FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

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FLOATING OFFSHORE WIND CENTRE OF EXCELLENCE

FLOATING OFFSHORE WIND DYNAMIC CABLE EMF ENVIRONMENTAL REVIEW

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In partnership with:

EVOLV ENERGIES

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EXECUTIVE SUMMARY

The environmental impacts of electromagnetic fields emitted from offshore electrical infrastructure on marine ecosystems remain unclear. As the offshore wind industry targets the deployment of floating offshore wind technology, understanding these impacts becomes increasingly important. Unlike static subsea cables used in bottom-fixed offshore wind farms, which are typically buried beneath the seabed or placed beneath rock armouring, floating wind utilises dynamic cables that are suspended throughout the water column. This development means EMF emissions would no longer be confined to the seabed, which presents a potential environmental consideration for pelagic species that inhabit the water column.

This report aims to provide an overview of the current knowledge regarding electromagnetic fields from dynamic cables and their potential environmental implications. The findings are presented in two distinct sections. The first section focuses on the technological characteristics of dynamic cable design, exploring the generation and behaviour of EMFs in the marine environment, as well as mitigation and attenuation strategies. The second section reviews existing literature on the environmental impacts of EMFs, with a particular focus on pelagic species – those that inhabit the open water column at varying depths, away from the sea floor – and broader ecological considerations.

A key outcome of this review is the identification of knowledge gaps in understanding the interactions between EMFs and marine life. Given the emerging nature of floating wind technology, these gaps highlight the need for further research to inform environmental assessments and industry best practices. This report offers a resource for industry, stakeholders, policymakers, and researchers, supporting informed decision-making as the offshore wind sector continues to evolve.

PREFACE

1.1 Floating Offshore Wind Centre of Excellence

The Floating Offshore Wind Centre of Excellence (FOW CoE) was established in 2020 by the Offshore Renewable Energy (ORE) Catapult with the vision:

To establish an internationally recognised centre of excellence in floating offshore wind which will work towards reducing the Levelised Cost of Energy (LCoE) from floating wind to a commercially manageable rate, cut back development time for FOW farms and develop opportunities for the local supply chain, driving innovation in manufacturing, installation and Operations and Maintenance (O&M) methodologies in floating wind.

The FOW CoE is a collaborative programme with industry, academic and stakeholder partners. At the time of writing, the organisations listed in Figure 1: Floating Offshore Wind Centre of Excellence Industry Partners are Industry Partners in the FOW CoE:

Figure 1: Floating Offshore Wind Centre of Excellence Industry Partners

The FOW CoE has established Strategic Programmes in high priority areas. Included among these is the Environmental Interactions Strategic Programme, which was launched in 2022 with the aim of coordinating and delivering a range of activities to address FOW-specific environmental and consenting knowledge gaps. The FOW Dynamic EMF Impact review was delivered under the Environmental Interactions Strategic Programme.

1.2 Project Partners

The Floating Offshore Wind Dynamic Cable EMF Environmental Review project was delivered on behalf of the FOW CoE by Kevin Scott, Petra Harsanyi and Erica Chapman at St Abbs Marine Station, and Claire Greig and Luke Eatough at the ORE Catapult. The FOW CoE would also like to state its gratitude to Evolv Energies, who provided extensive guidance and input to the technical review undertaken during the project, and summarised in Chapters 2 to 4 of this report.

To facilitate the technical input and guidance of the FOW CoE's Industry Partners, a Focus Group of partner representatives with relevant subject matter expertise was established at the outset of the project. This Focus Group included representatives from BP, CIP, EDF, Equinor, ESB, Mainstream Renewable Power, Northland Power, Ocean Winds, Ørsted, RWE, SSE, and TotalEnergies.

Additionally, a project Steering Group, listed in Figure 2, which includes Crown Estate Scotland, Defra, Department for Energy Security and Net Zero, Marine Scotland, Natural Resources Wales and The Crown Estate - was established to provide strategic guidance and input throughout the project's development and delivery.

Figure 2: Steering Group Members

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NOMENCLATURE

AC	Alternating Current
CoE	Centre of Excellence
DAS	Distributed Acoustic Sensing
DTS	Distributed Temperature Sensing
EIA	Environmental Impact Assessment
EMF	Electromagnetic Field
EPR	Ethylene Propylene Rubber
FOW	Floating Offshore Wind
HV	High Voltage
HVDC	High Voltage Dynamic Cables
LIR	Line Impendence Resonance
MTB	Magnetotatic Bacteria
MV	Medium Voltage
ORE	Offshore Renewable Energy
OSS	Offshore Substation
O&G	Oil and Gas
O&M	Operations and Maintenance
OWF	Offshore Wind Farm
PD	Partial Discharge
PE	Polyethylene

TLP	Tension Leg Platform
WTG	Wind Turbine Generator
WTR XLPE	Water Tree Resistant XLPE

1 INTRODUCTION

Floating offshore wind (FOW) technology is rapidly advancing to support global net-zero and energy security targets. The UK Government's British Energy Security Strategy and Offshore Wind Net Zero Investment Roadmap outline a target of up to 5 GW of FOW capacity by 2030 [1] [2]. Unlike fixed offshore wind farms, FOW turbines are moored in deeper waters and are connected using dynamic cables that accommodate the movement of floating platforms. The novel use of dynamic cables introduces unique challenges, both in respect of design, and in terms of the environmental considerations, such as the potential interactions of electromagnetic field (EMF) emissions with marine species.

Dynamic cables, often configured in shapes like 'lazy waves' or catenaries, extend EMF emissions into the water column, posing new ecological questions [3]. These emissions may interact with a wider range of marine organisms compared to the static cables of fixed wind farms, which primarily interact with benthic species – organisms that inhabit the seafloor. However, conclusive evidence on the impacts of EMFs on pelagic species – those that inhabit the open water column at varying depths, away from the sea floor – remains limited, creating potential consenting uncertainties for FOW developments. Addressing these gaps is important to streamlining the consenting processes and minimising risks to marine ecosystems.

This report investigates the current understanding of the technological characteristics and ecological interactions of EMF emissions from dynamic cables in FOW farms. The first section of the report examines the key technological characteristics, including how EMFs are generated and propagate in the marine environment. Potential strategies for their mitigation and attenuation are also considered. The second section provides a review of existing literature on the environmental impacts of EMFs. Where possible, emphasis is placed on the consideration of pelagic species; however, benthic species are also addressed, particularly where current knowledge and evidence specific to pelagic species is limited. Key knowledge gaps are highlighted and recommendations are outlined for future research to support informed decision-making and the sustainable development of FOW technology.

DYNAMIC CABLE ELECTROMAGNETIC FIELD IMPACT REVIEW – TECHNICAL REVIEW

2 OVERVIEW OF DYNAMIC CABLES

2.1 Dynamic Cable Design

Dynamic cables used in FOW applications are designed to withstand the unique mechanical and environmental stresses associated with floating structures deployed in deeper waters. These cables incorporate features such as double-armour wire layers, corrugated sheaths, and anti-abrasion sheathing, ensuring durability and flexibility under bending and tension. The cross-section of a typical 66 kV AC dynamic array cable is shown in Figure 3 below.

For current FOW projects, array cable systems predominantly operate with alternating current (AC). AC subsea cables are 3-phase systems that typically utilise a trefoil configuration of three conductors (as depicted in Figure 3). However, future advancements may involve high-voltage direct current (HVDC) systems, especially for far-from-shore sites, where HVDC floating offshore substations (OSSs) and cable exports could become necessary.

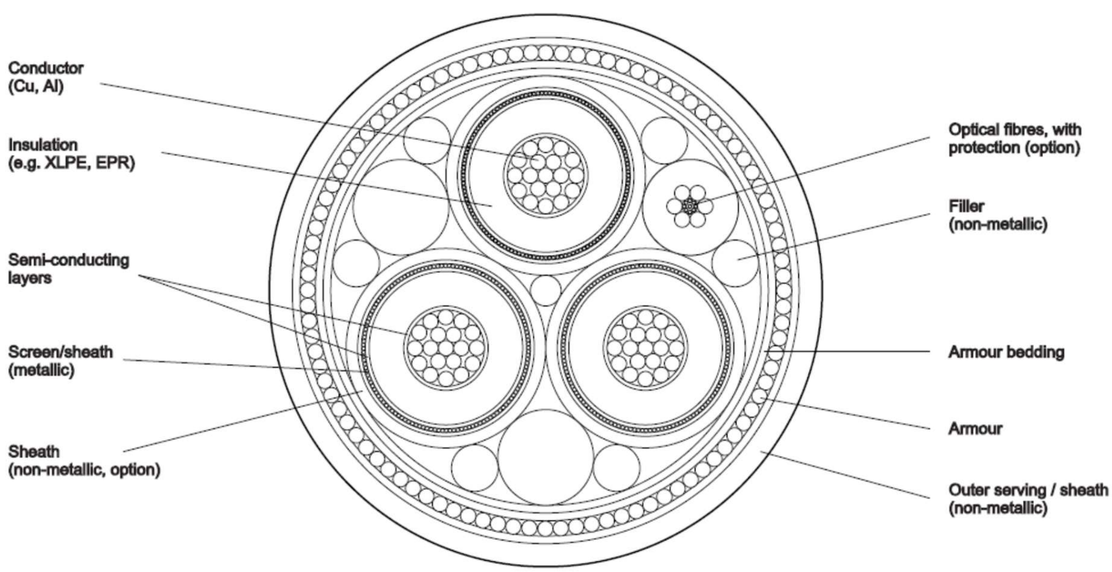

Figure 3: Typical 3-phase AC submarine power cable cross section [4]

Table 1 provides an overview of the key layers common to both static and dynamic cables, along with specific dynamic design elements and their relevance to EMF performance.

Table 1: Cable Cross Section Layers

Layer	General Description
Conductor	The conductor will be water-blocked, stranded copper or aluminum, and either round or sector-shaped. The cross-sectional areas of array cable conductors vary based on current-carrying requirements, which are influenced by thermal constraints and the positions of WTGs within the array network.
Conductor Screen	The conductor screen is made from a semi-conductive compound which is extruded around the conductor to reduce electric field stress at the conductor-insulation interface. Typically, 0.5-1.0 mm thick. The impact of the conductor screen on EMF reduction depends on its magnetic properties and thickness.
Insulation	Subsea array cables are generally XLPE-insulated, and dynamic cables either EPR or WTR-XLPE insulated. For an array voltage of 66kV, the choice of insulation material is influenced by the power cable design (dry, semi-wet, or wet). Thicker insulation increases the distance between current-carrying conductors and the external environment, affecting EMF exposure. Insulation thickness also contributes to trefoil axial distances between power cores, where the field-canceling effects of trefoil configurations help reduce EMF intensity. When considering EMF propagation, the insulation thickness should be compared to the EMF wavelength. At power system frequencies, the insulation is much smaller than the wavelength, so it does not significantly impact propagation. Typically, insulation, along with conductor and insulation semiconductive screens, is manufactured through a combined process known as triple extrusion. However, according to the Core Wind Design Practices and guidelines report, dynamic cable manufacturing would require separate production processes due to manufacturing constraints [3].
Insulation Screen	The insulation screen is a semi-conductive layer applied over the insulation to manage electrical stresses at its surface. The insulation screen requires a degree of flexibility to perform effectively in dynamic environments. Specific details on its material grades and thickness are usually not disclosed; the screen compound would likely be the same as the conductor screen.
Metallic Screen	Helically wound copper tapes or wires, sometimes combined with semi-conductive water-blocking tapes, form the metallic screen. It provides grounding potential, drains capacitive and fault currents, and mitigates EMF through material properties like thickness and conductivity.
Metallic Sheath	Corrugated copper or aluminum sheaths are typically used for dynamic cables, as they offer flexibility and fatigue resistance compared to lead which performs poorly under dynamic stresses. The sheath reduces EMF by generating induced opposing currents, with its effectiveness dependent on construction, material, and thickness.
Fibre Optic Cable	Fibre optic cables are embedded between power cores or within fillers and are designed to handle the bending, twisting, and movement associated with dynamic cables. They are shielded to prevent interference from induced voltages due to current flow in the conductors.
Fillers	Plastic, composite, or rope fillers are placed between the cable components to maintain a consistent round shape and structure. The number, dimensions, and materials of fillers are determined by the manufacturer.
Armour Bedding	A layer of polymeric tape applied around the power cores and fillers to reduce abrasion and provide a protective surface for the armour wires. This layer ensures durability without compromising the structural integrity of the cable.

Layer	General Description
Armour	Double layers of steel armour wires, applied in opposite directions, are common for dynamic cables to enhance torsional stability and resist mechanical stresses in deepwater applications. A polyamide tape may be applied between armour layers. Armour lay lengths and angles are not always declared by manufacturers but may be altered for dynamic applications. Armour wire diameters (thickness of armour layers) is important for EMF mitigation, as this increases the cable diameter. Conductivity of the steel influences absorption of the generated EMF. The helical period of the armour wires influences coupling and extents of EMF orientations. Further work would be required to assess EMF mitigation abilities of a double layer design.
Outer Sheath	A polyethylene outer sheath, typically 3-4 mm thick, encases the cable to provide abrasion protection and allow flexibility. The increased cable diameter resulting from the sheath indirectly reduces the observed EMF by increasing the distance between the power cores and the external environment.

The EMF produced by the cable and their attenuation are influenced by the system frequency, the magnetic permeability and electrical conductivity of surrounding materials, and the physical dimensions and layout of the cable. Armour wire layers will attenuate EMF intensities to some extent, dependent upon armour wire diameters, conductivity and degree of contact between neighbouring wires. The efficacy of armour wire layers to attenuate EMFs is dependent on its material properties as well as the alignment of the field lines with the path of the armour. The design of the cable, including power core spacings, sheath materials, structure and armour layers influences the intensity of EMF generation, the extent of EMF 'shielding' and how the EMF attenuates as it propagates through the cable.

To account for design differences, and to understand current technology advancements, various cable designs such as wet, dry, semi-wet and semi-dry were considered. A number of leading cable manufacturers were also contacted for market engagement; these companies operate globally, with manufacturing facilities in various regions, and produce a wide range of cable products suitable for offshore energy applications.

2.1.1 Dry vs. Wet Cable Design

The distinction between 'dry' and 'wet' cable design is determined by the cable's internal structure, materials, and its ability to manage water ingress. Traditionally, medium-voltage (MV) subsea cables (up to 33 kV, with a maximum of 36 kV) have been manufactured using a 'wet' design, while higher voltage cables, such as interconnectors or wind farm export cables, have typically employed a 'dry' design. Recently, there has been growing interest in adopting 'wet' or 'semi-wet' designs for 66 kV dynamic cables, particularly for array cable applications, to reduce costs.

Dry design: Features hermetically sealed cables with metallic water barriers, offering robust protection against water ingress. These designs use insulated sheaths and metallic barriers to minimise electrical losses and water-treeing, resulting in reduced EMF attenuation. Commonly used for high-stress applications, dry designs enhance cable durability and reliability under bending and twisting. The dry cable design typically uses a lead sheath as a reliable radial water barrier, but its poor fatigue performance and associated health, safety, environmental concerns make it unsuitable for dynamic applications, as well as costly to produce. Alternatives include corrugated copper or aluminium sheaths, laminated aluminium tape, or welded corrugated copper barriers. While these options address the limitations associated with lead, they can be complex and expensive to manufacture. Corrugated designs are favoured for dynamic applications due to their ability to handle movement, bending, and twisting.

Wet design: Typically used for lower capacity dynamic cables, wet designs lack a metallic water barrier which supports cost efficiencies but also leads to greater EMF exposure. The absence of barriers can influence system grounding and EMF attenuation. It is understood that wet design dynamic cables can only be qualified up to 66 kV, as the qualification of wet designs above 66 kV are currently focus of the CIGRE WG B1.92.

Some 33 kV array cables use semi-wet designs, featuring extruded insulation systems surrounded by an aluminium foil and a polyethylene (PE) over-sheath. At this voltage level, the electrical stresses at the conductor and insulation screens are not considered high enough to raise concerns about tracking or partial discharge (PD) activity. Consequently, the need for a fully dry design has generally not been considered necessary.

Semi-Wet/Semi-Dry Design: Semi-wet cable designs can vary, but they allow seawater to penetrate through the armour wire layer to the inner sheath. Typically, these designs include a PE sheath wrapped around a metallic screen that is not fully impervious, often incorporating swelling tapes to help manage moisture ingress. The metallic screen may consist of a copper tape or glued aluminium foil. The insulation material is generally WTR – XLPE.

It is understood that CIGRE is currently considering dry, wet, and semi-wet cable designs as part of the Working Group B1.92 studies. However, to date, only a limited number of semi-wet and semi-dry designs have been identified.

2.1.2 Qualification

Historically, the testing and qualification of dynamic cables and subsea umbilicals has been driven by industry guidelines and best practices, more aligned to oil and gas (O&G) industries, including ISO 13628-5 [5] and DNV-RP-F401 [6]. Relevant specifications for FOW applications include those published by CIGRE [7] [8] [9] and the IEC [10].

As with static cables, dynamic cables must undergo a series of mechanical and electrical type tests to ensure their performance and reliability [9] [10] [11]. EMF emissions assessment was not identified as a qualification test, likely due to the challenges of simulating installation conditions, calculating armour and sheath magnetic interactions, and accounting for unknown environmental and operating factors.

EMF emissions, a potential environmental concern, are not part of type testing or prequalification testing for dynamic cables. Instead, they are typically addressed during environmental impact assessments (EIA).

2.2 Dynamic Cable Components

This section identifies the components required for the connection of dynamic cables to a FOW turbine. Any cable component that can be magnetised or has some properties of conductivity may locally influence propagation and attenuation of EMF from the cable. From an EMF mitigation perspective, it is unlikely that components fitted to dynamic cables will have the required material properties (magnetic permeability or electrical conductivity) to effectively reduce the EMF emissions. However, additional components could increase the physical distance to the cable surface, thereby spatially reducing the EMF intensity at the point of observation. The key dynamic cable components are identified in this section and their possible influence on EMF emissions discussed further.

Figure 4 illustrates a dynamic cable configured in a lazy wave arrangement, connected to a spar buoy floating structure, transitioning to a static section of cable on the seabed. The additional components that may be required for FOW dynamic cables, including bend stiffeners, buoyancy modules, touchdown protection, bend restrictors and in-line terminations (optional, dependent on adopted design) are also illustrated. Table 2 provides further details on these ancillary components (note that this list is not exhaustive).

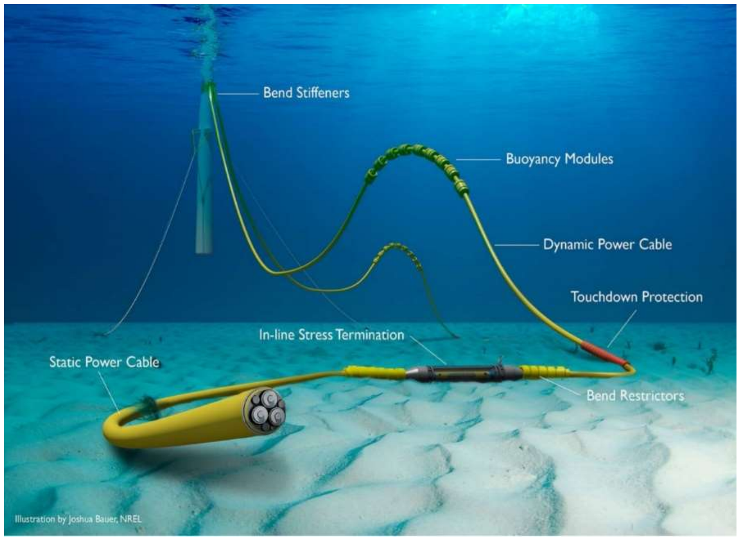

Figure 4 Illustration of a dynamic cable arrangement with components [3]

Table 2: Dynamic Cable Components

Dynamic Cable Component	**Description**
Bend stiffener	Reinforces and provides rigid support to dynamic cables where they enter the FOW turbine hang off and limits fatigue loads upon cables. Polyurethane is a material which cannot be magnetised to any significant extent and has limited conductive properties. Designs differ, although its most significant influence on dynamic cable EMF emission would be to place a greater distance between the EMF source, i.e. the cable, and the surrounding water column where any receptor species may be present.
Buoyancy modules	Attached to the dynamic cable section with a specified lifting force associated with each module. Along with ballast modules, if needed, these help to maintain the lazy 'S' or shape (shown in Figure 3 and Figure 6) or hanging 'W' shape. Buoyancy modules would add distance between the surrounding seawater and the EMF source along the sections of cable that they are installed.
Touchdown protection	Required to limit damage to the cable due to movement on the seabed. A tether may also be fitted near this point to limit the local movement of the dynamic cable. A touchdown protection sleeve may be manufactured from polyurethane. Its material properties would not significantly influence EMF attenuation, although it would slightly increase the distance between the EMF source and the water column.
In-line stress termination	Transition joints facilitate the connection of dynamic and static sections of power cables. The magnetic material properties of the transition joint outer body may increase EMF attenuation at this location as the joint body would present a solid screen (i.e. without openings) with some conductivity properties.

2.3 Dynamic Cable Configurations

Dynamic cable configurations are designed to allow movement within the water column while maintaining shapes that minimise forces acting on the cable. Cable configurations can influence EMF effects, which may combine or cancel out. The accurate definition of these configurations is therefore essential for evaluating EMF emissions, as permissible cable movements define the spatial limits of EMF emissions.

FOW substructures, such as semi-submersibles, spars, and tension leg platforms (TLPs), are anchored to the seabed using mooring lines. The design and behaviour of these structures can significantly affect array cable configurations. Figure 3 illustrates some of the potential cable configurations (other details including mooring lines, bend stiffeners, wet mate disconnectors, and touchdown protection are omitted).

Dynamic cable configurations are influenced by seabed conditions, water depth, and the expected movement of floating platforms (Table 3 outlines some key considerations for some of the principle configurations). Unlike static cables, EMF mitigation through seabed burial is not feasible for dynamic cables.

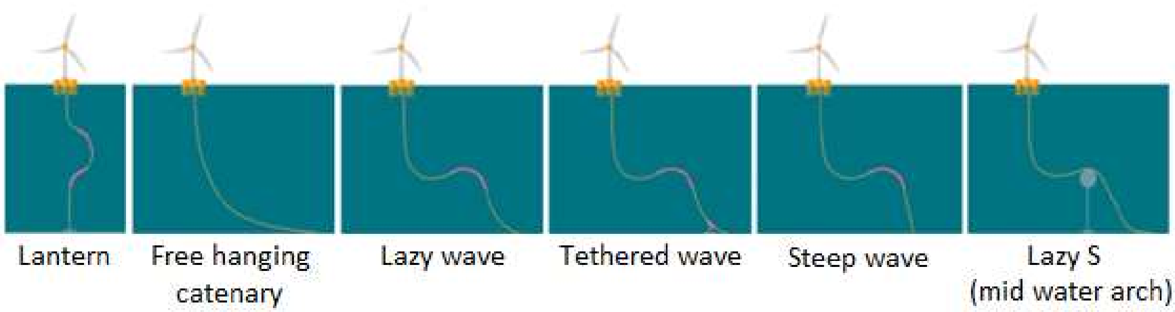

Figure 3. Dynamic cable configurations for FOW applications [3] (Dynamic cable is shown in grey, floating structure in yellow, dynamic cable section in light green. Buoyancy modules shown in pink and subsea tether/mid-water arch in blue green)

Table 3 Dynamic Cable Configurations

Configuration	Description
Catenary	The catenary configuration is a common configuration in FOW applications due to its simplicity, maintainability and cost. A dynamic cable, under its own weight, naturally forms a catenary when suspended between a floating structure and seabed touchdown point. Catenary shapes allow some extent of movement caused by hydrodynamic forces. The dynamic cable section would be connected to a floating WTG structure via a hang-off arrangement, ensuring armor wires and cable are sufficiently clamped. Free hanging catenary systems can be installed without the need for ballast modules or tethering systems.
Lazy Wave	The Lazy Wave configuration is a manipulated version of a free hanging catenary, which effectively comprises three catenary-shaped sections, allowing for more movement than if a simple free-hanging catenary is formed. To maintain a Lazy Wave shape, buoyancy modules are fitted around the cable to provide an upward lift. This is designed to minimise cable fatigue by allowing for the movement of the FOW substructure without exceeding the cable’s minimum bend radius.
Free Hanging ‘W’	Where seawater depths are considered too deep or seabed conditions are not favourable, it may be practical to suspend the dynamic cables according to a hanging ‘W’ shape (not illustrated above). The ‘W’ shape consists of two free hanging catenary sections and a buoyant section, maintained with buoyancy modules fitted around the cable.

2.4 Dynamic Cable Loading

Floating wind dynamic cable designers will select a cable configuration that can withstand the range of loads the cable will be subjected to during the wind farm life cycle. Dynamic cables must be mechanically and electrically robust to ensure installation, operational, and environmental conditions including, but not limited to:

- Tensile forces from self-weight and marine growth.
- Bending due to hydrodynamic forces like waves, tides, and currents, which affect cable behaviour near hang-off points.
- Water pressure at installation depths.
- Rotational forces from tidal currents generating torque.
- Cable elongation due to continuous movement.

Figure 6 shows forces, pressures and considerations for a dynamic cable, shown here configured as a lazy wave (lazy ‘S’) [12].

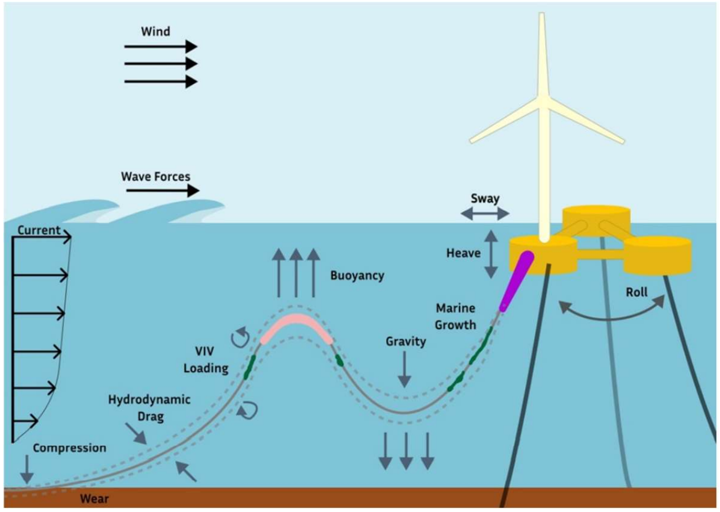

Figure 6. Lazy wave considerations [12] N.B. Dynamic cable = grey, cable movement envelope = dashed grey, buoyancy modules = pink, marine growth = green, bend stiffener = bright pink, mooring lines =bold lines, forces = grey arrows.

These movements may influence the propagation of dynamic cable EMFs into the marine environment, although it is currently unclear how significant these effects might be. As such, an accurate understanding a dynamic cable’s motions could be important for reliable EMF modelling and for assessing the potential interactions with marine life.

3 OVERVIEW OF ELECTROMAGNETIC FIELDS

3.1 Background

The Earth's internal physical processes give rise to a natural background geomagnetic field. This varies with location, being most intense at the poles and weakest at the equator, with field strengths typically varying between 25 µT and 65 µT, depending on geographic position. Although the Earth's geomagnetic field exhibits slight temporal fluctuation, it is typically treated as static (i.e. time-invariant) for the purposes of practical calculations.

When analysing power cable EMFs, the Earth's field is added vectorially. Generally, three-dimensional Cartesian coordinate systems – which represent the direction and magnitude of the field components – are used to facilitate the analysis of EMFs.

3.2 Subsea Cable Electromagnetic Fields (EMFs)

Submarine power cables are inherently associated with both electric and magnetic fields. The electric field component, which is produced by the voltage within the cable, is expressed in volts per metre (V/m). For high voltage cables, the electric field strength may be measured in kilovolts per millimetre (kV/mm). In subsea power cables, this electrical field is confined within its screened insulation system, between the conductor screen and sheath. The magnetic field component, which is produced by the current within the cable, is typically quantified in micro-Teslas (µT).

The intensity of both the electric and magnetic fields are proportional to a cable's voltage and current, respectively. An EMF can be resolved into spatial components, with the resultant vector direction determined by application of Ampere's Law and Lenz's Law [13] [14].

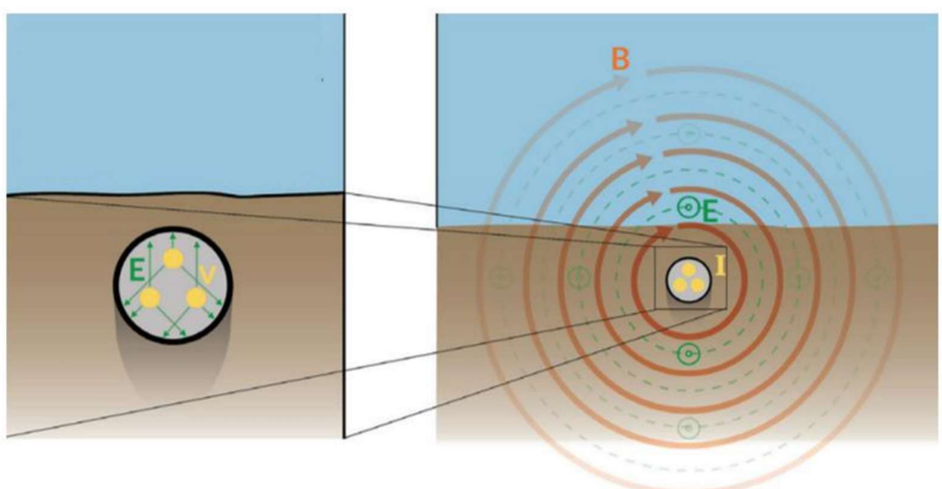

Figure 5 Electromagnetic Fields from AC Cables [13]

Figure 5 shows a three-core, buried subsea cable with voltages, current, electric field and EMF illustrated:

- E – Electric field (V/m) solid green arrows
- V – System voltage (V) yellow circles

- B – EMF (Tesla) brown arrows
- E – Induced electric field (V/m) dashed green lines
- I – Current (A) yellow circles

An EMF's intensity is attenuated significantly beyond a few metres from the cable. Extents of EMF attenuation are dependent on the magnetic permeability and electrical conductivity of the metallic layers within the cable, the thickness of layers, the structure of the cable sheath and armour layers, the power system frequency, and to, a certain extent, the conductivity of surrounding seawater. CIGRE TB 908 was published to provide guidance on these calculations, although their accuracy appears limited by how armour wire interactions are modelled.

At the time of writing, publicly available field data on EMF emissions from offshore wind farm subsea cables remains limited, and the existing measurements focus solely on static cables deployed on or buried within the seabed. Table 4 presents the findings of a review conducted by Hermans et al. published in 2024 [15] which summarised published magnetic field measurements from a series of 3-phase AC and bundled bipolar DC export and inter-array cables.

Although the reported values outlined in Table 4 represent the maximum measured field strengths, the power load in the cables at the time of measurement was not recorded. It is possible that these values do not reflect maximum possible emissions under full operational capacity, as measurements could not be conducted during periods of high wind. Magnetic field emissions from AC cables are generally lower than those from DC cables, due to partial cancellation of electromagnetic fields within the three-phase AC configuration.

Table 4 Magnetic field values measured from AC and DC subsea power cables. Reproduced from Hermans et al. (2024) [15], summarising data from multiple studies (see original article for full references).

Cable type	Maximum measured magnetic field/maximum level above geomagnetic field (µT)	Distance from cable (m)	Cable specifications	Reference
AC	0.008-0.020 0.015-0.039 0.004	1.5-2.0	34 kV, 108 MW 150 kV, 120 MW 150 kV, 129 MW	Snoek et al., 2020
	0.004 0.017	1.0-1.5 15	50 Hz 50 Hz, 70 A	Thomsen et al., 2015
	0.600	1.5	36 kV, 265 A	Gill et al., 2009
	0.050 0.056	0	33 kV, 50 A 11 kV, 60 A	CMACS 2003
	6.540	0.5	150 kV, 120 MW, 436 A	DNV-GL 2015

DC	51.7/0.46 51.9/0.64 65.6/14.3 72.0/20.7 56.3/4.7	1.3	300 kV, 330 MW, 0 A 300 kV, 330 MW, 16 A 300 kV, 330 MW, 345 A 660 MW, 500 kV, 1320 A 660 MW, 500 kV, 660 A	Hutchison et al., 2020a,b

Calculations of subsea power cable EMF emissions for both AC and DC systems are based on the Biot-Savart Law [14]. This law establishes that the magnetic field intensity at a given point in space is directly proportional to the magnitude of the electrical current and inversely proportional to the square of the distance between the current source and the point of interest.

The requirements for, and the importance of, EMF modelling for dynamic cables are addressed in The Crown Estate's report [16], published in 2023. The authors highlight the need to account for factors such as tidal current velocities, the geometry of the power cores, and the alignment or "straightness" of the dynamic cable. However, the report does not provide a detailed methodology for incorporating these parameters into EMF models. Recommendations are also made regarding the consideration of motion-induced EMFs. It remains unclear, however, whether these effects should be explicitly included in dynamic cable EMF models, or whether their influence can be considered negligible for most dynamic applications.

Graphical representations of dynamic cable EMF calculations could be enhanced by illustrating the spatial variation in EMF intensity resulting from the motion of dynamic subsea cables and associated floating structures. The development of methodologies to incorporate such dynamic spatial shifts into visual outputs may represent a valuable area for future work.

The calculations of EMF intensities from subsea power cables are limited by design parameters of the cable system, the variables incorporated into the modelling framework, and the extent to which installation and environmental conditions are accounted for. A number of limitations apply to the modelling of EMFs for dynamic cable systems:

- The motion of floating structures is difficult to characterise without detailed, site-specific analysis and engagement with relevant stakeholders.
- The behaviour of dynamic cables within the water column and at the seabed touchdown points needs to be fully established.
- Drag, buoyancy or pull caused by the build-up of marine growth and biofouling could influence a cable's positioning and alignment.
- Nearby subsea infrastructure – such as other cables, pipelines, or metallic structures - could distort EMF propagation.
- Interactions with marine species may need to be based on a combination of environmental habitat knowledge and statistical likelihoods of species encounters.

3.3 Dynamic Cable Impact on EMF Emissions

This section examines the impact of dynamic cable design features on EMF generation and attenuation. The ability of dynamic cables to “absorb” or attenuate EMFs is not yet fully understood. Relevant factors include EMF coupling and interactions, the magnetic properties of the cable materials, and the influence of dynamic cable positioning (including the placement of power cables at varying distances from EMF calculation points). The ability to carry out in-depth assessments would require access to detailed cable designs and specifications.

Static subsea cables are typically buried within the seabed to a depth of 1 metre or more. The burial depth helps to reduce the EMF intensity detectable at the seabed level. In contrast, dynamic cables do not have the benefit of burial as mitigation method, meaning the EMF intensity calculated at the cable surfaces reflects the EMFs exposed directly to the surrounding seawater.

3.3.1 Dimensions

A subsea cable’s current rating will influence its build dimensions, including its cross-sectional area and diameter. Array cables typically range from approximately 120 mm^2 to 1200 mm^2 in cross sectional area. As the cross-sectional area increases, both the conductor diameter and total external diameter, or outside diameter, also increase. The outside diameter and power core diameter influence EMF calculations by altering the distances between power cores and the point of EMF measurement. A larger outside diameter may reduce EMF intensity at the seabed by increasing the distance between the power cores and the seabed surface. In contrast, a larger power core diameter can increase EMF intensity by changing the electromagnetic interactions between the power cores. For dynamic cables, which typically have larger diameters due to additional armour layers, these factors should be considered in EMF assessments.

3.3.2 Current

The EMF intensity depends on current flow through the cable. EMF calculations typically assume steady-state operating conditions. Fluctuating currents, such as those from faults or transients, are generally excluded from EMF modelling. Variations in current, and therefore EMF intensity, can occur due to fluctuations in power generation, which in turn is driven by the wind speeds at an offshore wind farm. The configuration of the cable array can influence current distribution, but is unlikely to significantly affect EMF interactions unless the cables are in close proximity.

3.3.3 Sheath

Alternating currents in subsea cables induce currents in the cable’s metallic sheath. Sheath currents oppose the main conductor current and reduce the overall EMF intensity. The magnitude of these currents depends on factors such as sheath construction, material conductivity, and magnetic coupling. For accurate EMF modelling, sheath currents should be included and, where possible, validated against empirical measurements.

Induced sheath currents obey Lenz’s Law [17] and flow in a direction opposite to the current that produced them. Sheath currents therefore flow in an opposite direction to that of the main conductor current and their direction and magnitude of EMFs is in opposition to generated conductor current EMFs.

The array configuration would influence current flow within inter-array cables (i.e. radial, star, ring, fishbone, etc), however, array configurations are unlikely to directly influence the interactions of EMFs, unless array cables are in close proximity.

3.3.4 Armour

Cable armour is intended to protect against mechanical damage, but it can also influence EMF generation. Magnetic interactions within the armour wire layers can induce secondary EMFs, which may partially cancel out over the course one helical period. However, this effect depends on the insulation between armour wires and their magnetic properties. Dynamic cables, often featuring multiple armour layers, require careful consideration of how armour wire layers affect EMF attenuation. The impact of armour on EMF calculations, particularly for multi-layered armour, is not well understood and requires further study.

3.3.5 Manufacturing Tolerances

Cables Manufacturing tolerances, such as variations in power core dimensions, lay lengths, and material properties, can impact EMF emissions. The conductivity and permeability of metallic layers are particularly important for EMF attenuation. While cable insulation typically does not affect EMF attenuation, manufacturing variations in other aspects could influence the generated EMF.

3.3.6 Over Sheath and Fibre Optic Cable

Dynamic cables include HDPE outer sheaths that also offer mechanical protection. Due to their non-magnetic properties, they do not attenuate EMF propagation.

The position of fibre optic cables, which can induce EMFs if they are earthed, may also influence overall EMF generation. However, their impact is difficult to quantify due to the complexity of cable construction.

3.3.7 Validation of EMF Models

EMF emissions from subsea cables can be assessed through in-situ field measurements. However, comparisons with modelled results can be challenging due to fluctuating currents and varying installation parameters. Laboratory-based experiments have been conducted to validate EMF models, although it can be very challenging to replicate the complexities of real-world marine environments. To validate EMF calculations, sufficient technical details of the cable build and installation conditions is required. Software tools like COMSOL and QUICKFIELD can model EMF emissions in static conditions, but their applicability to dynamic cables, particularly with regards to movement in the water column, remains uncertain.

4 DYNAMIC CABLE ELECTROMAGNETIC FIELD STATE OF THE ART REVIEW

Based on the identified dynamic cable designs and specifications available, present challenges and uncertainties associated with FOW applications are outlined below. The challenges outlined in Table 5 may not necessarily influence EMF emissions or mitigation.

Table 5: Challenges identified in the deployment of FOW dynamic cables

Challenge Area	Challenge Description
Electrical Design	An increase in the voltage of array cables (i.e. up to 132 kV), as recommended by the Carbon Trust, could pose challenges for cable manufacturers and the qualification of higher-rated dynamic cables.

Challenge Area	Challenge Description
Electrical Stresses	Conductor and insulation screens help to manage electrical stress at the interface. Therefore, cable designs should account for electrical stress management and screen flexibility.
Degradation & Aging	Partial discharge (PD) does not significantly impact dynamic cable EMF emissions in normal operation. It generates impulsive, high-frequency EMFs, but does not contribute to harmonic order frequencies. Over time, PD degrades insulation and alters electric field distributions.
Industry Experience	To date, the handling, jointing, and testing of dynamic cables in the field has been limited. Field testing may be necessary to assess sensitivity requirements and to ensure sufficient physical space for conducting voltage withstand tests, particularly for 66 kV and 132 kV systems.
Structural & Cable Dynamics	The movement of dynamic cables in the water column shifts the position of EMF emissions accordingly. Further work may be needed to determine the extent of cable movement and to assess any subsequent interactions, as well as potential mitigation measures.
Monitoring & Measurement	The condition monitoring of dynamic cables can be facilitated using PD measurements and fibre optic techniques like distributed acoustic sensing (DAS) and distributed temperature sensing (DTS). Frequency-domain methods, such as line impedance resonance (LIR) measurements, are also available, though data collection can be challenging. EMF emissions data from subsea cables is very limited, with no records for dynamic cables. Field measurements are crucial for validating EMF models and can validate lab testing results. Therefore, monitoring at demonstrator sites may be highly valuable.
Design Approaches	For FOW dynamic cables, lead-alloy sheaths are not viable due to their poor fatigue properties. Manufacturers have explored alternative sheath designs, such as corrugated copper and aluminum. However, validating their long-term viability requires sufficient operational experience and real-world application, which remain limited in FOW.
Environmental Factors	The environmental challenges of umbilical and deepwater applications include the study of EMF emissions from dynamic cables and their potential impact on the surrounding environment. This was investigated as part of the Floating Offshore Wind Environmental Response to Stressors (FLOWERS) project, which examined species encounter rates and distributions.
EMF	Research publications present EMF intensities from AC and HVDC subsea cables, typically presented as 2D plots with horizontal distance along the seabed on the x-axis and EMF intensity (in micro-Tesla) on the y-axis, with height above the seabed varying. Challenges in modelling dynamic cable systems include setting up the geometry, selecting relevant variables, accounting for different cable design, representing EMF intensities in the water column, and considering whether cumulative EMF effects should be included.

4.1 EMF Calculation Approaches for Dynamic Cables

Reports and publications often lack detailed EMF calculations, making it difficult to assess methods and parameters used.

For both static and dynamic subsea cables, EMF calculations are based on Maxwell's equations, with dynamic cable setups requiring adjustments for their catenary configuration. AC subsea buried cable calculations typically follow the Biot-Savart Law, with variations to improve accuracy by incorporating factors that influence EMF. Common approaches include:

1. EMF calculation approach according to the Biot-Savart Law only.
2. EMF calculation approach with the inclusion of induced sheath currents.

3. EMF calculation approach with the inclusion of the power core and trefoil configurations.
4. EMF calculations approach with the inclusion of phase angle relationships between current sinewaves.
5. EMF calculation approach with the inclusion of power core helical periods.

Most calculations use either the first or second approach, as further refinements often require advanced 3D modelling. While complex models can improve accuracy, a simplified Biot-Savart approach is often sufficient.

The EMF generated by dynamic cables follows the same electromagnetic principles as static cables, acting orthogonally to current flow and intensifying near the cable surface. While burial helps mitigate EMF for static cables, dynamic cables rely on metallic sheath properties, power core helical periods, and cable dimensions for attenuation.

Unlike buried cables, dynamic cable modelling excludes burial depth, making geometric calculations more complex and requiring 3D spatial plotting of EMF intensities. The inclusion of parameters such as induced sheath currents and helical lay periods remains unclear. Attenuation depends on the structure, thickness, and conductivity of metallic layers, requiring manufacturer-specific analysis of cable sheath designs and double-armour constructions.

Given the current market projections for offshore wind farms and trefoil AC cable arrangements, EMF emissions from dynamic cables are unlikely to exceed the Earth's geomagnetic field. Assessments may therefore focus less on EMF intensity and more on species encounter rates and potential effects of low-intensity EMF within the water column.

Published research on EMF emissions from dynamic cables is limited, as noted in the EIA report for the Hywind floating OWF [18]. Marine Scotland recommended further investigation into potential entanglement and EMF effects from mid-water cabling, but few modelling approaches have been identified despite extensive literature searches [18].

DYNAMIC CABLE ELECTROMAGNETIC FIELD IMPACT REVIEW – ENVIRONMENTAL REVIEW

5 ENVIRONMENTAL OVERVIEW

5.1 Introduction to Key Effects and Impacts

Marine species have evolved in the context of Earth's natural geomagnetic field, which has provided stable magnetic and electrical cues over time. However, the introduction of anthropogenic EMFs alters this environment. Due to the minimal amount of research and conflicting or inconclusive results, there is no succinct list of specific behaviours that may be affected by EMF. Many marine organisms rely on magnetoreception to navigate and orient themselves. Magnetoreception is an organism's ability to detect a magnetic field within its environment subject to its properties, such as changes in intensity, gradient and field direction. There are three hypothesised ways these marine organisms can interpret the geomagnetic field: 1) a mechanically sensitive magnetite-based magnetoreceptor, 2) a light-sensitive chemical-based compass and 3) an anatomical structure that would enable electromagnetic induction [19].

Anthropogenic EMFs, which are often stronger than natural fields, may disrupt various behaviours, including spatial orientation (e.g. spatial preferences, attraction, or repulsion), locomotion (e.g. distance travelled, duration of movement, speed, and acceleration), prey detection, feeding behaviour, and righting reflexes [20] [21] [22] [23] [24]. In principle, such disruptions could impact migration, reproduction, and survival. For example, pelagic larvae may fail to reach critical habitats, and adults may struggle to locate mating or feeding grounds. Physiological effects of EMFs include potential disruptions to cellular signalling nutrient transport, and free radical metabolism. These disruptions may increase oxidative stress, leading to DNA damage, developmental abnormalities, and impacts on gamete function [25] [26] [27] [28].

5.2 Effects of Dynamic Cable EMFs on Environmental Receptors

The following section explores the potential effects of dynamic cable EMFs on various environmental receptors, considering both physical and biological components of the marine ecosystem.

5.2.1 Water

A wide range of magnetic field frequencies and densities can impact biological systems [29] [30] . It has been hypothesised that EMFs influence water's physicochemical properties rather than acting through specialised biological receptors [31] [32]. While the full effects of EMFs on water are not yet fully understood, studies suggest that they may induce changes in hydrogen bonding, surface tension, evaporation rate, ion mobility, and precipitation, with potential persistence for up to two days [31]. These changes can influence biomolecular structures, physiological processes, and information transfer. Studies show that irradiating water with EMF can elicit similar responses to exposing living systems to the same EMF [33] [34].

Studies investigating the effects of EMFs on water often use magnetic field strengths higher than those typically found around subsea power cables. Some of the reported effects are dependent on both the strength of the magnetic field and the frequency of the exposure [35] [36]. Studies suggest that changes in water parameters may be influenced more by the gradient of the magnetic field than by its strength. Magnetic field gradients can affect water by changing how protons in bicarbonate ions behave, which in turn impacts interactions between molecules [37] [38]. Further investigation is needed to determine whether weak EMFs around dynamic cables alter the physicochemical properties of seawater and elicit biological responses in living systems.

5.2.2 Microorganisms

Microorganisms can sense and be influenced by environmental features, such as temperature, light, pressure, gravity, and chemical signals. Magnetotactic bacteria (MTB) can detect magnetic cues of the environment. MTB mineralise and store different nanomagnets in their magnetosomes [39] [40]. The alignment of these magnetosomes allows them to navigate and move along geomagnetic fields (known as magnetotaxis). Other members of microbial communities such as algae and fungi occupy the same habitat as MTB and need to adapt to the same environmental pressures. Studies on the effect of EMFs on microorganisms often show mixed results, possibly due to differences in species sensitivity and EMF properties. Some studies suggest that EMFs emitted from subsea cables may influence magneto-responsive microorganisms. A laboratory study indicated that prolonged exposure to 120 µT AC EMF and 0 magnetic field reduced the concentration of MTB populations and altered their vertical distribution [41].

MTBs play a crucial role in the biogeochemical cycling of iron, sulphur, carbon, and nitrogen, making them key contributors to nutrient cycling in marine ecosystems [42]. Disruptions to their orientation caused by artificial EMFs may alter their distribution and behaviour, potentially impacting these critical processes. The metabolic activity of microbial communities plays a primary role in the flow of essential nutrients and energy in marine ecosystems. Although no information is available from the marine environment, research investigating the effects of electromagnetic fields generated by electric power substations on soil microorganisms found diminished nitrogen fixing capacity nearest to the substation. However, the broader implications for nutrient cycling and marine ecosystem dynamics remain uncertain [43].

Pelagic species, including microorganisms, may be affected by changes in EMF exposure due to biofouling on OWF structures. Biofouling, which affects submerged surfaces in the marine environment, can indirectly influence the effects of EMFs on pelagic species. During biofouling, a macromolecular film is first formed on the submerged surface, followed by microfouling with the growth of microorganisms such as bacteria and microalgae, and finally by the settlement of macrofoulers such as barnacles, mussels, and macroalgae [44]. The added extra layer of biofouling could affect the heat dissipation of dynamic cables, which would alter current flow and consequently EMF intensities. In principle, these changes could in turn affect pelagic species that are sensitive to EMFs. Biofouling could also impact cable movement due to the added weight, potentially altering the size of the EMF impact area. However, the specific effects of these changes on pelagic species remain unclear. Understanding how EMFs influence biofilm formation and microbial adhesion is relevant to pelagic species, as changes in microbial communities can affect food availability and ecosystem dynamics.

Artificial structures, such as OWFs could serve as pathways for the spread of invasive species and pathogens. EMF exposure has also been linked to changes in bacterial morphology, antibiotic susceptibility, and membrane fluidity in species such as *Salmonella enterica* [45] . Weak electric fields have been shown to enhance antibiotic effectiveness against biofilm bacteria [46] [47].

Throughout the Earth's history geomagnetic field shifts have altered microbial environments, but the extent and speed of microbial adaptation to changing magnetic conditions remain uncertain. The varied results across studies suggest that EMF effects on microorganisms depend on species, field intensity, frequency, and duration of exposure. Further research is needed to determine how weak EMFs from dynamic cables influence microbial communities, biogeochemical cycles, biofouling processes, and the spread of invasive species in marine ecosystems.

5.2.3 Invertebrates

Invertebrates are believed to use magnetoreception and electroreception as part of their ecology, but the specific pathways for these abilities are not yet fully understood. Magnetoreception, the ability to detect magnetic fields, is believed to occur in invertebrates, likely through biogenetic magnetite systems [48] [49]. While electro-sensitivity in aquatic invertebrates has not been extensively studied, some behavioural experiments using electric stimuli have triggered responses. This suggests that these invertebrates may possess passive or direct electroreception, potentially through an as-yet-undiscovered electroreceptor [50].

Electroreception, though not well-studied, has been suggested to occur via undiscovered electroreceptors. Research on EMFs and benthic invertebrates across various taxa, including decapod crustaceans, echinoderms, molluscs, and polychaetes, has yielded mixed results, with no clear conclusions regarding the potential effects of EMFs from dynamic cables on pelagic species or species with a pelagic component in their life cycle [20] [23] [51] [52]. Research is required to better understand potential impact pathways and to determine any potential effects, especially using appropriate EMF strengths and exposure durations.

Pelagic invertebrates such as jellyfish, octopus, squid and salps that live in the water column may interact directly with EMFs during their life history. Surveys conducted at Hywind revealed significant faunal coverage on infield cables [53] [54]. The species observed were predominately barnacles (Balanoidea, likely *Chirona hameri* or possibly *Balanus crenatus*), plumose anemone (*Metridium senile*), ringed tubularia (*Ectopleura larynx*), and tube worms (*Spirobranchus spp*.). Young colonies of deepwater corals, possibly *Desmophyllum pertusum,* were also detected on an infield cable [53]. Additionally, gametes and early life stages of coastal and benthic species may also be exposed to EMFs during spawning and larval development, such as zooplankton which was recorded at Hywind Scotland [55].

In situ spatial and behavioural studies on species affected by EMF have yielded mixed results. Two studies focused on animals around energised and unenergised subsea cables. The first study found no significant differences in invertebrate assemblages, except for a few species [56]. For instance, the red octopus was more abundant in natural habitats, though it was still commonly found around energised cables. However, the study did not report EMF values, so it remains unclear whether EMFs played a role. Other factors, such as depth and habitat structure, could also explain the results. The second study, conducted around two energised subsea cables (73.0 µT and 91.4 µT), found no change in behaviour (attractance or repellence) nor spatial distribution of any taxa studied (for pelagic invertebrates, this included octopus spp.) [57]. The Offshore Electric- and Magnetic-Field Assessment for the Revolution Wind Farm, compared the maximum magnetic field modelled for their cables (5.8 µT) with existing research, and concluded that cephalopod distributions, including octopuses, were unlikely to be affected [58].

Studies on the physiological effects of EMFs have largely focused on biofouling species and often used higher EMF levels than those expected around FOW dynamic cables. Research on blue mussels (*Mytilus edulis*), a common biofouling species on offshore wind structures, has shown no lethal effects at 3.7 mT DC, but higher EMFs (5.8 -8 mT) have affected hydration and feeding indicators, similar to reduced filter feeding observed in the lagoon cockle (*Cerastoderma galucum)* at 6.4 mT [59] [60] [61] [62].

EMF effects on gametes and early life stages of invertebrates vary, but most studies have used higher EMF levels than expected for FOW. Exposure to (DC-EMF of 2.8 mT – notably higher than the anticipated EMF intensities produced by FOW power cables) during egg development in brown crabs (*Cancer pagurus)* and European lobsters (*Homarus gammarus)* led to smaller larvae and, in lobsters, increased deformities and lower swimming fitness [25]. While these species are primarily benthic, their pelagic larvae could be exposed to FOW- related EMFs. Further studies using FOW-relevant EMF levels are needed to assess potential impacts on invertebrate reproduction and development.

Currently, there is no directly relevant dynamic cable EMF studies on pelagic invertebrates. And due to the mixed results, and often high EMF levels used in benthic invertebrate studies, no significant conclusions can be applied to FOW from the current research. Relevant research is therefore required to determine whether any of the results seen with high EMF levels on benthic invertebrates applies to pelagic species exposed to FOW EMF levels.

5.2.4 Teleost

Teleost fish exhibit various magnetoreception mechanisms. For example, haddock larvae have been shown to use a magnetic compass for orientation, both in situ and in the lab [63]. Magnetoreception can vary by species, life stage, and location. Atlantic herring (*Clupea harengus*) larvae (14-28 days post hatching) from Norwegian coastal spawners were found to not utilise magnetic compass orientation [64]. Whereas another study focusing on magnetoreception of juvenile herring (5-6 months old) caught in the Baltic Sea found evidence they use magnetic compass sensing during migration [65]. It is, therefore, worth considering the potential impacts of FOW on this species group. It is also possible that EMFs may affect non-electromagnetic receptive species, either adults or during the development of eggs and/or larvae stages [66].

Teleost species studied in relation to EMF impacts are mostly non-native to the UK, such as Chinook salmon and Yellowfin Tuna, or are more demersal, like European Eel or freshwater species [67] [68] [66]. While these species are unlikely to interact with FOW dynamic cables, they would be considered in FOW EIAs, as EMFs from static sections of cables placed on the seabed could affect demersal species. Unfortunately, there are no firm conclusions that can be drawn from other species or ecosystems and applied to UK pelagic species. The limited EMF research on UK pelagic species is summarised below, which primarily focuses on larvae or juveniles.

For instance, exposure to 230 µT EMF was unlikely to affect Atlantic lumpfish (*Cyclopterus lumpus*) migration, and no significant effects were observed in Atlantic Salmon (*Salmo salar*) or lesser sandeel (*Ammodytes marinus*) larvae exposed to EMFs [69] [70]. However, changes in swimming speed were noted in haddock (*Melanogrammus aeglefinus*) and cod (*Gadus morhua*) larvae, potentially altering dispersal patterns [21] [71]. It is unknown if these changes are behavioural or physiological and whether they would lead to a population level effect.

Beyond EMF studies, some preliminary research and environmental surveys have measured the distribution of pelagic fish species, offering potential insight into their general reactions to FOW and possibly EMFs. Surveys of pelagic fish distribution around OWFs suggest that cod may be attracted to cables, though this could be due to visual effects or food availability, not EMFs. Studies on fish composition near mackerel, show no conclusive effects from EMFs [72] [73] . Research around the Alpha Ventus OWF also found no significant impact on pelagic fish species [74].

While pelagic fish species like blue whiting (*Micromesistius poutassou*), and European anchovy (*Engraulis encrsicolus*) may be impacted, more research is needed to determine whether FOW operations affect their distribution and behaviour. Additionally, the Sea Lamprey (*Petromyzon marinus*), a non-teleost species with electroreceptors, may be sensitive to EMFs from dynamic cables, showing responses to electric fields [75].

5.2.5 Birds

Magnetic orientation in birds was first proven in the 1960s in a nocturnal migratory species, the European robin (*Erithacus rubecula*) [76]. It is believed that the magnetic compass of birds functions as an inclination compass, using the dip of the magnetic field lines rather than polarity [77]. This has the advantage of remaining unaffected during reversals of the geomagnetic field poles. Birds' magnetic compass is narrowly tuned to the intensity range of the local geomagnetic field; however, this range can be altered [76].

During migration from Europe to Africa, migratory birds encounter approximately 20 µT difference in the geomagnetic field intensity. Studies on temporal fluctuations of the geomagnetic field due to geomagnetic storms suggests that even 20-250 nT intensity range can affect homing ability and increase vagrancy [78]. Bird magnetoreception requires short-wavelength light; recent studies found that they can visualise magnetic fields through a blue light-sensitive protein in their eyes [79] [80]. Although magnetoreception has been explored in birds, there is no scientific evidence for electroreceptive capabilities to date [50].

Birds' magnetic field-based compass serves as a basic orientation mechanism in many land-migrating species. However, most studies on pelagic seabirds suggest they rely primarily on olfactory and visual cues for navigation, rather than magnetoreception [81] [82] [83] [84]. However, a recent study on the transglobal migrant, the Manx shearwater (*Puffinus puffinus*), showed that shifts in juveniles' return locations could be accurately predicted by changes in Earth's magnetic field, suggesting these birds rely on a geomagnetic map for navigation [85]. Research on other birds, such as chicken (*Gallus domesticus*) embryos and the wild great tit (*Parus major*), has shown that EMFs may affect embryonic development, brain function, and reproduction [86] [87] [88] [89], although it is highly unlikely that dynamic cables in the water column would interact with bird embryos.

The cumulative and combined effects of electromagnetic interference from dynamic power cables on Earth's geomagnetic field and its impact on birds' navigational ability remain unknown. EMF levels around turbines are relatively low and diminish with distance. Some species avoid OWFs, while others, such as cormorants and gulls, are attracted to them, potentially heightening the likelihood of interaction [90]. At present, there is currently limited evidence indicating that FOW dynamic cable EMFs would present a material risk in respect of the above considerations.

5.2.6 Marine Mammals

Based on strandings data, migration routes, and tagging studies, it is suggested that some cetacean species may use geomagnetic cues for navigation [91] [92] [93]. However, reviews on this hypothesis have been mixed, potentially due to species, population, or season-specific effects [94] [95]. Cetaceans are understood to rely on Earth's magnetic field's natural fluctuations and topography for orientation [96]. Species in UK waters that may possess magnetoreception include:

- Atlantic white-sided dolphin (*Lagenorhynchus acutu*),
- Bottlenose dolphin *(Tursiops truncatus*),
- Common dolphin (*Delphinus delphis*),
- Fin whale (*Balaenoptera physalus*),
- Harbour porpoise (*Phocoena phocoena*),
- Humpback whale (*Megaptera novaengliae*),
- Long-finned pilot whale (*Globicephala melas*),
- Pygmy sperm whale (*Kogia breviceps;* limited UK records),
- Sperm whale (*Physeter macrocephalus*),
- Striped dolphin (*Stenella coeruleoalba*).

Due to their large size and extensive migration patterns, controlled experiments on most cetacean species are not feasible. However, some studies have been conducted on trained, captive animals. One study on captive bottlenose dolphins used a neodymium block with a magnetic field strength of 1.2 T, much stronger than emitted from FOW cables. The study found that most behaviours were unaffected, except for a reduced latency to approach the magnetised device [97]. Whilst this may indicate that bottlenose dolphins could detect the magnetic field, there is no evidence to suggest detection of the weaker EMF's emitted from FOW dynamic cables. Another study on captive bottlenose dolphins found no evidence of magnetic discrimination in a 60 μT field. Models indicate that bottlenose dolphins may sense magnetic fields from subsea cables up to 50 meters away, which could potentially alter their travel direction. However, their orientation could be corrected by moving just a few meters away from the influence of the cable [23]. The risk of EMF from FOW is considered minimal, and due to the high mobility of cetaceans, the risk of prolonged exposure is also low. Any increased risk would likely arise from multiple cables along migratory routes [98].To date, there is no evidence that EMF from undersea cables has contributed to mass strandings of marine mammals [99].

As for UK seal species, grey seals (*Halichoerus grypus*) and harbour seals (*Phoca vitulina*) may forage farther offshore. While it has been suggested that seal whiskers could detect a magnetic field, there is currently no direct evidence supporting magnetoreception in seals [100]. A study on captive grey seals found that exposure to an artificial EMF of 8 Hz and 45-50 A/m altered behaviours such as target search time, target pointer hold time, and excitement when an error occurred, although the EMF strength is unspecified [101]. Harbour seals have been observed foraging in and around operational OWFs [102], and it is possible that FOW farms that are closer to shore may be within their range.

5.2.7 Elasmobranchs

The sensory abilities of elasmobranchs, particularly electroreception and magnetoreception, are critical to understanding their potential sensitivity to EMFs. Electroreception is primarily facilitated by the ampullae of Lorenzini, specialised electro-sensory organs that enable detection of weak electric fields, playing key roles in prey detection, social interactions, and predator avoidance [103] [104] [105]. These organs are highly sensitive, supporting the hypothesis that elasmobranchs could be impacted by anthropogenic EMFs, including those from subsea power cables [106] [107] [108] [109].

While direct evidence of magnetoreception in elasmobranchs remains inconclusive, several studies suggest that they may be able to detect magnetic fields, possibly through indirect mechanisms like electromagnetic induction or an undiscovered biogenic magnetite system [22] [110] [23]. Given that magnetoreception is hypothesised to aid in navigation, EMF exposure could potentially interfere with this process, although more research is needed [22] [111].

The majority of EMF research on elasmobranchs has focused on benthic species, including the small-spotted catshark (*Scyliorhinus canicula*) and thornback ray (*Raja clavata*), with studies revealing mixed results regarding the effects of EMFs on spatial use, locomotion, and prey detection [22] [107]. However, the relevance of these findings to pelagic species, such as those found in UK waters, remains unclear. Pelagic species like the Basking shark (*Cetorhinus maximus*) and Blue shark (*Prionace glauca*) are unlikely to experience prolonged exposure to EMFs due to their mobility, therefore may be able to avoid EMF sources [112] [113]. For example, the basking shark has been considered relatively resistant to EMFs. However, a Marine Scotland report called for further investigation into their distribution and behaviour in relation to EMFs [114].

Despite the lack of direct studies on the impacts of EMFs from offshore wind cables on pelagic species, some species have been inferred to be sensitive based on their electroreceptive abilities and migratory behaviours. Blue sharks, for example, have exhibited feeding behaviours toward artificial electric fields, and magnetic deterrents have attracted both blue and Greenland sharks [115] [116] [117]. These observations suggest that pelagic species could be sensitive to EMFs, though more research is required to assess the potential impacts comprehensively.

Moreover, while assumptions are often made based on electroreceptive structures conserved across elasmobranchs species, the effects of EMFs on pelagic species may vary. Pelagic species are expected to experience transient contact with EMFs, reducing the likelihood of significant effects. However, species like the tope and porbeagle, which migrate across multiple habitats during different life stages, could be more susceptible to EMF exposure due to their increased likelihood of encountering EMFs [118].

In summary, while current research on the effects of EMFs on pelagic elasmobranchs is limited, there is evidence suggesting potential impacts, particularly concerning their electroreceptive abilities and migratory patterns. More focused studies are needed to determine the direct effects of EMFs on these species and to evaluate any broader ecological implications, such as potential trophic cascades that could impact pelagic elasmobranch populations [118].

5.2.8 Wider Interactions

Beyond the direct impacts EMFs may have on individual species, it is crucial to consider their broader effects at different trophic levels, as well as the cumulative impacts of multiple stressors. For instance, if certain species are found to be affected by EMFs, their role within a trophic network could have implications for the wider ecosystem. Additionally, in principle it is possible that some species may not show a direct response to EMFs alone, but in-combination effects with other stressors (such as operational noise, for example) could result in potential impacts. Future research must account for these complexities, as current knowledge remains limited. Important areas of focus include trophic level impacts, effects on fisheries, interactions with other stressors (e.g., chemical pollution, collision, and entanglement), hydrodynamic changes, noise, and the spread of invasive species.

6 CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

As the offshore wind industry expands to meet deployment targets, the introduction of FOW technology presents new environmental considerations, including the EMF emissions generated by dynamic cables. This report reviews the existing body of knowledge relating to dynamic cable EMFs, identifies key research gaps, and offers recommendations for future investigations.

FOW dynamic cables produce time-varying EMFs which could have implications for pelagic species, particularly those relying on natural magnetic and electric cues for navigation, migration, and foraging. While EMF emissions from offshore wind inter-array cables are generally low, they can still fall within the sensory range of certain species.

This report identifies a number of knowledge gaps and uncertainties relating to the research on FOW dynamic cable EMFs. These include both technical and environmental considerations. While several engineering and design challenges for FOW dynamic cables are currently under investigation, the gaps highlighted here focus principally on our understanding of, and ability to assess, the environmental interactions of dynamic cable EMFs.

It is important to note that an absence of evidence should not be interpreted as evidence of adverse effects. Indeed, it highlights the requirement for further research to clarify the potential environmental implications of dynamic cable EMFs.

Technical knowledge gaps highlighted in the report include:

- Modelling Requirements for Dynamic EMF Emissions – Further refinement in EMF modelling capabilities is required to incorporate dynamic-specific variables, including: tidal current velocities, power core geometry, cable alignment or "straightness", and motion-induced EMF generation.
- Attenuation and Absorption Characteristics of Dynamic Cables – The ability of dynamic power cables to absorb or attenuate EMFs, is not yet fully understood.
- Role of Cable Armour **–** The impact of armour on EMF emissions and shielding effectiveness is not well defined. Further work is also required to assess the EMF mitigation abilities of dynamic cables with a double armour layer design.
- Influence of Cable Motion on EMF Emissions **–** The effects of dynamic cable motion on EMF emissions are not yet accurately characterised.
- Lack of Field Data from FOW Pilot Projects – There is a current lack of empirical field data from floating offshore wind demonstration or pilot sites to validate existing EMF models and theoretical predictions.

Environmental knowledge gaps identified in the report include:

- Influence of EMFs on Physical and Chemical Water Parameters – The potential effect of EMFs on physicochemical properties of seawater, is not well characterised.
- Effects on Marine Biofouling and Microbial Communities – The impact of EMFs on biofouling organisms, cable-associated marine growth, and microbial communities (e.g., biofilms or sediment microbes) is currently unknown.

- Ecological Effects on Invertebrates **–** Further research is required to better understand potential impact pathways and to determine any potential effects on invertebrates, especially using appropriate EMF strengths and exposure durations.
- Effects on Pelagic Elasmobranchs – Further research is required to understand EMF exposure effects on pelagic elasmobranch species, including potential disruption to their electroreceptive capabilities and migratory behaviour.
- Responses of Teleost Fish – There is an absence of conclusive research on the behavioural and physiological responses of teleost fish to EMF exposure, particularly under field-representative conditions.
- Combined and Cumulative Effects with Other Stressors – The potential for in-combination effects between EMFs and other anthropogenic stressors (e.g., noise pollution, habitat alteration, thermal effects) is currently unknown.

The development of a robust and validated EMF calculation methodology, supported by site-based measurements, would be a significant step in addressing a number of the identified technical knowledge gaps. The ability to account for the effect of floating structure dynamics, as well as the characteristics of HVDC systems, on EMF emissions would also be valuable. Advancing this knowledge could help to inform future cable design and operational practices that account for environmental considerations.

A combination of laboratory and field studies would be required to address the identified environmental knowledge gaps. Laboratory studies should include dose–response experiments to identify species- and life-stage-specific sensitivities to anthropogenic EMFs, with particular emphasis on mid- to long-term exposure, as well as the potential for recovery or habituation. Further, long-term ecological monitoring across the life cycle of FOWs would support the assessment of both spatial and temporal variations in EMF exposure, as well as cumulative effects from multiple environmental stressors. A holistic approach that integrates monitoring and modelling will be key to understanding the broader ecological consequences of dynamic cable EMFs and anticipating future impacts.

Ultimately, addressing the identified knowledge gaps will require a combination of targeted research, in-situ monitoring, and cross-disciplinary collaboration. A series of proposed next steps and enabling actions have therefore been outlined as the basis for further research to address these gaps.

6.2 Recommendations

The following recommendations have been developed in response to the range of knowledge gaps identified during this review. They are intended to guide future efforts through targeted research, long-term monitoring, and cross-disciplinary collaboration.

6.2.1 Technical Research Priorities

- EMF Calculation and Modelling – Develop a standardised approach for modelling AC dynamic cable EMF emissions, with consideration of trefoil arrangements.
- Cable Design Influence – Assess the influence of various dynamic cable designs effect on EMF generation and attenuation, engaging with CIGRE WG 1.92 on wet, dry, semi-wet, and semi-dry cable configurations.

- Experimental EMF Studies – Facilitate collaboration between cable manufacturers and testing facilities to conduct controlled experiments on EMF emissions from a range of dynamic cable designs. These studies should evaluate the influence of armour and sheath layers on EMF attenuation and investigate the effects of metallic layer conductivity through both laboratory testing and simulation.

- Cumulative EMF Effects – Develop an integrated EMF modelling approach that accounts for cumulative exposure by combining emissions from multiple dynamic cable sources.

- Induced Electric Fields – Integrate induced electric field calculations into EMF modelling frameworks and field measurement campaigns to ensure they accurately reflect conditions in dynamic subsea cable systems

- Floating Structure Influence – Engage with FOW designers and developers to assess how environmental conditions and dynamic cable movements affect EMF emissions and their propagation.

- HVDC Systems and EMF - Collaborate with HVDC converter specialists to characterise harmonic frequency outputs from filtering and power conversion equipment. This information can support research into the EMF emissions associated with HVDC export cables and floating substations, including the potential biological relevance of low-frequency harmonics.

6.2.2 Ecological Research Priorities

- Key species identification – Identify key species across relevant trophic levels that are likely to interact with FOW dynamic cables, and define appropriate assessment parameters (including behavioural and physiological indicators) to determine the key ecological considerations.

- Dose-Response Modelling – Develop dose–response models informed by both laboratory and field data to support scenario-based assessments of species exposure to dynamic cable EMFs. For FOW-specific analyses, it is important that the EMFs intensities applied are relevant to the values that would be observed within FOW farms.

- Long-Term Environmental Monitoring – Identify collaborative monitoring opportunities at pilot-scale and early commercial FOW farms to assess dynamic cable EMF emissions and the potential resulting medium-to-long term environmental interactions. Engagement with FOW owner-operators will support the selection of appropriate sensor deployment sites.

- Interdisciplinary Monitoring Methodology – Develop a dynamic cable EMF monitoring framework, incorporating expertise from engineering, biology, oceanography, and physics to support comprehensive environmental assessments.

- Standardised Laboratory Protocols – Establish industry-wide methodologies for laboratory studies on dynamic cable EMF emissions, ensuring environmental relevance, the applicability of the studies for FOW designs, consistency in data generation and analysis, and effective dissemination of results.

These recommendations provide a foundation for future research to establish a baseline understanding of the ecological implications of dynamic cable EMFs. Addressing these priorities will support both regional and species-specific assessments, supporting the responsible development of future commercial FOW farms.

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