz) fields do not interact due to their differing frequencies and should be considered separately. Consequently, there will be no interaction or cumulative impact from these fields, allowing each to be assessed independently.

As noted above, the IACs within the WFDA and the interconnectors within the OfTDA are both AC systems operating at 50 Hz. As such, there is potential for cumulative EMF effects in areas where these circuits are in close proximity. The resulting magnetic field magnitude will be governed by engineering parameters including, cable size, separation between cables, burial depth, and the use and thickness of metallic shielding or armouring. When AC circuits operate at the same frequency and are not spatially separated, their magnetic fields may constructively interfere, resulting in local field amplification.

Surrounding the Bellrock WFDA is the proposed Ossian OWF which is situated 8 km to the southwest, the proposed ChampionWind WFDA which is 23 km to the north, and the proposed Cedar WFDA which is 21 km to the east (Figure 8). While these projects are located some distance apart, Cedar may host circuits passing close to the Bellrock WFDA. Given the separation between the projects, direct overlap of EMF from multiple developments is unlikely, meaning fish are not expected to simultaneously experience EMF from different sources. However, the cumulative impact may still arise as mobile species such as fish encounter EMF from multiple projects over time, potentially interacting with larger or more frequent magnetic fields. Over the next decade, OWF developments around the Bellrock WFDA are expected to increase the complexity of regional electrical infrastructure (Figure 9).

Designed-in mitigation measures proposed by the Applicant are aimed at reducing direct and cumulative EMF effects on fish and shellfish, and benthic communities. This includes the use of armoured 3-phase single core (trefoil arrangement) high voltage submarine cables, to mitigate both electric and magnetic fields, to an extent. Static sections of cables will be buried or protected, with a target minimum burial depth of 0.5 m and maximum burial depth of 2.5 m (burial depth could be up to 5 m in certain areas depending on seabed conditions) (Chapter 4: Project Description, Volume II of the Bellrock WFDA EIA Report). Cable trench width may also vary to accommodate greater burial depths, subject to the conclusions of a Cable Burial Risk Assessment. This approach will help reduce magnetic fields and mitigate EMF impacts, ensuring that the magnetic fields diminish quickly with distance and remain highly localised due to the use of armoured 3-phase single core (trefoil arrangement) high voltage submarine cables.

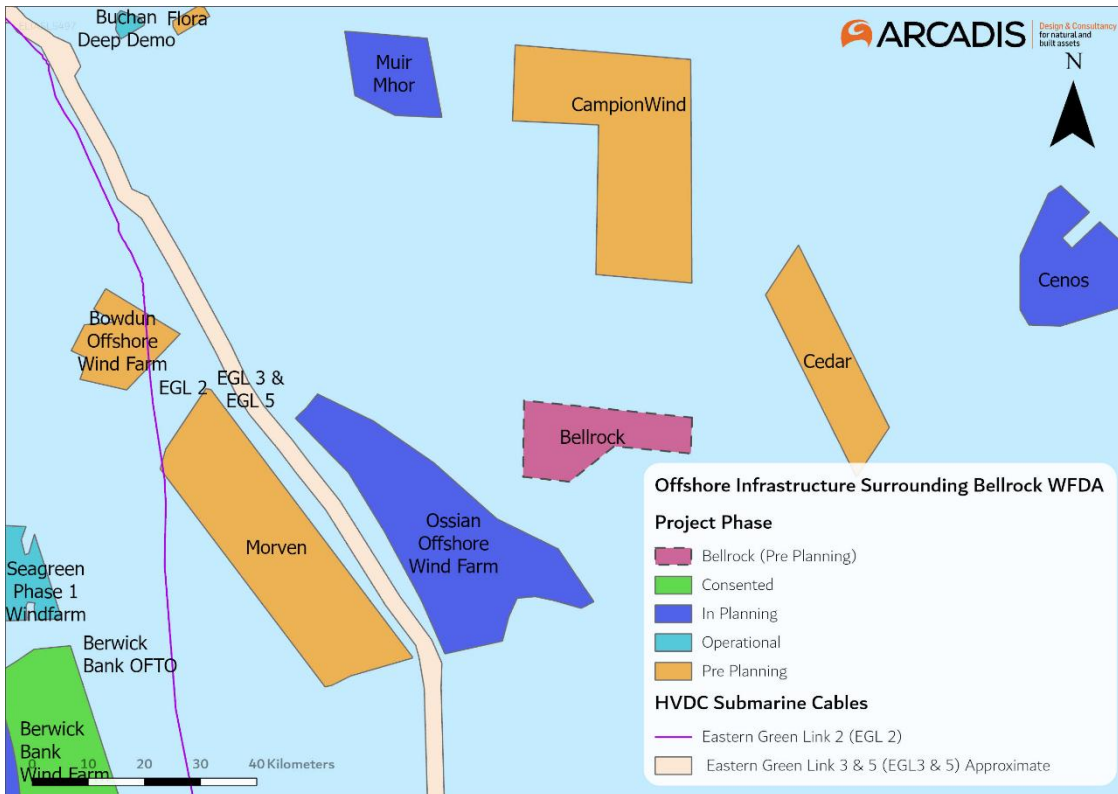


Figure 8: Bellrock WFDA with the closest surrounding wind farms. Offshore wind projects' data from [Crown Estate Scotland Spatial Hub](#) (with Haskoning edits as at: 01/09/2025). Eastern Green Link 2 (EGL 2) data from Scottish and Southern Electricity Networks (SSEN), Eastern Green Link 3 (EGL 3) and Eastern Green Link 5 (EGL 5) approximate data georeferenced from publications on the SSEN website.

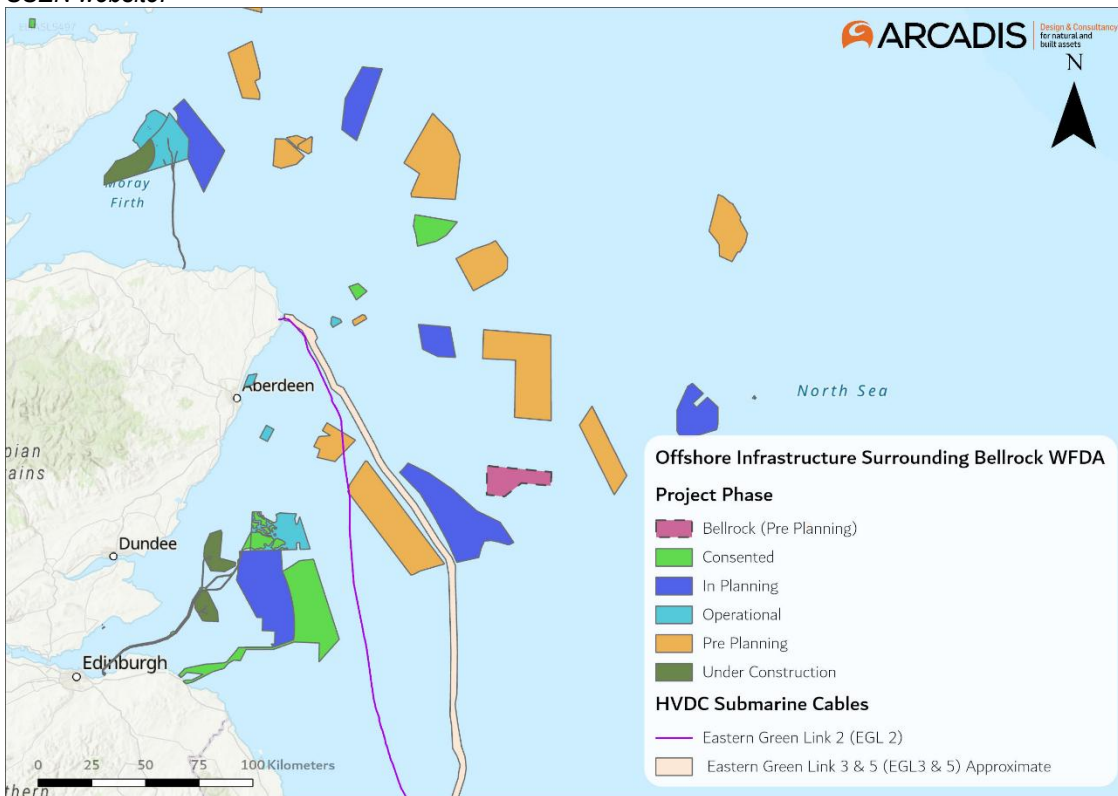


Figure 9: Map of Scottish offshore wind projects in the northeast. Offshore wind projects' data from [Crown Estate Scotland Spatial Hub](#) (with Haskoning edits as at: 01/09/2025). Eastern Green Link 2 (EGL 2) data from Scottish and Southern Electricity Networks (SSEN), Eastern Green Link 3 (EGL 3) and Eastern Green Link 5 (EGL 5) approximate data georeferenced from publications on the SSEN website.

## **5.2 Mitigation for the Bellrock Project**

### **5.2.1 Mitigation Measures**

As noted in the section above, designed-in mitigation measures comprise of armoured 3-phase single core (trefoil arrangement) and cable burial. Cable burial acts as a mitigation by placing physical distance between the submarine cable and marine organisms, effectively reducing the exposure to EMFs by diminishing their intensity with depth (Table 3). This spatial separation helps minimise potential behavioural changes or physiological effects on sensitive species.

The issue of cable biting by sharks and rays may present a potential risk, especially with dynamic submarine cables. This behaviour should be considered when designing the cable mantle and/or implementing additional shielding. This has since been added to the design. While cable shielding serves primarily as cable protection to ensure the structural integrity of the cables and prevent damage, it can also act as a mitigation measure by slightly increasing the distance between the source of the EMF and marine organisms. However, shielding primarily to mitigate EMF is not possible.

## 6 Conclusion

The assessment of EMF associated with the Bellrock WFDA concludes that designed-in mitigation measures incorporated into the project design (armoured 3-phase single core (trefoil arrangement) and cable burial) are sufficient to manage and significantly reduce potential impact on marine receptors. The implementation of armoured 3-phase single core (trefoil arrangement) high voltage submarine cables, combined with the burial or protection of static cable sections, is expected to localise magnetic fields and mitigate EMF-related effects on fish, shellfish, and benthic communities. It should be acknowledged, however, that thermal effects (such as cable heating and sediment temperature) and harmonics from the AC system were not considered in this assessment, and these factors could influence the EMF characteristics.

These measures otherwise align with engineering best practices and regulatory guidelines outlined in UK legislation and international standards.

These provisions, alongside adherence to regulatory frameworks such as the Marine Works Regulations (2007) and the Electricity Works Regulations 2017, ensure compliance with environmental protection requirements.

In conclusion, these proposed designed-in measures are sufficient to mitigate the EMF impacts on fish, shellfish, and benthic communities for the Bellrock WFDA and potentially a cumulative context.

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# Appendix A: Lateral Profiles Induced Voltage

Given here are the lateral profiles of the induced voltage on each species, given the closest approach of 20 cm to the center of the cable bundle and transversal movement.

## Common ray (at $y = 0.2$ m)

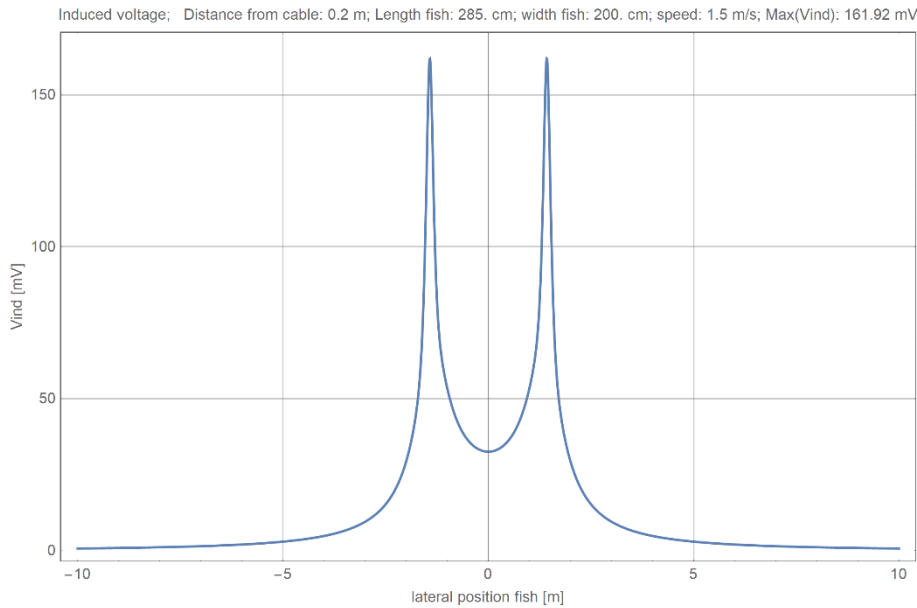


Figure 10: Induced voltage on a common ray as a function of lateral position with respect to cable bundle (at 0.2 m closest approach).

## Brown crab (at $y = 0.2$ m)

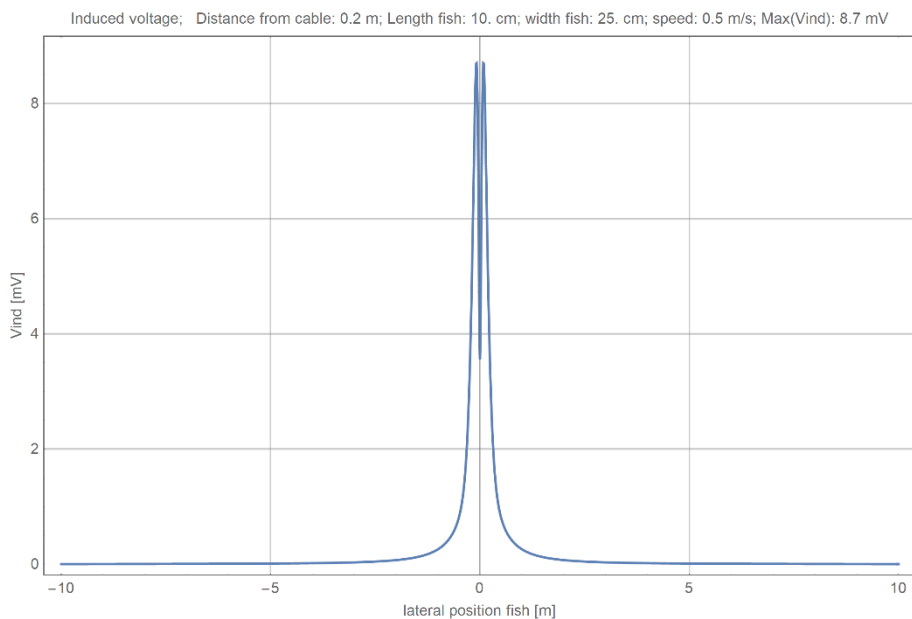


Figure 11: Induced voltage on a brown crab as a function of lateral position with respect to cable bundle (at 0.2 m closest approach).

### Atlantic salmon (at $y = 0.2$ m)

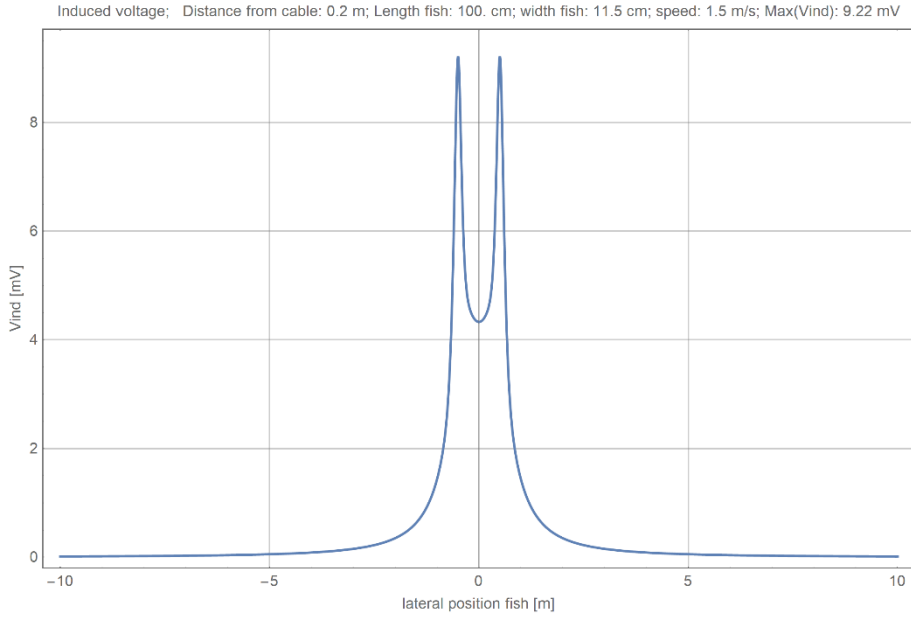


Figure 12: Induced voltage on an Atlantic salmon as a function of lateral position with respect to cable bundle (at 0.2 m closest approach).

### Basking shark (at $y = 0.2$ m)

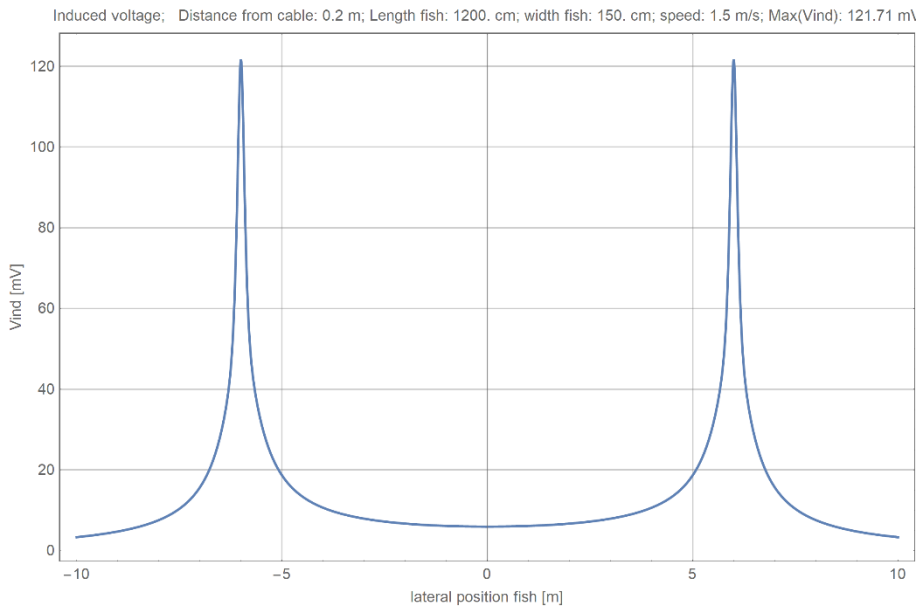


Figure 13: Induced voltage on a basking shark as a function of lateral position with respect to cable bundle (at 0.2 m closest approach).

# Colophon

ELECTROMAGNETIC FIELDS ASSESSMENT  
BELLROCK OFFSHORE WIND FARM - WIND FARM DEVELOPMENT AREA

CLIENT  
BELLROCK OFFSHORE WIND FARM LIMITED

AUTHOR  
Marine and Estuarine Biodiversity

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