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Potential effects of electrical energy transmission – the case study from the Polish Marine Areas (southern Baltic Sea)

by

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Abstract

The operation of offshore wind turbines and electricity transmission through submarine cables over long distances generate electromagnetic or static magnetic fields (depending on the technical solution) that may modify the natural geomagnetic field and cause induced electric and electromagnetic fields in the water. The present study synthesizes the current knowledge and speculates on the possible environmental impact of electrical energy transfer based on the example of the Polish Marine Areas (southern Baltic Sea). We review the possible effects of the electrical energy induction and transfer against the existing and planned wind turbine installations. Furthermore, we consider different cable design variants as a way of environmental impact mitigation. Possible impacts of induced magnetic fields on marine organisms and, consequently, on the ecosystem functioning are also addressed.

Key words: energy transfer, wind farms, physical fields, magnetic field, electric field, Baltic Sea, marine organisms, environmental impact

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Introduction

Marine pollution is commonly understood as "chemical pollution", i.e. pollution "by substances". This kind of pollution has been studied and monitored for decades and is currently relatively well understood. Much less is known about human-induced "anthropogenic energy pollution" (GESAMP 1991; EC 2008) related to the installation of technical constructions and their operation at sea. The growing intensity of shipping, exploitation of natural resources and new technical developments in the Baltic Sea have raised concerns about the effects of induced energy on the marine environment (HELCOM 2007; 2009; Andrulewicz et al. 2010). The European Commission expressed these concerns by including the "introduction of energy" into the marine environment as a mandatory descriptor in the assessment of the marine quality status (EC MSFD 2008).

Human-induced energy in the marine environment is related to:

- underwater noise resulting from the construction of required infrastructure, the use of sonars, dredging, mining and military activities,
- artificial electromagnetic and/or magnetic radiation generated by the operation of offshore wind turbines and long-distance transmission of electricity through cables.

Surprisingly, although the number of marine renewable energy projects and underwater cables is increasing worldwide, research focused on their effects on the marine environment is still rather limited (see the review by Taormina et al. 2018).

This paper presents an assessment of potential effects of electrical energy transmission based on a review of the available literature and theoretical considerations related to different variants of cable design as a way of mitigating the environmental impact. It analyses the current knowledge about the environmental impact of electrical energy transfer based on the example of the Polish Marine Areas (PMAs; southern Baltic Sea). The high power (600 MW) electricity transmission system in PMAs connecting Sweden and Poland over a distance of 230 km has been operating in the southern Baltic Sea since 2000 (SwePol Link). There are, however, extensive plans to install numerous wind turbines in PMAs, thus the scope of marine environment disturbance may rapidly

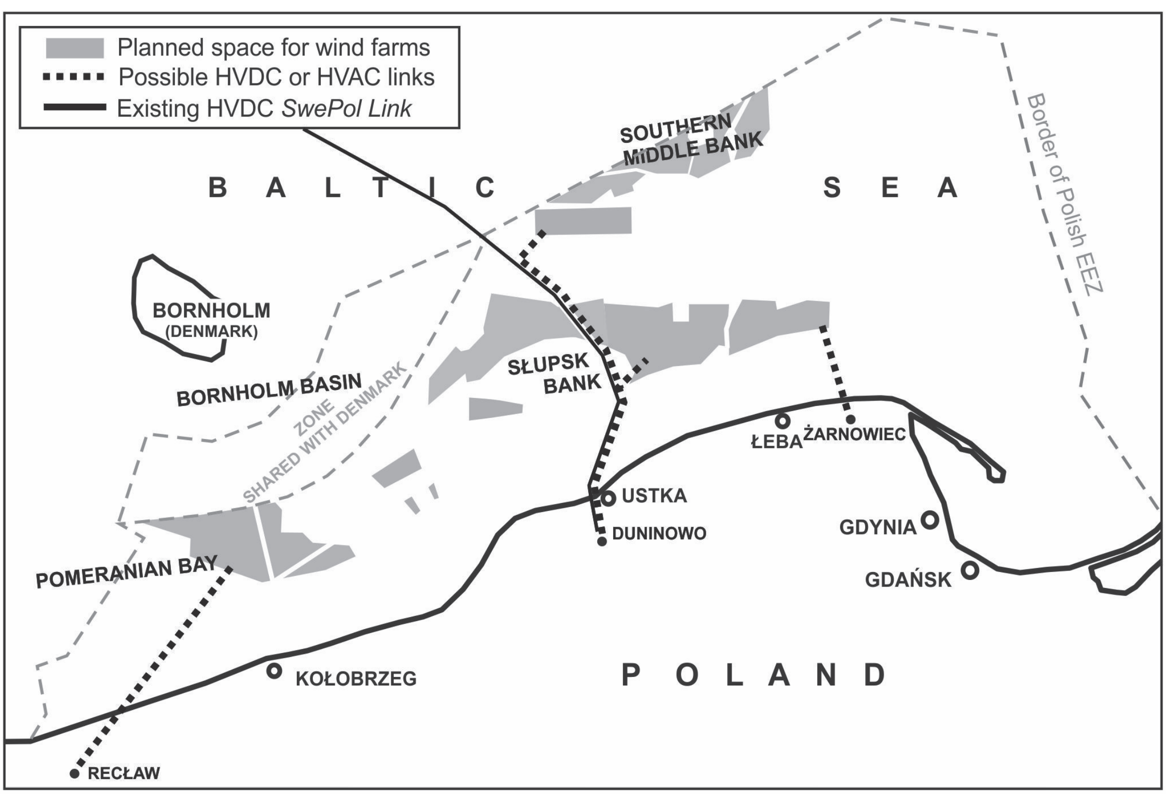

Figure 1

Present and planned high voltage electrical power systems in the Polish Marine Areas (Andrulewicz et al. 2013, modified) and dramatically expand in the near future. Among all possible industries that compete for marine areas, wind farms undoubtedly take up the largest space (Węsławski et al. 2010; Ciołek et al. 2018) (Fig. 1).

Energy transfer from power engineering constructions vs physical features of the marine environment

According to the European Environment Agency, the wind energy potential of the Baltic Sea exceeds 2000 TWh per year and is estimated to be the highest technical potential in the European Union (Schultz-Zehden & Matczak 2012). However, despite the fact that several wind farms – mostly situated in the economic zones of Denmark and Sweden – are currently operating in the Baltic area, there are no wind farms in the Polish Marine Areas (PMAs). However, 65 building permit applications for wind turbines in PMAs have been submitted by potential investors to the Polish Ministry of Transport and Maritime Economy. So far, two environmental decisions have been issued for two farms – "Central Baltic II" and "Central Baltic III" – 800 MW each, and these two farms will be constructed in the near future by the "Polenerga" company. Furthermore, plans to build "Baltica III" by the Polish Energy Group are currently under consideration (Polish Offshore Wind Energy Society, personal communication). The most likely locations of the planned wind farms are the slopes of the Słupsk Bank, the Southern Middle Bank and their surroundings as well as areas located north-east of the Pomeranian Bay (Fig. 1). These are relatively shallow regions that do not obstruct shipping routes and bypass environmentally sensitive regions.

Depending on the energy transmission technology, the electric current flow through cables laid or buried in the seabed may disturb natural physical fields in the vicinity of cables or introduce electromagnetic fields to the environment.

There are two types of electricity transmission systems that are crucial in terms of their effect on the marine environment: direct current (DC) and alternating current (AC) technology. The type of transmission technique used determines the type of magnetic field generated and thus the type of modifications of the physical marine space: the magnetic field (MF) is generated in the DC solution, while the low frequency electromagnetic field (EMF) is generated in the AC technology.

Geomagnetic field disturbances

The Earth's magnetic field varies depending on the geographical location, from approximately 25 μT at the Equator to 60 μT at the poles (Poleo et al. 2001). The magnetic field values in the Baltic Sea vary within a narrow range of 50.1–50.5 μT (Hulot et al. 2010). Daily fluctuations of the natural magnetic field direction in the southern Baltic are less than one degree for both declination and inclination (GOH 2010). These fluctuations are also modified locally by large ferromagnetic artifacts on the seabed (steel wrecks, pipelines, etc.) and by electrical energy transmission cables – usually high voltage direct current (HVDC) cables – because whenever electrical energy is transmitted from one point to another, the natural magnetic field is disturbed.

There are currently over a dozen HVDC systems in constant use in the Baltic Sea (Ardelean & Minnebo 2015). For instance, the SwePol Link transfer system with a return cable is monopolar, while many other HVDC systems are bipolar with twice the transmission power cables (Rudervall et al. 2000; Fig. 2).

The magnetic field value induced by an electric current flowing through a straight wire is described by one of the most important equations in the field of magnetism. This shows that the flux value of the magnetic field (induction) is linearly dependent on the amperage values and the distance from a cable (Formula 1).

$$\vec{B} = \frac{\mu \, \mu_o}{2\pi \, r} \, I \, \frac{\vec{I} \times \vec{r}}{\left|\vec{I} \times \vec{r}\right|} \tag{1}$$

where:

$\vec{B}$ – induction vector

μ – relative magnetic permeability of the medium

m_o – vacuum permeability ($4\pi \cdot 10^{-7}$ V s A^{-1} m^{-1})

$\vec{I}$ – electric current vector

$\vec{r}$ – distance from the wire assessing the induction

The only absolute value of induction is calculated according to Expression/Formula 2.

$$B = \frac{\mu \, \mu_o}{2\pi \, r} \, I \tag{2}$$

Superposition of induction produced by both the electric current and the Earth's natural magnetism depends on their spatial components. Components of

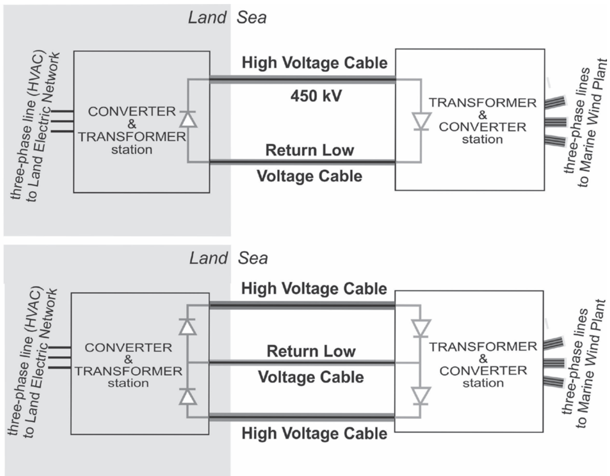

Figure 2

High voltage direct current (HVDC) transfer system – solution with a return cable, monopolar applied in the SwePol Link system (upper) and bipolar (lower)

the geomagnetic induction for the southern Baltic Sea are presented in Figure 3. Geomagnetic field values in the southern Baltic Sea fluctuate in a narrow range (Fig. 4).

Each component of the geomagnetic induction is superimposed on the related component of induction produced by the electric current flowing through the cable system, which leads to the modification of the geomagnetic induction (Fig. 5).

The example below shows how the geomagnetic field modification can be observed in the vicinity of the SwePol Link HVDC (Fig. 6).

The geomagnetic field can also be modified by energy transfer from offshore wind farms to the land electrical network. Assuming that the number of wind farms in the Baltic Sea continues to grow, one may expect that a cable network of over 1000 km will soon run across the Baltic Sea.

For DC, the transmission system usually consists of two cables, one of which (main cable) operates at a high voltage in relation to the sea water mass (up to 400 kV), while another (return cable) operates at a voltage close to zero. The electric current applied in the current underwater HVDC cables is usually 1330 or 1600 A (Andrulewicz et al. 2003; Öhman 2007). The electric current flow of this value generates a strong static magnetic field around the cable with a maximum value of 5.3–6.4 mT, which is superimposed on the natural geomagnetic field. Magnetic fields higher than the geomagnetic value are detectable within a radius of 6 m from the cable axis (Bochert & Zettler 2004; Taormina et al. 2018). Modification of the geomagnetic field related to the HVDC system for electrical energy transfer is assessed using the operating parameters of the SwePol Link [amperage 1330 A, voltage 400 kV, power 530 MW, return cable solution where a low-voltage cable (its electric potential with respect to water mass is zero) replaces a two-electrode solution]. In the DC solution, the magnetic field generated by the electric current flowing through the cable core interferes with the geomagnetic field, but these fields add non-additively due to their different directionality. Figure 7 shows the distribution of the field generated by a single cable as well as the resultant field corrected for the geomagnetic field. For comparison, Figure 8 shows an example of the distribution of the magnetic field originating from the double cable system where the distance between cables is 10 m.

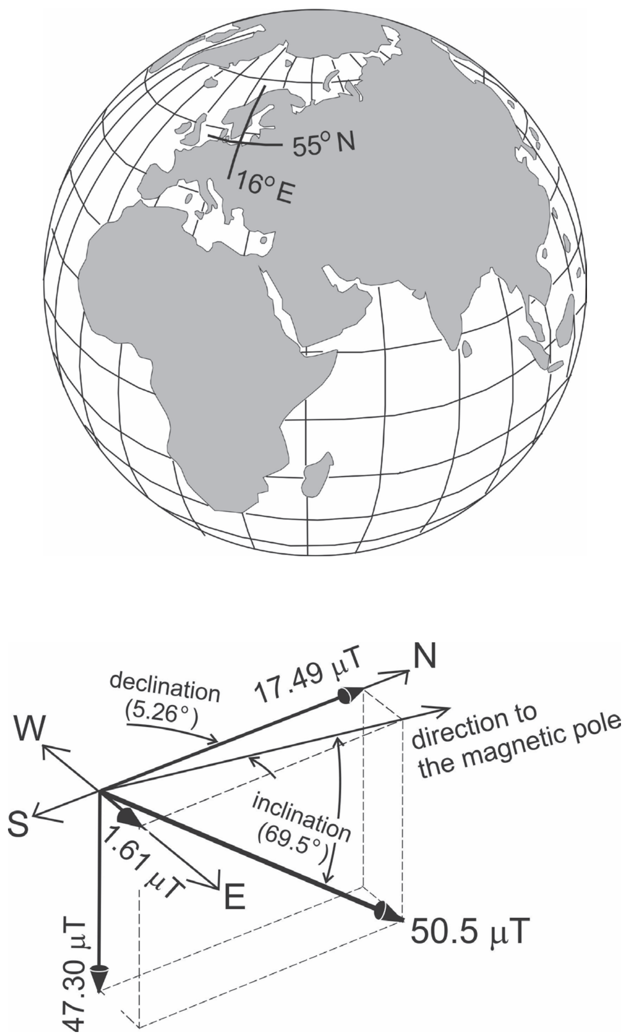

Figure 3

Geomagnetic field induction values in the southern Baltic Sea region (GOH, 2018)

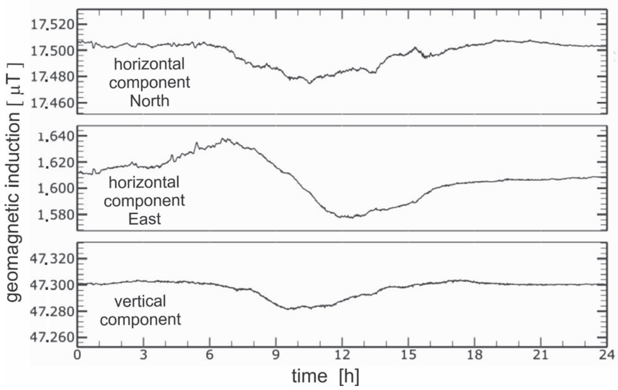

Figure 4

Typical daily (May 20, 2018) fluctuation of geomagnetic field induction in the southern Baltic Sea measured at Hel Geomagnetic Observatory (φ = 54°36.5′N, λ = 18°49.0′E), the Institute of Geophysics of the Polish Academy of Sciences (GOH, 2018)

Introduction of the electromagnetic field

The alternating current transmission involves an alternating, variable magnetic field, which is in fact an electromagnetic field (EMF) classified as a low frequency field. It is a completely new type of energy introduced into the sea. Three separate single-core or three-core cables (where all three insulated conductors are placed into a single cable) are used for AC transmission in the marine environment (Fig. 9).

Due to the close proximity of conductors in many AC three-core cables (in which all three insulated wires are placed into a single cable), the generated EMF is partially nullified (Meißner et al. 2006; Öhman et al. 2007). The 50 Hz alternating field generated by alternating currents flowing through three cores of the cable has a measurable range of up to several dozen centimeters and the magnetic induction usually does not exceed 5 μT at a distance of 1 m from the cable (Meißner et al. 2006; Zhan et al. 2018). In the case shown in Figure 10, the calculations were carried out with the assumption that the cable core axes are located at the vertices of an equilateral triangle with a 4 cm side.

However, AC three-core cables generating low magnetic fluxes can be used with decreasing transmission capacity and distance, for example, as power supplies for offshore platforms, to connect individual turbines within an array or for energy transfer from a windfarm situated less than 30 km from the shore to the power grid (Meißner et al. 2006; Gill et al. 2014). For larger amounts of transmitted power, e.g. from a farm to the shore, the AC systems are often composed of three separate single-core cables, usually laid from 10 to 100 m apart (Johansson et al. 2005). In the case of alternating electric current flowing through a single- and three-core cable as soon as two or even a single core are deprived of electric current, a low frequency EMF field spreads in seawater like a static magnetic field (see Fig. 7).

The above-mentioned facts indicate that accurate prediction of the induction of magnetic or electromagnetic fields and the scope of marine space modifications are not possible without the knowledge of the energy transmission methods. The type of future electricity transmission system used to transfer energy from wind farms installed in the Polish Marine Areas to the mainland will largely depend on various economic factors. However, knowledge of the existing installations and cable properties allows us to make predictions about the possible range of magnetic field values that can be generated after the construction of wind farms in the PMA.

Introduction of electric fields

Electric fields in seawater can be temporarily generated due to spatial changes in salinity and temperature as well as geophysical processes below the seabed (Webb & Cox 1984). Electric fields caused by seawater movements through the geomagnetic field have been measured to be between 5 and 50 μV m^{-1} (Enger 1992). Although electric fields can also be generated by ship movement (Nakamura et al. 2006), they are weak and possibly not significant for marine ecosystems. Electric fields (up to 1 mV m^{-1}) can also be created by some marine organisms (Moller 1995).

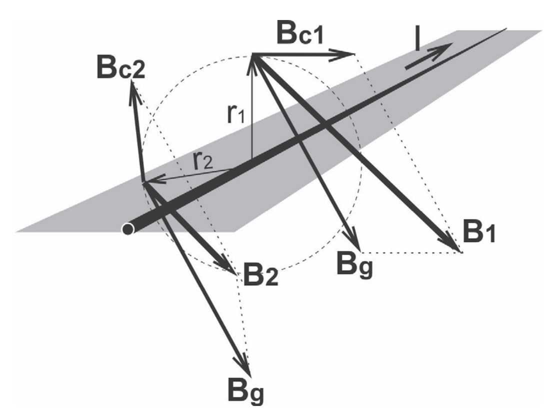

Figure 5

Two spatial configurations of combined natural and artificial magnetic fields in the vicinity of a power (cable B_{c1}, B_{c2} – induction from the core of the cable; B_g – geomagnetic induction; B_1, B_2 – resultant induction)

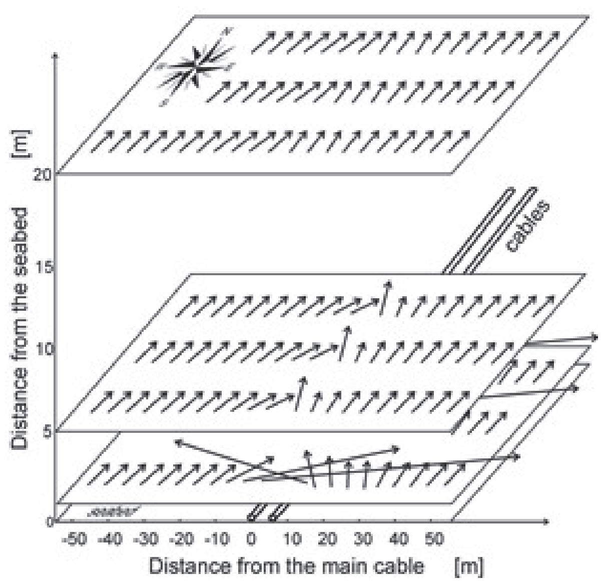

Figure 6

Example of modification of geomagnetic field declination in the vicinity of SwePol Link HVDC (calculated for the real data: power – 600 MW, voltage – 450 kV, distance between cables – 5 m, cable orientation – north–south)

Artificial electric fields in the marine hydrosphere can be generated during the transfer of electric currents by an electrode-type HVDC solution (Fig. 11). In this system, water masses serve as a conductor between two electrodes placed on the seabed. In the immediate vicinity of the electrodes, the strength of the electric field may reach a few volts per meter, although it declines rapidly over a short distance. This effect is shown in Figure 12 – the waveforms show the results of modeling the field distribution from the electrode, which is an equivalent sphere with the surface of a typical electrode. Taking into account the assumptions from Figure 12 (8 PSU, temperature 5°C – values typical for the southern Baltic Sea), the voltage values on the body profile were calculated (Fig. 13) and it was concluded that the electric field in the immediate vicinity of an electrode can be felt by large organisms (4 V for an organism with a length of 1 m).

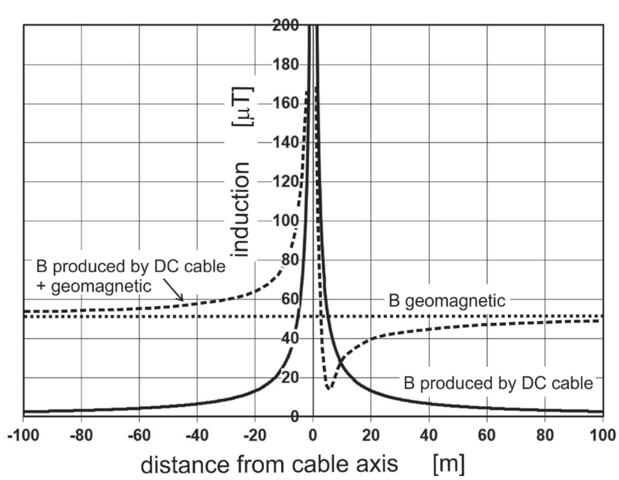

Figure 7

Magnetic induction produced by DC flow in a single cable

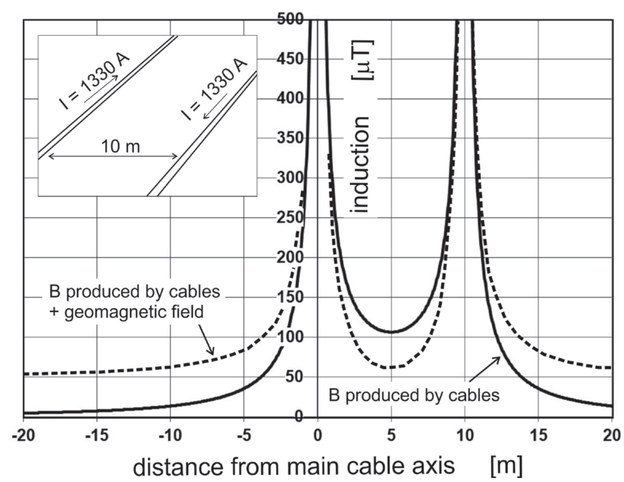

Figure 8

Example of magnetic induction spatial distribution produced by a DC double cable system

Documented and expected impact of submarine power cables on marine life

A relatively large amount of data indicate that various aquatic animals, such as some teleost fish and elasmobranchs, sea turtles or cetaceans, most likely due to the presence of magnetite ultrastructures in their bodies, are able to perceive and use the geomagnetic field as some kind of compass or navigational map (e.g. Kalmijn 1978; Kirschvink 1997; Tesch 1992; Wiltschko & Wiltschko 2005; Rochalska 2009). The geomagnetic field is considered as one of the cues responsible for orientation during migrations of salmonids (Quinn 1980; Dittman & Quinn 1996; Lohmann et al. 2008), e.g. brown trout *Salmo trutta* and Pacific salmon *Oncorhynchus* spp. (Quinn 1980; Formicki et al. 2004). In addition, the

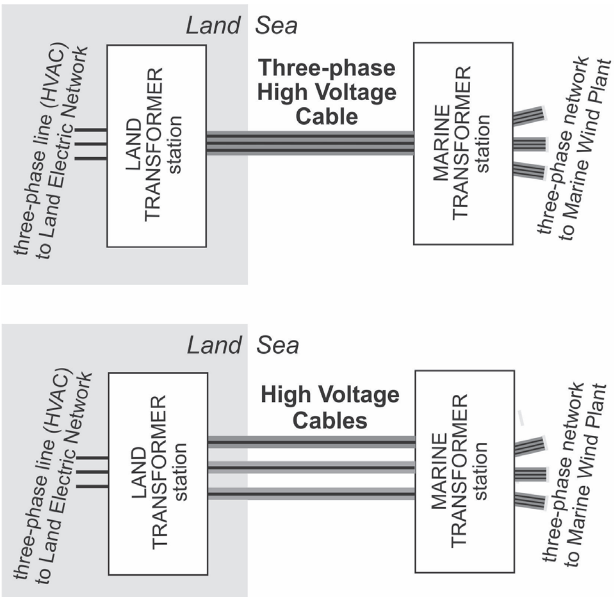

Figure 9

High voltage alternating current (HVAC) transfer system – a solution with three-phase cable, (upper) and three single-phase cables (lower)

capacity for magnetoreception has been confirmed for non-migrating salmonid species (Ueda et al. 1986; Mann et al. 1988; Chew & Brown 1989; Hellinger & Hoffman 2012) and non-migrating freshwater and marine fish other than salmonids (Hanson & Westerberg 1987; Formicki et al. 2002).

Magneto- and electro-sensitive species are likely to be able to detect MFs and EMFs from DC and AC cables, which may indicate that the vicinity of these cables may disrupt diadromous fish migrations (Karlsson 1984). However, the evidence that artificial magnetic fields can affect fish migration is inconclusive. For instance, it has been documented that EMF affects the Japanese eel *Anguilla japonica* (Nishi et al. 2004) but not the European or American species – *Anguilla anguilla* and *Anguilla rostrate* (Richardson et al. 1976; Westerberg & Begout-Aranas 2000).

In addition to the effect on behavior, there is also evidence of the impact of MFs on the development and physiology of early life stages of fish. Experimental studies have shown that a constant magnetic field affects the fertilization rate (Formicki et al. 2013; Formicki et al. 2015), the hatching period and the growth of larvae (Formicki & Winnicki 1998; Fey et al. 2019), increased egg shell permeability (Sadowski et al. 2007), locomotor activity, metabolic and heart rates (Formicki 1992; Perkowski & Formicki 1997; Formicki & Perkowski 1998; Winnicki et al. 2004) and the immune response of fry of marine species *Rutilus frisii kutum* (Loghmannia et al. 2015).

The main source of magnetic fields in the marine environment are submarine cables, thus all benthic and demersal species can be considered as potentially exposed to higher field values compared to other marine fauna. Surprisingly, knowledge of the effect of EMFs on invertebrates – the dominant group in benthic communities – is particularly scarce (Taormina et al. 2018). Magnetosensitivity has been confirmed for several benthic crustacean species, such as the Caribbean spiny lobster *Panulirus argus* (Lohmann 1985), spiny-cheek crayfish *Orconectes limosus* (Tański et al. 2005), sand hoppers: *Talitrus saltator* and *Talorchestia martensii* (Arendse & Kruyswijk 1981; Ugolini 2006) and one mollusk – the marine gastropod species *Tritonia diomedea* (Lohmann & Willows 1987; Cain et al. 2006). Experimental studies have shown the effects of MFs on changes in hydration and amine nitrogen values of the blue mussel *Mytilus edulis* (Aristharkov et al. 1988) and disturbances in the mitotic cycle in embryos of the sea urchin *Strongylocentrotus purpuratus* even after exposure to a 60 Hz electromagnetic field (Levin & Ernst 1995). On the other hand, Bochert and Zettler (2004) found no effect of a static magnetic field on the survival of Baltic crustaceans and bivalves.

In addition to the potential effects on animal behavior, artificial magnetic fields may negatively affect the biological structures at the cellular level. Wadas (1978) distinguishes three main mechanisms of the effect of static magnetic fields on living structures: through uncompensated electron spins, charges being

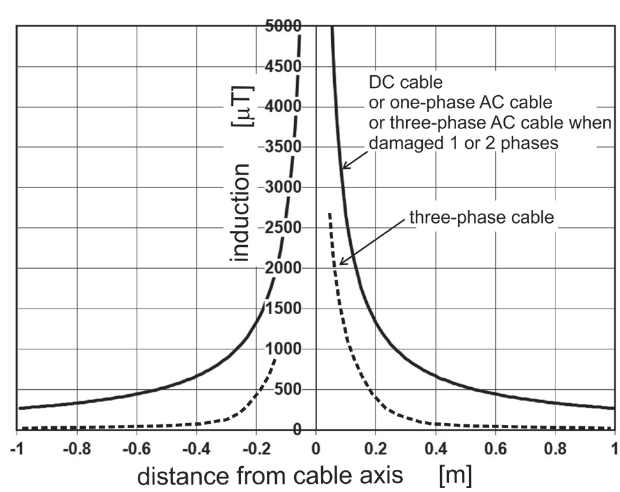

Figure 10

Example of magnetic induction spatial distribution produced by AC flow in a three-phase cable

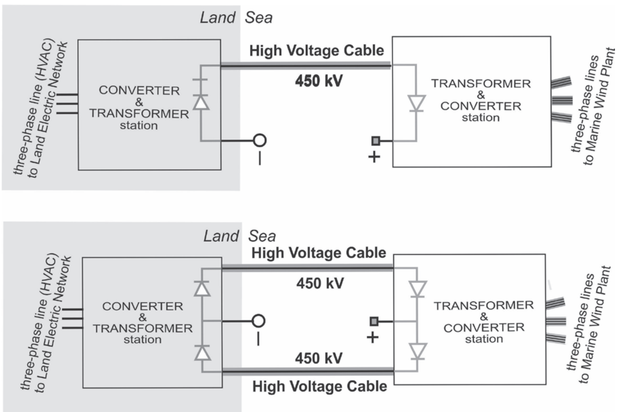

Figure 11

High voltage direct current (HVDC) transfer system – electrode solution monopolar (upper) and bipolar (lower)

in motion and crystalline structures located in the cellular membrane of phospholipids. Magnetic fields induce a partial realignment of liquid crystals within the cell membrane, thereby causing the deformation of imbedded ion channels, sufficient to alter their function and impair their kinetic activation (Wadas 1978; Rosen 1993; 1996). Magnetic fields may also cause the opening and closing of trans-membrane ion channels by interacting with magnetite particles within the cells and altering the electrical behavior of cell membranes (Kirschvink et al. 1992; Rosen 1996; Reina 2001). In addition, the interaction of magnetic fields with membrane-attached magnetite particles creates cell membrane pores, which allow different extracellular molecules to enter the cytosol (Vaughan & Weaver 1998). All these mechanisms may have a large impact on the permeability of biological membranes, causing the disturbance in the ionic transport across the membrane and inducing changes in the osmotic pressure (Wadas 1978; Reina et al. 2001). It has also been documented that artificial static magnetic fields may delay or activate enzymatic reactions (Wadas 1987), increase the concentration of paramagnetic free radicals, leading to oxidative stress, genetic damage and apoptosis induction (Ghodbane et al. 2013), and affect the hemoglobin content, heart rate and DNA synthesis (Zhadin 2001).

It should be noted that since human-induced static magnetic and electromagnetic fields represent different types of energy, the responses of living organisms to these physical fields may also vary (Gill et al. 2014; Otremba & Andrulewicz 2014). Both static and alternating magnetic fields interact similarly with magnetic material, but EMF additionally exerts an oscillating force on free ions in plasma and induces electric currents in conductive matter (Zhadin 2001; Öhman et al. 2007). Moreover, low frequency EMF is considered more harmful to biological structures than the static field (Panagopoulos et al. 2002; EC 2013). Low frequency EMFs can damage chromosomes, affect cell division and cause embryological disturbances (Delgado et al. 1982; Vijayalaxmi & Obe 2005). It is subject to debate whether they may also induce carcinogenic or teratogenic changes (Brent 1999; Simkó 2007).

Unfortunately, knowledge of the potential effects of electromagnetic fields generated by AC submarine cables on marine animals is very limited, thus the potential environmental effect of this factor remains speculative. It has so far been documented that short-term exposure to 50 Hz EMF of 400–600 μT induces a stress response – activation of MAP kinases and expression of heat shock proteins – in the blue mussel *Mytilus galloprovincialis* (Malagoli et al. 2003; 2004), 50 Hz EMF of 1 mT delays the hatching period of zebrafish *Danio rerio* (Skauli et al. 2000), while 1 Hz EMF of 40 μT causes an increase in the pineal melatonin level in freshwater brook trout *Salvelinus fontinalis* (Lerchl et al. 1998). It has also been documented that EMF values from the range typically generated by under-sea cables disrupt the behavior of redear sunfish but have no effect on other freshwater fish species (Bevelhimer et al. 2013). Recent studies have also shown that 50 Hz EMF of 1 mT, i.e. EMF typically recorded in the vicinity of submarine cables, induces genotoxic responses in the Baltic clam *Limecola balthica*, the polychaete *Hediste diversicolor* and the rainbow trout larvae (Stankevičiūtė et al. 2019).

It must be stressed that the results on the effect of MFs and EMFs on marine fauna described in the above-mentioned literature very often do not refer to human-induced magnetic fields, i.e. field induction values and/or field frequencies used do not represent environmentally realistic values typical for submarine cables already operating or planned as part of future investments. Nevertheless, based on the available results, the overall negative impact of magnetic fields on marine fauna is rated as low (Bergstrom et al. 2014; Taormina et al. 2018). Therefore, priority should be given to rapid and accurate assessment of all potential effects of submarine cables on marine life and all possible environmental impact mitigation measures.

The sensitivity to the electric field is species-specific (Gill 2005). In electrical energy transmission systems using an electrode solution, the fish-silhouette-voltage decreases with distance from an electrode and depends on the fish size (Otremba & Andrulewicz 2014). Elasmobranchs (e.g. sharks and rays) are the

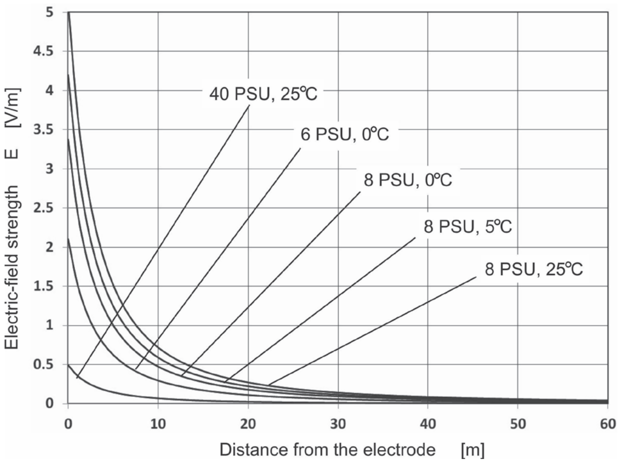

Figure 12

Electric field in the vicinity of an electrode introducing 1330 A current into seawater for selected salinity and temperature values

special group of fish with highly sensitive electrosensory systems that are used for prey detection or mate recognition (Montgomery and Bodznick 1999). Also their ability to navigate in the Earth's magnetic field is most likely related to their extreme sensitivity to electric fields (Kalmijn 1978; Molteno & Kenedy 2009). Therefore, these animals may be attracted or may avoid even very weak electric fields potentially generated by submarine electrode-type transmission systems (Gill et al. 2005), as electric fields even as weak as a few nV cm^{-1} may initiate their behavioral

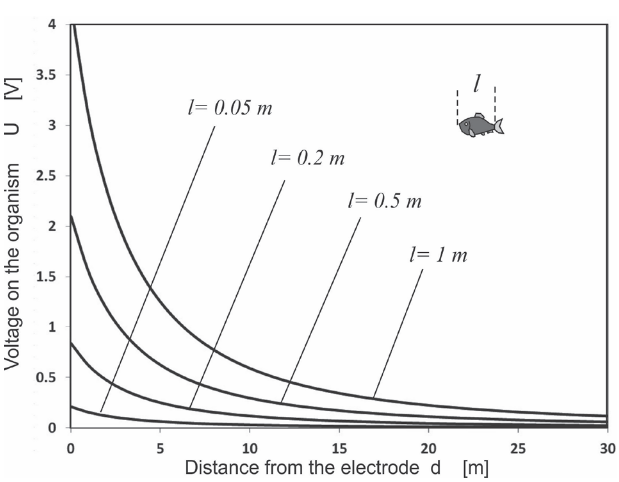

Figure 13

Electrical voltage generated on marine organisms of varying dimensions as a function of the distance from the electrode introducing 1330 A current into the seawater (salinity 8 PSU, temperature 5°C)

response (Wueringer et al. 2012). "Electrode-type" electrical energy transmissions (most of the transfer systems applied in the Baltic Sea) are dangerous for living organisms, but only in the close vicinity of electrodes. Although this is rather a local problem that does not cause large-scale effects, more "environmentally-friendly" technologies should be used (solutions with a return cable). In the case of the SwePol Link HVDC cable line, "electrode-type solutions" have been banned due to local environmental safety concerns.

Conclusions and comments

Until recently, environmental disturbances resulting from the induction and transfer of electrical energy in marine space have not been sufficiently addressed by scientists, engineers and officials, particularly in relation to the effects on marine biota. This situation may change upon the implementation of the Marine Strategy Framework Directive (MSFD), which introduces relevant Descriptors (D 11) related to the effects of introducing anthropogenic forms of energy. According to MSFD, it is mandatory to assess the effects of energy introduction when determining the Good Environmental Status (GES) of marine waters and to maintain a level that does not adversely affect the marine environment (EC MSFD 2008).

Public attention has recently been focused on the growing number of power cables crossing the Baltic Sea. The main environmental concern in this case is the disruption of the natural geomagnetic field in the vicinity of cables and lack of accurate guidelines concerning the cable design and technology used for energy transmission. The development of new technical use of marine areas will contribute to increasing environmental threats. It should be expected that this will raise public awareness and encourage developers to involve mitigation measures to minimize the deterioration of marine space. There are few ways to reduce the magnetic induction generated by underwater cables. In DC solutions, instead of a single DC cable, two high-voltage cables can be used in parallel, but with opposite polarity (so called bi-polar transmission). Laying cables in close proximity to each other also reduces the resulting magnetic fields (Ohman et al. 2007; Otremba & Andrulewicz 2014). In AC solutions, the three-core cables for three-phase current transfer would be more suitable for the environment due to the fact that the magnetic field has a shorter extension than in the case of transmission by triple single-core cables.

Although there are relevant technical solutions that may reduce the disruption of the Earth's magnetic field and the introduction of electromagnetic fields, the environmental effects of these factors have not yet been sufficiently studied (particularly in relation to the migration and physiology of marine organisms). Recently, environmental concerns related to submarine cables have been raised, thus the evidence of whether modification of the geomagnetic field or introduction of electromagnetic or electric fields may be harmful to marine organisms is still inconclusive and potential environmental effects of submarine cables remain mostly speculative. It is therefore difficult to assess to what extent different species might be affected by magnetic fields and for now, there is no list of recommended indicators of exposure to magnetic and electromagnetic fields. Also the variety of responses to magnetic fields in different animals does not clearly suggest which specific species or biological changes might be most suitable as bioindicators of environmental stress caused by artificial magnetic fields. Migrating fish species (due to their ability of magnetoreception) are probably the most vulnerable group, thus it is not surprising that they have already been the subject of some studies related to magnetic fields. However, further experiments on different species should be carried out in terms of their behavior, including various stages of their development. Further research should also focus on benthic and demersal species, which can be potentially exposed to the highest field values, generated both by cables laid on the seafloor and those buried in the sediment. Moreover, many benthic invertebrates are considered keystone species in marine ecosystems. Therefore, research related to their capacity for detection, thus their behavior, as well as research on physiological and biochemical changes, which may provide information about the potential stress caused by artificial magnetic fields are needed. In addition, according to the existing research, the potential of low frequency EMF to induce mutagenic changes is considered to be much more stronger than in the case of static MF. Therefore, any markers of cellular and cytogenetic damage may be very useful as indicators of EMF exposure.

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