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Svendsen, Jon Christian; Ibanez-Erquiaga, Bruno; Savina, Esther; Wilms, Tim

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DTU Aqua Report no. 411-2022

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List of abbreviations

AC: Alternating current
AEP: Auditory evoked potential
DC: Direct current
EMF: Electromagnetic field
EU: European Union
FA: Fluctuating asymmetry
GMF: Geomagnetic field
HVAC: High-voltage alternating current
HVDC: High-voltage direct current
MF: Magnetic field
OWF: Offshore wind farm
PCAD: Population consequences of acoustic disturbance model
PM: Particle motion
Re: Reference unit
SPL: Sound pressure level
UWN: Underwater noise

Preface

This report presents the results of the review study on “Effects of operational offshore wind farms on fishes and fisheries” carried out by scientists at DTU Aqua. The project is commissioned research financed by the Danish Energy Agency (DEA), which is a part of the Ministry of Climate, Energy and Utilities.

Energistyrelsen

Klima-, Energi- og Forsyningsministeriet

Offshore wind farms (OWFs) are a strong source of renewable energy and represent crucial elements for achieving a sustainable future. While a rapid expansion of OWF implementation is ongoing and planned, potential long-term impacts on biodiversity, specifically fish communities, remain uncertain. This may limit acceptance of OWF implementation in various areas, although some reports have indicated potential collaboration between OWFs and fisheries. Concurrently, researchers are gathering novel data regarding OWF effects on the marine environments as well as knowledge on suitable management plans to mitigate conflicts between OWFs and other users of the marine areas.

The present report details a scientific review study where we summarised available information on the direct effects of four potential stressors associated with OWFs: electromagnetic fields, underwater noise, particle motion, and vibration, considering the operational stage of OWFs. Our conclusions are meant to guide upcoming management plans, OWF implementations and future studies regarding OWFs and their diverse potential effects on the marine environments.

The review study has benefitted from input and comments from collaborators at DEA, including Charlotte Boesen, Sine Matzen Christiansen and Søren Enghoff. Despite this constructive collaboration, report conclusions and recommendations have been reached independently of DEA. Finally, the authors thank Birte Holst Jørgensen, Anni Tolborg Smith and Helle Holm Nielsen for enabling the economic parts of the project.

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Senior Researcher

Silkeborg, September 2022

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Summary

Offshore wind farms (OWFs) are a crucial element for achieving a sustainable future due to their provision of renewable energy. The rapid expansion and build-out scenarios of OWFs often surpasses the knowledge of their long-term impacts on biodiversity, specifically on fish communities. Therefore, acceptance of OWFs may vary between areas, and the fishing industry is often concerned, although some cases have revealed the potential for collaboration between OWFs and commercial fisheries. Worldwide, researchers are producing relevant information, ranging from OWF effects on different marine species and ecosystems to management strategies for dealing with conflicts in overlapping areas of OWFs and fisheries. However, the knowledge remains scattered in the scientific literature and may advance at a higher pace than the rate at which the observations are clustering. Aiming to provide an informed understanding of the potential influence of OWFs on fish and fisheries, we conducted a systematic review of peer-reviewed scientific literature. Specifically, we assessed the direct effects of four potential stressors: electromagnetic fields (EMFs), underwater noise (UWN), particle motion (PM), and vibration, relevant for OWFs during the operational stage. We targeted the operational stage, because it is the longest stage of an OWF, covering most of its lifetime. Moreover, to date, environmental research on the potential impacts during the OWF construction stage surpasses previous environmental research relevant for the operational stage. Using results from Web of Science and Scopus search engines, we covered a total of 5,181 records and applied scientific review approaches to identify 67 scientific publications of direct relevance to the review topics. We observed that most literature consisted of non-empirical studies (i.e., not producing new data; n=40), while empirical studies (i.e., producing new data; n=27) were scarce and mainly restricted to EMFs (n=17) and UWN (n=10). Our results show a positive trend in the number of peer-reviewed studies published per year, likely associated with increasing concern about anthropogenic impacts related to global OWF developments. Subsea cables used for inter-array and offshore-onshore transportation of energy emit anthropogenic EMFs into the surrounding environment that may be perceived by a range of electro- and magnetoreceptive fishes. While such emissions have the potential to alter the movement and migratory behaviour of fishes, our review indicates that current evidence of negative EMF effects are mainly limited to laboratory studies assessing early life development of fish. These laboratory studies generally indicate significant alterations in a variety of developmental processes, yet EMF intensities and exposure times are variable and often exceed values encountered near OWFs, making it challenging to extrapolate laboratory findings and assess wider population-level impacts for fish and fisheries. In addition, laboratory experiments may be associated with methodological artifacts. For example, when restricting the spatial positioning of the study organism within close proximity of the EMF source, the study results may not reflect realistic *in situ* exposure times and intensities. Although behavioural and physiological changes have been reported in fish exposed to UWN levels associated with operational OWF, the changes appear to be limited. Direct experiments covering the effects of OWF induced PM or vibration on fish were not found in the examined literature, however, PM and vibration were consistently highlighted as relevant but largely overlooked stressors. In addition, OWF structures may have several ecosystem effects in marine environments, including stepping-stone effects for indigenous and non-indigenous species and local artificial reef effects. Specifically, OWF structures may enable indigenous and non-indigenous species to occur in novel areas, while OWF scour protection and foundations may benefit species associated with hard substrates, providing shelter, food, and reproduction opportunities, similar to artificial reefs. As the OWF industry is rapidly expanding to meet the increasing demand for renewable energy, we also briefly explore floating OWF technologies that are currently emerging and discuss their potential effects on fish. In addition, we briefly outline management strategies that can be employed to minimize the risk of negative impacts on fish and fisheries due to future OWF expansion. Finally, we summarize important future research areas that were identified by this review as critical to advance our limited understanding of OWF impacts on fish and fisheries. In general, we recommend

allocating resources for experimental *in situ* research accounting for fish exposure to known levels of relevant stressors (e.g., EMF, UWN, PM, vibration) and assessments of physiological and behavioural responses in fish.

1. Introduction

1.1. Renewable energy transition

The global demand for renewable energy worldwide is at a record high, as current levels of fossil fuel use continue to exacerbate the loss of natural habitats, sea ice cover and biodiversity (Segan et al., 2016; Stroeve & Notz, 2018; Teixidó et al., 2018), while jeopardizing human health and wellbeing through air pollution, extreme weather events and global food and drinking water shortages (Mora et al., 2018; Shindell & Smith, 2019). Annual additions in renewable energy capacity broke a new record in 2021, adding 295 GW in renewables globally despite significant challenges related to supply chains, construction delays and high prices of raw materials as a result of the COVID-19 pandemic (International Energy Agency, 2022). While solar power accounts for the majority of growth in renewables globally (forecasted at about 60% for 2022), the development of the offshore wind industry is rapidly gaining momentum with an almost six-fold increase in offshore wind farm (OWF) installations in 2021 relative to the previous year (International Energy Agency, 2022). This is most evident within the European Union (EU), where member states have pledged to boost OWF energy production to a minimum of 60 GW by 2030 and 300 GW by 2050, requiring a massive change of scale at nearly 30 times the current capacity of offshore renewable energy and an estimated EUR 800 billion in investments (European Commission, 2020). Given the recent geopolitical events in Europe, including Russia's invasion of Ukraine, and the associated elevated urge to significantly reduce the EU's dependence on fossil fuels, the four EU member states of Belgium, Denmark, Germany and The Netherlands have now pushed for a further acceleration in OWF production. In the 'Esbjerg Declaration', the four member states pledge to produce 65 GW by 2030, and at least 150 GW by 2050, comprising half of the production planned by the entire EU (Bech-Bruun, 2022). While Europe has traditionally led the way in OWF development ever since the world's first OWF was commissioned in Denmark in 1991 (deCastro et al., 2019), other major world economies have notably increased their commitment to OWF development over the past decade. For example, China has recently become the world leader in total offshore wind capacity by installing 16 GW in a single year (Netherlands Enterprise Agency, 2022), while the Biden administration announced OWF development targets of 30 and 110 GW for the USA by 2030 and 2050, respectively (The White House, 2021). Clearly, such rapid accelerations of OWF development worldwide will significantly increase our anthropogenic footprint within offshore marine environments, while concurrently raising the potential for conflicts with various other ocean users (e.g., fisheries).

1.2. Offshore wind and fish

The expansion of the offshore wind industry may generate underestimated spatial conflicts with fisheries (Berkenhagen et al., 2010). Commonly, regulators dictate fishing closure or restricted activity areas within and surrounding OWFs for navigation safety and cable protection purposes (Halouani et al., 2020; Hammar et al., 2015). In an environmental context, the closure areas could benefit from the limited fishing pressure, or even act as *de facto* marine protected areas (Hooper et al., 2017). Although these closure areas could replenish overfished areas via spill-over effects (i.e., thriving fish populations within the closure area, and abundant fish leaving the area) (Halouani et al., 2020), the areas which remain open to fishing could be subjected to increased fishing pressure by relocated fishing fleets (i.e., effort displacement) (Ivens-Duran, 2014; Sen, 2010; Stelzenmüller et al., 2022). On the other hand, some policies seek to encourage opportunities for coexistence between OWF development, fishing, and other offshore activities (Hooper et al., 2015). For example, focus is being given to co-location of OWFs and aquaculture (Buck et al., 2004). In addition, empirical evidence is being gathered for the co-use of OWFs and passive fishing gears (Stelzenmüller et al., 2021). However, concern remains on the potential effects that OWFs could have on fish populations and fish landings. These concerns are mainly raised by the commercial fishing communities, where allegations refer to OWFs taking away fishing grounds and destroying the environment (Degraer et al., 2020). Traditional users (e.g., commercial fisheries, commercial shipping) even express concern about being marginalized in the long run and ending up with fewer resources (Buck et al., 2004). Conversely, other marine users support OWF development, including recreational fisheries reporting increases in fish abundance (Degraer et al., 2020). A study in New Hampshire, USA indicated an overall positive perception from recreational users of coastal areas, including fishing operators, towards offshore wind energy development (Ferguson et al., 2021).

Biotic and abiotic outcomes from OWF development are complex and may lead to changes in the biodiversity associated with natural habitats (Causon & Gill, 2018; Dannheim et al., 2020). On the one hand, OWF structures, such as monopiles and scour protection, may act as artificial reefs (Glarou et al., 2020), attracting fish species and even increasing local fish abundance in comparison to neighbouring areas (Mavraki et al., 2021; Methratta & Dardick, 2019). The hard substrate associated with OWFs is colonized by multiple species, often enhancing biodiversity and biomass locally, and this leads to increased availability of food for other trophic levels (Degraer et al., 2020). The OWF structures can also provide refuge or promote the growth of habitat-forming species (i.e., ecosystem engineers), which also provide refuge, settlement area, and foraging opportunities (Degraer et al., 2020; Glarou et al., 2020). On the other hand, OWF development may generate several potential stressors for fish (Petersen & Malm, 2006). These stressors include electromagnetic fields (EMF) (Dannheim et al., 2020), underwater noise (UWN) (Kikuchi, 2010), particle motion (PM) (Sigray & Andersson, 2011), and vibration (Popper et al., 2022), among others. The intensities and durations of emissions of these stressors are variable and often strictly associated to each stage of the OWF life cycle. The stressors are present to a variable degree during the commissioning and construction stages of OWFs, however, the durations of those OWF stages are relatively short. In contrast, the duration of the operational stage of OWFs is usually considerably longer (20+ years). In the present report, we examine the effects of the potential stressors EMF, UWN, PM and vibration within the context of the operational stage of OWFs.

1.2.1. Electromagnetic fields: electrosensory system, magnetoreception and subsea cables

Electromagnetic fields (EMFs) constitute a prominent abiotic feature within the marine environment and can be perceived and utilized by a range of marine organisms. An EMF can be divided into electric fields (also termed E-fields), measured in V/m, and in magnetic fields (MF) (also termed B-fields; i.e. magnetic flux density) that are expressed in tesla units (T), usually nanotesla (nT) or microtesla (μT). E-fields occur naturally in the marine environment, for example when an electric conductor (e.g., seawater or an organism) moves through a B-field (resulting in induced electric fields; iE-fields). Marine organisms also continuously generate electric fields (i.e., bioelectric fields) during key life processes such as ionic transport across membranes and rhythmic muscle contractions (Crampton, 2019), while a number of predatory fishes are known to actively produce electric discharges to stun their prey (e.g., torpedo rays; Lowe, Bray, & Nelson, 1994). Electric signals can be perceived by electroreceptive fishes either via ampullary receptors (e.g., in elasmobranchs) or via tuberous receptors (e.g., in electric knifefishes; Order: *Gymnotiformes*). However, while elasmobranchs like sharks and rays use their ampullae to detect very weak bioelectric fields that emanate from prey species (i.e., passive detection), electric knifefishes possess both tuberous and lateral line ampullary receptors that additionally allow these fishes to generate E-fields for navigation and communication (i.e., active detection), alongside prey detection (Crampton, 2019). Earth's geomagnetic field (GMF) is generally the dominant natural source of magnetic field that marine organisms are exposed to throughout their life and is generated by convection of molten iron in Earth's inner core (Copping et al., 2016; Nyqvist et al., 2020). Local anomalies in EMF intensity occur as a result of magnetized rocks present in the Earth's crust, which may locally enhance or reduce the intensity of the natural GMF (Nyqvist et al., 2020). Although magnetoreception, i.e., the ability of an organism to perceive a magnetic field and changes in its intensity and direction (Formicki et al., 2019), has been demonstrated through behavioural tests for life forms ranging from bacteria to mammals, the sensory mechanisms allowing for magnetoreception remain a scientific mystery (Nordmann et al., 2017; Warrant, 2021; Naisbett-Jones & Lohmann, 2022). For marine fishes, there is evidence suggesting that the GMF is used for a variety of navigational strategies (Klimley et al., 2021), including to determine directionality and maintain heading (i.e., compass use), to extract large-scale spatial information (i.e., magnetic map) and to identify local anomalies that can serve as 'landmarks' along migration routes (i.e., topotaxis). For example, scalloped hammerhead sharks (*Sphyrna lewini*) swim in a highly directional manner during nightly migrations from seamounts to their feeding grounds and back, movements shown to be consistently along magnetic maxima and minima leading away from the seamount, giving rise to the hypothesis that these sharks use geomagnetic topotaxis for navigation (Klimley, 1993). Although continuously changing, currently at an estimated rate of 0-120 nT per year depending on geographic location (Nyqvist et al., 2020), the natural GMF provides a reliable source of navigation for marine fishes within their relatively short lifespan. However, the increasing presence of anthropogenic EMF within the marine environment may alter the behaviour of marine organisms and impact their ability to utilize natural EMF for navigation and prey detection. Anthropogenic EMF signatures were already introduced to the marine environment through e.g., telecommunication and power cables as early as in 1811 with the first cable laid underwater (Taormina et al., 2018), as well as by bridges and tunnel constructions. Yet the rapid pace of ongoing OWF development will significantly increase the presence of anthropogenic EMFs and thereby the rates at which they are encountered by marine organisms. Subsea cables used during OWF operation produce anthropogenic E-fields and B-fields, with intensities depending on the type of electric current, type of cable and environmental conditions, among other factors (Gill & Desender, 2020). At present, high-voltage alternating current (HVAC) cables are used to interconnect individual turbines within individual OWFs and to their substations, while HVAC or high-voltage direct current (HVDC) cables can be used to export the energy to land (Gill & Desender, 2020). This implies that anthropogenic EMF are generated both within OWFs and along the cable routes connecting OWFs to land. While E-fields generated by both cable types remain confined within the protective layer of the cable, the generated B-fields cannot be confined and differ in characteristics depending on the cable type, thereby likely inducing differential effects on fish species (Öhman, Sigray, & Westerberg, 2007). The time-varying B-fields emitted by multiple cores within HVAC cables result in rotating B-field emissions and thereby locally create iE-fields above the seabed, in contrast to HVDC cables that emit static B-fields not accompanied by additional iE-fields (Öhman et al., 2007; Newton, Gill, & Kajiura, 2019). Anthropogenic B-fields emitted by subsea cables can have intensities exceeding that of the natural GMF field by hundreds of μT close to the cable, but approach natural intensities at about 6 m distance and beyond depending on the type of cable and electric current, indicating that the emitted B-fields can potentially affect magnetoreceptive fishes near the cables (Taormina et al., 2018). Likewise, anthropogenic E-fields associated with subsea cables have an intensity ranging approximately between 1-100 μV/cm, which is similar to the intensity range of bioelectric fields (used by electroreceptive predators to detect prey) and thus fall within the detection range of electroreceptive fishes (Gill & Desender, 2020). Therefore, anthropogenic EMF emissions associated with OWFs can be detected by marine fishes and have the potential to affect their migratory behaviour and prey detection capabilities.

1.2.2. Underwater noise, particle motion, and vibration

Under water noise (UWN) is typically described as the ocean background sounds, either natural or anthropogenic, with no biological meaning (Hildebrand, 2009; Thomsen et al., 2021). To further define UWN, it is relevant to scrutinize the term 'sound'.

The potential effects of sound on fishes are ecologically relevant. To comprehend sound effects, each sound constituent needs to be examined and assessed individually for potential impact (see Box 1; Popper & Hawkins, 2018). Using ISO Standards, sound is defined as an 'alteration in pressure, stress or material displacement propagated via the action of elastic stresses in an elastic medium and that involves local compression and expansion of the medium…' (synonym of 'acoustic' in compound words; ISO, 2017). The ISO definition uses 'elastic stresses' as pressure (force per unit of area) not strong enough to permanently deform a material, and 'elastic medium' as a medium that can change its shape when any deforming force is applied, and then return to its original shape once the force is absent (With, 2006).

In the ocean, several different sources of sound are composing a soundscape. A soundscape is defined as the 'characterization of the ambient sound in terms of its spatial, temporal, and frequency attributes, and the type of sources contributing to the sound field' (ISO, 2017). The sounds are mainly categorized based on their source as 'geophony' (e.g., wind, waves; geophysical), 'biophony' (e.g., scrapes, snaps, songs; i.e. biological), and 'anthropophony' (e.g., engines, explosions, sound based surveys; i.e. anthropogenic) (Nedelec et al., 2021). Many fishes, and other marine animals, depend on sound communication for biological activities such as navigating, finding mates, foraging, escaping predation and avoiding hazards. Increasing human activities may act as sound sources, with the potential to influence biological activities. Specifically, acoustic disturbance consequences could scale from individual to population level (Fig. 1) (Hawkins & Popper, 2017).

The Population Consequences of Acoustic Disturbance model (PCAD; National Research Council, 2005) provides a sequential method for evaluating the consequences of UWN (Hawkins & Popper, 2017). PCAD advises to (A) characterise the acoustic signal of stress first; then to (B) describe the resulting changes (physical, physiological, behavioural), and (C) measure any affected life functions (e.g., migration or response to predator). Subsequently, (D) investigate changes in vital rates (e.g. survival or maturation), or individual fitness, of the affected organisms, with implications for the associated populations. The last stage of PCAD (E) is to examine population impacts that affect subsequent generations (e.g., birth and death rates, fertility rates, age composition, growth structure dynamics, extinction probability) (National Research Council, 2005; Hawkins & Popper, 2017). Provided that the term 'sound' refers to the energy radiated from a vibrating object, without a reference to its function or effect, the term 'noise' is introduced to define sound that is not a useful signal (i.e., with no biological meaning) (Thomsen et al., 2021). Therefore, UWN, which is the ocean ambient noise, results from natural and anthropogenic sources (Hildebrand, 2009). Sound sources of UWN can be categorized as impulsive (e.g., percussive pile driving, explosions, seismic surveys; i.e., relatively short duration) or continuous (e.g., shipping traffic, operational wind turbines, operational oil and gas platforms; i.e., occurring consistently) (Thomsen et al., 2021).

Box 1. Brief description of sound and the links to particle motion (PM)

There are two elements, which comprise sound: PM and sound pressure (Sigray & Andersson, 2011). A disturbance in an elastic medium (e.g., seawater) will cause an oscillation of the particles (i.e., the smallest element of the medium, e.g., water molecules, representing the mean density of the medium; Popper & Hawkins, 2018) in the medium around the point of origin. This process is called PM. On the other hand, sound pressure is the consequence of PM, when the oscillation of the particles forms local compressions and expansions, transferring energy to nearby particles (Nedelec et al., 2021). The frequency of the oscillations is measured in Hertz (Hz; i.e. cycles per second). PM can be described by particle displacement (m), velocity (m/s) or acceleration (m/s^2). Sound pressure is described by fluctuations around the hydrostatic pressure as force per unit of area in Pascals (Pa) (Nedelec et al., 2021). The amount of energy propagating through a given area, and in a given time, is the intensity, for which units are watts per square meter (W/m^2). Sound intensity values frequently range through nearly 12 orders of magnitude, so sound intensity *'levels'* are used instead. A *'level'* is a logarithmic quantity expressed as 10 times the logarithm of the ratio of two given numbers (i.e., a value of interest and a value of reference). The term '*bel'* is the unit given to the logarithm of a number divided by a reference quantity, but in acoustics, the *'decibel'* (dB) (one tenth of a '*bel'*) has been adopted for working with numbers of convenient sizes (Long, 2014).

Level = 10 log [Number of interest/Number of reference]

The sound intensity is then usually expressed in *decibel* (dB) and calculated as $10\log_{10}(I/I_0)$, where I is the sound intensity, and I_0 is the intensity of human hearing threshold. Nonetheless, the most commonly used indicator of the strength of the acoustic wave is the sound pressure level (SPL) (Long, 2014). Sound pressure levels are referred to in dB, using the reference unit (re) of 1 µPa (Thomsen et al., 2021). SPL are used for indicating the strength of an acoustic wave because human perception correlates higher levels of SPL with loudness (Long, 2014). The dB level for SPL is calculated as $20\log_{10}(p/p_0)$, where p_0 is the reference pressure (usually 1 µPa in underwater acoustics), and p is the local pressure fluctuations (i.e., sound pressure) (Kanis, 2005; Long, 2014; Wahlberg & Westerberg, 2005). Thus, sound intensity level (in dB) denotes the acoustic energy flowing through an area in space, while sound pressure level (in dB re 1 µPa) is the amount of force at a given point in space.

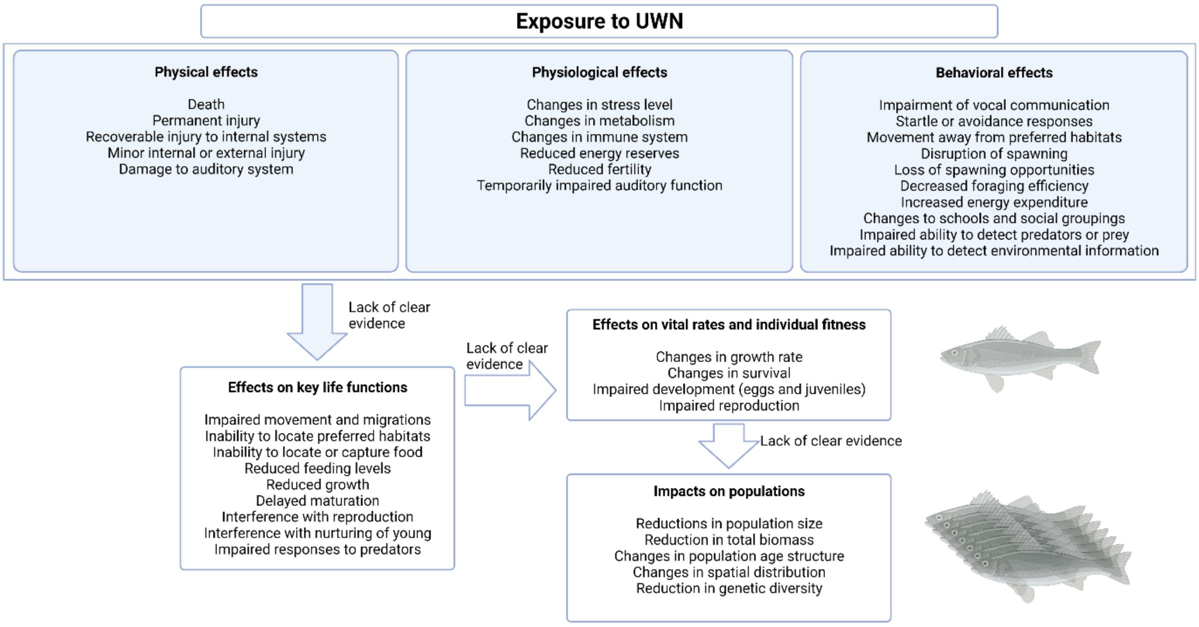

Figure 1. Population Consequences of Acoustic Disturbance model (PCAD; National Research Council, 2005). Framework for assessing the effects of underwater noise (UWN) on fish with respect to hypothesized impacts on key life functions, vital rates, and population parameters. Currently, there is limited evidence as to whether changes to key life functions and vital rates occur, with specific impacts on populations (Hawkins & Popper, 2017). This figure was redrawn from Hawkins & Popper, 2017 (Created with BioRender.com).

The stressor types UWN, PM and vibration are related (Fig. 2). Underwater sound is generated by the movement or vibration of objects (i.e., source) immersed in the medium (i.e., seawater) (Popper & Hawkins, 2018; Box 1). The medium particles next to the source are moved backwards and forwards in an oscillatory motion, causing the movement of their contiguous medium particles and resulting in the propagation of sound (Nedelec et al., 2016). The medium particles do not travel with the propagating sound; instead, they transmit their motion to their neighbouring particles (Nedelec et al., 2016). This process is known as PM. The compression and rarefaction (i.e., increase and decrease in density, respectively) of medium particles as sound propagates will generate a variation in hydrostatic pressure; this process is known as sound pressure (Nedelec et al., 2016). Sound is comprised of PM and sound pressure (Nedelec et al., 2021); however, it is commonplace to characterize sound by the sound pressure alone (Popper & Hawkins, 2018). Vibration is defined as ‘mechanical oscillations about an equilibrium point’ (ISO, 2018) and can be measured using the same terms used for PM (e.g., particle velocity, particle acceleration) (Kent et al., 2016). From a large-scale perspective, on land systems sound could be distinguished from vibration in that sound propagates through the air, whereas vibration propagates through the substrate (e.g., soil, a leaf, a stem; Hill, 2009; Roberts & Elliott, 2017). Provided that sound and water-borne vibration could relate to the same energy underwater, a differentiation becomes complex between vibration, sound, and/or PM (Roberts & Elliott, 2017). For example, in underwater bioacoustics, the term vibration is sometimes used as the PM component of sound (Popper & Hawkins, 2018). Also, a report from the European Commission defined ‘sound’ as vibration existing in a fluid, and ‘vibration’ as energy propagating through wave motion in a solid (Thomsen et al., 2015). As a result, the literature is replete with different terms used for PM and vibration (e.g., using vibration for describing all types of PM, the complete acoustic field, or seabed motion; Roberts & Elliott, 2017). Although the PM component of sound could also propagate through the seabed, in the present report, PM is defined as oscillation of seawater particles from their equilibrium (Box 1), which is common practice in the bioacoustics literature (Roberts & Elliott, 2017). Hence, the stressor PM is used for the water-borne stimulus, while vibration is restricted to substrate-borne stimulus. Popper et al. (2022) present priorities for OWF development, mixing primary research with coordination with OWF developers (e.g., during OWF project design stage), to enhance the understanding of the cumulative impacts of UWN (characterized by assessing values of sound pressure and PM), and vibration. In the same line, Roberts & Elliott (2017) highlight the need for assessing vibration as a stressor, proposing the existence of an analogue of the soundscape underwater (i.e., 'vibro-scape'). A 'vibro-scape' would be restricted to the sediment and would be composed by waves, turbulence, earthquakes, and biological activities affecting the sediment, such as movement, burrowing, and foraging (Roberts & Elliott, 2017). To assess how certain linked stressors (i.e., UWN, PM, and vibration) could potentially affect fishes, it is crucial to frame stimuli perception in fish, with a general description of the physiological pathways.

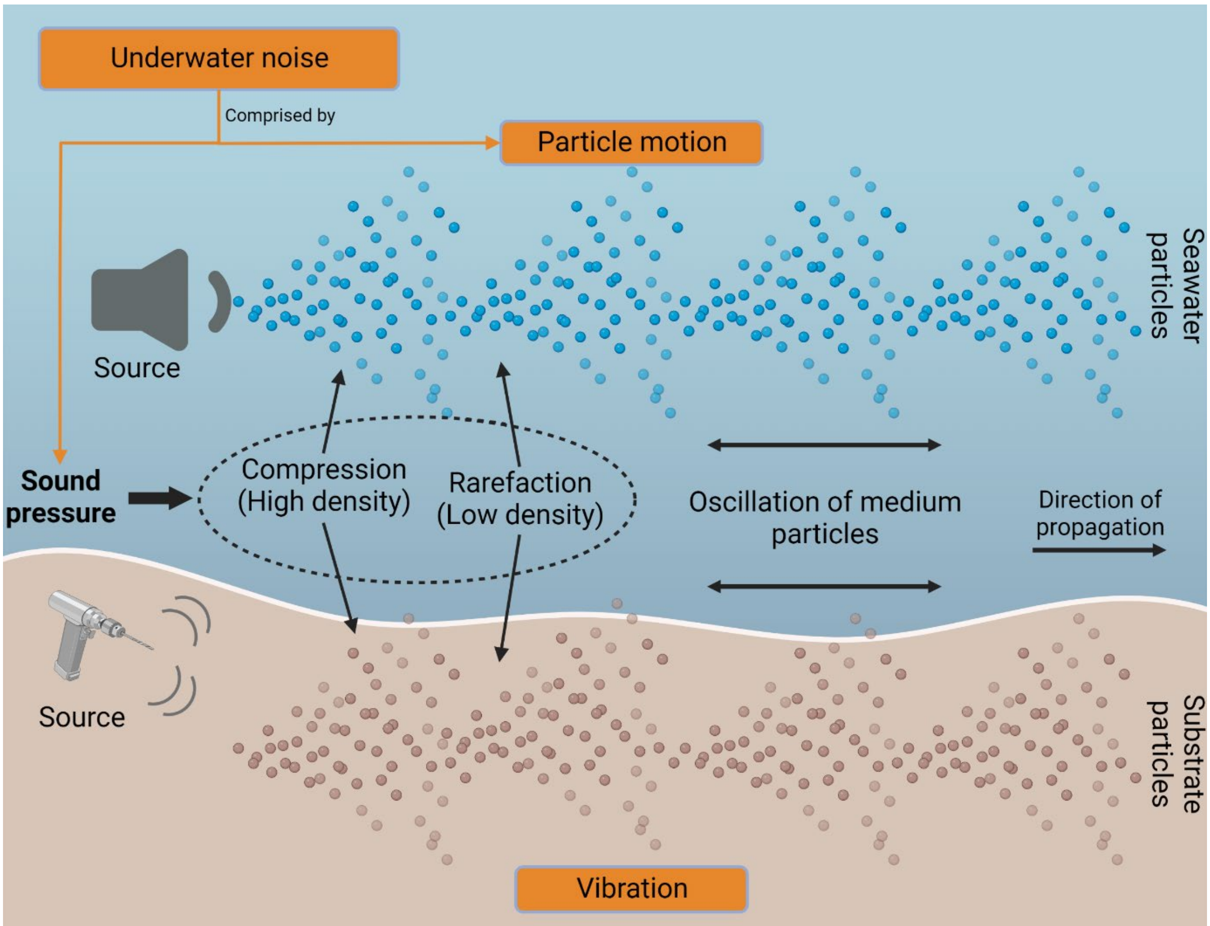

Figure 2. Conceptualization of the link between underwater noise, particle motion and vibration as stressors in this report. Underwater noise is comprised of sound pressure and particle motion. A noise source acts as a moving object. The movement produced by the noise source immersed in seawater causes the oscillation of the contiguous medium (i.e., seawater) particles. The oscillation of the seawater particles next to the noise source causes the oscillation of other neighbouring seawater particles, resulting in the propagation of the noise. During the oscillation, seawater particles come near (compression – increased density) and separate (rarefaction – reduced density). Therefore, the oscillation of seawater particles generate a variation in hydrostatic pressure in the seawater. This variation of hydrostatic pressure is the sound pressure. The oscillation of the seawater particles is the particle motion (PM). Similarly, within the substrate, a moving source will generate the oscillation of substrate particles. The substrate particles are solid, and their oscillation is labelled in the present report as vibration. The sources used in this figure do not necessarily represent real sources from OWF. Potential sources at wind turbines are discussed in section 4.2.2 (Created with BioRender.com).

1.2.2.1. Fish sensor physiology

Fish depends on hearing to sense the surroundings and respond to external stimuli. All fish retrieve information by sensing the soundscape and associated PM (Popper & Hawkins, 2018), whereas sound pressure detection is limited to certain species of fish (Wahlberg & Westerberg, 2005). Teleosts (i.e., bony fishes) have solid biomineralized calcium carbonate structures in the inner ear called otoliths (Fig. 3) (Schulz-Mirbach et al., 2019). Otoliths have a higher density compared to seawater and soft tissue (Schulz-Mirbach et al., 2020). An otolith is located close to a sensory epithelium (i.e., macula) that is composed of mechanosensory hair cells (Popper & Hawkins, 2018). The otolith and the macula are loosely connected by a membrane that lies between them called otolith membrane (Popper & Hawkins, 2018). Altogether, they form the otolith organ, which functions as an accelerometer. Due to the density properties of seawater, soft tissues, and otoliths, when acoustic PM is present, the tissues follow the movement while the otolith lags behind as an inertial mass (Popper & Hawkins, 2018; Schulz-Mirbach et al., 2020). The relative motion between the otolith and the macula generates the bending of the ciliary bundles of the hair cells, which produce electrical signals as a response (Popper & Hawkins, 2018).

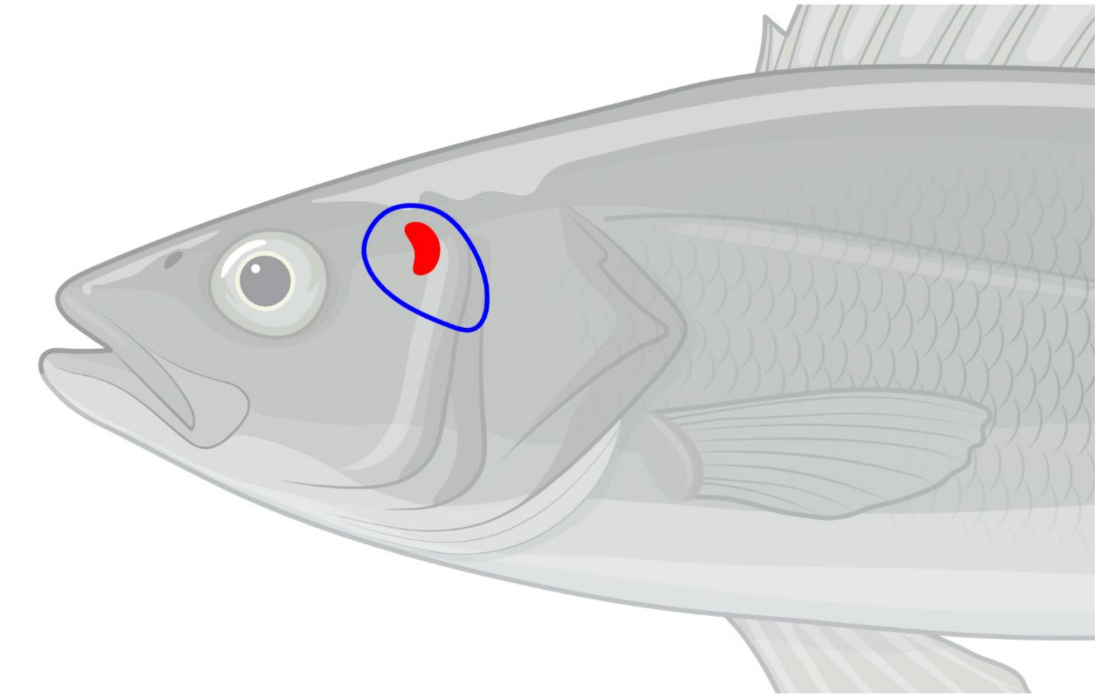

Figure 3. Schematic lateral view of a bony fish showing the position of the inner ear (dark blue circle) and the position of an otolith (in red). The schematic view is generic, and variations exist according to species (Created with BioRender.com).

Other sound detection pathways in the fish are dependent on soft tissue organs, like the swim bladder. The swim bladder is a gas-filled organ present in some fish species, which is mainly used to control buoyancy. The compression and decompression of gas in the swim bladder generate an oscillation of the swim bladder walls, which results in local PM. This local PM, and the resulting indirect pathway of stimulating the inner ear, may resemble sound-borne PM stimulation, especially if swim bladder and inner ear are coupled (Schulz-Mirbach et al., 2020). A gradient of hearing classes has been proposed to facilitate the determination of hearing sensitivity in fish by grouping them according to their anatomy (Hawkins & Popper, 2017). This gradient is composed by (1) fish without a swim bladder, (2) fish where the swim bladder does not aid the hearing, (3) fish where the swim bladder aids the hearing, and (4) fish with special structures mechanically linking the swim bladder to the ear (Hawkins & Popper, 2017; Wiernicki et al., 2020). Reportedly, morphology complexity of swim bladder may be linked to a broader range of detection frequencies (Wiernicki et al., 2020).

Another relevant sensor organ in fish is the lateral line system (Fig. 4). The lateral line system aids with short-range communication (Braun & Sand, 2013) by allowing fishes to detect weak water motions and pressure gradients (Bleckmann & Zelick, 2009). The lateral line is a mechanosensory system consisting of a subdermal canal populated with organs called neuromasts, which have hair cells identical to the ones in the inner ear (Kikuchi, 2010). These cells detect differences in the flow field (i.e., water movement) around the fish by ciliary bundle bending, similar to the inner ear. However, while the inner ear can detect signals from a substantial distance from the fish (several meters), the lateral line system primarily responds to signals detectable only within a few body lengths of the fish (Popper & Lu, 2000). The lateral line detects unidirectional flows and oscillatory flows. Fish use the lateral line for recognizing currents, environmental obstacles, preys, predators and other members of a group of fish (e.g., coordinated movement) (Bleckmann & Zelick, 2009). Moreover, fish may discriminate the size, shape, and speed of a moving object with the lateral line (Bleckmann & Zelick, 2009).

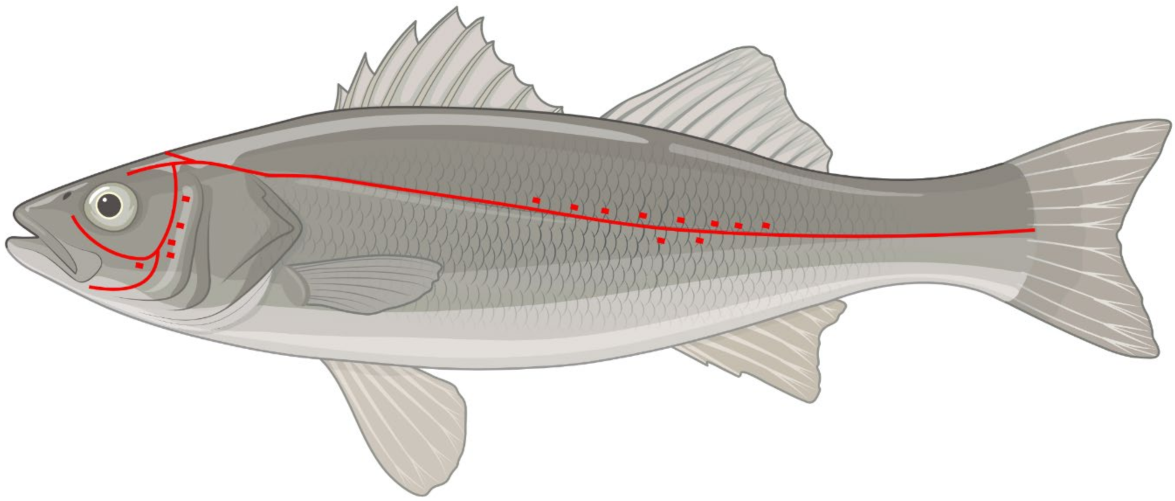

Figure 4. Schematic figure of a lateral line (sensory) system. The red line represents the subdermal canal. The red dots represent superficial neuromast. The lateral line is used for detecting weak water motions and pressure gradients (Created with BioRender.com).

Some species are known to strictly respond to PM, which is the case of fish lacking swim bladder (e.g., flatfish; *Pleuronectiformes*; and sharks, skates, and rays; *Chondrichthyes*) (Hawkins & Popper, 2017). This is problematic because sound exposure criteria for fish tend to be defined after controlled studies where only sound pressure is considered, and the PM that accompanies the transmission of sound goes overlooked (Popper & Hawkins, 2018). The species-specific responses of fish to sustained anthropogenic noise (Siddagangaiah et al., 2022) could then be explained by the different strategies of hearing in fish, which can be specialized on PM, sound pressure, or both (Hawkins & Popper, 2017). Operational windfarms produce background noise. During the operational stage, turbines (about 3.2 MW) generate structural vibrations associated to sustained low frequency noise (<1 kHz) of 80 to 150 dB re 1 µPa 100m away from the turbine foundation (Siddagangaiah et al., 2022). Reportedly, available underwater noise levels measured around operational wind turbines range between 81 dB re 1 µPa at a distance of 400m, and 137 dB re 1 µPa at a distance of 40m (Tougaard et al., 2020). A significant decrease of underwater noise levels with distance is observed, in accordance with the general trend of greater impact closer to the source (Mooney et al., 2020). Although the reported noise levels radiated from wind turbines may be low compared to cargo ship transits, some effects could be expected in areas with low noise stress (e.g., low levels of ship traffic; Tougaard et al., 2020). Thus, it is fundamental to understand how fish react to given levels of stress, while accounting for sound pressure and PM differential detection.

1.3. Aim of the report

Here, we systematically review the scientific literature available on potential negative impacts on fish and fisheries during the operational stage of bottom-fixed OWFs. From the fisheries perspective, we mainly focus on fish species targeted by commercial fishing activities, i.e., how OWF effects on fish are likely to affect the availability of the resource for the fishers. Importantly, we do not consider the technical and regulatory limitations that may or may not allow fishing activities within the OWF. Specifically, we aim to answer the following research questions:

1. What are the direct effects of EMFs emitted during OWF operations on fish and their fisheries?
2. What are the direct effects of UWN produced during OWF operations on fish and their fisheries?
3. What are the direct effects of PM related to OWF operations on fish and their fisheries?
4. What are the direct effects of vibrations associated with OWF operations on fish and their fisheries?

2. Methodology

This report is based on a systematic review of scientific literature. The review process for this report followed previously established guidelines for systematic reviews of scholarly literature (Khan, 2020) enhanced with methods specific to conservation science (Pullin & Stewart, 2006) and environmental management (Collaboration for Environmental Evidence, 2013). The selected guidelines appear in previous systematic reviews related to OWFs and the interaction of energy systems with ecosystem services in the ocean (Glarou et al., 2020).

Disclaimer
DTU Aqua is by no means responsible for observed effects of OWFs on fish and fisheries. DTU Aqua listed expected, possible, effects of OWFs, but DTU Aqua is by no means responsible for effects deviating from the expected, possible effects. Therefore, DTU Aqua is not, in any situation, responsible for the developments of fish and fisheries, whether the development is expected or not.

2.1. Search parameters

Provided the objectives of this report, the literature search was designed for a global assessment of the effects of EMF, UWN, PM, and vibrations from operational OWFs on fish and fisheries. Other stages of OWFs (e.g., decommissioning) were largely disregarded. For this purpose, different search strings were carefully tailored based on preliminary searches in the databases. In a search string, search terms are connected to one another using Boolean operators (‘AND’, ‘OR’, ‘NOT’, ‘SAME’, etc.). After testing multiple inputs of the search strings, we obtained thousands of flagged articles that served the purpose of the final review report. The main search was conducted in April 2022 after several pilot searches that helped enhance the search strings accuracy, following the iterative principle for completing a systematic review (Moher et al., 2009). Relevant peer-review articles were identified on Web of Science and Scopus publications databases. The selected databases index peer-reviewed scientific literature in English. This selection was made after running preliminary pilot searches using our search strings. Other scientific databases trialled in the preliminary searches were DTU-Findit, EBSCOhost, JSTOR, Google Scholar, ResearchGate, PubMed, and Research Square. The decision to disregard these databases from our methodology was due to severe redundancies within results (i.e., duplicated results) and a significant presence of grey literature (i.e., not peer-reviewed literature) in the search results. The refined search strings were:

- Q1 – electromagnetic fields:
    - ("magnetic field*" OR "magnetic flux*" OR electromagnet* OR "electric* field*") AND fish*
- Q2 – particle motion:
    - (particle* AND motion*) OR (particle* AND dynamic*) OR (particle* AND flux*) OR (particle* AND accelerat*) OR (particle* AND transport*) OR ("motion* of particle*") OR ("retention of particle") OR ("particle* retention")) AND fish* AND (offshore AND wind*)
- Q3 – underwater noise:
    - (aquatic* OR marine* OR ocean* OR underwater* OR pollut* OR anthropogen*) AND (noise* OR sound* OR "acoustic stress" OR "acoustic impact") AND fish* AND (offshore AND wind*)
- Q4 – vibration:
    - vibrat* AND fish* AND (offshore AND wind*)

The * next to some terms is a search engine wildcard. It allows the search engines to return results that contain the word regardless of what letter comes next (i.e., *fish** would return results containing *fish*, *fisheries*, *fishermen*, *fisherman*, *fishing* etc.). The word AND requests the search engines to return results containing both words, while words within quotation marks ensures that the words appear only in the given order (i.e., "*magnetic field**" will only return articles containing the words *magnetic* and *field** in this exact order). The inclusion of negative terms through the operator 'NOT' to further refine the search strings by removing impertinent results (e.g., to avoid errors related to the surname *Fisher* and related *Fisher distributions*, *Fisher matrices* etc.) was discarded after trial searching. We observed that negative terms could hinder relevant results. Thus, we opted for an approach without the use of the operator 'NOT'.

2.2. Screening

There were three sequential levels of screening for relevance in the papers returned by our search: title, abstract, and full text screening (Fig. 5). At each level, the compliance with inclusion criteria was revised (Table 1). Following a conservative approach, any article considered relevant, or raising acceptance uncertainty, was accepted for further scrutiny during the following level of screening. To meet our purpose, all included articles had to be peer-reviewed. We only considered research articles and reviews (e.g., systematic, narrative) due to vast amounts of inconclusive information in other types of peer-reviewed publications (i.e., in conference abstracts, conference posters). We opted for only including articles from the year 1991 and afterwards, as this was the year in which the first OWF was installed globally. As such, this approach disregarded potential research on subsea cables conducted prior to 1991 independently of OWFs. English was the only working language used. Preliminary pilot searches in French and Spanish did not return relevant articles that would justify systematic searches (and adapted search strings) in other languages than English. Selected literature was based on aquatic ecosystems. Article selection was based on the stressors EMF, UWN, PM and/or vibration. Other stressors were not considered provided the objectives of this report. Further, the selection targeted peer-reviewed articles that considered operational OWFs as a source (or potential source) of the stressor, including underwater cables and/or scour protection. The last inclusion criterion required a focus on the interaction between fish and one or more of the stressors. Relevant EMF literature focused mainly on subsea cables of a similar type as used at OWFs, without necessarily mentioning OWFs directly. Consequently, the search string for the EMF stressor was advertently designed without search terms associated directly to OWFs.

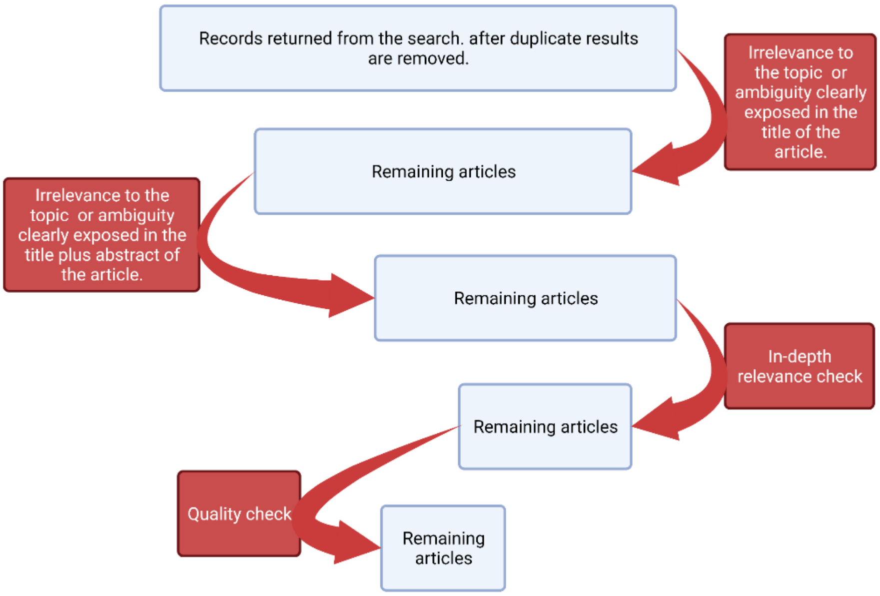

Figure 5. Outline of the search process flowchart following step-wise decision criteria.

Table 1. Inclusion/Exclusion criteria.

Criteria	Include	Exclude
Peer-reviewing	Peer-reviewed	Everything else
Article type	Research articles and reviews	Everything else
Years	Y ≥ 1991	Y < 1991
Text language	English	Everything else
Ecosystem	Aquatic	Terrestrial
Stressors	Electromagnetic fields, underwater noise, particle motion, vibration	Everything else
Source	Operational offshore windfarms, underwater cables, scour protection	Everything else
Subject	Fish	Everything else

2.3. Data extraction

Scientific articles meeting the inclusion criteria were selected for in-depth revision and extraction of data considered relevant for answering our questions and meeting the objectives of this report. Specifically, data were recorded from empirical publications and included year, country, type of investigation (e.g., laboratory, field), stressor of main focus, stressor of secondary focus, species, documented effects (e.g., behaviour, fitness, mortality), potential risk of negative OWF impact, and characterization of the stressor. The articles were classified as empirical (based on direct field or laboratory observations) or non-empirical (not based on direct observations - e.g., reviews, perspective, letters, or modelling studies). Relevant information provided by review articles is included throughout this text. Additional peer-reviewed articles of interest for achieving our objectives, located during the review process, were included as well. The articles detected outside the main search strings came from backward reference searching. Specifically, this involved reviewing reference lists in the located literature for potentially relevant publications, similar to previous studies (Burgers et al., 2019).

3. Results

3.1. Selection process

The conducted search returned 5,181 scientific articles in total, and 3,453 articles after duplicate removal (Fig. 6). Screening by title led to the removal of 3,171 (91.8% of the initial amount). Next, we screened the remaining 282 articles by abstract. During this process, 184 (65.2%) articles were removed, mostly due to lacking focus on OWFs. On the final screening level, 98 articles were revised by full-text content and further 39 (40%) articles were excluded. An additional 8 articles, which were deemed relevant for answering the study questions, but not picked up by our search strings, were manually added in a final step to reach a total of 67 articles included in this review (Fig. 6). This manual selection procedure applied the same inclusion criteria as used for the other articles (Table 1).

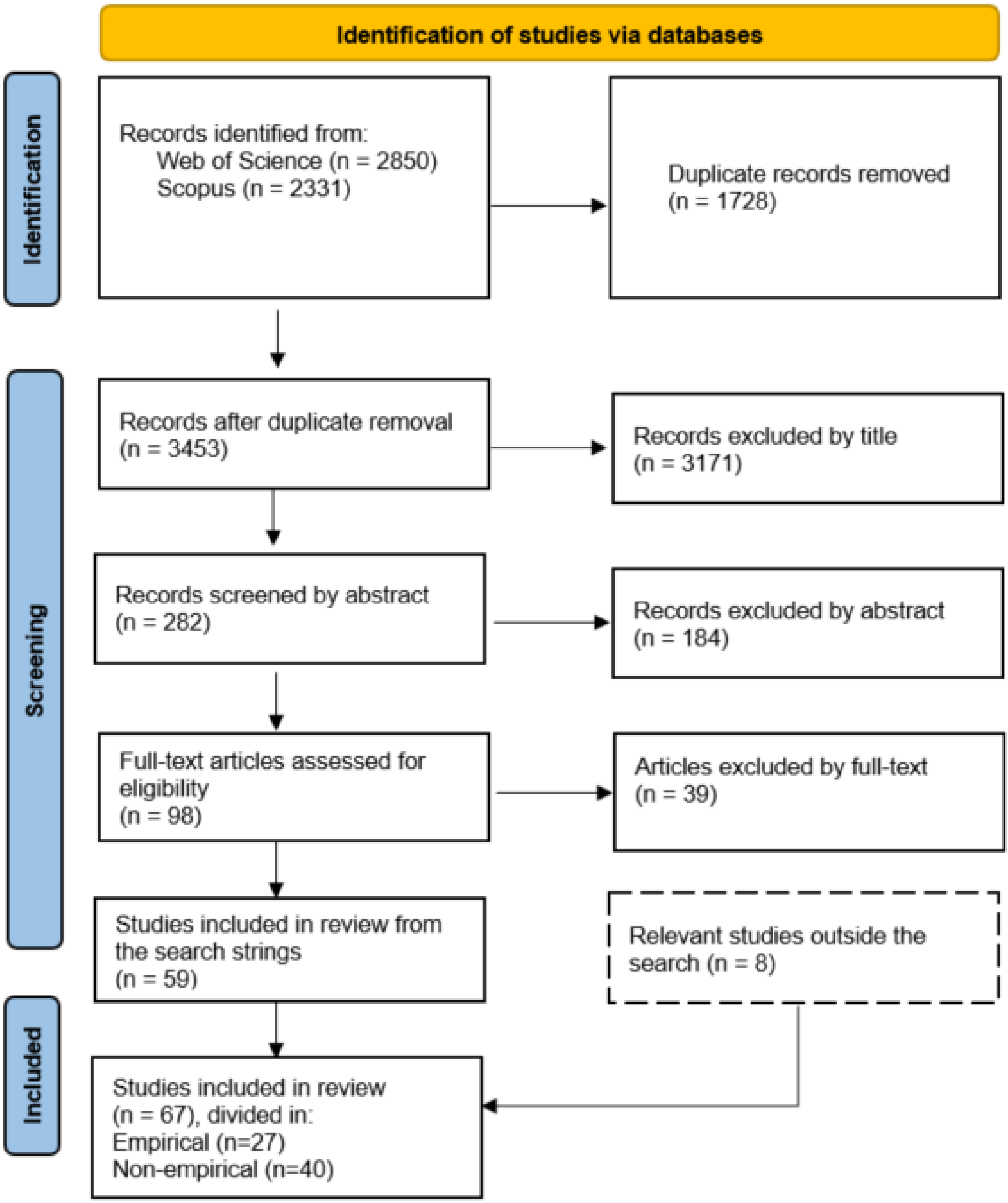

Figure 6. Flow diagram with number of scientific publications per stage of filtering, considering inclusion criteria (Adapted from Page et al., 2020).

3.2. General trends in the literature

While the world's first OWF started operations in 1991 (deCastro et al., 2019), potential negative effects from operational OWFs on fish did not receive any attention in the scientific literature until more than a decade later in 2004, according to our analyses. Since then, there has been a considerable increase in studies highlighting a possible risk from the different potential stressors (Fig. 7a), with UWN and EMF currently being most frequently mentioned in 69% and 67% of the included studies, respectively. Risks related to PM (i.e., oscillation of seawater particles from their equilibrium – see section 1.2.2) and vibration (i.e., oscillatory motion of substrate particles – see section 1.2.2) have originally received less attention, yet they have increasingly been identified as additional risk factors for fish and are currently mentioned in 28% and 27% of the studies, respectively. However, the number of empirical studies investigating the effects of the four potential stressors on fish (n=27) notably comprise less than half of the total studies included in the review (n=67). Analyses of the available articles indicated that effects of EMF have to date been investigated in 17 empirical studies (63% out of all empirical studies), UWN in 10 studies (37%) and PM in 3 studies (11%), with PM studies all simultaneously addressing UWN effects as well (i.e., sum of the percentages exceeds 100%). No studies have thus far conducted relevant empirical research on vibration impacts, as defined in the present study (Fig. 7b). Studies within the final selection originated from 21 countries (Fig. 7c), with most studies conducted in the US (16 studies), followed by the UK (10 studies) and Poland (7 studies). Among countries with > 1 study, Belgium and Taiwan conducted exclusively empirical studies, while the UK and Denmark contributed with non-empirical studies only, according to the present assessment. Empirical studies on EMF were mostly conducted in Poland, Canada and the US, while UWN studies originated mostly from Belgium and Taiwan. The geographical distribution highlights that PM and vibrations received significantly less attention, with three countries each conducting a single study on PM and no studies addressing the potential impact of vibrations, as defined in the present study (Fig. 7d).

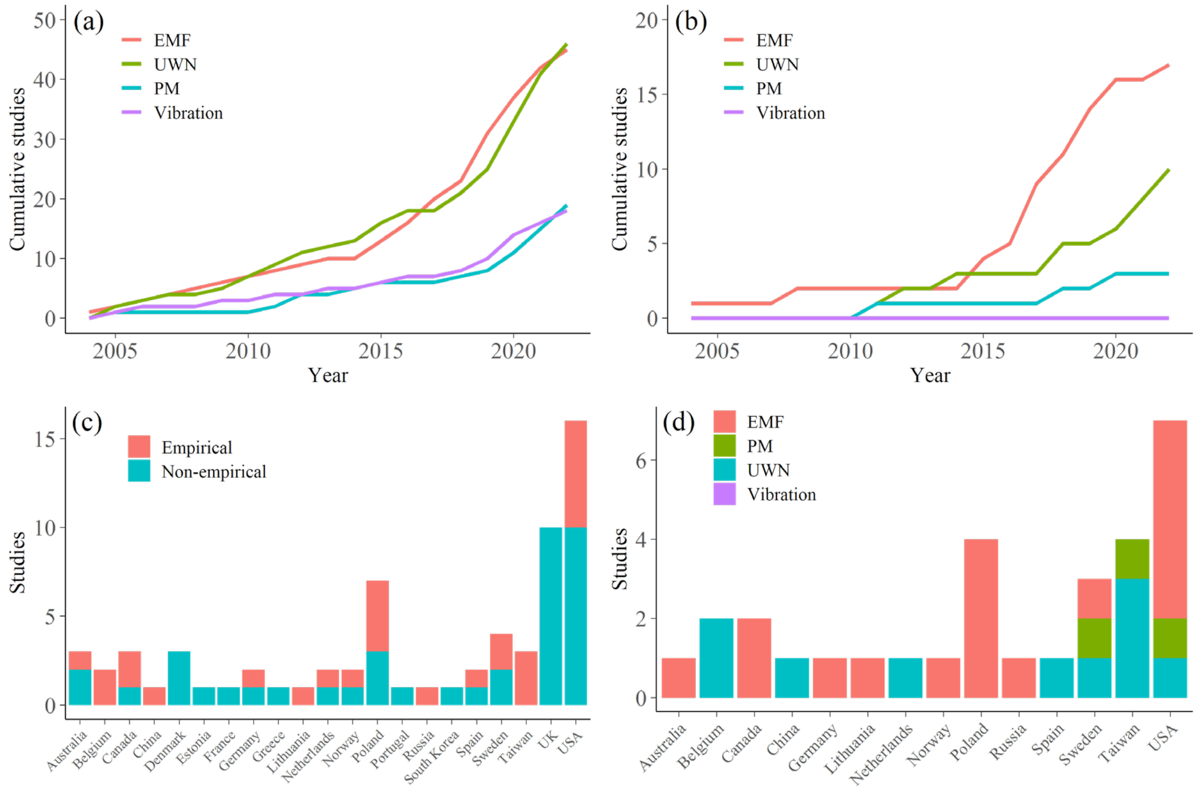

Figure 7. Temporal and geographical trends in the final selection of studies. (a) The cumulative number of studies over time for each potential stressor; (b) The cumulative number of empirical studies over time for each potential stressor; (c) The number of empirical and non-empirical studies per country; (d) The number of empirical studies on each potential stressor per country. Note that a number of studies address multiple potential stressors, implying that the total cumulative number presented exceeds the total number of studies within the final selection (67 studies). Empirical and non-empirical studies are defined in the text (see Section 2.3 – Data extraction). EMF: electromagnetic field; PM: particle motion; UWN: underwater noise.

3.3. Potential stressors

3.3.1. Electromagnetic fields

Out of the 67 studies remaining after carrying out the stepwise selection procedure (Fig. 6), 45 studies (67%) addressed the potential threat of EMFs to fish. Within this subgroup of EMF studies, 17 studies (38%) investigated potential EMF effects on fish empirically, while the remaining studies consisted of literature reviews synthesizing existing knowledge (58%) and short communications or perspectives (4%). Empirical studies either tested the effects on fish through laboratory experiments (53%), field experiments (41%) or both (6%). Field experiments generally involved comparisons of fish movement patterns, fish behavioural metrics or fish community metrics between energized subsea cables and either non-energized cables or natural habitats nearby. For laboratory experiments, main interests included studying the effects of manipulations in B-field intensity on fish, generally achieved with the use of Helmholtz coil systems surrounding experimental tanks, although one study used a large mesocosm positioned on top of a buried HVDC cable (Hutchison et al., 2020). Laboratory studies focused exclusively on early life stage of fish (i.e., from fish eggs until juvenile stages), except for the aforementioned mesocosm study that used adult skates (Hutchison et al., 2020), while field studies targeted both juvenile and adult life stages of target species, as well as entire fish communities. Therefore, empirical studies assessing EMF effects on fish can largely be categorized in three categories: early life stage, fish movement and migratory behaviour, and fish community metrics.

3.3.1.1. Early life stage

The majority of empirical studies on EMF effects focused on the early life stages of fish species (52% of EMF empirical studies; Table 2). An early lab study by Bochert & Zettler (2004) exposed several common Baltic Sea species to a static MF for four weeks to assess the effects on survival and fitness. The only fish species among the study organisms, young European flounder (*Platichthys flesus*), showed zero mortality among individuals for the entire duration of the experiment. Additional lab experiments have since then revealed that certain coral reef fish larvae (*Chromis atripectoralis*) utilize geomagnetic information in the absence of visual cues during the pre-settlement stage (O'Connor & Muheim, 2017), yet drifting larvae of a temperate fish species (*Ammodytes marinus*) did not alter their spatial distribution, swimming speed or distance moved when exposed to a MF of similar intensity as those produced by subsea cables (Cresci et al., 2022). Multiple studies have focused on rainbow trout (*Oncorhynchus mykiss*) and the effects of anthropogenic EMF on embryonic and larval development. For example, a lab study by Fey et al. (2019) exposed eggs and larvae to static MF and time-varying EMF for 26 days and another 10 days post-hatching. Results indicated that both MF and EMF significantly increased yolk-sac absorption rates, and it was concurrently shown that larvae with absorbed yolk-sacs were less efficient at first feeding, hinting at a potential disadvantage for larvae exposed to EMFs pre- and post-hatching. Furthermore, exposure of trout eggs and larvae to EMF of similar intensity was found to induce nuclear abnormalities and alterations in the number of cell nuclei (Stankevičiūtė et al., 2019), with the lab experiment notably involving substantial long-term exposure of 40 days. A more recent experiment revealed that rainbow trout larvae exposed to similar MF and EMF had a higher otolith fluctuating asymmetry (FA) index, relative to control conditions (Fey et al., 2020). Since the FA index is generally used as an indicator for developmental instability, results suggest that EMF exposure may negatively affect organs of hearing and balance in rainbow trout, although it remains unclear to what extent these findings translate to long-term survival of fish in marine environments. Finally, a lab study by Brysiewicz et al. (2017) evaluated effects of short-term (1-60 min.) and long-term (from the start of embryogenesis; i.e., formation and development of embryo) MF exposure on the development of pigment cells in European whitefish (*Coregonus lavaretus*) and vendace (*Coregonus albula*). The authors note that effects of MF exposure were significant for both time periods, with short-term exposure inducing movement of body cell pigment to central parts of the cells, while long-term exposure delayed the formation of pigment cells in the eyeballs and on the body of the embryos. These results hint at magnetoreception taking place within the pigment cells of the target species, although the potential impacts of altered pigment cell development on long-term survival and fitness remain unclear.

Collectively, laboratory studies on early life stages of fish provide species-specific evidence indicating potential negative effects of anthropogenic EMFs on fish development. However, it should be noted that the majority of studies that document negative effects use B-field intensities that are high relative to values typically encountered a few meters away from subsea cables (Table 2; Gill & Desender, 2020). It remains unclear to what extent the findings translate to long-term survival of fish in marine environments.

3.3.1.2. Fish movement and migratory behaviour

Considering all empirical studies investigating EMF effects, four studies (24%) focused on fish movement and migratory behaviour (Table 2). Westerberg & Lagenfelt (2008) investigated the migratory behaviour of European eel (*Anguilla anguilla*) in the field as they crossed a buried subsea cable within the Kalmarsund strait, Baltic Sea. Acoustic tracking data collected by four arrays of receivers spaced 3-4 km apart indicated that eel swimming speed was significantly reduced near the subsea cable. However, no behavioural details during cable passage could be extracted from the data and the physiological mechanisms responsible for the observed trend remained unknown. The authors therefore conclude that additional studies are required to understand the nature of the effects (Westerberg & Lagenfelt, 2008). Similarly, two acoustic telemetry studies on tagged Chinook salmon (*Oncorhynchus tshawytscha*) smolts (i.e., juveniles) examined their movement behaviour and migration success in relation to energization of a subsea power cable within San Francisco Bay (Klimley, Wyman, & Kavet, 2017; Wyman et al., 2018). The main findings from both field studies indicate that the smolts were not significantly affected by the presence of energized cables. The study by Wyman et al. (2018) found similar probabilities of migration success although a higher proportion of fish crossed the cable after it was energized, while Klimley et al. (2017) concluded that MF anomalies from the subsea cable as well as from local bridges did not present a strong barrier to smolt migration. In addition to smolts, the latter study also assessed the upstream and downstream migration of adult green sturgeon (*Acipenser medirostris*) within the same estuary, similarly concluding that the local MF anomalies did not prevent adult green sturgeon from successfully carrying out their migration (Klimley et al., 2017). Finally, a recent lab study by Hutchison et al. (2020) employed a combination of hydrophones and underwater cameras to track and quantify movement patterns of little skate (*Leucoraja erinacea*) in response to an anthropogenic EMF within a mesocosm experiment. The combined monitoring technique allowed the authors to record a substantial increase in distance travelled, slower swimming speeds and an increased number of large turns close to the seabed, collectively interpreted as a significant increase in exploratory behaviour when little skate was exposed to the EMF. Given that prolonged exploration without reward ultimately implies an energetic loss, unless sensitive species can adapt from experience with anthropogenic EMFs, the authors conclude that the effect is ecologically significant. The authors further argue that future studies should investigate EMF encounter rates for sensitive species to assess if the observed behavioural effect at the individual level may become a population level impact (Hutchison et al., 2020).

Overall, studies to date assessing EMF effects on migratory and movement patterns of fish may indicate that EMFs near subsea cables are unlikely to pose a barrier to migration success, while the limited alterations in movement patterns (e.g., swimming speed) appear to be contrasting and possibly species-specific.

3.3.1.3. Fish community metrics

Our literature review revealed four empirical field studies investigating the effect of EMFs on fish community metrics (24% of EMF empirical studies; Table 2). Dunham et al. (2015) collected video and still imagery using a remotely operated vehicle to investigate the effects of cable installation and operation on the condition of glass sponge reefs and associated megafauna in SW Canada. A diverse megafaunal community was observed at locations with and without cables present and although the abundance of several taxa was slightly lower along the cable transect, the effect of cable presence was not statistically significant (Dunham et al., 2015). Likewise, a study by Dunlop et al. (2016) investigated whether the presence of a high-voltage transmission cable affected the spatial pattern and composition of a Laurentian Great Lakes fish community by performing nearshore electrofishing and deep-water acoustic transects at various distances from the cable. The study concluded that there were no detectable effects of cable presence or proximity on both the nearshore and deep-water fish communities and that substrate type and depth were more important in explaining variations in fish density (Dunlop et al., 2016). The effect of energized versus non-energized cables on fish assemblages in southern California was investigated by Love et al. (2017) through underwater visual surveys along belt transects. Although the fish community at natural habitats was different from the community found near cables, there was no difference in communities between energized and non-energized cables. In addition, total fish density was found to be significantly higher around the cables than at natural habitats (Love et al., 2017). These results seem to suggest that the physical presence of the cable, rather than the emission of EMFs, was driving a distinct assemblage along the cables. Finally, a study by Kilfoyle et al. (2018) assessed whether cables transmitting an AC current, DC current, or no current had differential effects on coral reef fishes in Florida, again using underwater visual surveys. The authors found no significant difference in fish abundance, richness, or community composition between the three power states. However, the authors note that certain taxa (e.g., elasmobranchs) were not sampled in adequate numbers to statistically discern patterns (Kilfoyle et al., 2018).

Combined, the empirical studies assessing effects of EMFs on fish communities to date indicate either limited or non-existing evidence of negative effects.

Table 2. Direct effects of electromagnetic fields (EMF) on the early life stages and migratory behaviour of fishes, as documented by empirical studies conducted in the field or laboratory.

	Target species	Field/ Lab study	Documented EMF effect(s)	Risk for negative impact on fish	EMF/cable characteristics	Reference
Early life development	European flounder (*Platichthys flesus*)	Lab	No significant difference in survival between exposed and control group	Lack of evidence	B-field (static DC; up to 3.7 mT), 4-week exposure	Bochert & Zettler (2004)
	Crucian carp (*Carassius carassius*)	Lab	Significant decrease in digestive enzyme (proteolytic and amylolytic) activities in carp after a 1-hour exposure	Uncertain, focal species is a freshwater fish and there is a lack of OWF-related consideration	MF intensities of 24.2 µT (DC) and 44.5 µT (AC), 1-hour exposure	Kuz'mina, Ushakova, & Krylov (2015)
	Coral reef damselfish (*Chromis atripectoralis*)	Lab	Geomagnetic field information guides the swimming behaviour of coral fish larvae during pre-settlement stage	Not evaluated, changes to local GMF could impact spatial patterns of larval dispersal	Mimicked local geomagnetic field (48,691 nT, 41.2 degrees) and manipulated magnetic North by 90 degrees	O'Connor & Muheim (2017)
	European whitefish (*Coregonus lavaretus*) and vendace (*Coregonus albula*)	Lab	Short-term: displacement of pigment to central part of body cells Long-term: delayed pigment formation in eyeballs, lower number of melanophores relative to control group	Uncertain, as the strength of MF used is relatively high compared to OWF values	B-field (1, 3 and 5 mT) exposure for 1-60 min. (short-term) and from start of embryo-genesis (long-term)	Brysiewicz et al. (2017)
	Rainbow trout (*Oncorhynchus mykiss*)	Lab	1. Significant effect on micronuclei after 40 days of exposure (indicator of genotoxicity and chromosomal instability) 2. Increase in yolk-sac absorption rate, may indicate reduced efficiency at first feeding	1. Uncertain, long-term exposure and intensities high relative to OWF cables 2 ; 3 Uncertain, EMF/MF intensities high compared to OWF cables, may become risk under further expansion	1. EMF with frequency of 50 Hz and intensity between 0-1 mT (40 days exposure) 2 ; 3 Static MF (DC; 10 mT) and time-varying EMF (AC; 1 mT)	1. Stankevičiūtė et al. (2019) 2. Fey et al. (2019a) 3. Fey et al. (2020)

	Target species	Field/ Lab study	Documented EMF effect(s)	Risk for negative impact on fish	EMF/cable characteristics	Reference
			3. Statistical effect of MF on otolith fluctuating asymmetry (indicator of development instability)			
	Northern pike (*Esox lucius*)	Lab	Earlier time of hatching, smaller yolk-sac size, and faster yolk-sac absorption	Low, risk of increased pike larvae mortality seems negligible (intensity also high relative to OWF cables)	Static MF (DC) of 10 mT	Fey et al. (2019b)
	Lesser sandeel (*Ammodytes marinus*)	Lab	No effect on spatial distribution, swimming speed, acceleration or distance moved by sandeel larvae	Lack of evidence (no impact on sandeel larvae behaviour)	DC cable, MF intensity gradient of 50-150 µT	Cresci et al. (2022)
Fish movement and migratory behaviour	European eel (*Anguilla anguilla*)	Field	Significant decrease in swimming speed of migrating eel near power cable	No evidence for obstruction or significant delay to migration	130 kV, twisted three-phase AC cable	Westerberg & Lagenfelt (2008)
	Chinook salmon (*Oncorhynchus tshawytscha*)	Field	1. No effect on downstream migration of salmon smolts despite MF anomalies from bridges and cables 2. No significant effect of cable energization on migration success (although transit times were slightly reduced)	1. Lack of evidence 2. Low: limited effects on smolt migration. Further studies needed to study long-term impacts	1. Static B-field from DC cables, average MF anomalies between 94 nT (surface) and 518 nT (bottom) 2. HVDC cable of around 200 kV, mean MF anomalies of 543 and 185 nT at 5 and 10 m from the seabed respectively	1. Klimley, Wyman, & Kavet (2017) 2. Wyman et al. (2018)
	Green sturgeon (*Acipenser medirostris*)	Field	No effect on adult green sturgeon migration to and	Lack of evidence	Static B-field from DC cables, creating average MF anomalies	Klimley et al. (2017)

	Target species	Field/ Lab study	Documented EMF effect(s)	Risk for negative impact on fish	EMF/cable characteristics	Reference
			from their spawning grounds		between 94 nT (surface) and 518 nT (bottom)	
	Little skate	Lab (EMF measured in the Field)	Significant increase in exploratory behaviour	Uncertain: further studies needed to assess if behavioural effect may become population-level effect	HVDC cable. Max deviation from geomagnetic field at seabed: 14 µT	Hutchison et al. (2020)
Fish community metrics	Megafauna associated with glass sponge reefs	Field	Total megafauna abundance slightly lower at cable transects, but cable presence was not a significant predictor	Lack of evidence	Three old 138 kV HVDC cables, MF intensity not specified/measured	Dunham et al. (2015)
	Nearshore and offshore fish communities	Field	No detectable effects of the cable on the fish community: habitat variables were more important predictors	Lack of evidence	HVAC 3-core XLPE cable, 245 kV (highest voltage of any subsea cable at time of construction, 2008)	Dunlop, Reid, & Murrant (2016)
	Fish community	Field	No statistical differences in species composition between energized and non-energized cable. Total fish density around cables higher than at natural habitat.	Lack of evidence	Standard 35 kV cable, MF intensity range 51-205 µT	Love et al. (2017)
	Coral reef fishes	Field	No significant effects of cable power states (AC/DC/turned off) on reef fish abundance, richness or composition	Lack of evidence	Energized with AC (0.98-1.59 Amps at 60 Hz) and DC power (2-2.4 Amps). MF intensities: 401 nT (AC) and 559 nT (DC) at 0.1m distance from cable	Kilfoyle et al. (2018)

3.3.2. Underwater noise

In total, the systematic approach revealed 28 studies related to UWN, of which 15 studies targeted only the sound pressure component of sound. On the other hand, there were 13 articles focusing on both components of sound (i.e., sound pressure and PM), meaning that the potential stressor PM was of main or secondary relevance. Additionally, within the 28 UWN studies, there were 10 studies focusing on UWN, and briefly mentioning vibration (i.e., no research done specifically on vibrations). Therefore, studies assessing the PM component of sound were included here and under the PM subsection of the results (see section 3.4). Studies mentioning vibration are included in this section and in the vibration subsection of the results (see section 3.5).

From the total amount of studies included in the review (n = 67), 28 (42%) studies were related to underwater noise (UWN). The 28 articles included 12 (43%) literature reviews, 10 (36%) empirical studies, two (7%) modelling studies, one (3.5%) compilation, one (3.5%) forum (i.e., workshop), one (3.5%) meta-analysis, and one (3.5%) viewpoint. For analytical purposes, we grouped the articles in two main categories: empirical articles (forming 36%) and non-empirical articles (all others forming 64%). From the 10 empirical articles, four were experiments carried *in situ*, five in laboratory, and one was excluded from this subsection and included in PM given its experimental design (see section 3.4).

Non-empirical studies provided constructive input, ranging from perspectives for enhancing impact assessment to regulation of UWN. Wahlberg & Westerberg (2005) provided a review for understanding the principles of underwater acoustics, hearing in fish, and highlighted potential effects of UWN. Several non-empirical articles provided constructive summaries of OWF development and operation on fish and are recommended starting points for further perspectives (Kaldellis et al., 2016; Kulkarni & Edwards, 2022; Mooney et al., 2020). In addition, knowledge gaps and future research topics on UWN were present in the identified articles (Hawkins et al., 2015).

Empirical studies addressed a range of research questions and applied various experimental designs (Table 3). Some studies aimed at assessing hearing thresholds for a species in laboratory settings (Stanley et al., 2020; Zhang et al., 2021), whereas other studies explored the reaction (e.g., behaviour, physiology, ecology) of fish species to UWN using either direct exposure *in situ* or in laboratory settings (Bolle et al., 2012; Chang et al., 2018; Puig-Pons et al., 2021; Siddagangaiah et al., 2022; Wei et al., 2018). Importantly, all the studies included in our review examined operational wind turbine characteristics at some point during their experimental design.

3.3.2.1. Empirical in situ studies

UWN exposure, evaluated through sound pressure, triggered responses in fishes under experimental conditions or observational protocols. Behavioural responses to sound pressure were detected in semi-free bluefin tuna (*Thunnus tynnus*; Puig-Pons et al., 2021) and free-ranging Atlantic cod (*Gadus morhua*; van der Knaap et al., 2022). Bluefin tuna showed moderately altered movement patterns when exposed to playback of operational OWF noise, recorded 50 m away from a wind turbine. Tagged Atlantic cod, living near the foundation and scour protection of an operational wind turbine, showed modest variations of movement patterns when pile-driving activities were taking place >2.3 km away. The variations included approaching the scour protection and moving away from the noise source. Pile driving occurs during the construction stage of an OWF and is not within the scope of the present review. However, the findings show how relatively extreme UWN levels (compared to operational OWF UWN levels) may not produce dramatic effects, such as mortality. Siddagangaiah et al. (2022) recorded choruses (overlapping fish vocalizations produced by different individuals; Miles et al., 2016) of two species of fish inhabiting an operational OWF after its construction. Their results evidenced that one of the choruses increased in duration and decreased in intensity during the operational stage of the OWF. Fish chorusing is used for attracting mates during spawning, communication, and social cohesion. Thus, a disruption could affect behavioural and ecological processes (Siddagangaiah et al., 2022).

3.3.2.2. Empirical laboratory studies

UWN resulted in physiological responses in caged black porgy (*Acanthopagrus schegelii*; Chang et al., 2018) and milkfish (*Chanos chanos*; Wei et al., 2018) in a laboratory setup with restricted mobility. After being exposed continuously for two weeks to playback of operational OWF noise recorded 1 m away from the wind turbine, increased levels of reactive oxygen species (ROS) in plasma were detected in black porgy. Milkfish exposed to similar conditions had elevated cortisol levels after 24 hours of continuous exposure, but cortisol levels were normal in a corresponding group exposed continuously for 72 hours. Milkfish also had increased mRNA levels of hydroxisteroid dehydrogenase in individuals exposed for 72 hours, and in individuals exposed for one week. The increased mRNA levels were not observed in the milkfish individuals exposed for 24 hours. Notably, operational wind turbine noise is within the experimentally estimated hearing thresholds of black sea bass (*Centropristis striata*; Stanley et al., 2020), and marbled rockfish (*Sebastiscus marmoratus*; Zhang et al., 2021). No mortality was recorded in any fish species exposed to increased sound pressure levels in the studies identified by the present review. Moreover, an experiment on larval common sole (*Solea solea*) did not result in any mortality after exposure to pile-driving sounds (Bolle et al., 2012). The same trend of no mortality was observed with juvenile sea bass (*Dicentrarchus labrax*) exposed to pile-driving noise with sound exposure levels reported to cause injuries in other species (Debusschere et al., 2014).

These findings indicate that some fish species may exhibit behavioural and/or physiological responses to operational OWF UWN, but long-term effects remain uncertain.

Table 3. Direct effects on fish of relevance for operational OWF. The table shows studies covering underwater noise (UWN), as documented by empirical studies conducted in the field or laboratory. The table includes studies on pile-driving noise for perspectives.

Species	Field / Laboratory	Documented effects	Potential risk for negative operational OWF impact	Stressor characterization (e.g., frequency, SPL, particle velocity)	Reference
Larvae of common sole (*Solea solea*).	Laboratory	No mortality was observed, other effects were not evaluated.	Lack of evidence, but the study mainly covered pile-driving.	Playback of recorded pile-driving sounds in the frequency of 50 - 1000 Hz, at 0 to peak levels of 210 dB re 1 μPa^2, and at single pulses up to 186 dB re 1 μPa^2. Highest exposure level at 206 dB re 1 μPa^2, corresponding to 100 strikes at 100m away from a typical North Sea pile-driving site.	Bolle et al. (2012)
Juvenile sea bass (*Dicentrarchus labrax*).	Field	No instant nor delayed (post 14 days) mortality was observed, other effects were not evaluated.	Even though no mortality was observed, the sound levels measured *in situ* exceeded the thresholds for onset of injuries observed in laboratory experiments with other species.	Direct exposure 45 m away from a pile-driving activity. Exposure included sound exposure levels between 181 and 188 dB re μPa^2.s. The cumulative sound exposure level between 215 and 222 dB re μPa^2.s was reached from the number of strikes, ranging between 1,739 to 3,067 events.	Debusschere et al. (2014)
Black porgy (*Acanthopagrus schlegelii*).	Laboratory	Increased levels of reactive oxygen species (ROS) after two-week exposure. No elevated cortisol levels.	Stress could happen and increase levels of ROS under noise conditions similar to 1m away from the operational wind turbine foundation for continuous periods (2 weeks).	Playbacks of recorded operational offshore wind turbine noise (duration: up to 2 weeks). Two noise level categories based on the distance from the foundation where the noise was recorded. -Quiet: 109 dB re 1 μPa/125.4 Hz; recorded 100 m away from wind turbine. -Noisy: 138 dB re 1 μPa/125.4 Hz; recorded 1 m away from wind turbine. -Control: 80 dB re 1 μPa/125.4 Hz; no playback.	Chang et al. (2018)

Species	Field / Laboratory	Documented effects	Potential risk for negative operational OWF impact	Stressor characterization (e.g., frequency, SPL, particle velocity)	Reference
Milkfish (*Chanos chanos*).	Laboratory	No difference in survival rates, schooling or feeding behaviour. Noisy conditions resulted in: a) elevated cortisol levels (at 24 h, reduced to normal after 3 days); b) increased mRNA levels of head kidney hydroxisteroid dehydrogenase after 3 days, and 1 week, but not after 24 h.	For this species, near turbine exposure (<1 m from turbine) can trigger physiological responses. Response could be at gene expression level, and it may influence energy budget with long term exposures.	Playbacks of recorded operational offshore wind turbines noise (durations: 24 h, 3 days, 1 week). Two noise level categories based on the distance from the foundation where the noise was recorded. -Quiet: 109 dB re 1 µPa/125.4 Hz; recorded 100 m away from wind turbine. -Noisy: 138 dB re 1 µPa/125.4 Hz; recorded 1 m away from wind turbine. -Control: 80 dB re 1 µPa/125.4 Hz; no playback.	Wei et al. (2018)
Black sea bass (*Centropristis striata*).	Laboratory	Auditory detection thresholds for this species determined at 80 to 1000 Hz, with peak sensitivity at 150 Hz (where 75-90 dB was the threshold level, based on body size). OWF operational noise is within the detection window.	Potential risk of changes in physiology, behaviour, injuries, and acoustic masking.	Modulated tone bursts of 7 different frequencies from 80 to 2000 Hz. Order of presentation was random and increased in 5 dB increments until getting a response. Then continued using >10 dB to evaluate responses over the threshold.	Stanley et al. (2020)
Marbled rockfish (*Sebasticus marmoratus*).	Field measurements of UWN, then comparisons with available threshold values of the species in the literature.	Measured sound pressure at the operational OWF corresponded with the detectable sound thresholds found for this species. Also, the sounds emitted by the individuals of this species are faint (‘easily’ masked).*	Potential for interference with biological sounds from the environment (i.e., masking).	Underwater noise at the operational OWF values were 125 Hz with sound level range of 78 - 96 dB re 1 µPa at wind speed of 3 - 5 m/s.	Zhang et al. (2021)

Species	Field / Laboratory	Documented effects	Potential risk for negative operational OWF impact	Stressor characterization (e.g., frequency, SPL, particle velocity)	Reference
Bluefin tuna (*Thunnus tynnus*) in a commercial feeding cage.	Field	Behavioural response revealed as moderately altered movement patterns.	Individuals of this species could avoid OWF proximity (ca. 50 m).	Playback of a wind turbine recorded at 50 m from the source for 30 minutes, sampled at 350 kHz. The sound is a broadband noise 120 dB re 1µPa along the 30 Hz - 10k Hz with a maximum at 50 Hz (142 dB re 1 µPa).	Puig-Pons et al. (2021)
Free swimming tagged Atlantic cod (*Gadus morhua*).	Field	Modest changes in movement patterns: -Approaching the scour-bed -Moving away from the source.	Long-term changes in movement behaviour can produce changes in energy budget. Potential cumulative effects.	Pile driving activities at a distance ranging 2.3 to 7.1 km away from fish residence area (nearby an OWF). Sound pressure levels reached 199, 196 and 188 dB at 400, 500 and 1,700 m away from the source, respectively. Single strike sound exposure levels averaged 176, 175 and 168 dB re 1 μPa^2.	van der Knaap et al. (2022)
Chorusing of two different Sciaenid species.	Field	Increased duration and reduced intensity of chorusing in one of the species during operational stage. **	Changes in chorusing could generate changes in social interaction of the species.	Choruses recorded *in situ* within the area of an OWF. Operational noise comprised by low frequencies (25 - 200 Hz), sound levels reaching 130-150 dB re 1μPa^2/Hz.	Siddagangaiah et al. (2022)

*Sound pressure measured, and values compared with fish thresholds from literature. No fish was experimentally exposed.

**OWF operational stage measurements may have been completed too soon after the finalization of the construction stage.

3.4. Particle motion

From the total number of studies included in the review (n = 67), 15 (22%) studies mentioned PM. However, most of the articles approached PM partially, sharing the scope with UWN or vibration. The present review only identified one empirical study on PM (Table 4). The experimental design described in the single empirical study for PM included a field test that did not involve fish directly (Sigray & Andersson, 2011). In this study, a novel PM detector was developed and tested in the field to characterize PM 0.2, 1, 5 and 10 m away from an operational wind turbine. The values of frequency and amplitude (i.e., particle acceleration) estimated within the trialled distances demonstrated PM magnitudes theoretically audible for adult Atlantic cod and plaice (*Pleuronectes platessa*) (Sigray & Andersson, 2011).

Given the fact that a single relevant study was identified on PM, it remains impossible to make a firm assessment of PM in relation to the operational stage of OWFs.

Table 4. Direct effects of operational OWFs on fish. The table covers particle motion, as documented by empirical studies conducted in the field or laboratory.

Species	Field/Lab study	Documented effects	Potential risk for negative operational OWF impact	Stressor characterization (e.g. frequency, SPL, particle velocity)	Reference
Adult Atlantic cod (*Gadus morhua*) and plaice (*Pleuronectes platessa*).*	PM was measured in the field. The obtained PM values were compared to available audiograms for cod and plaice.	Measured PM reached audible levels near the wind turbine (<10 m proximity).	One wind turbine may be heard and cause change of behaviour if the fish is in the vicinity (less than 10 m away). A group of wind turbines could enhance the effect.	PM detector was placed in distance gradient at 0.2, 1, 5 and 10 m from an operational wind turbine. PM was characterized by measurements of frequency (Hz) and acceleration (m/s^2).	Sigray & Andersson, (2011)

*PM measured and values compared with fish thresholds from literature, no fish was experimentally exposed.

3.5. Vibration

From the total amount of studies included in the review (n = 67), 11 (16%) studies included vibration. Only one review article was fully focused on this potential stressor. Vibration appeared throughout the included studies in close relation to UWN, specifically with PM, sometimes using both terms to refer to a common stressor. The specific literature review on vibration approached the topic initially by describing substrate vibration, then describing how substrate vibration may affect the levels of PM near a wind turbine. Finally, the only review found for vibration mentions how wind turbine-borne substrate vibration could affect fishes and invertebrates in a local area (Hawkins et al., 2021). The remaining studies within our final selection that addressed vibration only mentioned the term to illustrate the potential stressors for fish in association to operational OWFs. Moreover, the term ‘vibration’ appeared either as a synonym of PM, referred to structural vibration of the wind turbine foundation, described the oscillation of particles of the substrate, or would not be described clearly after being mentioned. This confusing multiple use of the term ‘vibration’ in the literature has also been reported by Roberts & Elliott, 2017. We further discuss the need for standardization and recommend further research topics in the following sections.

Here, the lack of direct experimental studies on vibration limits the assessment of the effects that vibration, as an independent stressor restricted to the seabed substrate and produced by operational OWFs, may have on fish.

4. Discussion

4.1. Evaluation of review methods

This review identified trends in the scientific literature concerning the effects of four potential stressors related to operational OWFs on fishes. EMF was the stressor most addressed in the scientific literature, followed by UWN, PM and vibration. Improvement of the search strings could be made to capture publications of wider scopes with relevant information, possibly not detected here. Nevertheless, more generic search strings call for additional resources (i.e., planning time, research time, personnel etc.) for screening over a wider range of results. Likewise, the present review did not include any meta-analyses to summarize data series originating from different studies. Systematic reviews may have potential flaws associated with lack of transparency when applying the inclusion and exclusion criteria. Other potential sources of bias are related to lack of replicability, and incomplete reporting of the selected reviewing protocols (O'Leary et al., 2015). Our methodology followed established general guidelines for systematic reviews. Emphasis was placed on iteration and participation of all the authors for developing the final search strings. One of the investigated stressors (i.e., vibration) lacked experimental work, although the topic is mentioned in several reviews. The results show that the present research field is in an early stage of development. Our results evidenced increasing number of publications in the scientific literature, except for studies on vibration. Importantly, industry data produced for compliance purposes (e.g., EIA, monitoring) or internal use (e.g., ROV footage, survey reports) could prove useful for research purposes and accelerate scientific knowledge generation on the topic. In that line, initiatives applying existing and accessible databases for research purposes (e.g., the INSITE Data Initiative) could become widespread. Here, we provide an overview of the current scientific knowledge on the effects that the selected stressors from an operational OWF could have on fishes. Additionally, we feature information gaps concerning each stressor and provide insights on further research to address them (see Appendix B).

4.2. Stressors

4.2.1. EMF

The potential effects of EMFs on fish have received the most attention in terms of the number of empirical studies out of the four stressors covered in this report. While effects from EMFs emitted by OWF subsea cables may seem relevant only for coastal (i.e., offshore-onshore energy transportation) and offshore (i.e., inter-array energy transportation) marine species, subsea power cables are used in numerous applications or technologies that interact with aquatic environments (e.g., cables crossing rivers, lakes, and estuaries). Despite the increasing trend to move wind energy production further offshore, it thus remains important to consider EMF effects within diverse aquatic ecosystems and to include freshwater or brackish species, as well as diadromous fish species that migrate between freshwater and marine environments during their ontogeny (i.e., during different life stages) (Hutchison, Secor, & Gill, 2020). Our literature review indicates that this importance is reflected in empirical studies on EMF effects, which so far have focused on marine fishes (e.g., lesser sandeel; Cresci et al., 2022), freshwater fishes (e.g., crucian carp; Kuz'mina et al., 2015), and on species migrating between the freshwater and marine environments (e.g., European eel; Westerberg & Lagenfelt, 2008 and rainbow trout; Fey et al., 2020). Potential negative effects of anthropogenic EMFs are clearly concentrated within the findings of laboratory studies that focus on the early life stages of fish (Table 2). To date, these experiments have highlighted that the effects from exposure to anthropogenic EMFs can potentially be manifested genetically, physiologically and developmentally during early life stages. Rainbow trout subjected to long-term EMF exposure revealed genetic effects through nuclear abnormalities alterations in cell nuclei (Stankevičiūtė et al., 2019), while both static and time-varying B-fields triggered a physiological effect in crucian carp by reducing their digestive enzyme activity (Kuz'mina et al., 2015). Developmental effects have been suggested in multiple focal species, including indications of developmental instability of the inner ear organ in rainbow trout (Fey et al., 2020) and delayed pigment formation and lower number of melanophores in European whitefish and venace (Brysiewicz et al., 2017). However, it is important to note that the most laboratory studies that documented negative effects used B-field intensities that are relatively high compared to values typically encountered a few meters away from subsea cables at present (Gill & Desender, 2020), although the values may resemble maximum intensities encountered directly adjacent to the cables (Cresci et al., 2022; Jakubowska-Lehrmann et al., 2022). For example, studies by Brysiewicz et al. (2017) and Fey et al. (2019) used B-field intensities of 1000-5000 µT and 10,000 µT, respectively, while B-field intensities measured a few meters away from subsea cables at six different locations since 2016 are within the 0.04-150 µT range depending on the type of current (AC or DC) and the depth of the cable, among other factors (Gill & Desender, 2020). In addition, a number of these studies employed relatively long-term EMF exposure (e.g., 4-week and 40-day exposures in Bochert & Zettler, 2004 and Stankevičiūtė et al., 2019, respectively) while spatially confining the study organisms within the EMF. It remains unclear to what extent such prolonged exposures are realistic for fish encountering OWF subsea cables in the natural environment. As such, future studies need to account for species-specific encounter rates based on for example larval dispersal mechanisms, lifestyle (pelagic vs benthic species) and species mobility levels, as well as EMF intensity thresholds at which the observed effects occur (e.g., dose response curve) (Gill & Desender, 2020), to extrapolate such findings to wider population-level effects.

Apart from early life stage effects, a limited number of studies reported mixed effects of anthropogenic EMFs on the migratory behaviour of fishes. Specifically, while acoustic tagging of European eel revealed a significant decrease in swimming speed when the eels approached a subsea cable (Westerberg & Lagenfelt, 2008), tagging data for rainbow trout smolts instead showed faster swimming speeds during periods of cable activity versus inactivity (Wyman et al., 2018). However, both studies concluded that the anthropogenic EMF did not act as a strong barrier during migration and is unlikely to reduce the migratory success of these species. This example shows how the complex interactions between species-specific migratory behaviour, cable properties (i.e., activity vs inactivity; DC vs AC) and a diverse range of environmental parameters that differ among localities can complicate direct inter-study comparisons. As such, we highlight the need for replicated, long-term studies assessing migratory behaviour near cables and in reference areas, as well as detailed reporting on cable characteristics, to adequately disentangle the different variables explaining variations in migratory behaviour of fishes.

This review did not identify any negative EMF effects on fish community metrics, including fish abundance, richness and species composition (Table 2). A study by Love et al. (2017) revealed that fish communities differed between cables and natural habitat, yet communities were similar between energized and non-energized cables. Such findings are particularly relevant, as they highlight that habitat variables (e.g., physical structure) were more important drivers of the fish community compared with anthropogenic EMFs. This is further confirmed by Dunlop et al. (2016) who additionally note the importance of other variables, including substrate type and depth, in explaining variations in fish density, whereas proximity to the cable was less important. Furthermore, studies investigating potential effects of EMFs on commercial marine fishes are scarce, making extrapolations of documented effects to a fisheries level challenging at this stage. From the limited number of experiments targeting commercial species, it seems reasonable to conclude that there are currently no indications of negative EMF impacts on a population level that could affect marine fisheries. For example, Cresci et al. (2022) investigated the effect of static B-field exposure on lesser sandeel larvae (*Ammodytes marinus*), a commercially important species currently supporting the largest fishery in the North Sea (Langton, Boulcott, & Wright, 2021) and which distribution overlaps with that of planned OWFs in the North Sea. The authors found no effects on the spatial distribution of sandeel larvae, their swimming speed or distance moved, but concurrently note that EMF effects on sandeel adults targeted by North Sea fisheries currently remain unknown.

Collectively, potential negative effects from anthropogenic EMFs currently appear to manifest mostly within the early life stages of fish through genetic, physiological and developmental alterations. However, the long-term impacts of these effects remain unclear and urgently need to be considered (Formicki, Korzelecka-Orkisz, & Tański, 2021), as this information is required to define safe levels of EMF emission within industry standards and ultimately for estimating population-level impacts of the increasing prevalence of anthropogenic EMFs associated with the rapidly expanding OWF industry.

4.2.2. Underwater noise, particle motion and vibration

The revised literature contained mixed results regarding the potential effects of underwater noise (UWN) from operational OWF on fish. While the experimental research did not find fish mortality linked to UWN, other responses were reported. Experiments on milkfish demonstrated a physiological response (Wei et al., 2018). After experimental exposures under laboratory conditions to recordings made 1 m away from a wind turbine (138 dB re 1 μPa/125.4 Hz), elevated cortisol levels were detected. The elevated cortisol levels were observed in milkfish individuals exposed continuously for 24 hours, but not in individuals exposed continuously for 3 days, or a week (Wei et al., 2018). Thus, milkfish might habituate to the UWN under these specific experimental conditions. In addition, increased mRNA levels (i.e., gene expression changes) of head kidney 1-b-hydroxysteroid dehydrogenase were found in fish exposed continuously for 72 hours, and fish exposed continuously for a week. This enzyme is associated with stress responses, but Wei et al. (2018) did not confirm the physiological roles of the gene expression changes. A similar experiment with black porgy resulted in elevated plasma reactive oxygen species (ROS) levels after 2 weeks of noise exposure (138 dB re 1 μPa/125.4 Hz) (Chang et al., 2018). Elevated ROS is associated with pathological processes and ageing (Lushchak, 2016). These physiological responses were only observed in noise exposure conditions using recordings obtained 1 m away of the wind turbine, and in a restricted movement, experimental setting (i.e., floating cages in a pool). Potential avoidance from the turbine could be expected *in situ*, unless potential positive reef effects, often associated with the foundation (e.g., monopile) and scour protection of OWFs, exceed any negative effects. In another study, bluefin tuna showed limited behavioural changes when exposed to played recordings originating from an operational OWF (Puig-Pons et al., 2021). Limited behavioural reaction was also reported for cod; in this case, it was during a noise level of much higher magnitude, specifically pile driving (van der Knaap et al., 2022). Atlantic cod is a vocal species that communicates using low frequency sounds during migration, aggression and escaping behaviours, as well as courtship (Meager et al., 2017). OWF foundations and the scour protection can act as artificial reefs, enhancing local productivity, including availability of food and refuge (Gill et al., 2020). Such artificial reef effects should be considered when using escape behaviours and site fidelity as a proxy for *in situ* studies. The benefits of available resources could outweigh the disadvantages from potential stressors and mask the effects of the disturbance. Although pile driving is not directly within the scope of the present review, it is relevant to consider that even under extreme UWN levels, mortality was not observed, even in larval stages of sea bass. With operational OWF UWN, the effects on fish, especially associated with the long-term exposure, could go overlooked considering the relatively lower levels of noise during the operational stage. For example, even when subtle behavioural responses are observed in fish, direct damage from operational OWF UWN seems unlikely because of the relatively low noise level (Mooney et al., 2020). Even though UWN levels are lower than in the construction phase, the operational noise overlaps the frequency of many known fishes' auditory and vocal ranges (Mooney et al., 2020). Also, operational noise is much more long lasting compared to the UWN experienced during the OWF construction stage. In the present review, we observed that UWN may have potential effects on fish inhabiting the close proximities of operational wind turbines. However, to get a better understanding of the interaction between OWF and fish, the effects should be assessed using behavioural and physiological proxies for fish, and within a context of potentially beneficial effects (e.g., reef effects; see section 4.3). Importantly, the Population Consequences of Acoustic Disturbance model (PCAD; National Research Council, 2005) provides a framework for assessing the effects of UWN

(Fig. 1). The results discussed in this report present evidence of potential physiological and behavioural effects of operational OWF UWN on fish mainly under specific laboratory experimental conditions. Future field experiments should further inform how observed physical, physiological, and behavioural effects on fish modify key functions (e.g., movement, migration, feeding, reproduction), and influence individual fitness (Hawkins & Popper, 2017). In particular, this would provide a better mechanistic understanding of possible effects and enable advanced assessments of the noise impacts on fish at population levels.

Several reviewed studies emphasized that their results should not be extrapolated to other conditions or fish species. Studying the hearing abilities for estimating the auditory thresholds (i.e., audiogram) for every fish species at specific life stages could pose a challenge for researchers, authorities and OWF operators. A plausible solution could be grouping fishes based on anatomical differences and knowledge about hearing of other species with similar anatomy (Hawkins & Popper, 2017). In addition, some techniques have been developed, including the auditory evoked potential (AEP). AEP consists of a non-invasive recording of auditory neural electrical activity of the inner ear and lateral line of the fish, but it does not capture an absolute hearing sensitivity (Zhang et al., 2021). The results from the AEP technique could be troublesome due to high variability, and only measuring response of the ear and not the rest of the auditory system (Hawkins & Popper, 2017). Other aspects to consider when exploring UWN effects on fish include characterization of the infrastructure (e.g., size, design, type) acting as a source, and accounting for particle motion (PM) (Popper & Hawkins, 2018). The assessment of the potential effects of UWN from operational offshore wind turbines on fish has seen an asymmetrical progress between the components comprising sound. Most of the studies identified here were focused on the effects of sound pressure. On the other hand, PM was acknowledged as an unexplored field in drastic need for research. Stöber & Thomsen (2021) highlight the scarcity of documented measurements of PM at operational wind turbines, while it is the primary acoustic stimulus for most fishes (Stöber & Thomsen, 2021). The effects of OWF generated by PM on fish remain unclear. The levels of PM detected 1 to 10 m away from an operational wind turbine indicate limited impact for Atlantic cod and plaice when compared with their audiograms (Sigray & Andersson, 2011). Similar results were recorded from Block Island OWF in the US (Stöber & Thomsen, 2021). While the mechanisms for detection of PM by fish are known, limited access to the instrumentation needed for field measurements has apparently reduced research progress on PM (Nedelec et al., 2016). The recent mainstreaming of commercial class accelerometers and particle velocity sensors will likely help advancing knowledge on PM and its contribution to observed UWN effects on biota (Popper & Hawkins, 2018).

An operational wind turbine could generate UWN in several ways (Fig. 8). The greatest factor explaining UWN levels from wind turbines is the distance to the turbine (Tougaard et al., 2020). Turbine size and wind speed have lesser effects on UWN levels (Tougaard et al., 2020). As the size of the turbine increases, so does the mechanical forces on the gears and bearings, thus higher UWN levels could be expected (Tougaard et al., 2020). The gearbox in the nacelle is a source of low frequency noise (<1 kHz). Other sources of noise seemingly come from the structural vibration of the tower at high wind speeds (Kikuchi, 2010; Tougaard et al., 2020). This structural vibration also reaches the foundation and induces waves that travel through the seabed and may later propagate as sound into the water. Additionally, rotor blades generate aerodynamic noise that may enter the water through an air path (Kikuchi, 2010). Broadly, the sound is transferred through the tower down to the foundation, where it is then radiated into the water (Tougaard et al., 2020). Thus, structural vibration has a relevant role for understanding the acoustic dynamics between the wind turbine and the water column. Vibration studies were not common within our review results, and the term is usually accompanying UWN. A previous study provides insights to vibration as a stressor independent from PM or UWN (Roberts & Elliott, 2017). They suggest the existence of a 'vibro-scape', similar to the widely used 'sound-scape' concept, within the sediment. This 'vibroscape' would be comprised by biological activities on the seafloor (e.g., movement, burrowing, feeding), waves, turbulence, earthquakes, etc. In the context of a noisy water column, an organism may benefit from using vibration signals from the substrate, in addition to the sound signals (Roberts & Elliot, 2017). Demersal fishes may have developed higher sensitivity to vibration stimuli of the substrate (Hawkins et al., 2021), provided their sensibility to the motion of water particles (i.e., PM). For example, experimental trials with plaice (*Pleuroectes platesa*) showed its relatively acute sensibility to water particle velocities (i.e., PM) of 0.3 µm/s at around 20 Hz (Hawkins et al., 2021). Meanwhile, particle velocity (i.e., PM) measurements 68 m away from a test pile drive (Kinderdijk, Netherlands) reached values of 2500 µm/s (Hawkins et al., 2021). Although the PM and vibration produced by an operational wind turbine are of much lower magnitude than the pile-drive PM and vibration, *in situ* measurements would increase our knowledge on the effects of OWF on fish. Strong positive correlations have been reported between structural vibration of the turbine tower and produced sound pressure, and between vibration and PM in the water column (Yang et al., 2018). Therefore, understanding the mechanisms underpinning the effects of OWF will require data collection on sound pressure together with PM and vibration.

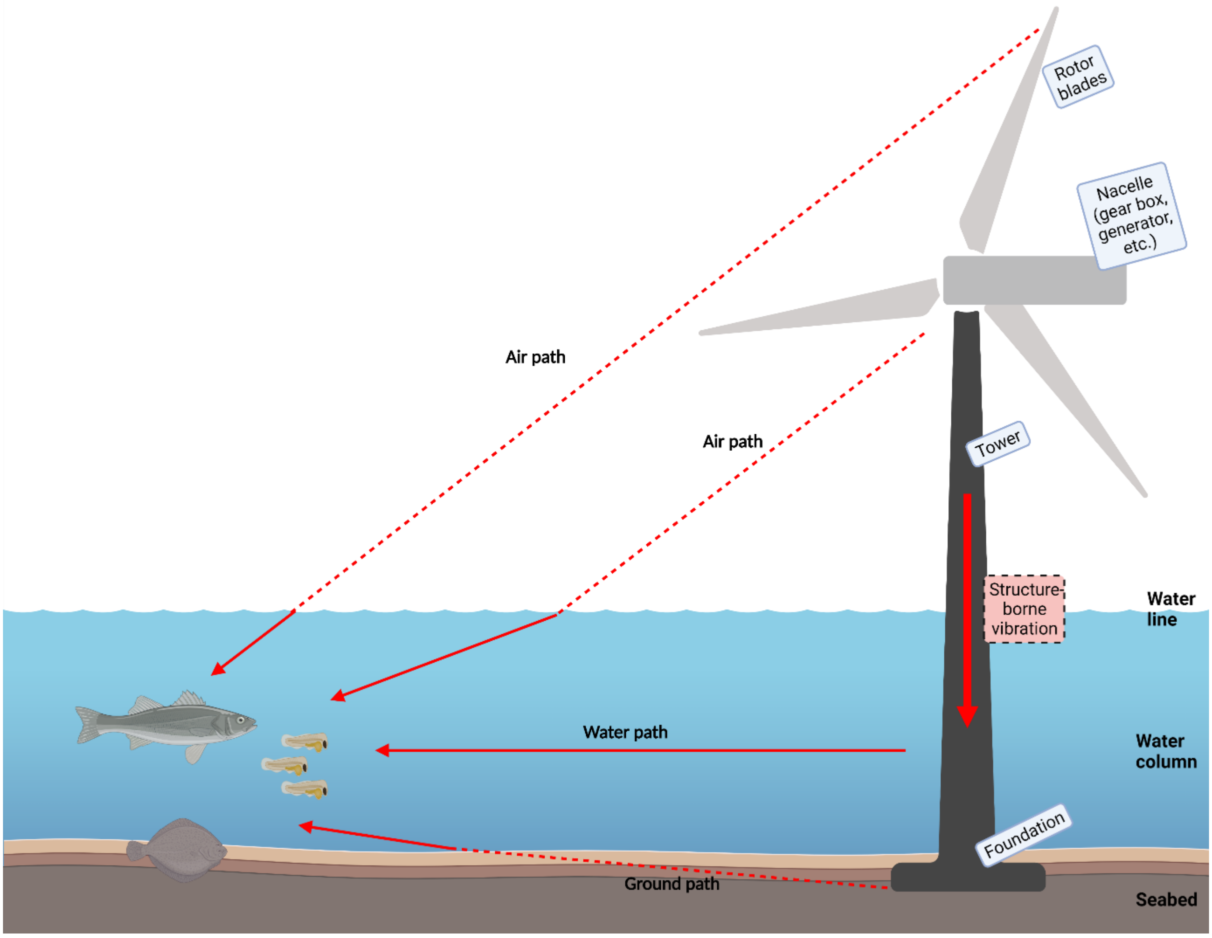

Figure 8. Transmission mechanism of UWN from an operational offshore wind turbine. The structural vibration of the tower is fundamental for transmission of sound (Redrawn from Kikuchi, 2010; Created with BioRender.com).

Briefly, research on the potential effects of UWN, PM or vibration, produced by operational OWFs, on fish is at an early stage. Reportedly, fishes may react to operational OWF UWN, however, we have a poor understanding of how sound pressure and PM, which comprise UWN, interact to produce observed physiological and behavioural responses. Moreover, we have limited knowledge of how vibration (i.e., the oscillation of substrate particles in the seabed) may act as a stressor for fish.

4.3. At a glance: stepping-stone effects and artificial reef effects of OWF and potential positive impacts on fish and fisheries

This systematic OWF review covered direct effects of EMF, UWN, PM and vibrations on fishes, including biological traits such as physiology, migration, and mortality. OWFs represent major physical structures in the marine environment and may have several ecosystem effects, including stepping-stone effects for indigenous and non-indigenous species as well as local artificial reef effects. Stepping-stone effects may allow indigenous and non-indigenous species to colonize and survive in novel areas. Specifically, novel habitats associated with installed OWF structures could connect indigenous and non-indigenous species to new areas and thereby enable a redistribution of the species (Langhamer, 2012). For example, the distribution of blue mussel (*Mytilus edulis*) in the North Sea is probably affected by OWF structures and other man-made offshore structures (Coolen et al., 2020). The authors concluded that blue mussels would be unlikely to survive at offshore locations in the North Sea if the artificial hard substrates were absent (Coolen et al., 2020). Similarly, fish species preferring hard substrate, and therefore either unknown or very rare on the surrounding sandy seabed, have been recorded near hard substrates associated with marine artificial structures (Degraer et al., 2020).

Reef effects of OWF structures have been described by several studies. Reviewing existing literature on artificial reefs and OWF, Glarou et al. (2020) concluded that OWF scour protection meets the requirements to function as an artificial reef, often providing shelter, nursery, reproduction, and/or feeding opportunities for a range of species. In agreement, Raoux et al. (2017) modelled effects of OWF foundations in France and reported that higher trophic levels, including piscivorous fish species, marine mammals, and seabirds, responded positively to the aggregation of biomass on piles and scour protections. In Denmark, Stenberg et al. (2015) conducted a long-term study and reported that fish abundance increased slightly in an OWF area, whereas fish abundance declined in the control area 6 km away. Species diversity was significantly higher close to the OWF foundations (Stenberg et al., 2015). At the Block Island Wind Farm in the US, recent studies on the operational OWF provided evidence for an artificial reef effect (Wilber et al., 2022), consistent with other studies (Degraer et al. 2020). For example, abundance measures of black sea bass (*Centropristis striata*) and cod were significantly higher during the OWF operation period near the wind farm compared to a dedicated control area. Data on the abundances of schooling species such as Atlantic herring (*Clupea harengus*), scup (*Stenotomus chrysops*), and butterfish (*Peprilus triacanthus*) did not indicate an effect of OWF operation (Wilber et al., 2022). Similarly, van Deurs et al. (2012) concluded that within a time frame of seven years after construction, an OWF in Denmark represented neither a direct benefit nor a definite threat to sandeels and their sand habitat (van Deurs et al., 2012). Based on such findings, Stenberg et al. (2015) concluded that most OWF structures are large enough to host fish species with a preference for rocky habitats, but not large enough to have adverse negative effects on species inhabiting the original sand bottom between the structures (Stenberg et al., 2015).

5. Conclusions

Given increasing demands for renewable energy, and the ambitious global energy targets to phase out fossil fuels in the near future, it is evident that the required OWF development and expansion will further increase our anthropogenic footprint in offshore marine environments and lead to diverse and complex interactions with marine life. Our systematic literature review focused on four stressors associated with the operational stage of fixed-bottom OWFs that could potentially cause negative interactions with fish and fisheries, including EMF, UWN, PM, and vibration. While our results suggest an increasing trend in research efforts allocated toward these four topics, we highlight that empirical studies are currently underrepresented and comprised less than half of the identified relevant studies in our review, largely driven by studies investigating EMF and UWN.

Negative effects from anthropogenic EMFs were mostly documented within laboratory trials on fish species, whereas field experiments investigating effects on fish movement, migrations, and community assemblages thus far reported limited or no discernible effects. Laboratory trials reveal significant effects from EMF exposure during early life stages of fish (i.e., from embryonic to larval stages), including genetic, physiological, and developmental alterations. However, such effects should be further tested using biologically and OWF relevant EMF intensities and exposure times while further incorporating existing knowledge on the movement ecology and dispersal capabilities of target species, to facilitate evaluations of potential long-term impacts on fish populations.

In terms of UWN associated with operational OWF, results from several experiments evidenced present but limited physiological and behavioural changes. These results have to be considered within the context of operational OWFs, taking into account exposure duration, the capacity of the OWF, fish species, movement ecology etc. Furthermore, the study of UWN effects on fish is becoming increasingly informative by accounting for not only sound pressure but also PM, which is another important component of sound. Records on PM levels at operational OWFs are scarce, and threshold levels for fish are rare in the scientific literature. A similar scenario exists for vibration. Currently, increasing data on fish hearing thresholds and operational OWF UWN demonstrate an overlap that could have the potential for masking vital sounds of biological importance to fish.

Collectively, significant uncertainties remain regarding potential negative impacts on fish and fisheries from the four potential stressors investigated in this review. Specifically, the research fields covering the examined stressors are still young and under development. Based on the limited knowledge available to date from this literature review, we found no evidence that directly indicates negative impacts of operational OWFs on fish populations and thereby their associated fisheries. However, this finding should be interpreted with caution, as the absence of evidence does not imply an absence of impact, and our findings are based on a limited number of empirical studies that partly used freshwater target species and generally tested highly variable exposure levels. Clearly, empirical studies need to collect data on biologically relevant exposure levels and identify species-specific intensity thresholds at which possible effects occur (e.g., dose response curve), such that this knowledge can be used in future syntheses or meta-analyses to ultimately advance our understanding of OWF impacts on fish and fisheries. Finally, studies should integrate habitat effects arising when new hard substrate (e.g., scour protection) becomes available via OWF installation. Based on the present literature review, we argue that EMF research should be given the highest priority due to the spatial extent of potential impacts (i.e., along inter-array and onshore-offshore cable routes), the significant EMF effects on early life stages found in lab studies, and the potential of EMFs to affect migratory behaviour of marine species. However, from a perspective of lacking scientific knowledge, the topics of PM and vibrations are clearly in urgent need of empirical studies investigating their potential effects on fish and fisheries.

Appendix A – Final selection of relevant articles identified and used in review

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Appendix B – Perspectives and outlook

As the OWF industry is rapidly expanding to meet the increasing demand for renewable energy, it is relevant to briefly explore emerging OWF technologies and management strategies that can be employed to minimize the risk of negative impacts to fish and fisheries in the future. In the following section, we briefly discuss the emerging technology of deep-water floating OWF and implications for the effects on fishes associated with the four main stressors that were the focus of this report. We subsequently summarize current recommendations for mitigation based on available knowledge and identify specific research areas requiring more attention to further advance this field and guide impact assessments and management efforts in the future.

B1. Floating offshore wind farms

There are multiple incentives to expand the OWF industry further offshore with the use of floating OWF, most importantly to harness the huge potential of stronger and more consistent winds offered by these offshore areas. Moving wind production further offshore also reduces the impact on important coastal ecosystems and potential conflicts among ocean users, while simultaneously minimizing visual impact to coastal communities, including for countries with steep continental slopes, previously confined to nearshore waters less than 60 m deep for OWF development (Farr et al., 2021; Maxwell et al., 2022). The first floating OWF was commissioned in Scotland in 2017 (Hywind) consisting of five turbines with a total capacity of 30 MW. Since then, nine additional floating OWF were installed, five in Europe and four in Japan with total capacities of 50 MW (Darwish, 2022). Given the low number of floating OWF currently in operation and a lack of publicly available empirical data, it is at present impossible to quantify the potential effects of floating OWFs on the surrounding environment. However, using existing knowledge from various analogues (e.g., fixed OWFs and onshore wind), recent literature reviews have highlighted key design differences to derive potential risks to marine life that are most likely to occur during floating OWF operation (Farr et al. 2021; Maxwell et al., 2022). Floating OWFs differ from fixed OWFs mainly in the type of platforms and anchoring methods (overview in Maxwell et al., 2022), as well as the mooring system used, with each platform type using at least 3 separate mooring lines (commonly made of steel or synthetic rope) connecting to the anchoring system on the seabed. Importantly, this implies that the mooring lines are generally suspended throughout the water column (i.e., at present between 100-200 m, but potentially up to 1000 m of depth in the near future), along with the power cables used to transport the energy from each turbine to a marine substation. Therefore, in contrast to fixed OWFs, floating designs will require the use of both suspended cables (inter-array connection) and buried cables (offshore-onshore connection) and are thereby likely to expose a more diverse range of fishes (i.e., pelagic, demersal and benthic species) to anthropogenic EMF emissions. While buried cables can reduce EMF effects by increasing the physical distance between benthic or demersal fishes and the cable, suspended cables through the water column may increase the risk for direct interactions at close proximity for many fish species. As this review report has highlighted a paucity of information on effects of anthropogenic EMF for many marine species, in particular pelagic fishes (e.g., electroreceptive elasmobranchs), empirical studies are urgently required to address this knowledge gap given the increasing global interest in floating OWFs. Additionally, a combination of wear in the power cables (due to e.g., biofouling or hydrodynamic forces in the water column) and the increasing cable length and capacity required to facilitate long-distance energy transport at increasing current strengths to shore, may further enhance emissions of anthropogenic EMFs associated with floating OWFs (Taormina et al., 2018; Maxwell et al., 2022). Regular monitoring and maintenance will therefore be required to minimize the risk of further EMF impacts and other technical issues associated with wearing power cables. For example, regular monitoring and maintenance may reduce wear in the power cables and may therefore keep EMF emissions relatively low. This seems particularly important considering that cable failures (e.g., due to abrasions) currently comprise a significant amount of the total financial losses related to OWF (Gulski et al., 2021). Regarding underwater noise, the crucial difference between fixed and floating OWFs is that the latter does not require pile driving during the construction phase, effectively eliminating one of the most impactful activities associated with OWF construction (though pile anchors are occasionally used that require pile driving to a lesser degree; Maxwell et al., 2022). In addition, many parts of floating OWFs can be assembled onshore prior to transporting the system to the offshore site, in contrast to fixed OWF structures that require on-site construction, implying a further reduction in on-site noise impacts associated with floating OWFs (Farr et al., 2021). At present, it is still largely unknown how operational noise produced by floating OWFs will differ from that of fixed OWF structures. Depending on the size of individual turbines and local hydrodynamic conditions, it currently seems reasonable to assume that noise levels associated with floating OWFs will similarly fall within regulatory levels and pose minimal risk to marine organisms in terms of physiological damage (Farr et al., 2021; Maxwell et al., 2022). This suggests that floating OWFs may ameliorate rather than exacerbate the combined impact of construction and operational OWF UWN on fish, compared to bottom fixed turbines. However, the potential effects of floating OWF vibrations and PM are still poorly understood and future research will need to establish how these stressors may potentially differ between fixed and floating OWF structures.

Apart from the four stressors that are the focus of this report, the entanglement of marine organisms is of particular concern in relation to floating OWF development (Benjamin et al., 2014). The risk of entanglement represents a key difference between fixed and floating OWFs, due to the presence of cables and mooring lines suspended in the water column that are required to install and operate floating OWFs. While the risk of entanglement seems negligible when considering a single floating OWF in isolation, this risk may become more substantial under increasing prevalence of suspended mooring lines and dynamic power cables (Taormina et al., 2018). Marine organisms may either become entangled through primary, secondary or tertiary entanglement. Risks of primary (i.e., direct) entanglement are mainly limited to large megafauna and marine mammals due to the large diameter and taut configuration of the lines, and even for those groups the risk is considered low (Benjamin et al., 2014; Harnois et al., 2015). The two remaining types of entanglement likely pose a greater risk to marine organisms, including small-bodied fishes. Secondary entanglement can occur when lost or discarded fishing gear (e.g., ‘ghost nets’) accumulates around a floating OWF and subsequently entangles organisms. Tertiary entanglement refers to organisms getting ensnared in discarded fishing gear and subsequently stuck in floating OWF components (Farr et al., 2021). Similar to the other stressors, quantifying risks of entanglement for marine species in relation to different designs will only be feasible once sufficient floating OWFs are operational and empirical evidence becomes available. Until then, potential risks of entanglement remain mostly speculative (Taormina et al., 2018) and mainly rely on qualitative risk assessment and numerical modelling approaches (e.g., Benjamin et al., 2014). However, with the expected massive deployment of floating OWFs in Europe by and from 2030 to meet the energy goals (Darwish, 2022), empirical evidence from operating floating OWFs may soon become available and allow for detailed environmental impact assessments.

B2. Mitigation strategies

Potential mitigation strategies addressing anthropogenic EMF emissions will mainly need to focus on preventing impacts from cable construction and presence on the marine environment, as the EMF emissions themselves cannot be avoided. While E-fields induced by cables are shielded within the insulated cores and thus remain confined within the cable, B-fields cannot be shielded and are emitted orthogonally into the surrounding seabed or water column relative to the direction of the electric current (Newton et al., 2019). In addition, out-of-phase B-fields emitted by AC cables create rotating iE-fields near the cables that may affect prey detection and behaviour of electroreceptive fishes (Newton et al., 2019). However, while emission of B-fields and iE fields are unavoidable, cables can still be buried to increase the physical distance between the cable and most fish species, which may lower the EMF level to which fishes and other organisms are exposed (Normandeau Associates Inc., 2011), although with the notable exception of local infauna and burrowing fish species. Subsea cables deployed on top of bare sediment can still be shielded by various types of protective layers, including rock layers, cast-iron shells and concrete mattrasses (Taormina et al., 2018), to avoid direct contact between the cables and benthic or demersal fishes. In terms of the construction and deployment of subsea cables, an important consideration is the type of habitat or seabed coverage encountered along the planned cable route. Care should be taken not to assign offshore-onshore cable connections to areas covered by vulnerable biogenic habitats (e.g., bivalve reefs or eelgrass meadows) that function as important nursery habitats for coastal fish species, or to areas with known contaminants in the sediment that could potentially be resuspended in the water column through cable construction (Taormina et al., 2018). In addition, converting cable routes into protected zones that restrict other anthropogenic activities (e.g., fishing or dredging) may minimize the risk of cable damage. Further potential measures to mitigate EMF impacts include the use of adequate cable technologies that reduce EMF emission (e.g., helically twisted, three-core AC cables) and avoidance of cable construction and maintenance activities within periods of known significance to local marine life, whenever possible (e.g., spawning events or feeding migrations; Table 5; Copping et al., 2016; Taormina et al., 2018).

In terms of UWN, PM and vibration, potential mitigation strategies involve structural vibration reduction. The main path of UWN transmission from the operational turbine into the water column is the tower and foundation through vibration (Fig. 8; Kikuchi, 2010). Applying successful structural vibration control technologies, such as tuned mass dampers (Hemmati et al., 2019), could allow to not only reduce the levels of vibration, but also UWN and its PM component. On the other hand, UWN criteria and guidelines need to be developed in terms of sound pressure and PM (Popper & Hawkins, 2019). Finally, the rapid expansion of OWFs could be surpassing research efforts for understanding the impacts of the wind turbines on fish. In this context, the monitoring of effects from operational OWFs would benefit from globally standardized survey methods designed in direct coordination between researchers and OWF project developers. Such coordination would allow for developing monitoring systems that produce data relevant for regulatory compliance and scientific research. Some examples are Offshore Windfarm Egmond aan Zee in the Netherlands (Lindeboom et al., 2011), and Block Island OWF in the US (Wilber et al., 2022).

Table 5 – Mitigation potential and future research for the four main stressors reviewed in this report.

Stressor types	Mitigation potential	Future research needs
Electromagnetic fields	EMF emissions: • Bury subsea cables whenever possible to increase physical distance between cable and fish species • Use protective layer (e.g., rocks, cast-iron shells, or concrete matrasses) to shield unburied cables Cable construction and deployment: • Critical considerations of cable routes to avoid sensitive areas, (e.g., vulnerable biogenic habitats such as biogenic reefs or seagrass meadows) or areas known to contain contaminants in the sediment • Assign protection status to areas along the cable route to avoid additional anthropogenic activities that could inflict damage to subsea cables and risk potential current leakage into the surrounding environment • Use cable design and technologies that are appropriate for minimizing the associated EMF emission • Conduct construction and maintenance activities outside of known periods of significant importance to local marine fishes (e.g., feeding migrations or spawning events)	• Better understanding of different EMF intensities and frequencies on receptive fish species via dose-response studies • Robust and long-term field monitoring studies (e.g., using acoustic or visual methods) employing BACI or more advanced sampling designs to disentangle anthropogenic EMF effects from diverse and fluctuating environmental parameters • Laboratory studies assessing the effects of biologically relevant EMF intensities on embryonic, juvenile and adult life stages, and incorporate relevant life history, habitat use, and movement ecology • Studies investigating how EMF effects scale with the power transmitted by different cable types, as well as the importance of cumulative EMF impacts under future scenarios of OWF development and expansion • Detailed measurements of EMF properties that account for local environmental conditions and employ standardized reporting methods
Underwater noise	• Structural vibration control technologies similar to technologies applied in buildings (e.g., mass dampers) • Wind turbine designed for reduced noise emission from the nacelle. • Reduction (when possible) of vessel traffic during maintenance operations	• Assessment of behavioural response in the field rather than the laboratory • Exploring physiological responses to operational OWF noise in species from different hearing groups • Evaluating ecological effect with long-term realistic field studies
Vibration (as substrate-borne vibration)	• Maintaining vibration levels during operational stage within harmless thresholds for local biota • Reduction of structural vibration of the tower using available technology on vibration suppression (e.g., tuned mass dampers)	• Assessing vibration thresholds for key species from the impacted ecosystems • Estimating vibration levels (e.g., particle velocity) in a distance gradient from the foundation of the turbine • Exploring the cumulative vibration levels originated for several operational turbines
Particle motion	• UWN mitigation strategies will likely also produce PM reduction • Incorporate PM level measurement as a standard environmental monitoring protocol	• Estimating PM threshold of key species. • Assessing PM levels nearby operational OWFs

B3. Future research needs

Table 5 provides a summary of important future research areas that were identified from the current literature review. Regarding studies assessing the effects of anthropogenic EMFs, significant research focus should be allocated toward dose-response studies that would facilitate a better understanding of complex relationships between EMF characteristics (intensity, frequency and duration) and the associated physiological and behavioural responses in sensitive fishes during their ontogeny (i.e., different life stages) (Newton et al., 2019). Furthermore, robust and long-term field monitoring studies are urgently needed and should whenever feasible, employ a before-after control-impact sampling design (or more advanced, e.g., progressive-change BACIPS; Thiault et al. 2017) to allow for disentangling diverse effects of local environmental fluctuations from the real EMF impact effect. Field studies using acoustic tagging of fishes would benefit from equipping the tags with accelerometer and magnetometer sensors, to allow for a simultaneous evaluation of swimming behaviour and measurement of the MF anomaly as the tagged fish approach a subsea cable (Wyman et al., 2018; Klimley et al., 2021). Future laboratory studies are encouraged to assess EMF effects at biologically relevant units and incorporate existing knowledge on movement ecology and life history of the target species to infer realistic encounter rates (Gill & Desender, 2020; Hutchison et al., 2020). Detailed reporting of EMF characteristics is warranted across all types of empirical studies and should to the best possible extent follow established guidelines and standards and be made publicly available, further allowing this information to be used in the calibration of EMF models used to simulate EMF emissions from cables under various conditions (Hutchison et al., 2021). Another important knowledge gap that requires urgent attention includes the potential cumulative effects on fish species arising from frequent exposure to anthropogenic EMFs. For example, if swimming speeds or directions of migratory fishes are consistently altered to similar degrees each time they encounter EMF anomalies, the cumulative effects in terms of e.g., energetic loss or total migration time could significantly compromise migratory species (Copping et al., 2016). The importance of cumulative effects remains poorly understood, as well as how potential effects might scale with energy levels transported within subsea cables, yet such considerations will likely become increasingly important under future expansions of the global OWF industry.

Finally, the effects of UWN on fish populations remain uncertain. To assess the impact of OWF development on fish, the existing knowledge gaps on *in situ* PM levels and biotic thresholds need to be addressed. The ability of fish to primarily detect PM, with only some species being able to detect sound pressure, calls for adopting PM monitoring at the sources (Popper & Hawkins, 2019). In addition, vibration as a stressor calls for evaluation together with the other stressors. Disregarding possible synergies between the stressors could result in inefficient decisions and undermine costly sustainability strategies. While research on physiological responses seem to be providing information on effects that otherwise would go overlooked, investigation of the effects on fish population levels are also needed. A standardization of methods would help gathering information that could be contrasted with results from other species, under similar conditions. Future studies on fish should evaluate behaviour and population dynamics in relation to stressor type, ideally using a dose-response approach. Field studies on fish behaviour using acoustic tagging (i.e., telemetry) at operational OWFs could provide an understanding of the interaction between fish, the local habitat, and the turbine foundations (Reubens et al., 2013; van Haal et al., 2017). Telemetry studies would provide valuable insight on habitat use, movement patterns, home range area, and site fidelity, among other and enable *in situ* measures of the effects of operational OWFs. This should be combined with concurrent measurements of EMF, UWN, PM and vibrations and supported by laboratory studies to reveal the involved mechanistic bases at the behavioural, physiological and biochemical levels.

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