Chapter 10
Environmental Issues

Contents

10.1 Environmental Assessment

For all industrial projects, the environmental impacts must be considered, the relevance of these impacts must be evaluated, and possibilities to reduce these impacts must be discussed. The delicate state of our planet, the industry's responsibility for its activities, and the public attention require a serious and honest assessment. Those who want to erect an industrial project such as a submarine power cable must perform regulated Environmental Impact Assessments (EIA). Within the EU, the directives 97/11/EG and 85/337/EEG regulate the legal background for the EIA process. Furthermore, authorities call for compliance with laws and rules.

The installation of a submarine power cable requires permits to be obtained in sometimes lengthy processes. Steps to be taken, and authorities to be approached, differ from country to country, and are subject to legislation, that sometimes is volatile. A treatment of permit issues would be insufficient in the framework of this book. Instead, some basic technical issues on the environmental aspects of

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submarine power cables are discussed here in order to facilitate a fact-based fruitful discussion between project developers, authorities, and the public.

The environmental impacts of submarine power cables have to be considered "from cradle to grave", i.e. all aspects of raw material production, transports, manufacturing, installation, operation, recovery, and recycling add to the overall impact of a submarine cable. Various LCA (Life Cycle Assessment) models are available. LCA models work with various categories of environmental impact. For a given product, the LCA can compute and compile the aggregate environmental impacts starting from the needed amounts of constituent and auxiliary materials, consumables, and energy. LCAs do not create new data; they just compile appropriate data from the underlying database. The quality of an LCA is hence depending on the quality of the data base entries. As an example, for the assessment of the influence of the use of copper, it is essential to make correct assumptions on the share of recycled and virgin material, as well as the mining and refining site on the globe. The skills of the LCA engineer are critical to assemble a correct model of the product and its peripheral processes, and to interpret the results. Various LCA tools are available on a commercial basis. The EIME tool has been developed by 6 major electronic companies 10 years ago, and has been adopted by "la Fédération des Industries Electriques, Electroniques et de Communication" (FIEEC) [1]. This tool has the following categories of environmental impact:

RMD	Raw material depletion
ED	Energy depletion
WD	Water depletion
GW	Global warming
OD	Ozone depletion
AT	Air toxicity
POC	Photochemical ozone creation
AA	Air acidification
WT	Water toxicity
WE	Water eutrophication (too much nutrients in water bodies)

Other tools have also Hazardous Waste Production as a category.

LCAs can support decision making on submarine power cables in different levels:

1. On the lowest level, the design engineer may apply LCA on different cable design solutions meeting the functional specification of the submarine power cable. Based on the result, the engineer may select the environmentally best solution.
2. If the purpose of a submarine power cable is to transmit power between two given points A and B, the LCA can help to rank possible routes with respect to their environmental impact. Alternative routes can sometimes also include overhead lines or land cables. In this case also demographic and socio-economic factors need to be taken into consideration.

3. Sometimes permission authorities require an environmental comparison between the planned project and the "zero alternative", i.e. the situation when nothing is being built. For submarine power cables, the zero alternatives could be continued operation of Diesel generators on unconnected islands, or the need of costly spinning reserve in autonomous grids. For wind farm export cables, the zero alternative would be that the harvested wind energy would not be available and must be produced in a different way, possibly with fossil fuels.

Unfortunately, LCA results are sometimes being used by various parties to promote their own agenda. Green groups, NGOs, and industrial lobbyist groups work with LCAs to proof their statements. Also, political parties, companies, and investment funds promoting "green" investments often present fragmentary LCA graphs or tables.

The task of this chapter is not to present the results of complete LCAs. This should be performed using individual data for each project. Here, we want to discuss some features specific to submarine power cables, which may help the LCA analyst to fine-tune models and assumptions. The factors related to the production and transport of raw materials are not listed here because they are highly depending on specific project circumstances, and would be outdated after only a few years. Commercial LCA tools hopefully provide updated databases.

10.2 The Influence of Cable Losses

A standard LCA includes the impact from the operation of a product/asset. The transmission losses of a power cable during service generate a much higher environmental footprint than the energy used for raw material production and manufacturing. In fact, the transmission losses and the environmental impact from their generation obscure almost all environmental impacts from raw material production, manufacturing and transport of the submarine power cable [2]. This leads to the unfortunate situation that the cable design engineer can put almost any questionable material in the cable without affecting the cradle-to-grave analysis. Only if the environmental impact from the cable operation losses is excluded for the moment, the environmental difference between design solutions becomes visible.

The environmental impact of transmission losses can only be assessed correctly with the knowledge of how the power for these losses is generated. Even if all facts and figures are firmly available, the conclusion is far from being unambiguous. As an example, the impact of transmission losses from an OWP submarine cable can be evaluated in at least four different manners:

1. The transmission losses are generated by clean wind power, hence the impact is zero.
2. The losses eat up some of the wind power arriving onshore and decrease the possibility of replacing fossil power generation. The impact of losses is the same as of an equivalent amount of fossil-generated power.

3. The wind power does not replace fossil power alone, but a typical power-mix in the country where the wind power is landed. This can be fossil, nuclear and sustainable power.
4. The losses are compared to an international power-mix of the future.

Table 10.1 illustrates the difference in CO_2 emission per kWh depending on the choice of reference power production [3]:

Table 10.1 CO_2 emission per kWh for different system borders

System borders for electrical power production	Average CO_2 emission Kg CO_2/kWh (2005)
Sweden	10
Scandinavia	58
EU (25)	415
Marginal power production from coal-fired plants	400–750

In any case, the reduction of losses improves the environmental impact of a submarine power cable more than any other detail.

10.3 Environmental Aspects Related to Cable Design

10.3.1 Conductor Materials

Within the framework of the project specification, the design engineer often has little possibilities to choose materials from an ecologic point of view. Submarine power cables can be designed with aluminium or copper conductor. The conductivity of copper is by 64% better than that of aluminium.

Table 10.2 shows the required amount of energy for the production of copper and aluminium conductors with equal conductance. It is obvious that a larger cross section is necessary for the aluminium conductor to achieve the same conductance, but a lower mass because of the low density of aluminium. With the base data and method used here, the energy required for the production of equivalent copper or aluminium conductors is almost equal.

A cable with aluminium conductor, however, requires more insulation and armoring material due to the slightly larger conductor diameter.

10.3.2 Choice of Other Cable Materials

The choice of insulation material is determined by the intended use of the cable and the state-of-the-art. Only sometimes there is a free choice.

Most modern submarine power cables have an insulation made from XLPE. The peroxide-based crosslinking process in the factory releases gaseous by-products such as acetophenone, alpha-methylene-styrene and cumyl-alcohol. These exhaust

Table 10.2 Energy vs. conductance needed to produce conductor material

	Cu-conductor, 1200 mm^2	Al-conductor, 2000 mm^2
Conductor resistance at 20°C	0.015 mΩ/m	0.015 mΩ/m
Conductance	66.666 m/Ω	66.666 m/Ω
Mass of conductor	10.7 kg/m	5.4 kg/m
Energy used for raw material production [4]		
Primary raw material (freshly mined)	60 GJ/t	164 GJ/t
Recycled raw material	20 GJ/t	20 GJ/t
Share of recycled material α	0.9	0.8
Energy used to produce raw material from mix virgin/recycled	24 GJ/t	48.8 GJ/t
Energy used for raw material for 1 m of conductor (MJ/m) with equal conductance	256.8	263.5

gases from the manufacturing are taken care of in the factory according to local regulations but might contribute to air toxicity. Later, during operation, no more by-products will be released into the atmosphere or water.

XLPE cannot be recycled by melting to new products. Instead, its energetic content can be used in suitable incineration plants releasing water and carbon dioxide. XLPE does not contain halogenides. However, some additives are used in the compounding of XLPE resin to improve production and electrical properties.

Thermoplastic polyethylene is an alternative extruded insulation material. The absence of cross-linking has some important environmental advantages. First, cross-linking by-products are not being generated. Second, less process energy is used in manufacturing. Third, thermoplastic polyethylene can be recycled easily.

The semiconducting layers of the conductor and insulation screen are made from carbon-black filled polymers that are compatible to the insulation material. Due to the cross-linking and the inseparable carbon-black filling these materials can hardly be recycled. The amount of these materials is in the range of 100 g/m of cable core. Replacement materials for carbon-black filled polymers are not known.

Most submarine power cables, especially those for rated voltages of 52 kV or above, are equipped with a metallic sheath. Lead alloy sheaths contain minute amounts of one ore more of the alloying elements antimony, tin, copper, calcium, cadmium, etc. Due to the large amounts of lead it constitutes a high value in the category "raw material depletion" in the environmental assessment. When enclosed in a plastic over-sheath the lead sheath will not release material into the ambient. Watertight sheaths made from aluminium or copper consume less material than lead sheaths, so they achieve better RMD scores. The environmental impact in different categories can be visualised in polar coordinate diagrams such as Fig. 10.1. The impact categories are distributed around the circle and the impact in each of these categories is shown by the distance to the centre. Figure 10.1 shows such a "radar plot" of two different land cable types [1]. The diagram is normalised, so that the values for the 1200 mm^2 Cu cable with Pb sheath are set to "1". Therefore,

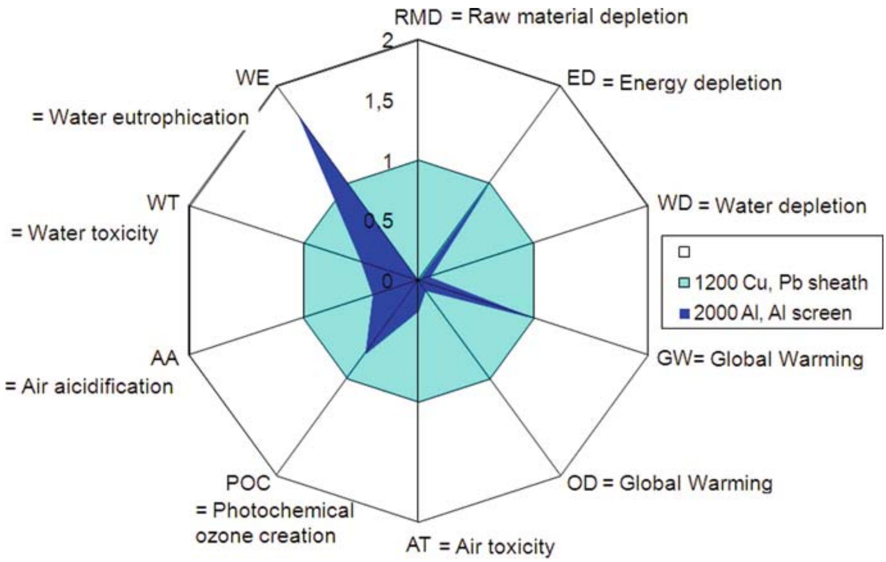

Fig. 10.1 Radar plot over the environmental impact in various categories of two cable types

the profile curve for the Cu/Pb cable is at “1” around the circle. In most categories the Al/Al cable has much lower environmental impact than the Cu/Pb cable. The two cable types are on a par in the categories Energy Depletion and Global Warming, and almost on a par in Photochemical Ozone Creation. Only in the category Water Eutrophication the Cu/Pb cable is more environmentally friendly than the Al/Al cable.

The radar plot of Fig. 10.1 has been established for underground cables and may illustrate the assessment method. Similar plots, comparing submarine high-voltage a.c. and HVDC cables, however, could not be found in literature.

The armoring is most often made from wires of steel or non-ferrous metals. Design and cost considerations usually dictate the choice of material. All metallic armoring can in principle be recycled. Anticorrosive materials, such as bitumen, or plastic coatings, can render the recycling difficult. Some anticorrosive agents contain large amounts of solvents that contribute to the total emission of volatile organic matter during manufacturing.

The interstices of multi-core submarine power cables contain filler materials. These materials are most often polymeric ropes or extruded profiles made from PVC or PE. These materials are functionally almost equivalent so that the cable designer can make a choice from cost and ecological criteria.

Table 10.3 lists the content of some materials in two typical submarine power cables. In the HVDC case, the listed material amounts refer to a pair of single-core cables. The pair of HVDC can transmit more than twice the power compared to the a.c. cable. It becomes clear that HVDC cables can transmit much more power per invested material than three-phase ac cables.

Table 10.3 Mass content of various materials in two types of submarine power cables. All mass figures in kgs

	170 kV a.c. 3 × 400 mm^2 Cu	HVDV 150 kV 1 × 1200 mm^2 Cu
Copper	11	22
Lead	22	13
Steel	20	16
XLPE	8.3	3.8
Other polymers	5.9	2.2
Tapes	0.8	0.8
Optical cables	0.2	–
Anticorrosion agents	<0.5	<0.5

10.4 Environmental Aspects of Cable Installation

Like any construction activity, the installation of submarine cables affects the environment. Encouraged by the requirements of the authorities and the public opinion, the client will follow rules and standards in order to minimize the environmental impact.

All cable installation starts with the transport of the cable. As most submarine cable factories have an own port, cargo vessels offer a cost-efficient transport method even for short drum lengths. Cargo ships are known to have the best fuel economy per payload unit of all transport methods. Transport by truck has a larger environmental impact than sea transports.

It is taken as a prerequisite that the contracted transport and installation companies comply with industrial environmental standards also for their offshore activities. It is recommended to subject contractors to an HSE (Health, Safety, and Environment) audit. An established HSE incident reporting system enables a close follow-up.

The installation of submarine cables may comprise a few separated activities along the cable route. The first thing to do, after the desk-top studies, is a marine survey. In most cases, this is performed using minor survey vessels that do not impose a greater environmental impact than any other equally sized vessel. There are no reported indications that the used high-frequency sonar methods with low audible amplitude affect cetaceans or other marine mammals.

After survey, the cable route sometimes needs to be cleared of obstacles. Different methods can be used:

Pre-Lay Grapnel Run (PLGR): A hooking device (grapnel) is pulled along the seafloor prior to the installation operation. The hooking device is much smaller than most commercial fishing gear. If existent, seafloor vegetation can be uprooted in a very narrow corridor defined by the grapnel size. The PLGR is considered non-invasive to the seafloor.

Singular actions can be taken where abandoned cables or lines are cut; wrecks or other man-made obstacles are removed. Abandoned anchors and fishing gear *en route* are removed to tidy up the seafloor.

Rectification of the cable route. When the seafloor is littered with outcrops, boulders or other obstacles it can be difficult to find a manageable cable route between these obstacles avoiding free spans and other hazards. A close-up optical survey can be done by non-disturbing ROV operation. In earlier times the cable route was rectified by blasting a clear "road" through the debris on the seafloor. This method would not be accepted today in most waters.

The cable laying per se is a quite slow and calm activity. The CLV is travelling slowly along the cable corridor (at 0–3 knots) emitting the typical noise of vessels of similar size. Cable laying equipment such as capstan wheels, linear cable engines, etc. are installed on-board and do not contribute to noise outside the hull. No chemicals or gases are released during the laying except for the normal exhaust fumes from the vessel engines. The waste from normal vessel operation is stored and processed according to vessel standard. If the CLV is travelling along close-to-beach routes, where large vessels normally not operate, the beach-side dwellers might sense some low-frequency engine noise and exhaust smell during the duration of operation. The CLV also can disturb marine fauna especially during reproduction periods. Usually the permitting authorities will restrict the laying time frame avoiding periods of animal mating and breeding.

The cable is fed out from the CLV in a slow pace and moves down to the seafloor while the CLV is moving forward. Often the laying is monitored by ROV. ROVs use electric thrusters and bright lights that may frighten off animals and may disturb their behaviour for a short time. Some fish however seem to be very curious and look straight into the cameras of the ROV. Other animals can be observed while continuing with feeding under the close-up eyes of the ROV.

During the laying or afterwards ("post-lay trenching") most submarine power cables are buried into the seafloor. The burial by plough or waterjetting involves a vehicle moving on the seafloor either pulled by a surface vessel or by own propulsion. The trenching gear usually stirs up a lot of sediment in a narrow corridor (0.5–2 m) along the cable. Although most of the sediment settles back within short time, the sediment plume can, depending on sediment character and water currents, move hundreds of meters from the origin. Also, a local disorder in the natural layers can occur in the trenching zone. The degree of impact is depending on the trenching method and the soil conditions. The seafloor vegetation, if existent, will be disrupted in parts of this corridor. Benthos organisms[1] will be disturbed during laying operation, either by mechanical impact, or by scaring away. Animals living on these benthic organisms may leave the place with them.

Soft seafloors such as in the North Sea, or Baltic Sea, start to reorganize rather quickly after the burial operation. The trench refills itself unless it was cut in rocky soil. Mobile organisms like zoo benthos return to the area above the cable, and the vegetation recovers after a few growing seasons. In most cases the cable route is indiscernible within a year after burial. In the case of the SwePol HVDC cable in the Baltic Sea the zoo-benthos had returned completely within one year

[1] "Benthos" is the collective term for organisms living close to and in the seafloor.

after trenching [5]. The disturbances from the cable laying and burial are considered as temporary and small-size. Cable laying and burial is a singular event and should be evaluated in relation to other repeated disturbances by fishing gear ripping up the seafloor regularly. In the seafloors of the North Sea or the Baltic Sea that are being ruptured by trawling repeatedly, a single cable trenching would not make a difference. Comprehensive analysis and evaluation of the disturbances from cable laying can be found in the permits issued by the German marine authority BSH (Bundesamt für Seeschifffahrt und Hydrographie) for cable links to North Sea OWP [6].

However, there may be exceptions from this. Cable laying and burial in coral reefs and mangrove forests may cause irreversible damages. Every new cut can endanger the integrity of these biotopes. Other sensitive habitats such as sanctuaries for fish, mammals, amphibiae and waterfowl, might suffer damage, especially when the operation is being done during mating or nesting seasons.

Hazardous waste from hidden burdens, such as chemical dumps, ammunition dumps, also dumps of chemical warfare, can be stirred up and released into the sea water in critical areas during trenching. It is often not feasible to trench the cable in rocky seafloors. In that case, the cable can be protected by rock dumping or covering with concrete mattresses or something similar. The used materials must be compatible with salt water, neither must they leach out adverse substances.

Waterfowl react differently on the presence of the installation vessels. Some species are repelled for the time of installation, while others are attracted, as they would be by any other vessel. There is no obvious danger for waterfowl as long as the installation does not infringe their nesting habitat.

Concerns have been expressed for the noise impact on marine animals by submarine construction works. The sensitivity to noise of marine mammals is extremely difficult to access. The mammals live in environments that are not silent even in the absence of human activity. Marine mammals represent an extreme example of not only habitat adaptations but also adaptations in ear structure and hearing capabilities. Audiograms are available for only a few out of 119 different species of marine mammals, and these audiograms were recorded from captive individuals [7]. Marine mammals as a group have functional hearing ranges of 10 Hz–200 kHz. They can be divided into infrasonic balaenids (probable functional ranges of 15 Hz–20 kHz; good sensitivity from 20 Hz to 2 kHz), sonic to high-frequency species (100 Hz–100 kHz; widely variable peak spectra), and ultrasonic dominant species (200 Hz–200 kHz general sensitivity; peak spectra 16–120 kHz) [8]. Mammals use their voice and hearing capability for communications in the lower frequency range and for echolocation in the ultra-high frequency range. Most pinnipeds, such as seals, have their best hearing sensitivities at 10 kHz or above. Many documented examples show that cetaceans react on anthropogenic sound. Sound sources were sonar pingers, seismic equipment, vessel engines, industrial sounds etc. Behavioural changes in the presence of sounds range from shorter diving intervals, decrease or cessation of calls, avoidance of the place or escape. However, there is no evidence that these behavioural changes are biologically significant. Massive whale stranding has been associated to the use military of high-energy mid-frequency sonar. A clear demonstration of the causal relation is still to be done. Very little is known about the hearing capabilities of fish, marine invertebrates or marine reptiles.

For the case of noise generation, submarine cable installation should not be confused with other offshore activities involving hammering down poles into the seafloor.

10.5 Environmental Impacts from the Operation of Submarine Power Cables

10.5.1 Thermal Impact

Power cables transmitting electric power dissipate losses in form of heat. The amount of heat losses at full transmission power is 10–100 W per metre of cable, which is corresponding to the heat from a household light bulb every metre. Inevitably the heat is transferred into the surrounding ambient. Cables installed on the seafloor do not heat up their surrounding as the water washes away almost all heat. However, the cable surface of the freely installed cable might be some degrees warmer than the surrounding water. Buried cables warm up the surrounding soil in the long run. Figure 10.2 shows the isothermal lines of temperature rise around a typical HVDC cable installation under the seafloor. It is a pair of 100 mm dia HVDC cables buried 1.0 m under the seabed. Each cable has a heat loss of 30 W/m. For the sake of clarity the isothermal lines are drawn only up to 26 K. The cable surface temperature is approx. 32 K above the seabed temperature.

The temperature rise in the immediate vicinity of the cable may alter the conditions for deep-dwelling cold-adapted organisms. In most cable projects this limitation is of no great concern as submarine power cables are designed to eliminate excessive losses. From subsea inspections and recovery operations it is known that many submarine power cables are colonialized by molluscs, starfish and other species. Probably submarine power cables, similar to artificial reefs made by OWP foundations or sunken ships, constitute new habitats in otherwise featureless seafloors.

10.5.2 The 2 k Criterion

The losses in buried submarine power cables generate a temperature rise in the surrounding soil. If the cable is fully loaded over months the cable surface can reach a temperature of 40–50°C. This is, however, an extremely rare situation. Most submarine power cables have an average load much lower than the maximum rated load. The temperature decreases with the distance to the cable. A few meters from the cable there is practically no sediment warm-up (cf. Fig. 10.2). The

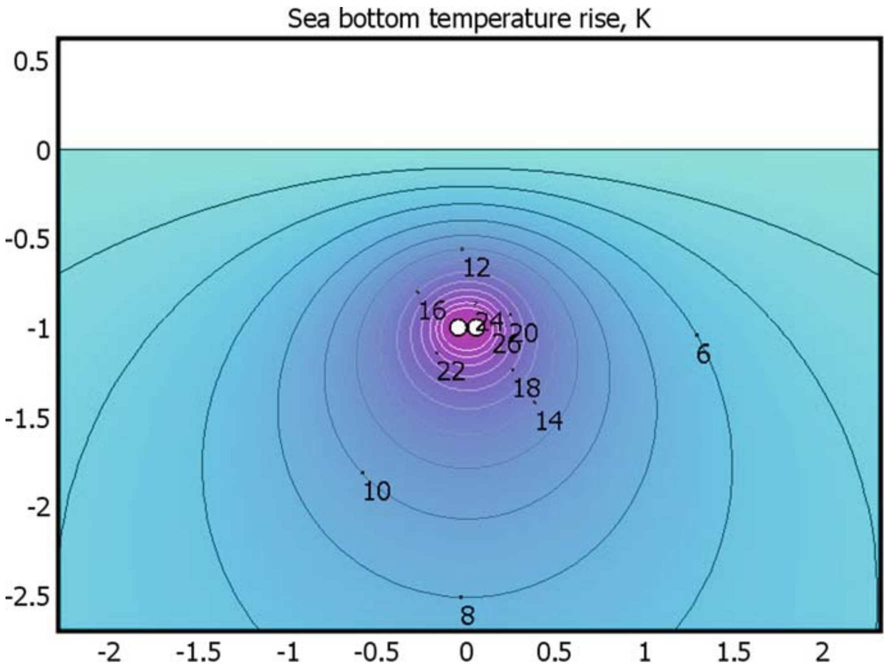

Fig. 10.2 Isothermal lines around a pair of submarine HVDC cables. The horizontal line at "0" represents the seabed. The *y*-axis is the vertical position and the x-axis the horizontal position, expressed in m. The numbers in the diagram express the temperature rise above the temperature of the seabed, expressed in K. Spacing between isothermal lines is 2 K

changed temperature situation in the soil close to the cable alters the living conditions for *benthos*. Most of sub-seafloor dwellers live in the upper few centimetres of the seafloor. There are concerns that the temperature change could change the metabolism and reproductive behaviour of the zoo-benthos. Psychrophilic (cold-loving) organisms within the benthos might be expelled from the cable corridor, while new, foreign species may be attracted to the new "warm" habitat. Neither of this is wanted. Also, the contents of nutrients and oxygen can possibly be changed by altered temperature profiles. Still, there is no scientific evidence for any of these concerns. If there is a measurable impact of the local heat generation on marine life, it is limited to a very narrow corridor along the cable.

The question was discussed in greater detail when a number of submarine cable projects were filed for permission in the Wadden Sea off the German North Sea coast. The Wadden Sea is a national park and biosphere reserve recognized by UNESCO. Naturally, environmental issues came into focus when cable project applications arrived at authorities. To cope with the situation and to prevent possible damages to the environment, a German environmental authority (Nationalparkverwaltung Niedersächsisches Wattenmeer) has issued a recommendation that the temperature rise over a buried submarine power cable should not exceed 2 K[2] at a depth of 0.3 m below the seafloor, compared to the undisturbed seafloor. Another German environmental authority (Bundesamt für Naturschutz) has recommended a 2 K limit for a depth of 0.2 m, valid for the German Exclusive Economic Zone outside the 12-sm national zone. The German marine authority (BSH), which is in charge for the permits for submarine power cables in the EEZ, also defines a 2 K limit for a depth of 20 cm under the sea bottom [9]. Empirical support for this recommendation is not available. Perhaps the defined limits will be changed when evidence condenses.

The temperature rise at the –0.2 and –0.3 m levels, respectively, can easily be calculated with FEM software. Another simplified calculation method is described in Chap. 3, which can be performed with a simple pocket calculator. No matter which method is used, a good knowledge of the thermal resistivity of the seafloor and the expected cable load scheme is necessary.

What happens if a cable project does not meet the 2 K criterion as formulated above? A strategy to reduce the warm-up at the –0.2 and –0.3 m levels, respectively, is a deeper burial depth. Deeper down the cable has a smaller impact on the reference levels, everything else unchanged. For a single cable with 50 W/m losses and a burial depth (BD) of –1.0 m the temperature increase at –0.2 m would be 3.23 K.[3] To meet the 2 K criterion at –0.2 m the BD must be increased to –1.6 m. However, this strategy also has negative impacts on the environment. As outlined above, all benthos will be disturbed in a small corridor during the burial operation. Burying the cable down to –1.6 m would affect more benthos than a –1.0 m burial, both due to the larger depth and due to the wider corridor associated with a greater burial depth. Also, since a deep burial operation is more complicated than a shallow, the duration of the construction work is prolonged. The same applies for the recovery of the submarine cable after end of life.

Furthermore, the cable operation temperature (both on the cable surface and the cable conductor) increases. In the example above, the cable temperature is expected to increase with 4 K. At higher temperatures, the cable losses increase and destroy valuable electric energy. Using a greater burial depth to meet the 2 K criterion would result in extra environmental impacts, such as more seafloor disturbances, higher cable temperature, larger energy losses, and a larger volume of seafloor being subjected to cable heating. These effects should be accounted for when discussing the 2 K criterion in environmental assessments.

Another strategy to meet the 2 K criterion is the reduction of cable losses. For the situation described in the previous paragraph the cable at –1.0 m should have losses of 31 W/m rather than 50 W/m to meet the 2 K criterion. Loss reduction in submarine power cables can be achieved by different design measures. The most prominent is the investment in a larger conductor. In HVDC cables, the reduction from

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[2] 1 K is one degree step on the Celsius scale.

[3] This has been calculated for a seafloor thermal resistivity of 1.0 K.m/W. To adopt the result to a real situation just multiply with the actual thermal resistivity.

50 to 31 W/m would require a conductor area growth by 61%. Increased conductor area would benefit the environment also by reduced energy loss, but is difficult to negotiate with investors. Furthermore, the environmental footprint of the production of the large conductor cable is obviously much larger than for the smaller cross section.

It is not the task of this book to argue the reasonability of the 2 K criterion. However, for the sake of better understanding, it could be useful to put the temperature rise of 2 K into perspective. The annual variation of the seafloor temperature can be as much as 15 K in shallow waters. It is also known that the seafloor temperature can vary considerably between different locations in the same area. That means that a seafloor which is 2 K warmer than another place in the neighbourhood, is probably not a "disturbed" environment. It seems that the environmental concerns would benefit from a wider view on the matter. Maybe a narrow corridor of 5 K warm-up (from a shallow cable) makes less harm than a wide corridor with 2 K warm-up and a larger heated soil volume (which would be the case with a deeper cable).

10.5.3 Electromagnetic Impact

The nature of electromagnetic phenomena is not easy to grasp for non-electric engineers. The public is concerned about the exposure to all kinds of electromagnetic fields in daily life. Sometimes things are confused and pre-mature conclusions are drawn. Fortunately, the issue is not as complicated as it might seem. To start with, two properties of the electric and magnetic fields from power cables should be mentioned:

- Due to the low frequency, the fields around the cable do not constitute a "radiation" such as radiation from cell phones, antennas etc. The intensity decreases very strongly with distance.
- The fields from the cables contain so little energy that any ionising or cell disruptive effects are excluded.

For the consideration of power cables, electromagnetic fields can be separated into electric fields and magnetic fields. In the cable case, these fields are independent from each other except a few cases.

Electric fields are confined between conductive surfaces with a potential difference in-between. This is the case in power cables. The electric field exists between the high-voltage conductor and the grounded screen/armoring. As the screen/armoring is on the same electric potential as the ambient outside, there is no electric field outside the cable. The screen/armoring efficiently confines the electric field to the inside of the cable. This is valid for any power cable, regardless the design, rating, single-core or three-core cable, a.c. or d.c.

A secondary electric field effect is caused in the vicinity of a.c. cables. The a.c. current in the conductor creates a magnetic field outside the cable. This alternating B-field generates, according to the Maxwell laws, an alternating electric field with very tiny amplitude within the range of a few μV/m. This is much less than the electric field produced by the battery in the LED-lit key chain in our pocket. Some *elasmobranch* fish species such as sharks, rays, and skates, can sense these extremely small electric fields. They are assumed to use electric field sensation for orientation in the electric fields generated by water movement in the geomagnetic field, and for detection of prey. The *elasmobranch* detection level is within the range of 0.5 ... 1000 μV/m, the avoidance limit being assumed at >100 μV/m.

The magnetic field is somewhat different. Any conductor is surrounded by a magnetic field generated by the current. The intensity of the magnetic field at a certain distance from the linear conductor is according to the Biot-Savart law:

$$B = \frac{\mu_0 \cdot I}{2\pi \cdot d}$$

where B is the magnetic field[4] at distance d from the conductor, I is the conductor current,[5] μ_0 is the magnetic constant $\mu_0 = 4\pi\ 10^{-7}$ T·m/A, where T (Tesla) is the unit for the magnetic field (also called magnetic flux density).[6] As an example, the magnetic field at 1 m distance to a conductor carrying 1000 A would be $2{\cdot}10^{-4}$ T = 200 μT. Most often HVDC cables are installed in pairs with currents flowing in opposite direction. Therefore their magnetic fields are also anti-directional and cancel each other to a large extent, depending on the distance between the conductors. As a result, the magnetic field decreases very rapidly as a function of distance from the cable pair. Figure 10.3a shows the magnitude of the magnetic field vector over a pair of HVDC cables carrying 1000 A each. The cable pair is installed at the level –1.0 m under the seafloor. The axial distance between the two cables is 0.1 m, i.e. they are laid touching each other, or close to. The lateral distance from the centre axis between the cables is drawn on the *x*-axis. The upper curve illustrates the B-field on the seafloor. The next curve is the B-filed at the +5 m level and the lowest curve represents the B-field 10 m above the seafloor. Here the B-filed is far below 1 μT. Figure 10.3b shows the magnitude of the magnetic field vector over a pair of HVDC cables laid with 10 m distance to each other. Again, both cables carry 1000 A in opposite direction. The sequence of the three curves is equivalent to that in Fig. 10.3a. At the seafloor, 1 m above the cables, the B-field reaches values of 200 μT. At 10 m above the cable pair the B-field has decreased to 10 μT.

Most countries have developed recommendations or limitations for human exposure to electromagnetic fields. In 1992, the International Commission on Non-Ionizing Radiation Protection (ICNIRP) was established to investigate possible

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[4]Strictly spoken, the symbol B stands for the magnetic induction with the SI unit Tesla, while the magnetic field is denoted H with $B = \mu_0 H$. However, in power engineering context B is called magnetic field.

[5]The Biot-Savart formula assumes that the current flow is confined into a filament with zero diameter. For some distance from the cable conductor (>10 × conductor diameter) the Biot-Savart law can be used without any practical restrictions.

[6]The "Tesla" is a unit of the magnetic induction. Another unit is "Gauss". 1 T = 10,000 G = 1,000,000 μT.

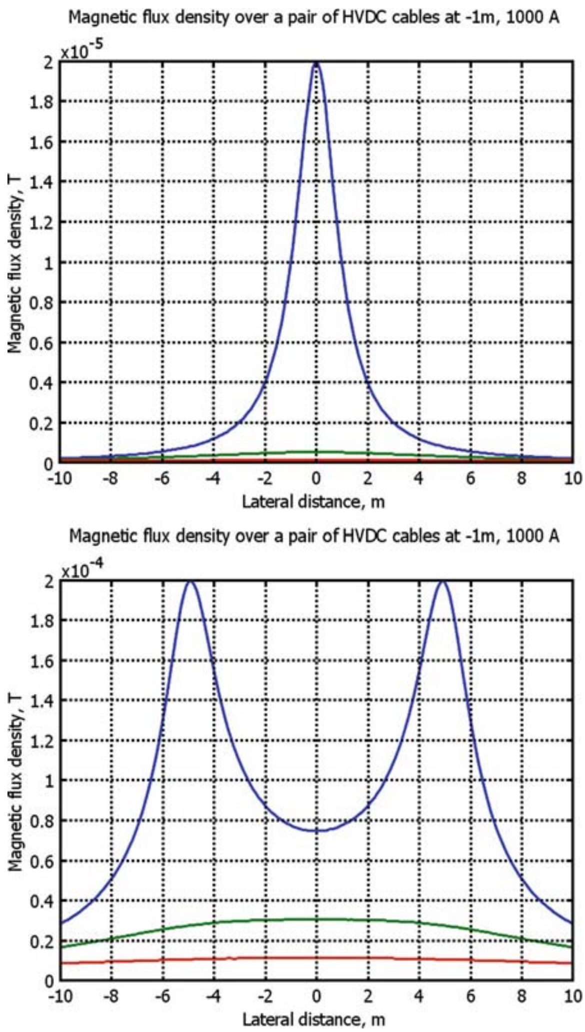

Fig. 10.3 Magnetic field around a pair of submarine HVDC cables carrying 1000 A. As the magnetic field is proportional to the current, the results can easily be scaled up or down for other current values. Upper diagram: cable pair installed touching. Lower diagram: cable pair installed with 10 m distance

hazards from electromagnetic fields, and develop international guidelines in radiation exposure. This work resulted in the "Guidelines for limiting exposure to time-varying . . . electromagnetic fields. . ." [10]. The guidelines cover frequencies up to 300 GHz (radio signals, mobile phones etc.), but for submarine power cables only two frequency ranges are relevant: 0 Hz (d.c.) and 50/60 Hz (a.c.). The recommended limits for human exposure for these frequencies are given in Table 10.4. Most European countries and Singapore, South Africa, South Korea, and Taiwan have adopted the ICNIRP values.

It is obvious from the diagrams that the magnetic fields emitted from d.c. cables are far below all known limits, even in close vicinity. Therefore no risks for human life or health can be anticipated from the magnetic field of HVDC cables. Concerns

Table 10.4 ICNIRP Guidelines for magnetic fields

	Occupational exposure	Public exposure
0 Hz (d.c. cables)	200,000 μT	40,000 μT
50 Hz (a.c. cables)	500 μT	100 μT
60 Hz (a.c. cables)	417 μT	83 μT

have been raised on the impact of d.c. magnetic fields from HVDC cables on submarine organisms, in particular fish relying on geomagnetic orientation during reproductional migration. Investigations carried out by the Swedish Fishery Authority demonstrated that some fish species obviously are not affected by the magnetic field of the SwePol cable, one of the highest rated submarine HVDC cables. Eel, known for its ability to navigate using the geomagnetic field, showed no abnormal behaviour when crossing HVDC cables.

Sometimes the magnetic field from HVDC cables is compared to the geomagnetic field, which is considered harmless to organisms. The intensity of the geomagnetic field is different at each location on earth but it is within the range of 0–50 μT. More serious than the impact on animals of magnetic fields from d.c. cables is their possible influence on the function of magnetic compasses. Magnetic compasses rely on the geomagnetic field and can be disturbed by other magnetic sources. Magnetic compasses can suffer a deviation in the immediate vicinity of powered submarine HVDC cables. The amount of deviation is depending on:

- Distance between the conductors of a cable pair
- Magnitude of the d.c. current
- Vertical distance between cable pair and compass localisation. The distance is the sum of burial depth, water depth, and height of the ship's bridge over the water surface. On large vessels, the bridge can be some 10–30 m over the water surface
- Magnitude and orientation of the local geomagnetic field
- Cable route heading. An East–West cable produces magnetic fields in N–S direction, which add to the geomagnetic field but do not alter the direction. The impact on magnetic compasses is much less than from a N–S cable under similar conditions.

For a small vertical distance between cable pair and the compass, considerable deviations (30° and more) can be observed directly over the cable pair. The corridor of noticeable disturbance along the cable is only a few tens of meters m wide.

It could be demonstrated that ships steered by autopilots based on magnetic compasses may suffer considerable route changes when passing over a single-pole HVDC cable [11]. When the vessel travels towards an HVDC cable the increasing deviation may trigger the magnetic autopilot to take action to correct for the perceived erroneous heading. In the worst case, the autopilot will steer the vessel so that it follows the cable route; the vessel is "captured" by the cable. Tests with a 17 m vessel with non-metallic hull were conducted over the Kontiskan cable in monopolar operation at 1200 A and 20 m depth [11], and confirmed the risk of "capturing". This risk is larger if the vessel heading at small angle to the cable route before crossing. In less onerous cases the autopilot steers the vessel over the cable route with unchanged heading but with a lateral displacement. Vessels are affected in different ways depending on their size.

Small vessels such as leisure vessels navigate shallow waters where the vertical distance between cables and compass can be very small. The magnetic compass of these vessels may suffer large deviations in the immediate vicinity of the HVDC cables. Normally, these vessels are navigated also by visual orientation and/or GPS based systems, which are not affected by magnetic disturbance. In a risk evaluation, the additional risk due to compass deviation seems small compared to risks from ignorance and bad seamanship. The consequences of a vessel accident are quite small.

Medium size vessels (draught 2–4 m) can normally not navigate into the shallowest waters. The magnetic compasses of these vessels can still be affected by magnetic deviations. The result can be a lateral set-off of the vessel′s position. This would be serious in a ship separation lane, where the vessel, involuntarily, could be steered into the lane of opposite direction. But in ship separation lanes the water depth is large enough to provide a sufficient vertical distance between the HVDC cables and the magnetic compass.

Large vessels (draught < 5 m) have usually a large vertical distance between the compass position and the cable pair. These vessels have a long response time for course changes. They travel through the influence corridor before the magnetic autopilot can turn the vessel very much. The risk for these vessels is considered very low.

Only magnetic compasses and magnetically controlled autopilots can be affected by cable's magnetic field. Almost all commercial vessels have redundant gyrocompass or GPS based navigation and steering systems, which are not affected by magnetic fields.[7] HVDC cables do not impose a risk to marine traffic. Still, some countries require that commercial vessels have magnetic compasses as back-up systems.

In a.c. cables the current in each conductor is changing its direction 50 or 60 times a second, and so is the magnetic field. In three-phase cables the three magnetic fields from the conductors are superimposed to each other. For an observer at large distance (called "far-field", e.g. 25 times the cable diameter) all three conductors seem to have the same distance and direction. Hence the three magnetic fields cancel out each other almost perfectly. To a near-field observer close to the cable, the conductors are not exactly at equal distance and hence their magnetic field does not cancel out each other's perfectly. A minute residual magnetic a.c. field can be measured.

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[7]Some GPS use incorporated magnetic compasses to detect global directions when the vessel is not moving and the NSWE direction cannot be determined from incremental positioning.

Single core cables often have a much larger distance between the conductors resulting in a poor cancelling of magnetic field at least in the near-field range. However, in single-core a.c.cables the conductor current induces a counter-directional current in the screen of the cable, resulting in a largely decreased external magnetic field.

10.5.4 Chemical Impact

Under normal operation conditions submarine power cables do not release chemicals, consumables, or other agents to the ambient. The materials are designed to be stable under the influence of seawater for decades. Cables with solid insulation (XLPE, EPR, mass-impregnated) do not contain fluids that can leak in case of cable damage or rupture. The impregnation compound in mass-impregnated HVDC cables is so viscous (thick-flowing) that there is practically no outflow from the cable even if it is cut [12].

A different situation arises for oil-filled cables with low-viscosity insulation oil. These cables are now installed only for the highest voltages (230 kV and above) as they have a long operational record. The oil inside these cables is pressurized from onshore feeder stations, and pours out into the sea when the cable is damaged. In case of damage the cable owner tries to counteract the intrusion of water by pumping in more oil into the cable. It can take days and weeks before the cable leakage can be localised, and the cable can be picked up and sealed. A damage on a 420 kV Öresund cable between Sweden and Denmark in 1979 could be localized only after observations of the oil plume [13]. When an oil-filled cable on the Oslo fjord was damaged in April 2008, oil leaked out from the cable initially at a rate of 80 l/h. When one of the 138 kV Long Island cables was damaged by a ship anchor, the initial outpour of cable oil was 450 *l* a day; it took 10 days to seal the faulty cable [14]. The good thing is that the cable insulation oils have so low viscosity that they usually evaporate rather quickly from the water surface. The cable insulation oils used to be low viscosity mineral oils. Since the 1980s synthetic cable oils have been used both for refurbishment and production of cables. Most of the synthetic oils are linear alkylbenzenes (LAB) with varying molecular weight composition. LAB is miscible and compatible with mineral oils. LAB is biodegradable, but little is known on the rate of degradation under the exclusion of air. The toxicity of LAB has been demonstrated by tests showing that the LC_{50} mortality concentration in soil for a nematode species is less than 1% [15]. A study on the subject and further references have been published in [16].

10.6 Recycling of Submarine Power Cables

There are few options to proceed after the useful life of a submarine power cable. It is easy to leave the defunct submarine cable in place and announce it as "abandoned" to authorities. It is difficult to pull up buried cables, and the scrap value might not pay the salvage costs. Abandoned cables continue to be an obstacle for fishermen (a late revenge of the cable owner perhaps?) and must be cleared before new cables are being laid. If it is decided to leave the cable in place, it is possible to remove the insulation oil by subsequent flushing the cable with solvents and fill it finally with water [17].

Another solution, sometimes also required by permit authorities, is the recovery of the cable from the sea floor. Recovery of buried cables can be difficult. Even heavy-armored cables can break under the load of a pull-up operation, but recovery is possible. As an example, 76 km of 138 kV submarine power cable were removed from the Georgia Straight between Vancouver Island and the Canadian mainland in 2007 after 51 years of service [18]. Once the cable has been recovered from the seafloor, it can be recycled in a number of different ways. The first step of every recycling is the separation of materials. The metal fraction in the cable (steel, copper, lead, and other non-ferrous metals) can be separated easily by mechanical disintegration and separation using the large difference in specific gravity of metals versus other materials. The value of the metals can partly pay for the cost of the cable recovery. A promising method to cut open long lengths of cable is the use of water-jets running along the cable.

The clue to a successful recycling of polymeric components (polyethylene, XLPE, polypropylene, PVC, EPR, EPDM, etc.) is the separation of the cable constituents into clean material streams. A sink-and-swim separation in water creates a polyolefin stream with PE, XLPE, PP, and the “PVC” stream containing conductive materials, PVC, EPR, polyester, etc. A material recovery (using it for production of new materials) is only possible with very clean homogeneous streams. The chemical recycling of silane-linked XLPE has been demonstrated in Japan [19]. The most cost-efficient and environmentally wise methods seem to be the use of the cable polymers as fuel in thermal power plants normally fuelled with waste or biomass. A comprehensive overview on recycling possibilities can be found in [20].

No methods have yet been reported to re-use paper insulation. Paper insulation makes up a good fuel for biomass fuelled power plants or district heating plants.

The third solution is the use of submarine cables to build habitats for marine life, or artificial reefs. It has been observed many times that organisms, such as molluscs, algae, starfish, corals, crustaceans, etc., settle or live on submarine cables. Marine organisms are in general attracted to items different from a flat seafloor, so artificial reefs have been built from all sort of structures. Of course, the materials must be cleaned from all residual fluids and other hazardous items. Both defunct cables and defunct cable laying ships have been used for this purpose [21].

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