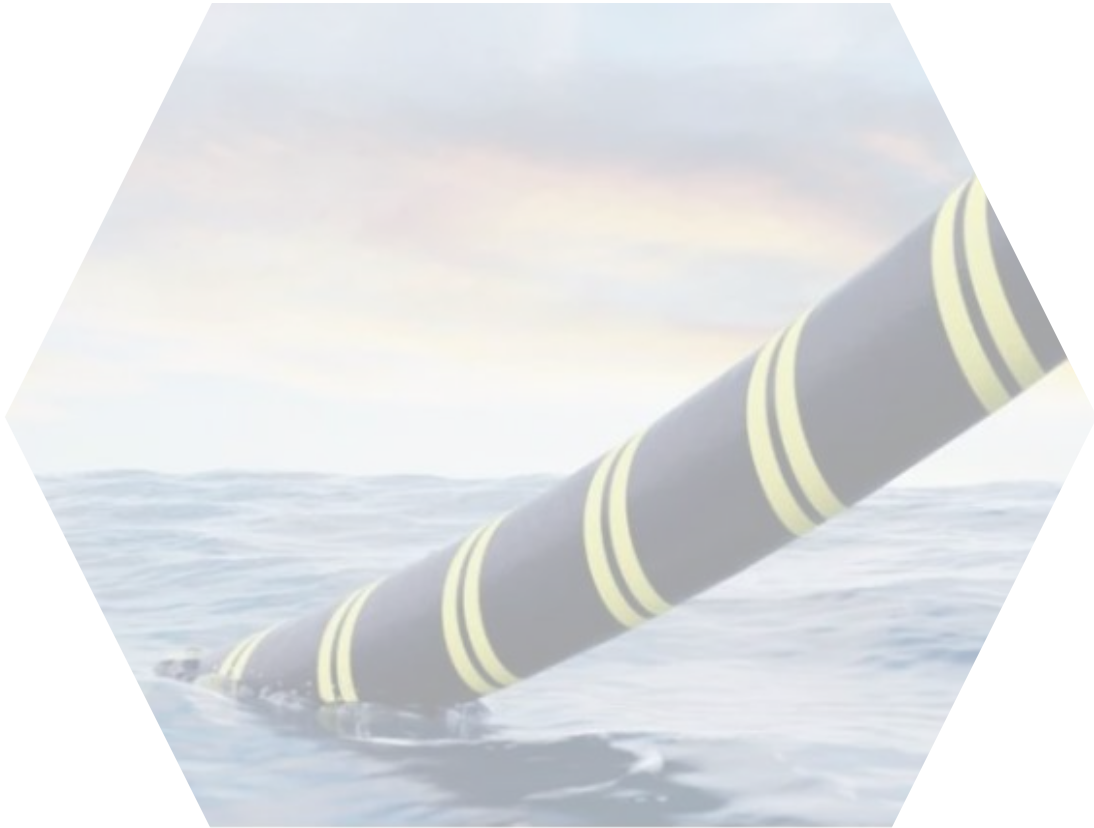




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EXECUTIVE SUMMARY

This document specifies the relevant material development, norms, restrictions, cross sectional areas and operational temperatures that apply to the planned HVDC cable development. It outlines objectives, including eco-design and environmental considerations. It also presents the initial cable design description along with performances that can be expected from such.



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ABBREVIATIONS AND ACRONYMS

Abbreviations / Acronyms	Description
AC	Alternating Current
CB	Carbon Black
DC	Direct Current
DOS	Density of States
EF	Environmental Footprint
EoL	End of Life
EPLCA	European Platform for Life Cycle Assessment
FAT	Factory Acceptance Test
FIMT	Fiber in Metal Tube
GWP	Global Warming Potential
HDD	Horizontal Directional Drilling
HL	High Load
HV	High Voltage
HVDC	High Voltage Direct Current
IEC	International Electrotechnical Commission
IPL	Inverse Power Law
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LC	Load Cycle
LCA	Life Cycle Assessment
LCC	Line Commutated Converter (also Life Cycle Costing)
LDPE	Low-density Polyethylene
LI	Lightning Impulse
L-XLPE	Low Crosslinked polyethylene
PDP	Peroxide Decomposition Products
PE	Polyethylene
PEA	Pulsed-Electro-Acoustic (method)
PQ test	Pre-Qualification test
SC	Semi-Conductive
TRL	Technology Readiness Level
TB	Technical Brochure
XLPE	Crosslinked polyethylene
VCV	Vertical Continuous Vulcanization
VSC	Voltage Source Converter
ZL	Zero Load



1 INTRODUCTION

This report will outline the innovations relevant to the HVDC cable system. It assessed relevant standards and requirements that apply to the new enhanced insulating material and its qualification programme. The theoretical background and from it the relevant parameters that affect the cable design will be outlined:

- The operational cable temperature impact
- The cable cross-sectional impact
- The electrical resistivity and space charge accumulation

Since full-size cable manufacturing encompasses long lead and set-up times, the first cable design description is made allowing for preparation for the coming manufacturing and testing campaigns.

The regulatory framework presented hereby is also designed to guide the development of high-voltage direct current (HVDC) cable technology toward sustainability. This is addressed in Chapter 5, which describes a sustainability assessment framework that should be used to guide the innovation. To ensure comprehensive performance, the framework includes two key stages: an eco-design assessment and a full cable system assessment. Recognizing the critical importance of sustainability in innovation, the eco-design assessment process is proposed to inform the selection of optimal material and manufacturing processes for the developed HVDC cable. The cable system sustainability assessment complements the eco-design assessment by evaluating the entire life cycle from cradle to grave. The assessment framework employs indicators that reflect the multifaceted nature of sustainability, spanning environmental, social, and economic dimensions. To regulate the achievement of optimal solutions, thresholds are defined for the indicators. Therefore, the framework enables a more sustainable approach to HVDC cable innovation, driving advancements that align with sustainability goals embedded in the EasyDC-FOS project.



2 Standards, materials and manufacturing

This chapter outlines the standards, materials and manufacturing methods relevant for HVDC cable systems with extruded insulation.

2.1 Prevailing standards

The CIGRE TB 852 is the prevailing standard for testing high voltage direct current (HVDC) extruded cable systems and sets the requirements for evaluating new insulation materials. The introduction of materials like low cross-linked polyethylene (XLPE), nano-filled materials, and thermoplastic insulations has led to updated and more rigorous testing procedures. For these new materials to be considered suitable, they must go through a series of tests designed to evaluate their performance under various conditions. This process begins with the early stages of technology readiness, moving from experimental proofs of concept (TRL3) to validation in real-world, relevant environments (TRL5), where the materials undergo qualification testing.

The transition from TRL3 to TRL5 is crucial in determining if a new insulation material can be successfully integrated into HVDC systems. At TRL3, the material undergoes experimental testing in a controlled lab environment to demonstrate that it works as intended. As it progresses to TRL4, the material is tested further to ensure it can meet specific technical requirements. By TRL5, the cable system must pass qualification tests in conditions that simulate real operating environments, such as prequalification testing, type testing, and thermal stability testing. These tests, outlined in TB 852, ensure that new insulation materials are reliable and safe for long-term use in HVDC applications.

2.1.1 TB 852

TB 852 is a technical brochure that provides updated recommendations for testing DC extruded cable systems used for HVDC power transmission. It serves as the prevailing standard for testing cables rated up to 800 kV. The increasing demand for HVDC systems, along with the continuous advancements in cable technology, necessitated the development of a comprehensive guide that reflects the latest materials, testing methods, and industry requirements. TB 852, which replaces the earlier TB 496, addresses these changes by introducing new testing procedures and extending the voltage range to meet current market needs [1].

This standard has become the reference for the industry because it incorporates the most recent international standards, such as IEC 60840, IEC 62067, and IEC 62895, and introduces more flexible testing methods. Furthermore, it covers a wide range of cable materials and manufacturing processes, including the latest insulation materials like L-XLPE and thermoplastics. Extruded insulation systems, in particular, are based on XLPE, L-XLPE, and thermoplastic insulation. L-XLPE, a variant of XLPE with a lower crosslink density, is evaluated using specific Hot Set Test requirements and has a lower by-product content compared to standard XLPE. By considering new tests such as the thermal stability test and temporary overvoltage test, as well as updating



qualification and routine tests, TB 852 ensures that cables are rigorously tested to guarantee their reliability and performance in modern HVDC applications [1].

2.1.1.1 Inverse power law

The Inverse Power Law (IPL) is used to simulate the aging process of high voltage cable systems over an extended period, typically up to 40 years. Since it is impractical to test the cables for such a long duration, this model helps accelerate the testing by applying higher voltages over a shorter time period. The relationship between the voltage and time is expressed as:

$$V^n \cdot t = \text{const} \quad (1)$$

where V is the applied voltage, t is the time, and n is the life exponent, which is determined from empirical data on the endurance of the cable materials. The IPL assumes that as voltage increases, the time to failure decreases, allowing manufacturers to predict the long-term performance of the system by testing at elevated stress levels for shorter durations.

Using the IPL approach, the test voltage V_{dc} is calculated to ensure that the cable system undergoes equivalent stress during the test as it would over its entire design life. The formula for determining the test voltage is:

$$V_{dc} = V_0 \times K_1 \quad (2)$$

Where V_0 is the system's rated voltage and K_1 is the test voltage aging factor. The aging factor K_1 accounts for the difference between the design life t_0 and the test duration t_1 and is expressed as:

$$K_1 = \left(\frac{t_0}{t_1} \right)^{\frac{1}{n}} \quad (3)$$

This formula helps adjust the test voltage based on the expected design life of the cable (e.g., 40 years) and the actual test duration (e.g., 1 year, 82 days, 30 days). TB 852, for example, identified that a test voltage factor of 1.45 applied for 1 year simulates 40 years of operation. Similarly, a factor of 1.68 for 82 days and 1.85 for 30 days corresponds to the same operational period [1].

The IPL method ensures a conservative and reliable approach to testing cable systems, allowing for the accelerated validation of their long-term performance in HVDC applications. By simulating

decades of operation in a compressed time frame, manufacturers can confidently ensure that their cable systems will remain reliable and durable throughout their intended service life [1].

2.1.1.2 Type test

The type test is an essential procedure carried out before a cable system is supplied on a commercial basis. It is designed to verify the performance characteristics of the system to ensure it meets the intended application. These tests are conducted on all components of the cable system, including both the cable and its accessories. While it is acceptable to test different parts of the system in separate loops, it is crucial that all relevant components are thoroughly tested to ensure the overall reliability of the system [1].

The type test includes both non-electrical and electrical tests. The non-electrical tests focus on evaluating the physical properties of the cable system. For example, insulation materials are checked for by-product content, and cross-linked insulation is subjected to a Hot Set test to measure how it behaves under mechanical stress. If the cable system is designed for land installations with water-blocking features, it must also undergo a water penetration test, as specified in the IEC 62895 standard, to ensure the system's resistance to moisture [1].

In the electrical type tests, the cable system is mechanically preconditioned before any electrical testing. This mechanical preconditioning simulates the stresses that the cable might experience during real-world handling and installation, ensuring that the system is robust enough for practical use. The electrical tests include the load cycling test, which simulates varying operational loads over time. For cables intended for Voltage Source Converter (VSC) technology, the load cycle test does not include the polarity reversal test that is commonly used for Line Commutated Converter (LCC) systems. This is because VSC systems do not require polarity reversal, making the test conditions specific to their operational environment. Additionally, the cable system undergoes the superimposed impulse voltage test, where it is subjected to high voltage impulses to evaluate its durability under sudden voltage surges, followed by a subsequent DC test to ensure stability post-testing [1].

The success of the type test is determined by the system's ability to pass all these tests without breakdown (and no signs of deterioration during dissection of the test loop components) and by meeting all non-electrical as well as electrical requirements. *Figure 1* shows a flow chart outlining the principal overview of electrical type tests, which provides a visual summary of the key stages in the testing process [1].

For a type test to be validated, it must be certified by an independent third party or a qualified representative from a recognized witnessing body. This certification ensures that the test was conducted under strict conditions, with proper verification of all key elements, including the voltage wave shapes, test loop components, and overall test setup. Alternatively, a report from the manufacturer, signed by an authorized official, or a type test certificate from an independent test laboratory, is also acceptable as proof of successful type testing. This independent certification provides confidence in the test results and guarantees that the cable system meets the required standards [1].

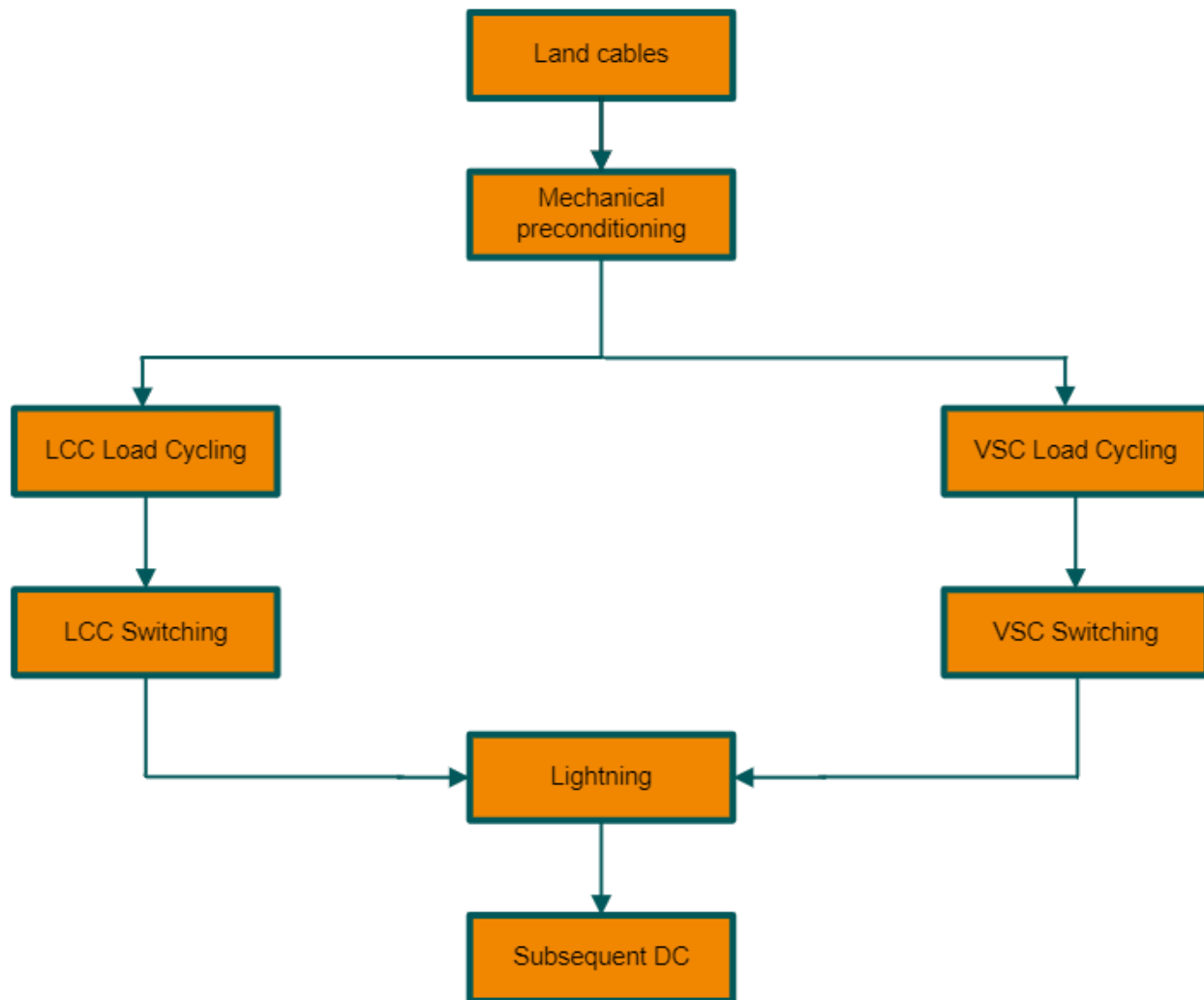


Figure 1: Principal overview of electrical type tests [1]

This comprehensive testing ensures that the cable system is reliable, durable, and ready for safe installation and operation in HVDC systems.

In testing cable systems for VSC technology, load cycling tests are critical to evaluate how the system responds under different operational conditions. The test involves applying multiple blocks of load cycles, where each cycle consists of an 8-hour heating phase followed by a rest period for cooling. These cycles simulate real-world operating conditions, where cables are subjected to varying loads, causing temperature changes that impact the DC electric field distribution within the cable [1].

The load cycling tests are carried out under both negative and positive polarities. First, twelve 24-hour load cycles are performed at negative polarity at the test voltage U_T , followed by twelve 24-hour load cycles at positive polarity at the same voltage. Additionally, the test includes three 48-hour load cycles at positive polarity, as positive polarity is considered to be the most demanding

condition for cable accessories. Rest periods are permitted between blocks of different polarities to ensure proper system stability and reset before continuing the test sequence [1].

The influence of resistive fields during these tests is significant, as the loaded and unloaded conditions impact the DC electric field distribution across the cable system, affecting its overall performance and longevity.

Below is a summary of the load cycle sequence for VSC systems:

Table 1: Load cycle sequence and test voltages for VSC systems [1].

Load Cycle Type	Number of Cycles/Days	Test Voltage
LC (Negative Polarity)	12 cycles (24 hours each)	U_T
LC (Positive Polarity)	12 cycles (24 hours each)	U_T
LC48 (Positive Polarity)	3 cycles (48 hours each)	U_T
S/IMP (Switching Impulses)	± 10 impulses	$U_{P2,S}, U_{P2,O}$
S/IMP (Lightning Impulses)	± 10 impulses	U_{P1}
Subsequent DC	2 hours	U_T

This testing process helps ensure that the cable system can handle the dynamic stresses of VSC applications and operate reliably over long periods under varying load conditions.

2.1.1.3 Performance demonstration

The performance demonstration of a cable system, as outlined in TB 852, focuses on ensuring that system meets the required standards through comprehensive type tests. The approval of a type test is valid for a range of cable systems if several important conditions are met. These conditions include ensuring that the designs, materials, and manufacturing processes of the new system are equivalent to those tested, and that the system's service conditions – such as voltages and mechanical stresses – are no greater than those tested. For example, the service voltages and the maximum conductor temperature must not exceed the levels used in the approved type test. Similarly, the temperature drop across the insulation layer and the conductor cross-section must be within the limits of the tested system.

If any of these factors, such as higher stress, higher temperature, or significant changes in materials, exceed those of the tested system, the cable must undergo requalification to ensure it can still meet the required performance criteria. This ensures that systems operating under more demanding conditions are still reliable and safe for use. If there are significant deviations from the

original test conditions, the system may no longer qualify under the existing approval, and further testing would be necessary to maintain certification.

The EasyDC-FOS task four (T.4) focuses on ensuring that the system passes a full-size qualification test without deviating from the standard. This is important because pushing beyond the limits of the standard during R&D testing could potentially damage the cable system, rendering it non-compliant with the established test criteria. For instance, testing a system beyond its intended performance range, such as by increasing voltage or temperature beyond the tested limits, could cause deterioration of the cable test loop, leading to failure in meeting the type test requirements. This is why experimental R&D tests should remain at lower TRL levels, such as TRL3 or 4, while TRL5 testing focuses on passing the standard type test.

A key performance indicator (KPI) for this process is to ensure the **cable passes the type test at 90 °C, demonstrating its reliable operation under full and dynamic load conditions**. Additionally, it is essential that **relevant cable accessories, which are part of the test loop, also pass the type test** to confirm the overall system's integrity.

2.1.2 Other standards

In addition to TB 852, there are other important standards related to HVDC cable testing and design. IEC 62895 is a standard specifically for testing land HVDC cables, and it is very similar to TB 852 in terms of its requirements and procedures. Both standards aim to ensure the safe and reliable operation of HVDC cable systems, but IEC 62895 focuses more on land applications. Another standard, TB 496, was the pre-runner to TB 852, but it is now obsolete as TB 852 provides more updated and comprehensive guidelines.

Other relevant standards include TB 623, which outlines the mechanical requirements for HVDC cables, such as the bending test that ensures cables can withstand mechanical stresses during installation and operation. For cable rating calculations, IEC 60287 is used to determine the current-carrying capacity of cables, ensuring that they are properly rated for safe operation under different load conditions. Together, these standards provide a comprehensive framework for testing and evaluating HVDC cable systems.

2.2 HVDC insulation materials

XLPE is a suitable material for HVDC cable insulation due to its durability and stability under high temperatures. XLPE starts as low-density polyethylene (LDPE), which has a melting temperature of around 110 °C. However, LDPE begins to soften well below this temperature, and international standards limit its continuous operating temperature to 70 °C. To enhance its properties for high-voltage applications, LDPE is treated with a crosslinking agent in a process known as vulcanization. This process creates chemical bonds, or “cross-links,” between the polyethylene molecules, transforming LDPE into a more robust material that can withstand higher temperatures.

The crosslinking in XLPE prevents the material from turning into a liquid when it reaches its melting point, enabling it to retain a solid structure even in a semi-melted, amorphous state. This structural

integrity allows XLPE to operate continuously at temperatures up to 90 °C, and sustain short circuits above the melt temperature, as permitted by international standards. This makes it an ideal material for HVDC applications where the cable experiences prolonged exposure to high temperatures and mechanical stresses.

During the crosslinking process, however, byproducts known as Peroxide Decomposition Products (PDP) are produced. These byproducts are a natural outcome of the chemical reaction that strengthens the polyethylene, but they can affect the DC performance of the insulation over time. Managing and minimizing these byproducts is a key part of producing high-quality XLPE insulation, ensuring long-term reliability and stability in HVDC systems.

2.2.1 Electrical properties of DC-XLPE

The steady state solutions of Gauss law and the current continuity equation respectively shape capacitive and resistive field distributions, relevant for HVDC cable systems, as:

$$\nabla \cdot \vec{E} = -\frac{\rho}{\epsilon_0 \epsilon_r} \xrightarrow{\rho=0} \nabla \cdot (\epsilon \vec{E}) = 0 \quad (4)$$

$$\nabla \cdot \vec{J} = -\frac{\partial \rho}{\partial t} \xrightarrow{\partial \rho / \partial t = 0} \nabla \cdot (\sigma \vec{E}) = 0 \quad (5)$$

where E is the electric field strength in V/m, ϵ is the material permittivity in F/m and ρ is the charge density in C/m³. Furthermore, the scalar electrostatic potential is defined as:

$$\vec{E} = -\nabla V \quad (6)$$

where V is the applied voltage in volts. Ultimately, it can be concluded that capacitive and resistive field distributions are governed respectively by the material's permittivity and its conductivity. An HVDC cable system may initially, upon stepwise or sudden (transient) voltage application, experience a capacitive field distribution which may gradually shift to a resistive field distribution if the voltage level is maintained. While the permittivity of an HVDC cable insulation may exhibit low variations under different loading conditions, conductivity variation may span over several orders of magnitude.

2.2.1.1 Conductivity/resistivity

An HVDC cable insulation system experiences ohmic leakage and polarization currents as a function of applied electric field strength as:



$$\vec{J} = \sigma \vec{E} + \frac{\partial(\epsilon \vec{E})}{\partial t} \quad (7)$$

Where J is the current density in A/m^2 , σ is the conductivity in S/m and E is the electric field strength in V/m . When neglecting polarization currents (assuming steady-state), direct proportionality between leakage current density and field strength is invalidated since conductivity may exhibit field strength dependency. It must therefore be expanded through a Klein's conductivity expression to:

$$\sigma(E, T) = \sigma_0 e^{\alpha T} e^{\beta E} \quad (8)$$

Here σ_0 is the base-level conductivity in S/m , α is the temperature parameter in $1/^\circ C$ and β is the electric field parameter in mm/kV . It can be considered that a multitude of field and temperature dependencies are present within bipolar electronic (and ionic) carrier transport, and that such effects are averaged into a single macroscopic material-specific conductivity parameter set.

As earlier mentioned, the resistive field will be governed by the conductivity, and its field and temperature dependency will shape the degree of field inversion experienced during the load cycling in the type test.

The relevant task is thus to measure the conductivity parameters on relevant cable peeling samples and to use such to assess the steady-state electric fields in the cable insulation under loaded & non-loaded conditions.

2.2.1.2 Space charge

HVDC cable insulation hosts an intricate balance between different field and temperature dependent charge generation (injection, ionization, dissociation and other processes), transport (including trapping and detrapping) and recombination processes, which can result in local charge density variations disturbing the Laplacian field distribution. For electronic conduction the insulation's conductivity can be estimated from mobile carrier densities and mobilities as:

$$\sigma = e \left(n_e \mu_e + n_h \mu_h + \sum n_k \mu_k \right) \quad (9)$$

where n_e and n_h respectively are the mobile carrier densities. The sum is used to define additional ionic carrier types, with densities n_k (negative and positive) which's transport add to the total leakage current in the insulation. While electronic carriers typically are generated through charge injection at electrodes, ionic carriers can originate from chemical impurity ionization (e.g. by impact

ionization or dissociation within the material bulk) or by migration of ions from surrounding materials.

The material's charge carriers also give rise to a dynamic evolution of the total (net) charge density, C/m^3 , defined at each point in the material as:

$$\rho_{tot} = e(n_h + n_{ht} - n_e - n_{et} \pm \sum n_k) \quad (10)$$

Where again n_k represents additional ionic charge carrier densities and “ $\pm$ ” indicates the inverse local contribution between positive and negative carriers. Equations 9 and 10 can be simplified if electronic conduction prevails in the material.

2.2.1.3 Electrical evolution and ageing

During cable lifetime, the insulation is submitted to thermal cycles causing charge dynamics, where resultingly each cycle sub-phase makes a unique contribution to the overall ageing rate. In a pre-qualification test such as a type test, this ageing rate is enhanced by the elevated electric field strength such that the thermo-electric ageing quanta equals 40 theoretical years of operation. While such XLPE ageing can be accelerated by oxygen, the impermeable cable sheath limits oxygen supply.

Apart from a distortion of the PDP distribution, local molecular sites of the material matrix may be damaged over time causing an evolution of the material's density of states (DOS). The DOS evolution, exhibiting gradual addition of shallow, inter-level or deep states, is expected to influence charge trapping, mobility as well as charge injection rates. This DOS evolution can gradually reduce the material's conductivity, but when deep and inter-level states densities increase to significant densities, such a trend may be broken.

Space charge measurements, provide good insight as increased densities of trapping sites are expected to increase the net charge density ρ_{net} . The homogenous electric fields and temperatures in cable peelings greatly reduces measurement complexity versus a full-size cable measurement, and additionally allow for assessing statistical variance amongst such results. Space charge measurements using Pulsed-electro-acoustic (PEA) method on cable peelings extracted post and prior to a type test can thus be used to verify the insulation performance and possible material evolution during the test.

A relevant task is thus to measuring the space charge accumulation in cable peelings samples before and after the type test

2.2.1.4 Electrical breakdown and extrapolation to the 640 kV level

The power energy density in W/m^3 due to joule insulation losses is defined as:



$$w_e = \sigma E^2 \quad (11)$$

The total losses in the insulation system of an HVDC cable in W/m are estimated as:

$$W_d = \frac{2\pi\sigma U_0^2}{\ln(r_{outer}/r_{inner})} \quad (12)$$

As seen in equations (11) and (12), an estimation of the insulation joule losses is needed as such losses exhibit a conductivity dependency. According to the relevant standard TB 852, a thermal stability test (TST) may apply that specifies that such losses, when testing the cable at rated temperature and $1.45 \cdot U_0$, shall not contribute to more than 2K of additional heating during the test. Since there is a quadratic voltage dependency in equation (12), on the cable peelings estimated conductivity parameters and cable design can be used to estimate if the 400 or 525 kV qualified design would also fulfill such requirements for a **640 kV voltage level**.

Furthermore, since the type tests simulated a wear out portion in the type test, the electrical results after the type test may also provide insight on residual margins in the cable system and the possibility to extrapolate the performance to a 640 kV level.

Lastly, the steady state resistive fields can also be estimated for the 640 kV level to anticipate the degree of field inversion and electrical stress in such a cable design.

The task is thus to use the measured conductivity from after the type test for ohmic losses and field distribution evaluations up to a 640 kV // 90 °C level.

2.2.1.5 XLPE byproduct control

The key difference between AC-XLPE and DC-XLPE is the methodology to limit the PDP, as such crosslinking byproducts contribute negatively to the aforementioned conductivity parameters and the space charge accumulation in the material.

The traditional approach has been to make a DC-XLPE with a lower degree of crosslinking agent and resultingly yielding a lower PDP amount (while also maximizing the crosslinking efficiency during the process). As per the prevailing standard TB 852, a low-crosslinked PE (LXLPE) has been defined, demanding an elongation of only 5 N/cm² compared to the traditional 20 N/cm² load to be applied during the standardized hot set test. While this is a mechanical disadvantage, as the hot set correlates to the mechanical rigidity during high thermal loads, this has resulted in excellent dielectric HVDC properties.

Today, a new DC grade XLPE also exists using a fundamentally different approach. It uses a conventional amount of crosslinker yielding a higher amount of PDP, but uses proprietary technology to limit the impact from the byproducts over the electric DC (conductivity and space

charge transport) processes. Mechanically, this material behaves and is classified as ordinary XLPE, which is typically suitable for 90 degrees as has been the case for HVAC applications for decades. It is this novel XLPE that will be evaluated in EasyDC-FOS.

While other means to control the DC byproducts issue do exist, such as the use of nanofillers or using thermoplastic insulation (which intrinsically has no PDP), such materials typically also feature some drawbacks. Typical drawbacks can be extrusion inhomogeneities and cases of agglomeration. Such issues may limit the material's performance under severe electrical impulses, caused by grid disturbances or lightning strokes onto nearby circuits in connection to the DC link.

2.3 HVDC cable manufacturing aspects

The manufacturing of HVDC cables involves key processes such as **conductor stranding**, **insulation extrusion**, **copper screening**, **aluminium sheathing**, and **PE sheathing**. Each of these stages is essential in creating a durable and reliable cable that meets the high-performance standards required for HVDC applications. Together, they ensure the cable's readiness for long-term use under demanding conditions.

2.3.1 Conductor stranding

In the conductor stranding process, the stranding machine is used to form the cable conductor in a single run. Each layer of wires is wound in alternating directions to enhance the conductor's stability and strength. Additionally, semiconducting tapes can be applied over the conductor to ensure stability and watertightness before adding insulation for the next stages of cable manufacturing.

2.3.2 Insulation extrusion

The insulation extrusion process for HVDC cables is performed on a horizontal or vertical Continuous Vulcanization (CV) line, which uses a triple-head extruder to apply the XLPE insulation system around the conductor. This process, carried out in Nexans extrusion lines, is crucial for producing reliable cables. The high-pressure cross-linking of the XLPE insulation occurs in a controlled nitrogen environment to prevent contamination and ensure quality.

To maintain the cable's long-term reliability, strict cleanliness standards are upheld throughout the entire supply chain, as even minor impurities can compromise performance. Due to the thermal impact of the conductor, precise temperature control is required to keep the extrusion within the optimal processing window. This rigorous approach justifies the use of commercial materials that have reached high TRL, ensuring the materials and cable's intrinsic capability to meet industry standards and support a high-quality, reliable insulation system.

2.3.3 Degassing

The degassing process for the insulation system takes place in a specially designed degassing chamber, where the cable is held at a specific temperature and duration. This process continues until methane and other by-products (PDP) from the insulation are reduced down to target levels



set by Nexans, ensuring the insulation system meets quality and safety standards for reliable performance.

2.3.4 Copper screening

The copper screening process involves a screening machine that wraps various layers around the insulated cable. These include a swelling tape, a copper wire screen (which may incorporate the Fiber in Metallic Tube, or FIMT), a helically applied copper tape, and a second swelling tape. This multi-layered approach provides the cable with enhanced protection, contributing to its overall durability and performance.

2.3.5 Aluminium sheathing

The aluminium sheathing process involves wrapping a laminated aluminium foil around the cable in a lengthwise direction, forming a protective cylindrical layer. Such sheathing is typically welded in-line during the sheathing process. This aluminium sheath enhances the cable's mechanical strength and provides an effective barrier against moisture and environmental factors, contributing to the cable's overall durability and stability.

2.3.6 PE sheathing

The PE sheathing process adds an impermeable water barrier to the cable, enhancing its protection against corrosion. This outer PE sheath is extruded continuously alongside the aluminium sheathing process to create a seamless protective layer. A thin layer of semi-conductive polyethylene (SC skin) is then applied over the insulative PE sheath, which serves as the external ground electrode during sheath testing. Additionally, the cable is marked with non-contaminating, long-lasting markings that will remain legible throughout the cable's lifespan.

3 Cable system design

This chapter presents the design specifics for a 525 kV land cable system with a 3000 mm² conductor, which serves as the base case for this high-capacity configuration. The design accommodates a large conductor size, essential for the system's 2 GW power capacity in a bipolar VSC setup. *Figure 2* will provide a cross-section view of the **TSLE-L 525 kV 1x3000 mm² KQ cable**, featuring 4 FIMT for enhanced communication and monitoring capabilities. This robust design meets the high-performance requirements of large-scale HVDC transmission.

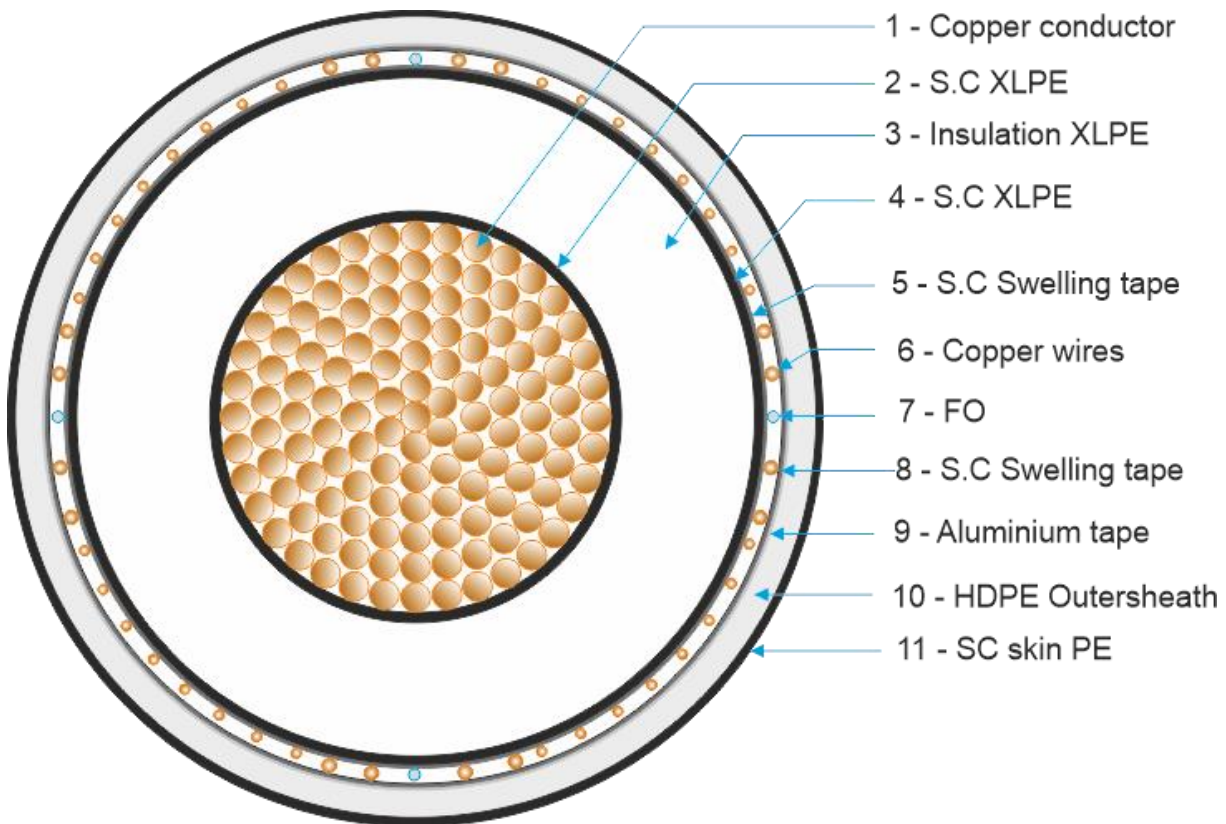


Figure 2: Cross-section drawing of TSLE-L 525 kV 1x3000 mm² KQ + 4x FIMT.

The cable in figure 2 will have the dimensional, electrical and thermal parameters as follows in the table below. Here, the DC resistance in the conductor $R_{DC}(T)$, the permittivity ϵ and the conductivity $\sigma(T,E)$ of the insulation system (*conductivity measured later in peeling tests) form the main electrical parameters. For the thermal parameters, the thermal conductivity k , the specific heat capacity C , and the density D , and the surface emissivity e .

Table 2: Summary of relevant cable design parameters.

No.	Layer	Material	Dimensions	Electrical parameters	Thermal parameters
1	Conductor	Cu or Alu	Radius (mm), cross section	$R_{DC}(T)$	k, C, D
	Conductor tape	Woven fabrics	Thickness (mm)	N/A	k
2	Inner semiconductive layer*	New insulation system XLPE + carbon black	Thickness (mm)	N/A	k
3	Insulation layer*	New insulation system, XLPE	Thickness (mm)	$\varepsilon, \sigma(T,E)^*$	k, C, D
4	Outer semiconductive layer*	New insulation system, XLPE + carbon black	Thickness (mm)	N/A	k
5,8	swellable tapes	Woven fabrics	Thickness (mm)	N/A	k
6	Screen wires	Copper	Thickness (mm), cross section	N/A	k, C, D
7	FIMT	FO	For info	N/A	N/A
9	Water barrier	aluminium	Thickness (mm)	N/A	k, C, D
10	Oversheath	HDPE	Thickness (mm)	N/A	k
11	SC skin	HDPE + carbon black	Thickness (mm)	N/A	k
N/A	Thermal insulation used in type test	Thermal foam	Thickness (mm)	N/A	K, e

The results in table 2 will be specified once the cable design is fully settled in deliverable D4.1



3.1 Conductor design

While specifying the conductor material and its cross-section typically requires tailoring its current carrying capability (ampacity) to project specific installation conditions, during qualification tests it is typically preferred to qualify a large aluminium or copper conductor to make sure that the insulation material can be extruded over a large thermal mass. Since the cable designed is a land cable, its water-blocking capability is designed for accidental water ingress under moderate pressures. The geometry of the conductor's individual layers, as well as the degree of compaction, has been pre-designed to suit the needed electrical and mechanical requirements of a 3000 mm² copper conductor. However, there remains an option to reduce the conductor sizing to better accommodate the insulation extrusion process.

The KPI is thus to at least achieve 2500 mm², but preferably a 3000 mm² sized conductor

3.2 Insulation system

The insulation system contains the new cable insulation and accompanying inner and outer semiconductive layers, all supplied from the same manufacturer tailored to work together. While the semiconductive layers span just a few millimetres thickness, the insulation layer is typically a few tens of millimetres. Here, the cable design is nearly identical to the original insulation, even though resistive design stresses may ultimately differ.

Process wise, slight modification of processing parameters (line speed, temperature zone settings, etc.) is foreseen. One fundamental difference of the new XLPE over the conventional L-XLPE, is its superior mechanical rigidity once the crosslinking is completed. This may be beneficial to subsequent processing steps. Here, the conductor size plays a factor as well and it is essential that the large thermal mass can be heated up and subsequently cooled down in the CV line.

The cable prototype with its new XLPE insulation system may however still require some fine-tuning of extrusion parameters during its production which may, along with foreseen scrap from the start and stop of the manufacturing sequences, and possible defects that are screened away (next chapter) result in shorter length of the final prototype. While a prototype length of 500 m may be targeted, only about 100 m of output may be needed to successfully assemble the type test loop

KPI from manufacturing: at least 100 m of cable prototype that has passed the relevant screening tests.

3.2.1 Screening tests

In HVDC cable manufacturing, screening tests are essential to ensure the quality and reliability of cables and their accessories. According to TB 852, the LI sample test is one such test performed on cable samples and certain accessories. This test involves applying 10 negative and 10 positive high-voltage impulses to the sample, with an electric field strength of 75 kV/mm. Several options exist for defining the test voltage U_t , and calculations are made to create an equivalent stress level

that simulates operational conditions. The purpose of this test is to confirm the durability of the insulation system against sudden, high-voltage impulses [1].

Another key test, the Routine AC test, is considered on every delivery length of cable to check the material and manufacturing quality of the insulation. This test uses AC voltage with an electric field inner gradient of at least 23 kV/mm, applied for one hour. The AC test frequency should be between 49 Hz and 61 Hz, particularly for land cables. TB 852 recommends performing the AC test before the DC test to prevent any issues that might arise from the polarization effect in the insulation after a DC test, which could impact safety and test results. Routine testing helps identify any life-limiting defects that could compromise the cable's longevity [1].

The Factory Acceptance Test (FAT) is another critical step, performed as per TB 852 or IEC 62895 standards for land cables. In this test, the cable is subjected to a DC voltage of 971 kV (1.85 times the rated operating voltage, U_0) for 60 minutes at ambient temperature, with a negative polarity. This high-stress test is designed to confirm that the cable insulation is free from any defects that could lead to breakdowns under real-world conditions. The target or KPI for LI test on samples, routine test, and FAT is that no breakdown should occur, ensuring that the insulation system meets the necessary standards for safety and reliability [2].

The table below summarizes the screening tests for HVDC cables:

Table 3: Summary of screening tests for HVDC cables [1] [2].

Test Type	Conditions	Standard	KPI/Target
LI on Samples	10 positive & 10 negative impulses, $E_i = 75 \text{ kv/mm}$	TB 852	Verify insulation durability
Routine AC Test	Inner gradient 23 kV/mm for 1 hour; frequency 49-61 Hz	TB 852	No life-limiting defects
FAT	971 kV DC (1.85 U_0) negative polarity for 60 min at ambient	TB 852 / IEC 62895	No insulation breakdown

These screening tests ensure the cable system is robust, safe, and meets all required standards before commercial use.

3.2.2 Space charge measurement

Cable peelings can be extracted radially from the full-size cable, on unaged and aged cable specimens, respectively obtained prior to and post type test (as such a test equals a 40 years ageing quanta). A proprietary cutting method will be used.

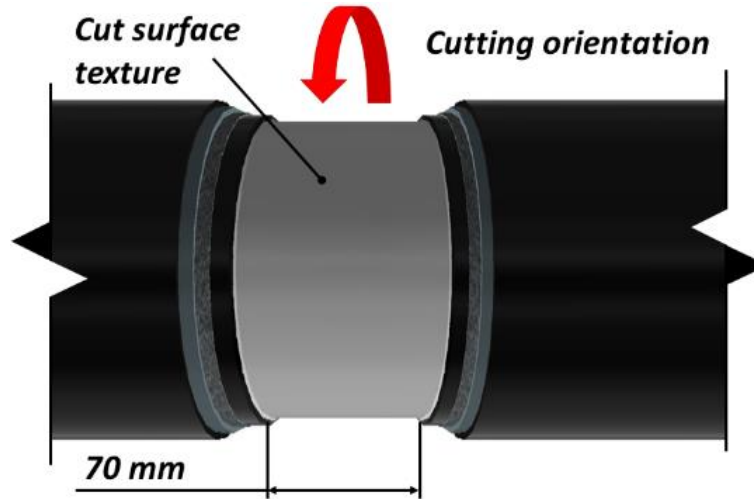


Figure 3: Cable peeling extraction method.

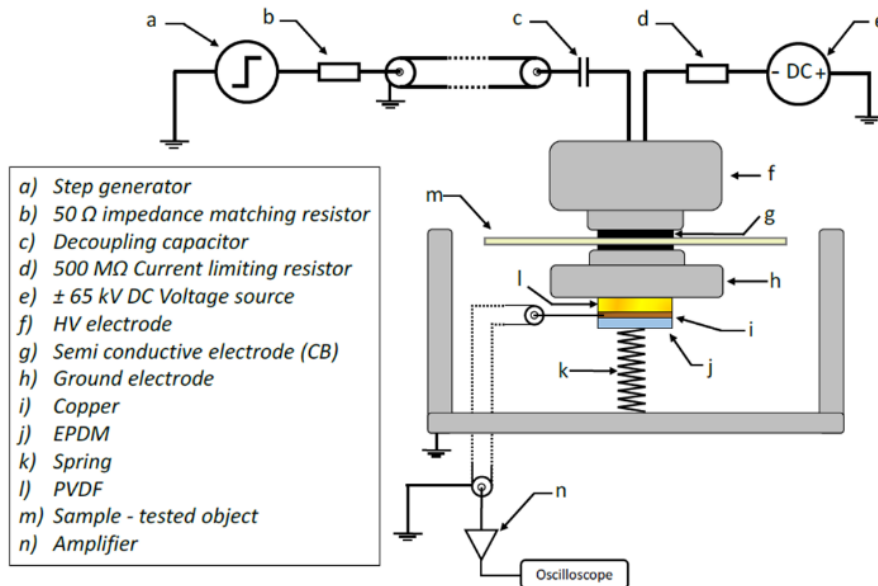


Figure 4: PEA setup for space charge measurements.

Such peelings exhibit limited levels of surface roughness owing to the high quality cut texture, and no heat development occurs during their production. Space charge measurements are performed on cable peelings by means of the PEA setup which included the components in *Figure 4*, and is mounted inside a heating chamber for temperature control. To deduce the net charge density from the time dependent voltage signal, signal calibration is needed. The corrected voltage signal $V_{corr}(t)$ was obtained from the PEA output $V_{meas}(t)$ as:

$$V_{meas}(t) = h(t) * V_{corr}(t) \quad (13)$$

where “*” denotes a convolution product with the transfer function $h(t)$. This function depends on the test bench, material and temperature, requiring re-calibration for each test. The value of $h(t)$ is estimated from two signals, the former with DC application at the end of poling and the latter without DC application just after the end of poling. From the corrected signal, net charge density ρ_{net} can be estimated, from which mean charge density in C/m^3 is subsequently estimated as:

$$\rho_{mean} = \frac{1}{d} \int |\rho_{net}(x)| dx \quad (14)$$

where the integration is carried out over the sample thickness d in mm excluding the capacitive charges at the electrodes. The net charge density ρ_{net} after 24 hours polarization was used, to ensure stable conditions in the measurements.

The mean charge density, measured at different temperatures and field strengths, may allow for comparing the material evolution before and after type test. However, the net charge density signals during polarization and depolarization will also allow to calibrate the charge transport parameters for space charge modelling purposed.

A relevant KPI for the PEA measurements is thus to map space charge on cable peelings, before and after the type test, under different field and temperature conditions, ensuring that the mean charge density ideally remains below $2 C/m^3$.

And, to provide a set of net charge density data suitable for model calibration.

3.2.3 Electrical resistivity measurement

Using the same cable peelings, the resistivity can be assessed. Here, parallel plane setups may allow for straight forward determination of leakage current, and therefrom conductivity. A guard ring setup is typically used to shield away stray currents at the edges of the electrodes as seen in Figure 5.

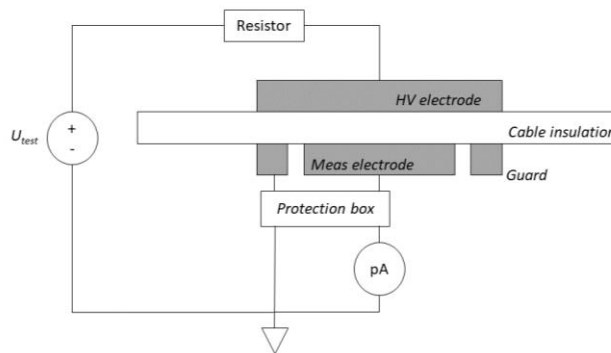


Figure 5: Typical conductivity measurement setup

Leakage current from the sample can be measured by means of a picoammeter, such that the conductivity can be assessed for different voltages and temperatures applied on the measurement setup. The conductivity is calculated as:

$$\sigma = \frac{\vec{J}}{\vec{E}} = \frac{I_{meas}}{A} \bigg/ \frac{U_{meas}}{d} = \frac{dI_{meas}}{AU_{meas}} \quad (15)$$

where d is the sample thickness in m, A is the area of the measurement electrode in m², I_{meas} is the measured leakage current in Amperes and U_{meas} is the applied test voltage in volts.

By performing this test at different levels of applied field (voltage) and at different temperatures, the materials conductivity parameter set can be determined.

A relevant KPI for the conductivity measurement is to map the conductivity at more than two temperatures and more than two field strengths to map the exponential field and temperature dependencies.

3.3 Outer layer selection

The smooth aluminium serving (SAS) along with its copper wire screen and PE sheath is a very typical outer serving for a land cable. As its main functionality, maintaining an impermeable moisture barrier, is identical between the conventional and new cable design, no special aspects or tests apply to this layer. Furthermore, the FIMT included in the original design is optional, as such is not an integral part of the qualification test.

3.4 Reservations for the 2GW design

Since the now newly proposed 2 GW design is the state of the art of HVDC cable capability, exceeding the cable design set up in the original proposal, fallback reservations must be made to enable that an albeit less impressive, but still relevant cable design can be testing in accordance to the timeline of the EasyDC-FOS project.

The following fallback solutions are of relevance:

- A lowering of the insulations system's rated voltage U_0 to 400 kV (as specified in the original proposal).
- Changing the conductor material to aluminium and/or its size down to 2500 mm².

It shall be noted that, the reduction of conductor sizing and material (resultingly reducing the cable rating of the prototype) may be needed to guarantee insulation extrusion stability in the cross-head and subsequent CV line. However, as per table 10.4 in the Cigre standard TB 852, The aluminium conductor typically qualifies a copper one, as **aluminium is regarded as more demanding for the qualification tests.**

In addition to the above fallbacks, there shall be **no lowering of the 90 °C** rated operational temperature, as the type test shall demonstrate the new insulation materials capability to operate at such a temperature level.



Conclusively, a fallback to 400 kV and a conductor with lower ampacity applies.

3.5 Cable system operational aspects

The operational aspects of HVDC cable systems require a careful balance between temperature, spacing, material efficiency, and environmental considerations to ensure optimal performance and cost-effectiveness. Operating at a higher temperature, such as 90 °C instead of 80 °C, can increase the cable's power capacity but also generates more heat and energy losses. Accurately estimating these losses is essential, as extrapolating them across an entire HVDC link without a standardized approach can lead to overestimations. A practical solution could involve assessing a 1 km of land portion under extreme conditions, which hence may somewhat over represent the average conductor losses for the full link.

Land spacing between cable poles is another important consideration. Increasing the distance between cables in a trench (e.g., 1 m, 2 m, or 3 m) can improve thermal performance by reducing interference between cables, allowing for a higher rating. However, wider spacing requires more land, which affects right-of-way needs and may have ecological implications. Hotspot areas, such as locations where horizontal directional drilling (HDD) is applied or where cables cross, also require careful planning to manage additional thermal and mechanical stresses.

Optimizing the conductor cross-section is also key to making the cable system more cost-effective and bear a lower environmental footprint. Reducing the cross-sectional area of the conductor uses less material, which lowers costs, but this must be balanced against the need to handle the cable's operational load. Additionally, considering different loading factors in environmental calculations –such as 30% or 50% of time spent at the systems HL level –can further influence efficiency, allowing for a tailored approach to meet the system's performance requirements while managing costs and minimizing environmental impact. It shall be noticed that such a loading degree can still be conservative as the time at which the cable is at its ambient peak temperature (hot summer days) is limited as well.

The way forward is to simplify any further rating scope to 1 km of buried land cable, part of a space bipole configuration, at 30 or 50% of its operation under max load and max ambient temperature.

4 Cable thermal environment scenarios

This chapter covers relevant calculations made to define the cable performance for a given thermal environment. From the cable performance, and specifically its current carrying capability and losses, it's up front resource and manufacturing cost (in gCO₂ equivalents) can be weighed against operational performance and losses, and carbon penalty related to the latter one (in gCo₂/kWh) over its operational lifetime of 40 years.

4.1 Cable rating equations

The external thermal resistance of buried cables is calculated according to IEC 60287: "Calculation of continuous rating of cables". The conductor resistance, neglecting AC skin and proximity effects, is estimated for DC cables as:

$$R_{DC}(T) = R_0(1 + \alpha_{20}(T_c - 20)) \quad (16)$$

Where R_0 is the electrical resistance in ohms/m at 20 °C, α is the metal specific temperature dependency and T_c is the conductor temperature in °C. The conductor resistance is used to specify the conductor losses from the current I in the conductor as:

$$W_c = R_{DC}(T) I^2 \quad (17)$$

Where W_c is the defined conductor loss in W/m that must be dissipated through the thermal surroundings. In steady state, assuming:

- a single core with the cable only
- negligible eddy current losses induced in screens (valid for DC operation)
- negligible dielectric loss, (valid for most DC-XLPE materials under moderate operational stresses)

The rated current in the cable conductor can be estimated as:

$$I = \sqrt{\frac{T_c - T_{amb}}{R_{DC}(K_1 + K_2 + K_3 + K_4)}} \quad (18)$$

Where T_{amb} is the ambient temperature (far away from the buried cable) and K_1 , K_2 , and K_3 respectively are the cable's thermal resistance of the Insulation system, the metallic sheath and its protective outer sheath, the armour package (if subsea cable) and, K_4 is the thermal resistance of the surrounding environment.

According to IEC 60287, K_4 can be specified for a buried set of cables at spacing (axial separation) S_1 , as per the equation:

$$K_4 = \frac{\rho_T}{2\pi} \left(\ln(u + \sqrt{u^2 - 1}) + \frac{1}{2} \ln\left(1 + \left(\frac{2L}{S_1}\right)^2\right) \right), \quad u = \frac{2L}{D_e} \quad (19)$$

Where L is distance from surface and S_1 is the axial separation in m, D_e is the cable diameter in m and ρ_T is the soil resistivity in K.m/W.

4.2 Cable rating and loss estimations

In order to set up relevant use-cases for the new cable design versus its state-of-the art counterpart, it makes the most sense to perform three cases of comparison. These cable ratings calculations can be made for an equivalent 1km land cable portion*, all having an identical **2 GW** rating in a bipolar scheme:

- **A:** The original 80 °C rated land cable, with the **large 3000 mm² copper conductor** using the existing insulation. This reference cable will have the lowest conductor losses, but largest costs
- **B:** The new 90 °C rated land cable, with a **smaller 2600 mm² copper conductor**** thanks to using the new cable insulation. It will have lower up-front environmental cost, but, operate at higher conductor losses.
- **C:** The new 90 °C rated land cable, with the large 3000 mm² copper conductor, where the new insulation material capability is instead used to **reduce spacing in between the two poles*****
- **D:** The new 90 °C rated land cable, with a **large 3000 mm² aluminium conductor** using the new insulation. This yielded a significant increase in losses

*yielding units per km for conditions relevant to today's "2 GW" HVDC OFW cable projects in Germany.

**The reduction achieved depends on the thermal environment, here the results were tailored to a realistic burial scenario.

*** Exact lower distance subject to detail engineering in section below.



The rated current is calculated using equation (18), where T_1 - T_3 where specified from the specified XLPE cable in the previous chapter, and T_4 is specified using equation (19) at a 30 °C ambient temperature, 1.9 m burial depth, and a soil resistivity of 2.2 K.m/W. These parameters simulate a warm period where some dry out of the soil may occur, increasing its resistivity. From these parameters, in the Table 4 displayed cable ratings, K_4 and losses were estimated.

Table 4: Power ratings and losses of the relevant cable design cases.

Scenario	Cross-section	Rated temp	Voltage	TR, insulation*	K_4 thermal resistance	Power in pole	Losses
A	3000, copper	80	525	3.5, old insulation	1.44	1005	27.1
B	2600, copper	90	525	3.5, new insulation	1.44	1003	32.1
C	3000, copper	90	525	3.5, new insulation	1.75	1003	27.8
D	3000, aluminium	90	525	3.5, new insulation	0.82	1001	48.9
Units	mm ²	°C	kV	W/mK	K.m/W	MW	W/m

*TR = Thermal resistivity. Note that if thermoplastic (non-XLPE) insulation were to be used, substantially higher TR applies, hence having higher losses to reach same rated power.

From the estimated ratings and losses in Table 4, it can be seen that the KPI from the original EasyDC-FOS call text: **“Improved temperature performance up to 90 °C, material volume reduction on XLPE DC cable systems of 10%.”** Is certainly attainable, as a 13% conductor reduction was estimated for scenario B. Furthermore, in Scenario C it is seen that the new insulation allows a soil resistance up to 1.75 K.m/W. Scenario D demands a significantly improved environment due to the higher losses- and resistivity of aluminium. All scenarios feature increased losses over the reference scenario A. For these cable scenarios, the axial separation in between the power phases is estimated as shown in Table 5.

Table 5: Environmental route design and axial separation between the three scenarios.

	A: 3000 // 80 °C	B: 2600 // 90 °C	C: 3000 // 90 °C	D: 3000 // 90 °C	Unit
ρ_T	2.2	2.2	2.2	1.3*	K.m/W
L	1900	1900	1900	1900	mm
s_1	7	7	1.5	7	m



K ₄	1.43136	1.44365	1.73696	0.81327	K.m/W
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*More favourable soil condition needed to render the aluminium design feasible (no dry-out).

From Table 5 it is seen that Scenario C reduces the spacing between the bipole from 7 to 1.5 meters. This enables to skip the displacement of about 10450 m³ of soil, each kilometre, when the cable is installed. From the calculations performed in this chapter, relevant losses have been deduced for the four scenarios, which allows weighing such against these up-front benefits.

4.3 HV Cable specific aspects for LCA

Specific conditions may apply for environmental and LCA calculations due to the nature of the HV cable product, for example, its in-line manufacturing techniques, large shipment batches, and maintenance-free operation. This section aims to specify these aspects

4.3.1 LCA limitations

Relevant limitations that must be applied to further losses, cost and environmental calculations are to simplify the scope into a relevant case of a technological demonstrator. Such limitations are as follows:

- Only 1 km of cable shipped from a relevant factory to a land site in central EU (e.g., Germany)
- One cable drum with no transport restrictions.
- A simplified transport; only one means of transportation covering the full way
- End of life re-cycling may occur after >40 years (though cable may still live >40 years)
- No joints considered, (smaller cross sections may feature fewer joints)
- No outages, 100% uptime
- Aforementioned 30% to 50% at full loading/rating, with the rest at negligible load
- No metal scarcity

4.3.2 Scope 3 emissions; HV cable specific

To correctly assess the scope three emissions of the relevant 1 km of a “2 GW” land cable, its shipment methodology must be assessed. Today, such cables are spooled onto large cable drums, housing approximately 1km each at the largest cross-section, with a combined weight up to 70 tonnes. Such heavy transports, can in theory be made via different carriers such as:

- Transport by ship



- Transport by train*, diesel or electric
- Transport by truck, diesel or electric*

*Not commonplace today due to weight or dimensional restrictions, yet feasible.

For such transport modes, emissions and distances may differ, and the latter will be estimated from Nexans Charleroi land cable factory to today's landfall of the 525 kV OFW projects in Germany. Since these transportation means can strongly influence scope 3 emissions, it is recommended to evaluate further the impact between these different carrier types, and a result could look as in Table 6 below.

Table 6: Example of shipment scenarios relevant for LCA assessment in gCO₂eq/km.

Shipment method	Weight of 1 km cable on drum	Realistic shipment distance	gCO ₂ eq
boat, heavy fuels	70 T	TBA	TBA
Truck, diesel	70 T	TBA	TBA
Truck, electric	70 T	TBA	TBA
Train, diesel	70 T	TBA	TBA
Train, electric	70 T	TBA	TBA

4.3.3 Accounting for the evolving power grid

In order to correctly weigh the environmental impact of cable losses against the environmental impact from cable manufacturing and installation, it is important to factor in the ever evolving carbon intensity in EU's power grid, as displayed in *Figure 6* below.

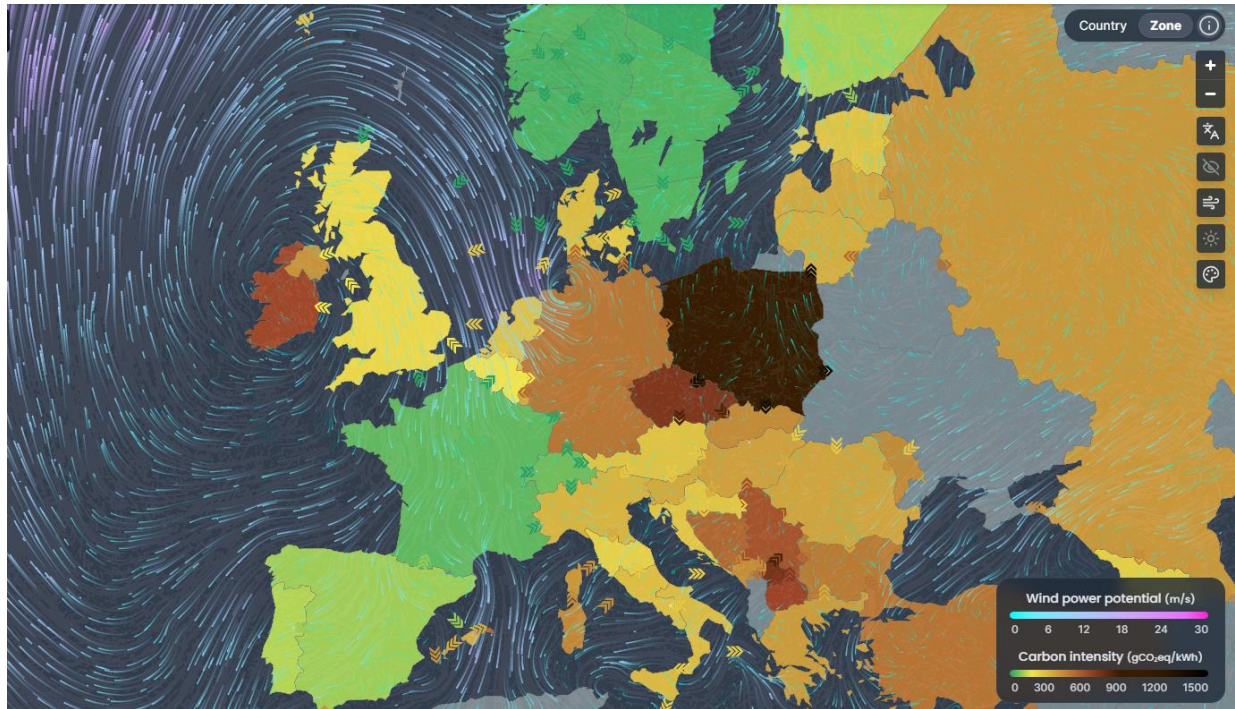


Figure 6: CO₂ intensity in EU power generation, as per 13:57 11/11 2024 [3].

As seen in *Figure 6*, the carbon intensity gCO₂/kWh in electricity generation may today differ significantly dependent on geography, and especially, due to the different generation sources in the grid. As seen above, on a day with low wind, intensities of up to 500 gCO₂/kWh can be measured today, while it is expected that such will, during the coming decades be strongly reduced down to below 50 gCO₂eq/KWh. Also, OFW is typically reported to have an intensity of 13 gCO₂eq/kWh. For such a spread in greenhouse gas (ghg) emissions, yearly emissions due to HVDC cable losses can be estimated for the different scenarios, with results seen in *Table 7*.

Table 7: yearly losses experienced for the for 40 years of operation. * per 1 km of cable.

Scenario	Cross-section	Rated temp	Losses	Yearly losses, 30% at max loading	Yearly losses 50% at max loading	Yearly emissions 30% load 13g/kWh (OFW)	Yearly emissions 30% load 50g/kWh (Clean grid)	Yearly emissions 30%load 500g/kWh (Today)
A	3000, cu	80	27.1	71.16	118.59	0.93	3.56	35.58
B	2600, cu	90	32.1	84.45	140.75	1.10	4.22	42.23
C	3000, cu	90	27.8	73.11	121.85	0.95	3.66	36.56
D	3000, Alu	90	48.9	128.54	214.24	1.67	6.43	64.27

Units	(mm ²)	(°C)	(W/m)	(MWh*)	(MWh*)	TCO2eq*	TCO2eq*	TCO2eq*
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As seen above, Scenarios B and D contribute to significantly larger equivalent emissions, while scenario C makes for a significantly smaller impact (only marginally increased conductor resistance due to its temperature dependency). The evolving grid allows evaluating for which scenario the up-front emission savings are not offset during the theoretical 40 year cable lifetime.

4.3.4 Preliminary break even estimation

In perspective to the initially estimated 5450 kg CO₂eq/km saved on the conductor that was estimated in the EasyDC-FOS proposal, the ghg emission savings results, especially by comparing scenario B to scenario A in Table 8, are significantly higher as here metal processing is factored in.

Table 8: Carbon intensity for conductor only, for 1 km of cable.

Scenario	Cross-section	Conductor Weight	Equivalent carbon dioxide
A	3000, cu	26.8	123
B	2600, cu	23.2	107
C	3000, cu	26.8	123
D	3000, Alu	8.17	94
Units	(mm ²)	Tonnes/km	Tonnes CO ₂ eq/km

From Table 8, scenarios B and D are seen to save 16 and 29 tonnes of *ghg* emission per kilometre on the conductor material only. From here it may also be possible to estimate a break even duration, defining the amount of years until such up-front *ghg* savings are offset by the higher losses, as shown in Table 9. Here, any the downwards evolution of carbon intensity foreseen in the EU grid can be averaged, where the “clean grid” scenario was estimated to have 50 gCO₂eq/kWh.

Table 9: Duration (years) until which the losses costs offset the conductor CO₂eq savings, for 1 km of cable, 30% loading. Higher utilization (up to 50%) may proportionally scale the durations.

Scenario	Cross-section	Rated temp	Break even OFW	Break even clean grid	Break even today
A	3000, cu	80	reference	reference	reference
B	2600, cu	90	95.1	24.7	2.47
C	3000, cu	90	N/A	N/A	N/A
D	3000, Alu	90	39.16	10.18	1.018
Units	(mm ²)	(°C)	years	years	years

From Table 9 in can be concluded, that when the new insulation is used for OFW projects, considerable up-front environmental savings are foreseen already on the conductor sizing, which

may not be offset during its lifetime. For aluminium conductors, similar benefits may be feasible for smaller rated projects, or, if state-of-the art conductor sizing can be extended beyond today's limits. For the clean grid scenario, similar benefits may still be feasible, though if greenhouse emission intensities stay as today, it is recommended to use the new insulation capabilities for local hotspot mitigations only and not for the full land portion of the HVDC link. To these preliminary results, manufacturing and shipment costs will still apply, as well as special environmental considerations, and such will be described in the next chapter.



5 Eco-design and sustainability KPIs

The regulatory framework for eco-design and assessment of sustainability impacts is visualised in *Figure 7*. The framework consists of two stages. In the first stage, an eco-design assessment is carried out for cable materials and manufacturing processes. Based on the eco-design assessment, the most environmentally sound materials and manufacturing processes are selected to be used for the developed cable. In the second stage, the newly developed cable system is assessed on a system level and compared with the baseline scenario.

The decisions within the framework are made based on the tests conducted against pre-determined thresholds. The thresholds are specific values assigned to the indicators used in the framework. There are two types of thresholds defined and used in the framework, obligatory thresholds and preferable thresholds. Obligatory thresholds specify the indicator values (or ranges) that the results of the assessment must not surpass to comply with the regulatory framework. Preferable thresholds specify the indicator values (or ranges) that, if met, grant the given assessed alternative or scenario a preference during prioritization.

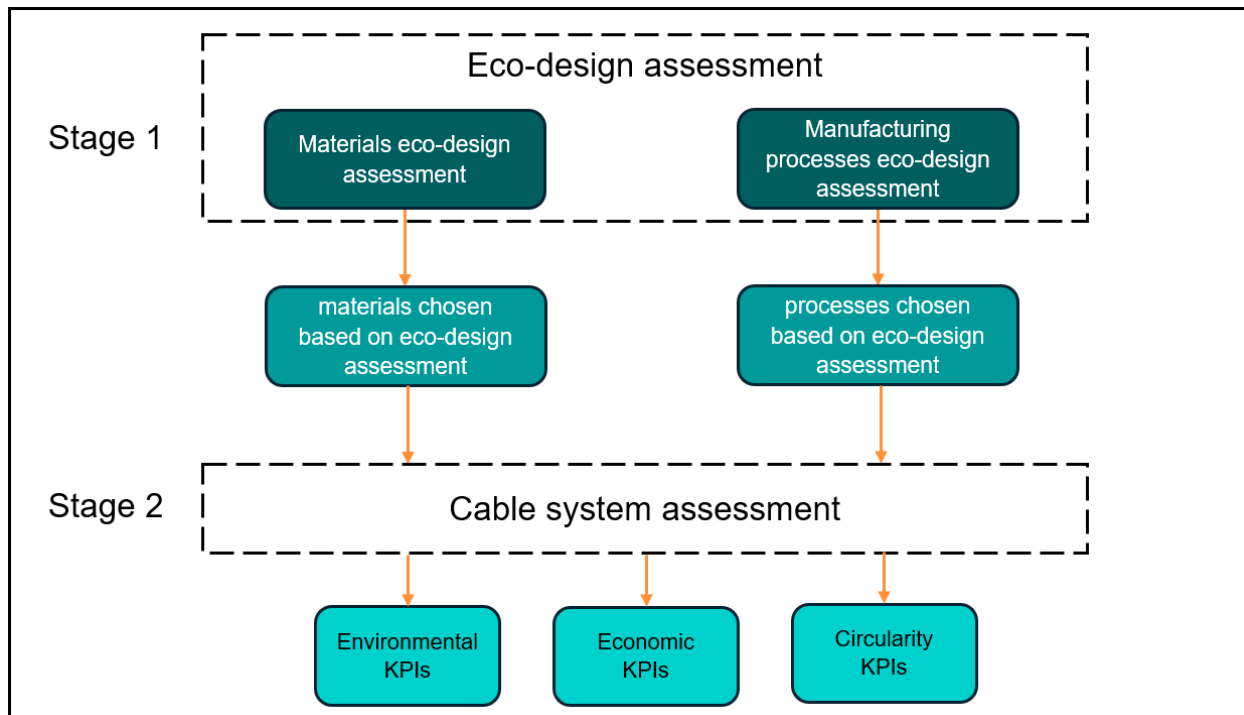


Figure 7: Eco-design and sustainability assessment framework.

5.1 Eco-design assessment for materials

In this section, a methodology to be used for conducting the eco-design assessment for cable materials is described. The purpose of this assessment is to screen and assess a set of cable materials according to the established criteria that reflect environmental performance. The results of this assessment shall inform the decision-making process during the cable design.

5.1.1 Scope

The scope of this assessment is cradle to use phase, i.e., starting from the raw material extraction and ending with the use of the material. This assessment is comparative, i.e., several alternative materials that could be used for HVDC cables are evaluated. More specifically, the materials considered and compared during this assessment can be categorized as insulating materials and conducting materials. The cable insulating and conducting materials considered for the assessment are defined based on the technical specification of the manufacturer. While the primary focus of the innovation process in the EasyDC-FOS project is on insulating materials, it is important to address the impacts of the conducting material as well. Considering both insulating and conducting materials enables material selection decisions to be based on comprehensive understanding of cable materials. The materials selected for this assessment are determined considering the flexibility of the innovation processes in place, and feasibility and time requirements of the research and development activities. The functional unit of the assessment is defined as the “the transfer of 1 GW over 1 km of cable, with an operating temperature of up to 90 °C, a transfer voltage of 525 kV, and single-pole transfer capability of 1 GW, in a relevant thermal environment.”

5.1.2 Indicators

The indicators that shall be used for this assessment are presented in Table 10. From the set of indicators defined by this framework, only the environmental ones are to be used for this assessment. The economic and circularity indicators are assessed during the Stage 2. The method for evaluating the indicators is elaborated in more detail in section 5.4, being based on standardised practices such as Life Cycle Assessment with a reference to the ISO 14044 [4] standard and Environmental Footprint method version 3.1 [5].

5.1.3 Thresholds

Obligatory thresholds

In the context of the eco-design assessment, the obligatory thresholds must be met in order for the material assessed to be considered for the selection. The obligatory threshold defined for this assessment is as follows:

- The novel cable assessed in this study must not surpass 150% of the assessed environmental impacts in comparison to the baseline cable. This threshold pertains to all environmental indicators as defined in section 5.1.2. This threshold ensures that materials with high impacts are avoided during the design stage.

Preferable thresholds

In the context of the eco-design assessment, the compliance with preferable thresholds grants a priority during the material selection process. Hence, if there is a cable material meeting such a threshold, it shall be prioritised for the selection. However, a failure to meet this threshold does

not disqualify the material from the selection process. The preferable thresholds are defined as follows:

- 15% reduction of the Climate change (total) (GWP 100a) as compared with the baseline cable.
- 15% reduction of impacts in all Climate change impact subcategories (fossil, biogenic, land-use-and-land-use-change).
- Positive reduction of impacts in all environmental indicators.

5.1.4 Baseline materials and alternatives

The baseline scenario for the HVDC cable materials is defined with copper or aluminium as a conductor and DC-grade cross-linked polyethylene (XLPE) as an insulator. The alternative XLPE to be screened during the eco-design assessment may include an XLPE with a modified formulation (e.g., the concentration of a type of cross-linking agent) and its polymeric material base. Conductor sizing may vary as per the relevant ratings calculated for the 1 km land cable and its environment. This baseline scenario was specified by Nexans based on the industry knowledge and insights.

5.2 Eco-design assessment for manufacturing processes

In this section, a methodology to be used for conducting the eco-design assessment for the cable insulation manufacturing process is described. This assessment is conducted to identify the hotspots of environmental impacts within the cable manufacturing process chain. The outcome of this assessment shall be used for finetuning the cable manufacturing process.

5.2.1 Scope

The scope of this assessment is gate-to-gate, i.e., only the manufacturing process itself is assessed. This assessment is comparative. i.e., alternative manufacturing processes are compared based on their performance. The cable insulation manufacturing processes considered for the assessment are defined based on the technical specification of the manufacturer. Moreover, the processes to be considered during this assessment are determined by the flexibility of the innovation processes in place, considering the feasibility and time requirements of the research and development activities. The functional unit is defined as “The production of 1 km of the cable insulation with a cross-sectional area of 3000 mm²”.

5.2.2 Indicators

The environmental indicators that shall be used for this assessment are presented in Table 10 and are identical to those assessed during the eco-design assessment for cable materials. From the set of indicators defined by this framework, only environmental ones are to be used for this assessment. The economic and circularity assessments are assessed only on the level of the whole cable system during the Stage 2 of the assessment. The method for evaluating the indicators is elaborated in more detail in section 5.4, being based on standardised practices such



us Life Cycle Assessment with a reference to the to the ISO 14044 [4] standard and Environmental Footprint method version 3.1 [5].

5.2.3 Thresholds

Obligatory

No obligatory thresholds are defined for this assessment.

Preferable

The preferable thresholds defined for this assessment are as follows:

- Climate change (total) (GWP 100a) reduced by 15% compared with the baseline scenario
- Positive reduction of impacts in most or all environmental indicators

5.2.4 Baseline scenario

The baseline manufacturing process involves these standardised steps: conductor stranding, insulation extrusion, degassing, copper screening, aluminium sheathing and PE sheathing. While the baseline process is standardised and tested, any potentially feasible modification of it will be explored as assessed. Since the established manufacturing processes are optimised in terms of reliability and production of the desired results, the explored modifications will focus on finetuning rather than abrupt processing changes.

5.3 Cable system impact assessment

In this section the sustainability assessment of the novel cable system is described. In this assessment, the model of a novel cable system is established based on the innovation and eco-design assessment carried out during the Stage 1 of the framework. Within the cable system assessment, several scenarios are explored, reflecting differences in the implementation of the cable system. The outcome of this assessment will be an analysis of hotspots of the impacts, sensitivities to changes of the cable system design and a comprehensive overview of sustainability impacts. The specifications described hereby are to be used as a basis for the sustainability assessment of the novel cable system carried out in Task 4.4 of the project.

5.3.1 Scope

The scope of this assessment is cradle-to-grave and the assessed system is defined to be comprised of the cable made of insulation and conductor, taking into account also the auxiliary systems (sensors). More specifically, a case of land cable installed in Germany is assessed. The functional unit of this assessment is **“transfer of 1 GW over 1 km”**.

5.3.2 Indicators

The indicators that shall be used for this assessment are presented in Table 10, Table 11 and Table 12. The assessed indicators are related to environmental, economic and circularity impacts. The procedure of the selection of the indicators is described in section 5.4. These indicators shall

be assessed in accordance with the standardised and consensus-based methodologies as described in section 5.4.

5.3.3 Thresholds

Obligatory thresholds

Within the context of this assessment, the obligatory thresholds are required to be met by the developed system. They are defined as a means to achieving project goals. The obligatory threshold of this assessment is:

- **15% reduction** of carbon footprint (Climate change (GWP100)) as compared with the baseline scenario.

Preferable thresholds

The preferable thresholds for the cable system sustainability assessment are as follows:

- 15% reduction of impacts in Climate change impact subcategories (fossil, biogenic, land-use-and-land-use-change)
- Positive reduction of impacts in all environmental indicators (compared with the baseline)
- Positive reduction of life cycle costs and increase of net value added (compared with the baseline)
- Increase in circularity indicators (compared with the baseline)

5.3.4 Scenarios and sensitivity analysis

The scenarios defined for the cable design and described in the section 4.2 (scenarios A, B, C and D) will be assessed. In addition to these scenarios described, life-cycle-stage-specific scenarios will be assessed for the transportation (examining different modes of transport) and end of life (examining the potential behind recycling of cables after completing their operation years, i.e. 40 years).

5.4 Indicators

The indicators were selected for this regulatory framework following a multi-stage assessment approach combining quantitative and qualitative assessment methods. The process of indicator selection started with a definition of a broad list of indicators that were then shortlisted based on criteria related to relevance and feasibility. The assessment process is detailed in *ANNEX 1 – Indicator selection procedure*, while the selected indicators are presented in Table 10, Table 11, and Table 12. The indicators are grouped based on the sphere that they exhibit impact on. The indicators belong to three categories: environmental, economic, and circularity indicators. The Environmental Footprint (EF) method version 3.1 [5] developed by the European Platform for Life Cycle Assessment (EPLCA) was used as a basis for environmental indicators. The EF3.1 methodology establishes a clear procedure of evaluating impacts based on depletion and releases of substances and energy between the anthroposphere and nature. The impacts associated with these flows are quantified in the form of characterization factors provided by the EF 3.1 [5].

The indicators reflecting the economic sustainability and circularity were chosen based on established assessment methods and scientific literature [6, 7]. In addition to the indicators specified hereby, also social impact indicators shall be assessed. The social impact indicator selection process shall be done by involving relevant stakeholders and ensuring their interests are represented. This procedure shall be done as part of the Task 4.4 of the project.

Table 10: The list of selected environmental indicators

Impact category	Indicator	Reference unit
Acidification	Accumulated exceedance (AE)	mol H ⁺ -Eq
Climate change	Global warming potential (GWP100)	kg CO ₂ -Eq
Climate change: biogenic	Global warming potential (GWP100)	kg CO ₂ -Eq
Climate change: fossil	Global warming potential (GWP100)	kg CO ₂ -Eq
Climate change: land use and land use change	Global warming potential (GWP100)	kg CO ₂ -Eq
Ecotoxicity: freshwater	Comparative toxic unit for ecosystems (CTUe)	CTUe
Energy resources: non-renewable	Abiotic depletion potential (ADP): fossil fuels	MJ, net calorific value
Eutrophication: freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P-Eq
Human toxicity: carcinogenic	Comparative toxic unit for human (CTUh)	CTUh
Human toxicity: non-carcinogenic	Comparative toxic unit for human (CTUh)	CTUh
Material resources: metals/minerals	Abiotic depletion potential (ADP): elements (ultimate reserves)	kg Sb-Eq
Particulate matter formation	Impact on human health	disease incidence
Photochemical oxidant formation: human health	Tropospheric ozone concentration increase	kg NMVOC-Eq
Water use	User deprivation potential (deprivation-weighted water consumption)	m ³ world Eq deprived

Table 11: The list of selected economic indicators

Indicator	Description	Reference unit
Life cycle costs	Cost arising from acquisition through operation to disposal	€
Net present value [6]	The value acquired through investment	€



Table 12: The list of selected circularity indicators.

Indicator	Description	Reference unit
Product recycling rate	Fraction of the mass of the product at EoL that gets recycled	%
Circularity index [7]	Ranges from 0 to 1, a function of recovered recycled material and energy required for the material recovery	dimensionless

6 CONCLUSIONS

The key KPIs related to the full-size prototype and its type-test are as follows:

- Design of a $U_0 = 525$ kV, 2 GW rated cable system, with fallback to 400 kV and lower cable rating (by means of changed conductor material and/or lower cross-section).
 - The aim is thus to at least achieve 2500 mm², but preferably a 3000 mm² sized conductor.
- The cable insulation system designed passes the electric quality controls specified in Table 3.
 - Where at least 100 m of cable prototype has passed such relevant screening tests, yielding enough length to perform a type test.
- The cable passes the type test ran at $1.85 \cdot U_0$ and 90 °C, demonstrating its reliable operation under dynamic load conditions.
 - Relevant cable accessories, part of the test loop, also pass the type test to confirm their compatibility the new insulation material.

Achieving these KPI will demonstrate the new insulations performance and technical maturity achieving TR5 on a highly relevant cable design.

Further KPIs listed related to the small-scale electrical assessments are:

- Achieving a mapping of the conductivity parameters on relevant cable peeling samples and to use such to assess the steady-state electric fields in the cable insulation under loaded & non-loaded conditions.
 - To map the conductivity at more than two temperatures and more than two field strengths to estimate the exponential field and temperature dependencies.
 - And to use the measured conductivity for ohmic losses and field distribution evaluations up to a 640 kV // 90 °C level.
- To map space charge using the PEA method on cable peelings, before and after the type test, under different field and temperature conditions, ensuring that the mean charge density ideally remains below 2 C/m³.
 - And, to provide a set of net charge density data suitable for model calibration.

Such measurements will provide additional insight into the ageing rate of the material as well as its capability to operate at higher voltage levels.



The indicators to be evaluated during the sustainability assessment process address environmental, economic and circularity impacts. Two-stage sustainability assessment framework proposed hereby addresses the need for sustainability information during the design of the cable and its production processes as well as during the decisions making for the implementation of novel cable systems. The methodology for these assessments, as well as potential assumptions and limitations were described. The indicators that will be assessed by applying the sustainability assessment framework proposed hereby are as follows:

- Accumulated exceedance (mol H⁺ eq.) indicating acidification
- Global warming potential (GWP100) indicating climate change (kg CO₂ eq.)
- Global warming potential (GWP100) indicating climate change: biogenic (kg CO₂ eq.)
- Global warming potential (GWP100) indicating climate change: fossil (kg CO₂ eq.)
- Global warming potential (GWP100) indicating climate change: land use and land use change (kg CO₂ eq.)
- Comparative toxic unit for ecosystems (CTUe) indicating ecotoxicity: freshwater
- Abiotic depletion potential (ADP): fossil fuels (MJ, net calorific value) indicating energy resources: non-renewable
- Fraction of nutrients reaching freshwater end compartment (kg P eq.) indicating eutrophication: freshwater
- Comparative toxic unit for human (CTUh) indicating human toxicity: carcinogenic
- Comparative toxic unit for human (CTUh) indicating human toxicity: non-carcinogenic
- Abiotic depletion potential (ADP): elements (kg Sb eq.) indicating material resources: metals/minerals
- Impact on human health (disease incidence) indicating particulate matter formation
- Tropospheric ozone concentration increase (kg NMVOC eq.) indicating photochemical oxidant formation: human health
- User deprivation potential (m³ world eq. deprived) indicating water use
- Life cycle costs (€) indicating the costs arising from acquisition during the life cycle
- Net present value (€) indicating the total value acquired by investment
- Recycling rate (%) fraction of the mass of the product at its end of life that gets recycled
- Circularity index indicating the degree of recycling and energy recovery over the life cycle

Obligatory thresholds were defined within the framework, specifying the sustainability performance that should be achieved by the project. The following obligatory thresholds were defined:

- The novel cable assessed in this study must not surpass 150% of the assessed environmental impacts in comparison to the baseline cable. This threshold pertains to all environmental indicators as defined in section 5.1.2. This threshold ensures that materials with high impacts are avoided during the design stage. This threshold applies to the eco-design assessment of cable materials.
- 15% reduction of carbon footprint (Climate change (GWP100)) of the novel cable system as compared with the baseline scenario. This threshold pertains to the cable system sustainability assessment.

7 References

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ANNEX 1 – Indicator selection procedure

The indicators selection process was carried out in three stages: indicators gathering, evaluation and selection. In the gathering stage, a broad set of indicators was defined. The EF3.1 impact categories were chosen as a basis for the environmental indicators, as they reflect all relevant environmental issues that are conventionally assessed in life cycle assessment.

The indicators evaluation was based primarily on two criteria, relevance and feasibility (of assessing). The relevance assessment consisted of several sub-evaluations, as described in the figure below. The assessment of the relevance consisted of two main parts, project goal relevance and impact significance screening that were aggregated later on. The overview of the indicator relevance rating process is presented in *Figure 8 (A.1)*.

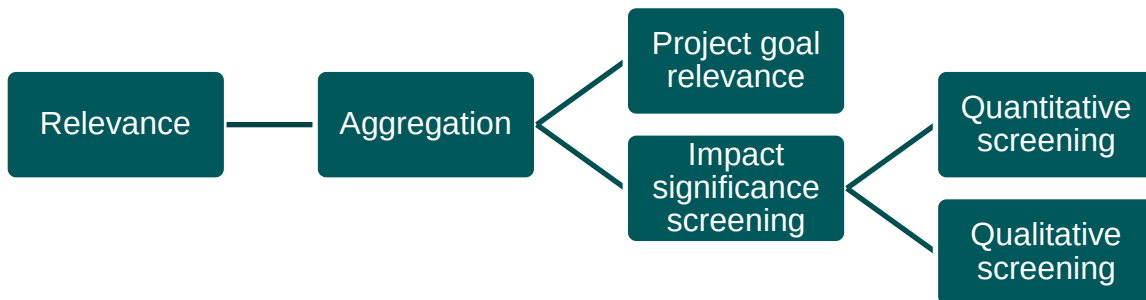


Figure 8 (A.1): Overview of the indicator relevance rating procedure

The impact significance screening process involves both qualitative and quantitative assessments to evaluate environmental impacts. The qualitative assessment relied on expert judgment, using a three-point scale to score impacts as either 0 (insignificant), 1 (considerable), or 2 (critical). This scoring considers anticipated emissions and depletions of elementary flows relevant to each impact category. Scores were then aggregated: individual scores for each indicator were summed, normalized by the average score per evaluator, and averaged across evaluators.

The quantitative assessment includes a pre-assessment screening based on modeling a suitable proxy dataset from ecoinvent 3.10 Unit Cut-off database. In this case, the dataset “cable production, unspecified” was used due to its alignment with the developed product's materials. In specific, the significance was derived from the contribution to the single score, based on normalization and weighting factors provided by the EF3.1 method 1. The calculated single-

¹ https://eplca.jrc.ec.europa.eu/permalink/EF3_1/Normalisation_Weighting_Factors_EF_3.1.xlsx

score contributions considered are presented in *Figure 9 (A.2)*. The single-score contributions which is then normalized by dividing each score by the average score.

▼ Single score

Impact category	Amount
Material resources: metals/minerals	0.00590
Human toxicity: non-carcinogenic	0.00058
Eutrophication: freshwater	0.00053
Acidification	0.00043
Climate change	0.00018
Ecotoxicity: freshwater	0.00015
Particulate matter formation	0.00014
Energy resources: non-renewable	0.00012
Photochemical oxidant formation: human health	9.44947E-5
Human toxicity: carcinogenic	8.64970E-5
Eutrophication: terrestrial	5.75717E-5
Water use	3.28814E-5
Eutrophication: marine	3.01246E-5

Figure 9 (A.2): Single score results calculated for indicator selection using openLCA software

Finally, the qualitative and quantitative scores were combined by averaging the normalized values from each assessment, leading to an aggregated impact significance score. This overall score is then translated into a three-point relevance scale, where the highest relevance score (3) is assigned to scores at least twice the median, while scores above the median receive a relevance score of 2, scores lower than the median are assigned an overall score of 1. This structured approach provides a balanced, evidence-based assessment of environmental impacts aligned with project goals.