Environmental assessment of submarine power cables

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Topic: Transportation & Distribution Power System

1. Introduction

Extensive analyses conducted by the European Community revealed that offshore wind energy have relatively benign effects on the marine environment by comparison to other forms of electric power generation [1]. However, the materials employed in offshore wind power farms suffer major changes to be confined to the marine environment at extreme conditions: saline medium, hydrostatic pressure … which can produce an important corrosion effect. This phenomenon can affect on the one hand, to the material from the structural viewpoint and on the other hand, to the marine environment.

In this sense, to better understand the environmental impacts of generating electricity from offshore wind energy, this study evaluated the life cycle assessment for some new designs of submarine power cables developed by General Cable. To achieve this goal, three approaches have been carried out: leaching tests, ecotoxicity tests and Life Cycle Assessment (LCA) methodologies. All of them are aimed to obtaining quantitative data for environmental assessment of selected submarine cables.

LCA is a method used to assess environmental aspects and potential impacts of a product or activity. LCA does not include financial and social factors, which means that the results of an LCA cannot exclusively form the basis for assessment of a product's sustainability.

2. Systems, Scenarios and Methods

2.1. Systems and Scenarios

In this study two different types of submarine power cables were evaluated in terms or resource, energy and environmental behavior.

2.1.1. System 1

This system consists of a three-core cable designed for wet electrical conduction with conductor element surface of 300 mm^2, Fig. 1. In this system, both leachability and ecotoxicity studies were performed for the complete and systematic evaluation of their potential environmental impact.

Two scenarios were considered simulating two different situations:

a. Undamaged cable: A sealing with polyurethane was performed onto the two cross sections of the specimen to simulate this situation, Fig. 2.

b. Damaged cable: The polymeric layers, metallic shields and copper conductors are fully exposed to the marine environment, Fig. 3.

Figure 1: Three-core cable (System 1).

Figure 2: Sealed three-core cable specimen (System 1-Scenario a).

Figure 3: Cross section in three-core cable specimen (System 1- Scenario b).

Leaching and ecotoxicity tests were conducted in specimens simulating both scenarios aimed to obtaining quantitative data for LCA evaluation.

2.1.2. System 2

This system considers two single-core cables with different metallic shields: one comprised of aluminium sheet and copper wires, and the other comprised of helicoidally copper tape, Fig. 4.

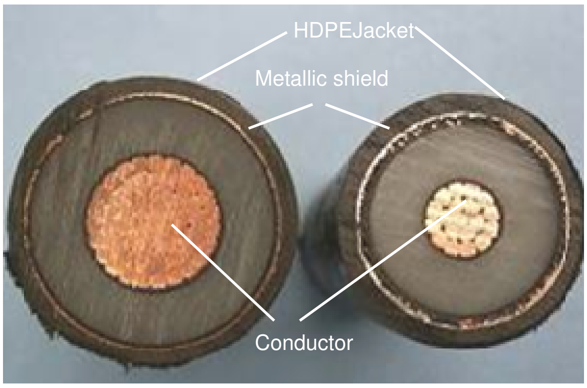

Figure 4: Cross section of the two single-core cables with aluminium sheet and copper wires (right) and with helicoidally copper tape (left).

The environmental comparison by LCA methodology is not possible in system 2 as the function of these single-core cables is not the same because each of them will drive different amounts of power. In this sense, only leaching and ecotoxicity tests were carried out.

2.2. Leaching methods

Leaching tests can predict the amount of heavy metals and other contaminants that may migrate from one material or product in contact with water. In this study, leaching tests were carried out in order to evaluate the chemical pollution caused by the presence of the cable in the highly corrosive marine environment.

The leaching tests were carried out based on NEN 7375:2004 standard [2] for monolithic materials (test tank). The purpose of this test is to simulate the diffusion of sample components under aerobic conditions in a period of 64 days performed in 8 stages. In these tests, samples are exposed to the leaching solution in a container under the laboratory test conditions set in the standard. The concentration of metals and other chemical parameters are measured in the solution at different times of exposure. Because the studied cables will be installed in the ocean, the leachant liquid (demineralized water in the standard) was replaced by synthetic sea water, prepared according to ASTM D 1141 [3].

Each sample was placed in a PET container filled with the liquid leaching agent. After an initial period of 6 hours, all the eluate volume was collected and replaced with the same volume of fresh leachant fluid. The process was repeated for the next 7 stages. The sampling frequency is shown in Table 1. In every obtained fraction, values of pH, concentration of Al, Cu, Fe, Zn and Dissolved Organic Carbon (DOC) were measured according to standardized methods of analysis [4]-[6].

The procedure was applied to cable specimens of 150 mm in length. An additional blank sample made of polyurethane was placed in contact with sea water in order to determine the organic matter that could migrate from this material, not attributable to the plastic components of tested cables.

Table 1: Sampling frequency for leaching tests.

Fraction (n)	Time (days)
1	0.25 ± 10%
2	1 ± 10%
3	2.25 ± 10%
4	4 ± 10%
5	9 ± 10%
6	16 ± 1%
7	36 ± 1%
8	64 ± 1%

In case of system 2 the external high density polyethylene (HDPE) jacket was partially removed in order to expose the metallic sheath to the seawater environment (see Fig. 7). This fact contributes to accelerate the migration of copper and aluminum due to corrosion phenomena. The ends of these single-core cable samples were sealed with polyurethane. Thus, metals in the eluate can be only attributable to the migration from the metallic shield.

2.3. Ecotoxicity methods

Ecotoxicity tests were conducted to determine the maximum limits for contaminants that may migrate from the submarine cables to the marine environment, taking into account the toxic effects that could result in the marine ecosystem. These tests consist basically of exposing certain aquatic organisms to some possible toxic concentrations for a specific time. The biological effects have been measured in each sample and control group, and subsequently performed a statistical analysis of the data. The ecotoxicity tests performed in this study have served to quantify the acute toxicity which is usually expressed as median effective concentration (EC_{50}), corresponding to the experimental effluent concentration that causes significant negative effects in 50% of the test population.Two ecotoxicity bioassays have been carried out. Firstly, the bioluminescence assay based on inhibition of luminescence with freeze-dried bacteria strain *Photobacterium phosphoreum (Vibrio fischeri)* at 15ºC for 15 minutes as incubation time. The test objective is to determine the concentration of the sample which inhibits the emission of light to 50% in the test conditions. Secondly, the inhibition test based on the inhibition of the mobility of *Daphnia Magna* [7]. According to the European directive [8], a sample is considered toxic if its leachate has an EC50 less than or equal to 750 mg/L. The cladoceran microcrustacean *Daphnia Magna* is universally used as short-term test to determine acute toxicity. Infants of *D. Magna* are placed in contact to the leachate of the sample and with different dilutions (usually 5 dilutions) for 24 h at 21 ± 1ºC. Afterward the loss of mobility of the organisms is registered. The result is expressed as EC_{50}-24 h (%) equivalent to the concentration of sample that inhibits 50% movement of the *Daphnia* in a batch being tested over a period of 24 hours. In this study, acute toxicity tests were performed according to protocol C-2: Acute toxicity to Daphnia described in Royal Decree 363/1995 [7].

2.4. LCA methods

This LCA methodology was prepared according to the principles published by the International Organization for Standardization (ISO 14040-14043) [9]-[12] with the exception that a critical review has not been carried out. The goal was to determine the potential environmental effects of the three-core cable in both scenarios studied: running submarine cable (undamaged) and fully sectioned cable by an accident (damaged). In order to compare the results of these two situations, the same basis of calculation and same potential impacts was considered.

The function of the submarine cables is to transport electric power. As the selected cable in the two studied scenarios has an equal power capacity, it was possible to use a specific quantity of cable as the functional unit of the model. Thus, 1 km of three-core cable was chosen as functional unit.

The system boundaries of LCA include all the energy, fuels, chemicals, and transportation needed to operate all phases of the life cycle of a product. The life cycle of a cable includes several stages starting with the production of the different raw materials used in the cable production, followed the assembly of components, the submarine cable installation, the use at the offshore wind power farm and finally the end-of-life stage covering the disassembly and recycling. The LCA of this study was only applied for the operation stage because it is the only different step for both scenarios. Therefore, the inputs (materials and energy resources) and the outputs (emissions and waste) were only considered for the cable in undersea conditions, excluding the previous and post-stages and those operations or stages with the same inputs and outputs in both scenarios, i.e., the raw materials extraction, transport to the equipment manufacturing, the assembly of components, transport to site, set-up of the submarine cable and dismantling stage.

Concerning to the temporal and geographical specifications, this study was performed considering 2009 as the year of data collection and the European area where the submarine cable will be running.

Pathway diagrams of used models for each scenario are shown in Fig. 5 and Fig. 6.

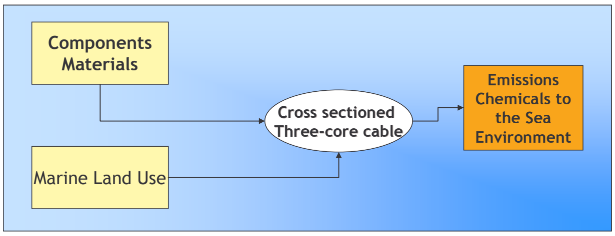

Figure 5: Pathway diagram of scenario A.

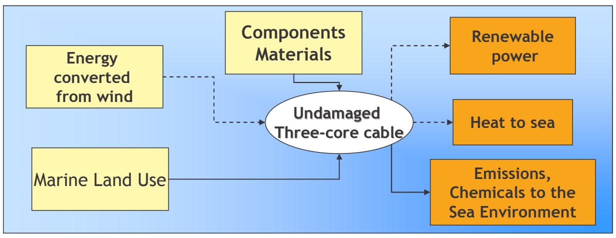

Figure 6: Pathway diagram of scenario B.

In Fig. 5, the energy flows are in dot line, because they can be considered according to different situations: the cable is not running (scenario A.1) or the cable is running and the power electricity is transported through the cable (scenario A.2).

In scenario B the major difference in the pathway diagram is due the absence of energy flow. If the cable is broken power conduction is not possible.

For Life Cycle Inventory (LCI) a set of inputs and outputs was utilized from literature sources, information of manufacturer General Cable Group, S.A. and data from Ecoinvent database [13]. Besides, the results of leaching [14] and ecotoxicity tests were taken into account as outputs of the two proposed models. All data resumed in Table 2 were entered into the LCA software SimaPro 7.1. The calculations were made with the methodology Ecoindicator 99H/A. The potential environmental impacts included in this study can be divided into three main groups: environmental impacts on the ecosystem quality (acidification, eutrophication and ecotoxicity), damage to the human health (carcinogens, radiation, respiratory effects, global warming and ozone-depletion) and damage to the natural resources (minerals and fossil fuels extraction).

3. Results & discussion

3.1. System 1: three-core cable.

3.1.1. Leaching test results:

Fig. 7 shows the appearance of the damaged tested sample after the leaching test, whereas Fig. 2 gives the appearance of the undamaged cable after this test.

Figure 7: Final appearance of damaged three-core cable after leaching test.

Table 3 shows the obtained results for the three samples considered: the two specimens of three-core cable and the blank of polyurethane. Their different behaviors can be seen in Figs. 9-11.

As it was expected, the pH values were nearly constant in both cases, Fig.8, with similar pH values for both cables. However, the changes of heavy metals concentration and DOC are very different. Fig. 9 and Fig. 10 show the change of iron and copper concentrations of both eluates. In the case of undamaged cable, the eluate composition was not modified, because no metals migrated from the cable to the seawater environment. On the opposite side, the two ends of the broken cable exposed to the seawater were liberating iron and copper to the marine medium. The both metals concentration were increasing for the 63 test days. For iron, the concentration was stabilized around 6.7 mg/kg dry matter, whereas copper had a growing trend.

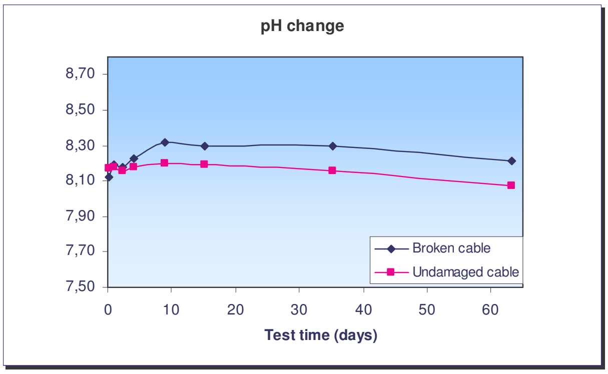

Figure 8: pH change during leaching tests of three-core cables.

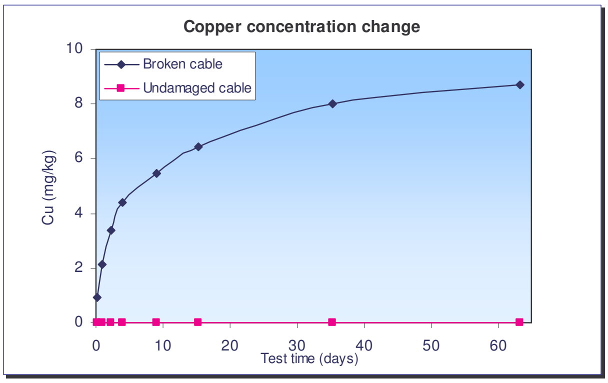

Figure 9: Copper concentration change during leaching tests of three-core cables.

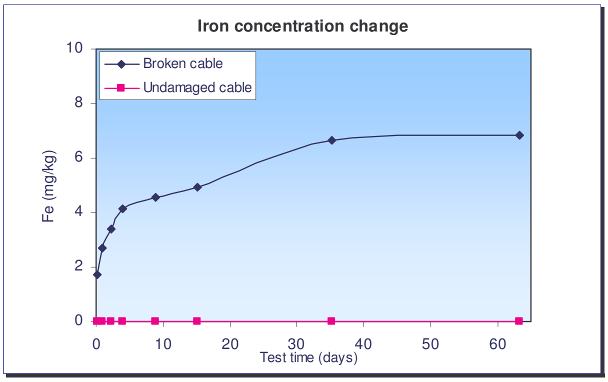

Figure 10: Iron concentration change during leaching tests of three-core cables.

Zinc behavior can be seen in Fig. 11. For the undamaged cable zinc migration is due to the corrosion of the galvanized wires which are not fully isolated by the outer cover. In both cables, the concentration was not stabilized and it can be expected the concentration could be increasing for some days. It is important to remark the gap between the two final concentrations, approximately 70% higher in case of broken cable.

DOC changes can be observed in Fig. 12. The trend is similar to that observed for zinc. The migration rates are very different in both cables: around 63 mg/kg in broken cable vs. 40 mg/kg of undamaged cable. A slight stabilization effect in final concentration can be seen and no much more dissolved organic matter is expected in seawater.

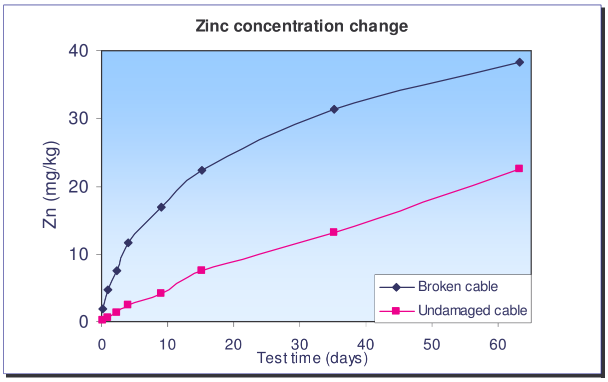

Figure 11: Zinc concentration change during leaching tests of three-core cables.

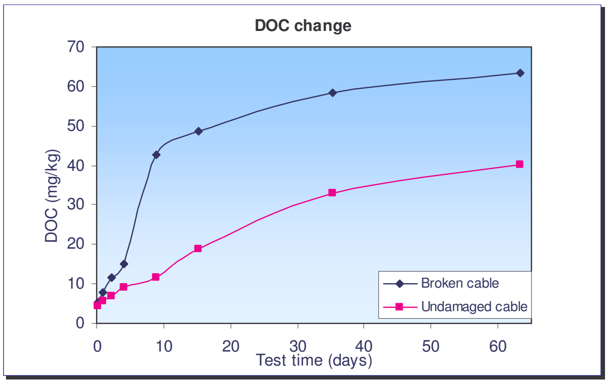

Figure 12: DOC change during leaching tests of three-core cables.

3.1.2. Ecotoxicity results

The ecotoxicity tests were performed on the last fraction obtained after leaching tests, because these fractions correspond to the higher contact time between seawater and cable specimens. Thus, it can be expected those eluates could be more toxic.

According to the national regulation [15], a sample is ecotoxic if the EC_{50} (*Photobacterium phosphoreum*) is lower than 3000 mg eluate/L. Table 4 shows the obtained results for three-core cable scenarios.

Table 4: Results of the bioluminiscence and ecotoxicity tests.

	Scenario A (undamaged cable)	Scenario B (broken cable)
EC_{50} (*Photobacterium phosphoreum*) mg/L)	> 450,000	> 450,000
EC_{50} (*Daphnia Magna*) (mg/L)	> 750	> 750

As both specimens had eluates with EC50 higher than the established threshold, then samples can be considered non-ecotoxic for the aquatic organisms.

That law defines that a sample can be considered ecotoxic if the EC_{50} (*Daphnia Magna*) is lower than 750 mg/L. Therefore, the acute toxicity results on the three-core cables eluates during 24 h were negative as it can be observed in Table 3, which corroborate the results of the bioluminiscence tests.Besides the European directive 2009/2/CEE [16] considers a substance as toxic for aquatic organisms if its EC_{50}

(*Daphnia Magna*) is equal or minor than 1 mg/L, and nocive if its EC_{50} (*Daphnia Magna*) is between the intervale 10 mg/L and 100 mg/L. Therefore, the three-core cables eluates could be considered non-toxic and non-nocive for aquatic organisms.

3.1.3. LCA results

Table 5 and Fig. 13 show the comparative results of three studied scenarios according to the Ecoindicator99 (EI99) methodology.

Table 5: Results of LCA according to EI99 methodology

Damage category	Scenario A.1	Scenario A.2	Scenario B
Total ecopoints (Pt)	0.794	0.766	3.975
Human Health (Pt)	0	-0.016	0
Ecosystem Quality (Pt)	0.794	0.792	3.975
Resources (Pt)	0	-0.011	0

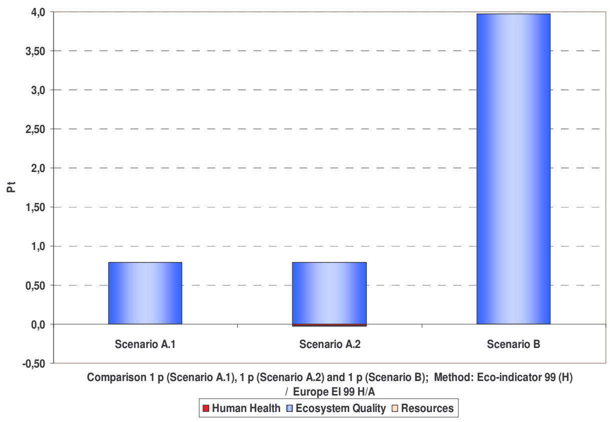

Figure 13: Scoring according to EI99 methodology.

The environmental impacts were very low in the three studied scenarios. Even for the less favourable case (scenario B) corresponding to a fully broken cable, the effects would not be serious. In all cases, the higher contribution to the environmental burden corresponded to the land use and the migration of chemicals to the sea environment. Thus the major damage category was the Ecosystem Quality in all of them. However, the potential impact on Ecosystem Quality due to a broken cable was near 80% higher than the impact in cases A.1 y A.2, due to the effect of migrated chemicals on seawater.

The scenario A.2 was calculated to quantify the potential positive impact due to the renewable power transport. The results showed that the impact is negligible and could represent 3% of total score.

Fig. 14 shows the detailed results by impact categories. In all cases, the higher contribution to the final score is due to the ecotoxicity category, i.e., by the chemicals migration from the submarine cable to the seawater.

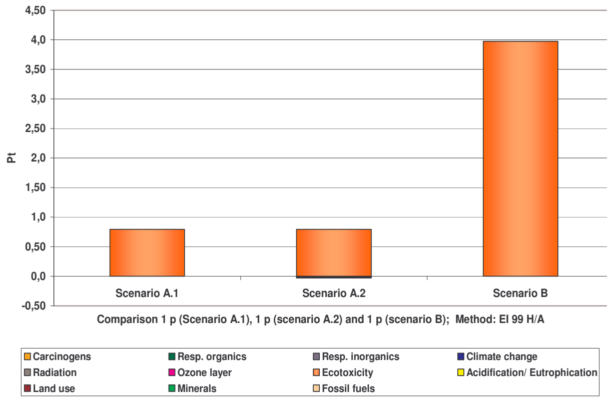

Figure 14: Scoring by impact categories according to EI99 methodology.

3.2. System 2: single-core cable.

3.2.1. Leaching tests results.

Fig. 15 shows the appearance of tested single-core specimens after the leaching tests. Results were quite different in both cables. Significant corrosion damage with greenish corrosion products generation was observed in the exposed area of the helicoidally copper tape, whereas the copper wires coupled with aluminium were almost uncorroded. For this latter case white voluminous corrosion products from the aluminium tape were observed. This behaviour is mainly attributed to a galvanic effect. Aluminium is more electronegative, this is the anode when coupled with copper. Thus copper is protected, whereas the corrosion rate of aluminium is promoted.

Figure 15: Final appearance of single-core cable with helicoidally copper tape (top) and single-core cable with aluminium sheet + copper wires (bottom).

The changes in the concentration of copper and aluminium in seawater exhibit this behaviour, Figs. 16-17. Whereas the single-core cable with the copper tape had a growing trend in copper concentration, the single-core cable with aluminium sheet + copper wires gave important quantities of aluminium in seawater but did not gave signal of copper. In both cases, the migration rate was significantly fast. The aluminium concentration migrated from the single-core cable with Al sheet was stabilized around 719 mg/m^2. On the other hand, the copper concentration in case of single-core cable with copper tape showed a fast growing without stabilization, and a continuous migration of copper to the seawater could be expected.

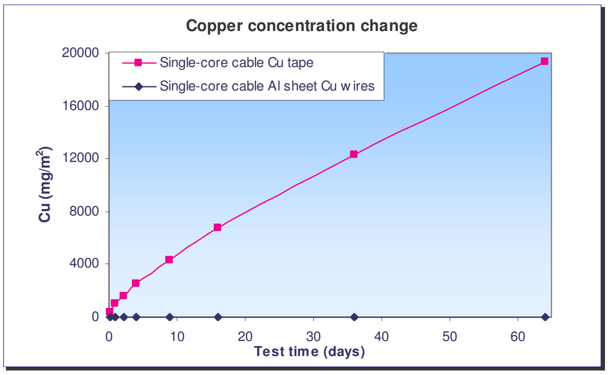

Figure 16: Copper concentration changes.

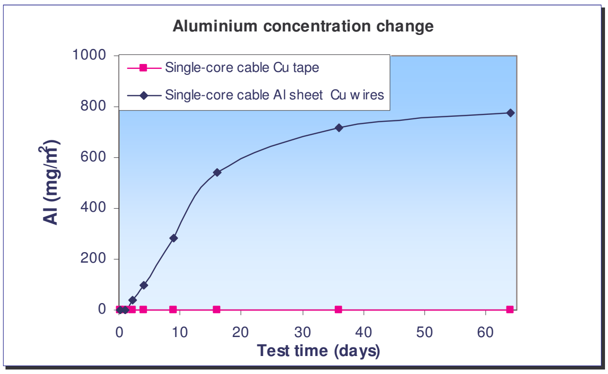

Figure 17: Aluminium concentration changes.

3.2.2. Ecotoxicity tests results.

The obtained results are shown in Table 7. As both specimens had eluates with EC50 higher than the established thresholds, then samples can be considered non-ecotoxic for the aquatic organisms.

Table 7: Results of the ecotoxicity tests.

	Single-core cable with Cu tape	Single-core cable with Al sheet+ Cu wires
EC_{50} (*Photobacterium phosphoreum*) (mg/L)	> 450,000	> 450,000
EC_{50} (*Daphnia Magna*) (mg/L)	> 750	> 750

4. Conclusions

Leaching tests results allowed to conclude that pH of seawater did not significantly changed by the presence of submarine three-core cables. Although, it was slightly higher in case of broken cable, pH values were nearly equals.

Concerning to the heavy metals which could migrate to the aquatic medium, there were significant differences in both scenarios. The leaching of zinc is the major environmental concern during undersea operation of undamaged cables whereas the fully sectioned three-core cable produced the migration of significant quantities of copper and iron apart from the zinc migrated from the galvanized steel. Thus, the tar-impregnated external sheath is not enough as isolation material to avoid the chemicals of galvanized impact on the sea environment. However the HDPE jacket avoids the pollution of sea by the other inside heavy metals like iron and copper.

The DOC results showed growing trends in all cases, although the growing rate in broken cable was higher than rate of undamaged cable. As the tar-impregnated external sheath liberates organic compounds to the sea, the organic matter migrated from the inside of cables can not be determined.

On the other hand, for damaged jacket single-core cables the concentration of corroded copper and/or aluminium increased in the seawater leachant solution. In the case of the aluminium plus copper sheath, the only detected metal was aluminium, while the copper is practically non-corroded. This can be attributed to the galvanic effect when coupled with aluminium.

Tests on bioluminescent bacteria and inhibition effects on *Daphnia magna* indicated a non- toxic effect of all studied undersea power cables (according to pertinent directives).

The results provided by the LCA study indicated a low potential impact during the undersea operation of the submarine cable, even for severely damaged cables. The major environmental impact of submarine three-core cables during their use in seabed was associated to the damage category of Ecosystem Quality due mainly to the organic matter and heavy metals emissions (zinc and copper).

The impacts due to the electric power transmission were not significant considering the total impact in both studied cases. Also, the effect of the oceanic land use was negligible.

Acknowledgement

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Table 2: Life Cycle Inventory of three-core cables scenarios.

		Scenario A.1 (undamaged cable without electric power transport)	Scenario A.2 (undamaged cable with electric power transport)	Scenario B (broken cable)
INPUTS	Oceanic Land conversion to benthos (m^2/km cable) [13]	2.46	2.46	2.46
	Conversion to industrial land (m^2/km cable) [13]	2.46	2.46	2.46
	Industrial land use ($m^{2.}$ año/km cable) [13]	49.2	49.2	49.2
	Converted wind energy (MJ/km cable) [13]	--	3.87	--
OUTPUTS	DCO (kg/km cable) [14]	1.12	1.12	1.7
	Zn, ion (kg/km cable) [14]	0.624	0.624	1.03
	Cu, ion (kg/km cable) [14]	n.m.	n.m.	0.23
	Fe, ion (kg/km cable) [14]	n.m.	n.m	183.04
	Thermal energy (kwh/km cable) [13]	--	0.05	--
	Electric power (kwh/km cable) [13]	--	1	--

n.m. = not measurable

Table 3: Changes of three obtained eluates for system 1.

Sample	Test duration (days)	0.25	1	2.25	4	9	15.25	35.25	63.25
Blank	Ratio L/S	0.72	1.49	1.49	1.49	1.49	1.49	1.49	1.49
	pH	8.16	8.17	8.13	8.17	8.2	8.19	8.18	8.17
	DOC (*)	2.16	5.77	10.02	14.13	28.96	34.08	40.50	41.44
Scenario A (undamaged cable)	Ratio L/S	1.44	2.88	4.33	5.77	7.21	8.65	10.10	11.54
	pH	8,17	8.18	8.16	8.18	8.2	8.19	8.16	8.07
	Cu (*)	< 0,05	< 0.05	< 0.05	< 0.05	< 0.05	< 0,05	< 0.05	< 0.05
	Fe (*)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0,05	< 0.05
	Zn (*)	0.20	0.56	1.23	2.35	4.21	7.53	13.18	22.51
	DOC (*)	6.49	11.39	16.88	23.37	40.53	52.76	73.53	81,75
Scenario B (broken cable)	Ratio L/S	1.44	1.44	1.44	1.44	1.44	1.44	1.44	1.44
	pH	8.12	8.19	8.18	8.23	8.3	8.32	8.3	8.21
	Cu (*)	0.94	2.15	3.37	4.39	5.46	6.43	8.00	8.69
	Fe (*)	1.72	2.69	3.37	4.12	4.55	4.91	6.67	6.83
	Zn (*)	1.94	4.64	7.54	11.72	16.96	22.25	31.33	38.28
	DOC (*)	5.22	7.76	11.49	14.93	42.69	48.66	58.51	63.43

(*) expressed as mg/kg dry mass

Table 6: Concentrations of the eluates of single-core cables (system 2).

Specimen	Time test (days)	0.25	1	2.25	4	9	15.25	35.25	63.25
Single core cable with Cu tape	Cu (**)	387.5	987.5	1625.0	2493.8	4325.0	6775.0	12306	19369
	Al (**)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Single-core cable with Al sheet + Cu wires	Cu (**)	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
	Al (**)	< 0.05	< 0.05	38.0	100.0	281.0	544.0	719	775

(**) expressed as mg/m^2