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NEWGEN

New generation of HVDC insulation materials, cables and systems

D2.4 - LCA and Sustainability model of HVDC cables and current technology, report and datasets

WP2 – Reliable-by-design manufacturing of HVDC cables

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Abbreviations

CF – Characterization Factor

DB – Database

FU – Functional Unit

HVDC – High-Voltage Direct Current

IC – Impact Category

LCA – Life Cycle Assessment

LCC – Life Cycle Costing

LCIA – Life Cycle Impact Assessment

MCI – Material Circularity Indicator

PE-g-MAH – Polyethylene grafted with Maleic Anhydride

PP – Polypropylene

PP-g-MAH(-X) – Polypropylene grafted with Maleic Anhydride

SEBS-g-MAH – Styrene-Ethylene-Butylene-Styrene grafted with Maleic Anhydride

S-LCA – Social Life Cycle Assessment

XLPE – Cross-Linked Polyethylene

Executive summary

This deliverable reports the Life Cycle Sustainability Assessment (LCSA) of the NEWGEN HVDC cable, comparing it to a conventional benchmark cable. It integrates the environmental, economic and social aspects of both cables throughout their whole life cycle.

The study comprises the main stages of the product life cycle: the supply and processing of raw materials, manufacturing of the cable, transportation and installation, operation and maintenance and end-of-life treatment. Of particular interest are the differences due to the NEWGEN design, including the use of a PP-based insulation system and related additives, and different material composition, cable performance and maintenance needs.

The study combines environmental Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Social Life Cycle Assessment (S-LCA), and Material Circularity Indicator (MCI) Assessment. The environmental impact assessment covers both production-related effects and the impact of losses occurring during transmission operations. The economic analysis comprises an evaluation of life-cycle costs associated with the cable, including material, manufacturing, installation, maintenance and end-of-life costs. The S-LCA builds on the results of the other analyses to identify social-risk hotspots in the supply chains and main drivers of the cables studied. A supplementary circularity assessment is conducted using the Material Circularity Indicator (MCI) to compare the benchmark and NEWGEN cable systems in terms of material consumption, recovery and overall circularity across their life cycles.

The assessments are based on primary technical and inventory data provided by NEWGEN project partners: in particular, information on cable design, material composition and production provided by work packages (WPs) 1 and 2, and reliability data from WP4. In the absence of primary data, the assessment uses data from literature, market surveys and databases, notably for the upstream supply-chain processes.

The overall aim of the study is to identify the main environmental, economic and social differences between the NEWGEN and the benchmark cable, to identify the key life-cycle stages and parameters contributing to these differences and to provide a basis for further development of the NEWGEN technology.

1. Environmental Life Cycle Assessment

1.1 Goal of the study

The goal of this study is to assess the sustainability performance of the NEWGEN HVDC cable concept and compare it with a conventional XLPE-insulated benchmark cable. The NEWGEN design is based on a polypropylene (PP) insulation system with additives developed to reduce space charge accumulation while retaining the advantages of a thermoplastic insulation concept.

Because the insulation system is one of the main differences between the two cable designs, the assessment pays particular attention to the consequences of replacing conventional XLPE with the NEWGEN PP-based concept. At the same time, the analysis is not limited to the insulation material itself. The complete cable system is considered over its life cycle, including raw material supply, manufacturing, transportation and installation, operation and maintenance, and end-of-life treatment.

The comparison considers differences in material composition, manufacturing requirements, transmission losses, maintenance needs and end-of-life treatment. Where relevant, the transition from laboratory to pilot-scale production is also considered to evaluate how changes in manufacturing scale may influence resource and energy requirements.

The analysis therefore focuses on the following questions:

- Does the NEWGEN cable provide environmental advantages over the conventional XLPE benchmark?
- Which materials, processes and life-cycle stages are responsible for the main differences between the two systems?
- How do transmission losses, reliability and maintenance requirements influence the overall comparison?

The results are intended to support the further development of the NEWGEN cable by identifying where design improvements, better data or changes in the supply chain could have the greatest influence on its sustainability performance.

1.2 Scope of the Study

The production of XLPE or PP HVDC cables is generally similar in terms of assembling the same types of components, such as the conductor, insulation, jacket, and steel-wire armor, using a similar production process. Since this study focuses on the insulation material, both the selected benchmark XLPE model and the NEWGEN PP model will share the same cable structure and life cycle stages but differ in terms of the insulation materials and corresponding production processes. Table 1 below summarizes the main estimated differences and similarities between conventional XLPE insulation and the newly developed PP insulation with additives.

Table 1: Comparison of currently used HVDC cable insulation with the newly developed NEWGEN composition.

Material group	HVDC with XLPE insulation	HVDC with NEWGEN PP insulation
Conductor	Aluminium	Aluminium
Outer jacketing	HDPE	HDPE
Metal jacketing	Lead	Lead
Steel wire	Low-alloy steel	Low-alloy steel
Main insulation polymer	XLPE / LDPE-based insulation	PP-based insulation
Crosslinking/peroxide system	Peroxide: 2,5-dimethylhexane-2,5-dihydroperoxide	Not used as conventional XLPE crosslinking system
NEWGEN insulation components	—	PP, ethylene, additive
NEWGEN additive system	—	PP, o-dichlorobenzene, maleic anhydride, PP-g-MAH-(x), SEBS-g-MAH, PE-g-MAH-(x)

Based on this comparison, the NEWGEN sustainability assessment considers both conventional and innovative cable scenarios. The latter includes alternative additive formulations, evaluated through sensitivity analysis, as well as the newly developed production technology.

The following section presents environmental assessment, followed by material circularity indicator assessment, economic and social assessments. The two cable systems were modelled separately using technical information provided by VTT and Maillefer, and their results were compared to identify potential improvements.

1.3 Functional Unit and System Boundary

Functional unit

The functional unit (FU) provides the reference to which all inputs, outputs and assessment results are related. Cable-related LCA studies commonly use either a length-based functional unit, such as 1 km of cable, or an energy-based functional unit, such as 1 kWh or 1 MWh of electricity transmitted. A length-based approach is useful for comparing cable construction and material requirements, while an energy-based functional unit also reflects differences in electrical performance and transmission losses during operation.

A service life of 25 years is conservatively assumed for the HVDC cables, corresponding to the typical minimum durability guarantee for submarine cables (Ardelean and Minnebo, 2015). However, several studies report a technical design life of 40 years (Mazzanti, 2023). To account for this uncertainty, a sensitivity analysis comparing both lifetime scenarios will be conducted in this study.

Since the primary function of an HVDC cable is the transmission of electricity, the functional unit selected for this study is defined as:

1 MWh of electricity delivered through the HVDC cable system over a reference service life of 25 years.

Delivered electricity is used rather than electricity supplied to the cable so that transmission losses are reflected in the functional comparison. The cable inventories are initially developed for 1 km of cable and subsequently scaled to the functional unit.

The baseline comparison is performed at a common input power of 1,029 MW for both cable systems, ensuring a consistent operating condition. Based on the updated steady-state electrical and thermal model, the corresponding transmission losses are approximately 31.99 W/m for the benchmark XLPE cable and 32.77 W/m for the NEWGEN PP cable, at an operating voltage of 525 kV. The power delivered at the receiving end is calculated as:

$$P_{delivered} = P_{input} - P_{loss}$$

where P_{input} is the power supplied to the cable at the respective operating load and is the corresponding transmission loss for 1 km of cable.

The total electricity delivered over the reference lifetime is then calculated using 8,760 operating hours per year and a lifetime of 25 years:

$$E_{delivered} = P_{delivered} \cdot 8760 \cdot lifetime$$

where 8,760 represents the assumed annual operating hours and 25 years represents the reference operational lifetime.

The inventories associated with raw materials, manufacturing, transportation, installation, operation and maintenance, and end-of-life treatment are scaled by the total amount of electricity delivered and are therefore expressed per functional unit.

Transmission losses are modelled separately in the use phase using the updated cable-specific loss data. The total electricity loss over the reference service life is calculated from the power loss per unit length, cable length and operating time:

$$E_{loss} = P_{loss} * t * \mathrm{L}$$

where P_{loss} is the cable-specific power loss per unit length (W/m), t is the total operating time (h), and L is the assessed cable length (m).

The resulting electricity loss is converted to MWh and normalized to the total electricity delivered over the reference lifetime to obtain the loss per functional unit (1 MWh delivered). The common input power of 1,029 MW is used for the baseline comparison, while alternative operating conditions are considered separately in the sensitivity analysis.

System Boundary

The product system was divided into seven main life-cycle stages, as shown in Figure 1, ranging from primary production of the materials used in the cable to end-of-life processing.

The raw material stage covers the production and processing of the main cable materials. For NEWGEN it also includes the production of the PP-based insulation system and associated additives as an alternative to XLPE insulation. The transport stage includes the transportation of materials and components to the manufacturing site.

The manufacturing stage covers all the processes necessary for the production of the cable, including the consumption of auxiliary materials, water, and electricity, as well as production losses and waste. Where relevant, differences in the manufacturing process at laboratory and pilot scale were considered for the NEWGEN insulation system. The installation stage covers the transport of the manufactured cable to the installation site, as well as the installation of the submarine cable on the seabed.

The use stage comprises transmission losses specific to each cable system and associated voltage. Operation and maintenance (O&M) include maintenance, repair, and renewal of the cable during its 25-year lifetime, as well as the additional consumption of materials and associated processes.

The end-of-life stage covers cable recovery, transportation, material treatment and recycling, including the associated waste flows. The treatment of aluminium, steel, lead and polymer-based insulation materials follows the defined end-of-life scenarios.

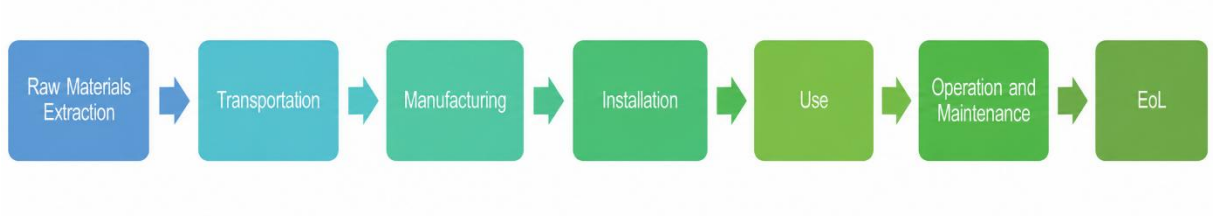


Figure 1: Flow chart representing the system boundaries under study

1.4 Impact assessment method

For the environmental LCA, the impact assessment method was selected based on its suitability for the scope of the study and the relevance of the covered impact categories. Following the initial environmental screening and comparison of alternative methods, Environmental Footprint (EF 3.1) was selected as the main LCIA method for the assessment.

The impact categories considered during the screening and the corresponding methods are presented in Table 2.

Table 2: EF 3.1 Method: Impact Categories and Descriptions

Name	Description	Reference units
Acidification	European country-dependent.	mol H+ equivalents
Climate change	Baseline model of the IPCC 2021	kg CO2 Equivalents
Climate change-Biogenic	Baseline model of the IPCC 2021	kg CO2-Equivalents
Climate change-Fossil	Baseline model of the IPCC 2021	kg CO2 Equivalents
Climate change-Land use and land use change	Baseline model of the IPCC 2021	kg CO2-Equivalents
Ecotoxicity, freshwater	USEtox consensus model for freshwater ecotoxicity at continental and global scales.	CTUe
Ecotoxicity, freshwater inorganics	USEtox model for inorganic substances affecting freshwater ecosystems.	CTUe
Ecotoxicity, freshwater organics	USEtox model for organic substances affecting freshwater ecosystems.	CTUe

Name	Description	Reference units
EF-Particulate Matter	Based on the emission-response relationship between particulate matter exposure and health effects.	disease incidence
Eutrophication, marine	European model using averaged country-specific characterization factors.	kg N equivalents
Eutrophication, freshwater	European model using averaged country-specific characterization factors.	kg P equivalents
Eutrophication, terrestrial	European model with country-specific characterization factors.	mol N equivalents
Human toxicity, cancer	USEtox consensus model for potential carcinogenic effects on human health.	CTUh
Human toxicity, cancer inorganics	USEtox model for carcinogenic effects of inorganic substances.	CTUh
Human toxicity, cancer organics	USEtox model for carcinogenic effects of organic substances.	CTUh
Human toxicity, non-cancer	USEtox consensus model for potential non-carcinogenic effects on human health.	CTUh
Human toxicity, non-cancer inorganics	USEtox model for non-carcinogenic effects of inorganic substances.	CTUh
Human toxicity, non-cancer organics	USEtox model for non-carcinogenic effects of organic substances.	CTUh
Ionising radiation, human health	Characterization applicable at European and global scales.	kBq U235 equivalents
Land use	Based on JRC characterization factors derived from LANCA® v2.2.	dimensionless (pt)
Ozone depletion	Based on ozone depletion potentials from the WMO assessment.	kg CFC11 equivalents
Photochemical ozone formation – human health	European model including spatial differentiation.	kg NMVOC equivalents
Resource use, fossils	Abiotic depletion potential for fossil energy carriers based on CML methodology.	MJ
Resource use, minerals and metals	Abiotic depletion potential for mineral and metal resources based on CML methodology.	kg Sb equivalents

Name	Description	Reference units
Water use	Water deprivation potential based on regional water scarcity.	m3-world equivalents

1.5 Life Cycle Inventory and Modeling

The Life Cycle Assessment (LCA) in the NEWGEN project aims to assess the environmental impacts associated with two types of HVDC cable insulation, with a primary focus on polypropylene (PP) with space charge mitigation additives. The development of the life cycle models is divided into three main activities, which are summarized in Table 3.

Table 3: LCA structure of NEGEN project

ACTIVITY	GOAL	DETAILED TASKS
LCA 1 - benchmark	Establish the environmental performance of the conventional HVDC cable with XLPE-based insulation.	Development of the life-cycle inventory for the benchmark cable; modelling of raw materials, manufacturing, transportation, installation, use-phase losses, O&M and end-of-life; calculation of LCIA results using EF 3.1.
LCA 2 – PP with additives	Assess the environmental performance of the NEWGEN HVDC cable with PP-based insulation and additives.	Integration of NEWGEN material and production data provided by project partners; modelling of the PP-based insulation and additive system; inclusion of manufacturing, transportation, installation, use-phase losses, O&M and end-of-life; calculation of LCIA results using EF 3.1.
LCA 3 - comparison	Identify the main differences between the benchmark and NEWGEN cable systems and the parameters driving the results.	Comparison of the life-cycle impacts and environmental hotspots of the cable designs under equivalent operating conditions, i.e., at the same current and conductor temperature; assessment of the influence of transmission losses and operating conditions on the overall environmental performance; sensitivity analysis of the cable service life (25 years vs. 40 years); evaluation of different end-of-life scenarios for the cables; assessment of the effect of different additives used in the insulation materials

The life cycle inventory was compiled using primary data provided by NEWGEN project partners and secondary background data. Primary data from Maillefer, VTT and the University of Twente included cable composition, insulation materials and additives, as well as manufacturing inputs such as energy consumption, auxiliary materials, packaging, transportation and production waste.

Secondary data were mainly sourced from the ecoinvent 3.9 APOS database and supplemented by literature and other sources cited throughout the report. These sources were used to model life-cycle stages and processes for which primary data were unavailable. A consistent modelling approach was applied to both the benchmark and NEWGEN cable systems to ensure comparability.

The NEWGEN concept has the potential to improve the environmental performance of the cable through changes in insulation composition, manufacturing requirements, operational performance and end-of-life treatment. These effects are assessed through the LCA and compared directly with the benchmark cable. The initial project ambition included a reduction of at least 20% in life cycle GWP (kg CO_2-eq.), although the actual improvement depends on the assessed operating conditions and modelling assumptions.

1.6 Inventory data types

The production processes for high-voltage cables within the NEWGEN project are modelled in the following sequence for each stage, together with the information required to calculate the associated environmental impacts (Figure 2).

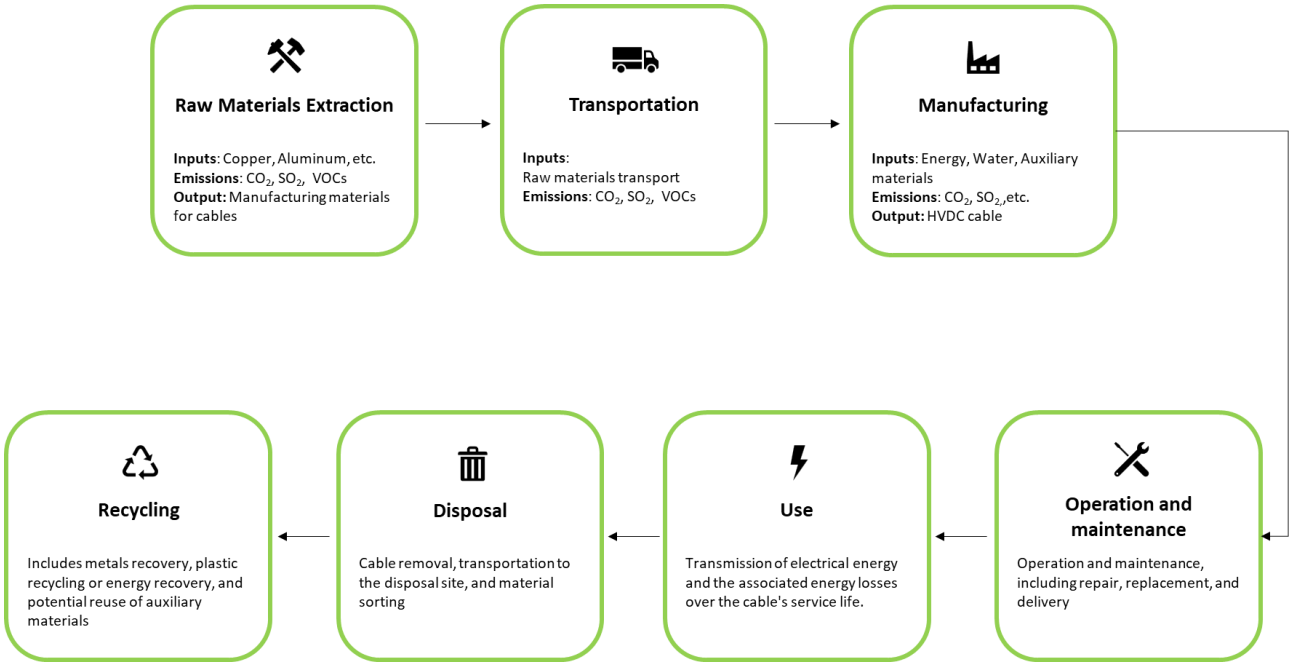


Figure 2: HVDC Benchmark and NEWGEN Production – Flowchart

First, the cable sources raw materials from various suppliers. This stage includes extracting, processing, and refining primary materials, as well as producing prefabricated components required for manufacturing. It also accounts for associated energy and water consumption, emissions, and other relevant upstream impacts.

Next, the materials are transported to the manufacturing site. This stage considers the relevant transport modes, distances, vehicle types, and fuel consumption. In this case, inland

transportation by truck was selected. The associated energy use and emissions are included in the life cycle inventory.

This is followed by the manufacturing stage, which includes all processes required to convert raw materials into the HVDC cable, such as material preparation, extrusion, degassing, finishing, and quality control. The assessment accounts for energy and water consumption, direct emissions, production waste, and auxiliary materials. It also considers impacts associated with machinery operation, internal logistics, and, where relevant, facility infrastructure.

The next stage is the use phase, which accounts for energy losses during electricity transmission and their influence on the cable's efficiency and environmental performance.

The operation and maintenance stage include all activities required to ensure the proper functioning of the HVDC cable throughout its service life. These activities may include routine inspections, repairs, and the replacement of damaged components, together with the associated transport and energy use. Where applicable, the assessment also considers environmental impacts related to material consumption, waste generation, and maintenance emissions.

The disposal and recycling stages address the end-of-life treatment of the HVDC cable. This includes cable removal, transportation to disposal or recycling facilities, sorting of materials, and appropriate processing.

Metals are typically recovered, plastics are either recycled or sent for energy recovery, and any non-recyclable components are disposed of by regulatory requirements. Environmental impacts from these activities, including emissions, energy use, and residual waste, are accounted for in this stage.

More detailed information regarding the stage inventories, including the assumptions, will be provided in the following sections.

1.7 Life cycle inventory and modelled processes

The inventory phase includes data collection and the modeling of the production system under study. The data collection incorporates primary data as well as secondary data from LCA databases, primarily ecoinvent APOS (version 3.9.1). The following paragraphs describe the modeled processes and the collected data, which are categorized into energy and material flows.

The benchmark cable is a 525 kV HVDC cable (AL3500, 400 km), with material composition data provided by Maillefer. The NEWGEN cable, with the main insulation layer comprising of a thermoplastic PP insulation compound provided by VTT, is likewise assumed to be an AL3500, 525 kV cable, with additional information on the additives provided by the University of Twente.

Table 4 presents the compositions of two different cable types assessed under the baseline scenario. These inventories served as a starting point for modeling the entire supply chain, which will be discussed in the following sections.

Table 4: Composition of Benchmark and NEWGEN cables.

Benchmark Cable (HVDC AL3500 525kV, 400 km)	
Component	**Fraction of total mass**
Steel wire	27.92%
Metal jacketing	16.65%
Conductor	10.27%
PE insulation mix	8.30%
Jacketing PE	1.34%
Carbon black additive to XLPE	0.28%
Peroxide SC XLPE proxy	0.06%

NEWGEN Cable	
Component	**Fraction of total mass**
Steel wire	43.1%
Metal jacketing	25.7%
Conductor	15.86%
PP Insulation NEWGEN	13.26%
Jacket PE	2.07%

1.7.1 Steel wire production

Steel wire accounts for 27.92% and 43.1% of the total cable weight in the benchmark and NEWGEN compositions, respectively. In both cases, it was modeled using the dataset *"steel, low-alloyed | steel production, electric, low-alloyed | APOS, U – Europe without Switzerland and Austria"* from ecoinvent 3.9.1 APOS. This dataset represents the supply of 1 kg of steel wire from raw material production activities within the average European geography, excluding the specified countries. The process is an average representation of similar production activities combined into a single unit process, enabling the tracking of the upstream supply chain.

However, the dataset does not include the manufacturing of the wire itself. Therefore, a separate process, *"wire drawing, steel | wire drawing, steel | APOS, U – RER,"* must be introduced to account for the upstream impacts. This dataset represents a multi-output process that delivers steel wire produced through drawing. It includes associated waste and emissions, as well as the auxiliary chemicals required for production and infrastructure, such as rolling mills and sheet rolling activities.

1.7.2 Metal jacketing production

The metal jacketing represents the next major material component, accounting for 16.65% and 25.7% of the total cable composition in the benchmark and NEWGEN cases, respectively. The production of the lead jacketing is modelled using the ecoinvent dataset "primary lead production from concentrate | lead | APOS, U – GLO", selected in accordance with Maillefer's recommendations. To account for the prefabrication of the metal jacketing, the model is supplemented with the ecoinvent process "electricity, medium voltage | APOS, U – DE", representing the electricity consumption associated with the manufacturing step.

1.7.3 Conductor production

The cable conductor accounts for 10.27% of the total cable composition in the benchmark case and 15.86% in the NEWGEN case. Based on input provided by Maillefer, both copper and aluminium were considered representative conductor materials for HVDC cables. For this study,

aluminium was selected due to its increasing relevance in current cable designs, particularly in the context of material cost optimisation and evolving market trends.

The conductor is modelled using the ecoinvent dataset “aluminium alloy production, AlMg3 | aluminium alloy, AlMg3 | APOS, U – RER”. The dataset represents the production of the AlMg3 aluminium alloy under average European conditions and includes the relevant upstream production of alloying and auxiliary materials, such as zinc and cast iron.

1.7.4 Insulation production of benchmark and NEWGEN cable

This section describes the major polymers and other components used in the production of the insulation, which are the main focus of this study. The following subsections explain the materials used and the manufacturing process, beginning with the benchmark cable.

1.7.4.1 Insulation production of benchmark cable

The primary component of conventional cable insulation is cross-linked polyethylene (XLPE). Because Ecoinvent 3.9.1 APOS and subsequent database versions do not contain a dataset for the specific XLPE used in cable insulation, the dataset *polyethylene production, low density, granulate | polyethylene, low density, granulate | APOS, U – Europe without Switzerland* was selected as a proxy for the base polymer.

To achieve the required mechanical and technical properties, the polyethylene is cross-linked using a peroxide-based additive. As no dataset was available for the specific cross-linking agent used in the insulation, 2,5-dimethylhexane-2,5-dihydroperoxide was selected as a proxy following consultation with a chemical expert at GreenDelta. The corresponding dataset, 2,5-dimethylhexane-2,5-dihydroperoxide production | APOS, U – GLO, was therefore included in the assessment.

1.7.5 Insulation production of NEWGEN cable

For the NEWGEN insulation system, several alternative additive formulations were developed and tested specifically within the project. In this section, the different NEWGEN additive options are assessed, including PE-g-MAH, PP-g-MAH (-X), and SEBS-g-MAH, in order to compare their potential contribution to the insulation formulation and their associated environmental impacts.

As mentioned above, the novel insulation composition is predominantly based on polypropylene (PP), which accounts for approximately 72.5% of the total insulation mass. Note that herein the focus is on plain polypropylene (homopolymer) part (i.e. propylene-rich); considering the fact that the NEWGEN PP insulation is a mixture of (ethylene-containing) PP copolymers, the rubber/elastomeric (or ethylene-rich part) is considered separately below. This component is modelled using the ecoinvent dataset “polypropylene production, granulate | polypropylene, granulate | APOS, U – RER”.

The remaining formulation consists of synthetic rubber, ethylene, and the NEWGEN additive PP-g-MAH-(X), contributing approximately 19.5%, 5.5%, and 2.5% of the total mass, respectively. Ethylene is represented by the dataset “ethylene production, average | ethylene | APOS, U – RER”. The PP-g-MAH-(X) component is represented by the project-specific process “NEWGEN additive (PP-g-MAH-(X)) production”.

For the elastomeric fraction, a generic “synthetic rubber production | synthetic rubber | APOS, U – RER” dataset is applied as a proxy. As the intended material is an ethylene-propylene rubber,

this dataset represents a modelling approximation and may not fully capture the specific composition and production route of the actual elastomer used.

1.7.5.1 Insulation additive PP-g-MAH-(x)

The novel NEWGEN insulation composition is predominantly based on polypropylene (PP), which accounts for approximately 72.49% of the total insulation mass. The polypropylene fraction is modelled using the ecoinvent dataset “polypropylene production, granulate | polypropylene, granulate | APOS, U – RER”.

The remaining formulation consists of synthetic rubber, ethylene, and the NEWGEN additive PP-g-MAH-(X), accounting for approximately 19.50%, 5.51%, and 2.51%, respectively. Ethylene is represented by the dataset “ethylene production, average | ethylene | APOS, U – RER”, while the PP-g-MAH-(X) component is modelled using the project-specific process “NEWGEN additive (PP-g-MAH-(X)) production”.

For the elastomeric fraction, the ecoinvent dataset “synthetic rubber production | synthetic rubber | APOS, U – RER” is used as a proxy for ethylene-propylene rubber. As the available dataset does not represent the specific composition and production route of the material used in the NEWGEN formulation, this modelling choice introduces a degree of approximation.

The material inputs were normalized to a reference flow of 1 kg of insulation, while preserving the relative proportions of the original formulation.

1.7.5.2 Insulation additive PE-g-MAH-(x)

The production of PE-g-MAH is modelled based on a reactive extrusion process for maleic-anhydride-grafted linear low-density polyethylene (LLDPE-g-MAH). In this process, LLDPE is first melted in an extruder, after which maleic anhydride (MAH) is introduced and brought into contact with the molten polymer under conditions that promote grafting of MAH onto the polyethylene backbone. The literature describes extrusion as the main processing step, with twin-screw extrusion being the preferred configuration. Following the reaction, volatile compounds may be removed by venting, and the grafted polymer can subsequently be cooled and pelletized.

For the LCA model, 0.985 kg of LLDPE is represented by “market for polyethylene, linear low density, granulate | polyethylene, linear low density, granulate | APOS, U – GLO”. Maleic anhydride accounts for 0.015 kg and is represented by “market for maleic anhydride | maleic anhydride | APOS, U – GLO”. The grafting step is approximated using “market for extrusion, plastic film | extrusion, plastic film | APOS, U – GLO” as a proxy for the extrusion processing of the polymer. In addition, 0.005 kg of an organic chemical, represented by “market for chemical, organic | chemical, organic | APOS, U – GLO”, is included as a proxy for an organic peroxide initiator used to facilitate the grafting reaction.

The selected MAH input corresponds to approximately 1.5 wt.% relative to the LLDPE input, which lies within the range described for LLDPE-g-MAH production in the literature. The patent reports MAH contents of 0.01–3 wt.%, with 0.5–1.5 wt.% identified as a preferred range(JR u. a. 2016).

1.7.5.3 Insulation additive SEBS-g-MAH

The SEBS-g-MAH alternative is modelled as a maleic-anhydride-functionalized SEBS thermoplastic elastomer. The formulation assumes 0.985 kg SEBS and 0.015 kg maleic anhydride per kilogram of product, corresponding to an MAH content of approximately 1.5 wt.%, which is

consistent with values reported for commercial SEBS-g-MAH grades. The grafting step is approximated using “market for extrusion, plastic film | extrusion, plastic film | APOS, U – GLO”.

The SEBS feedstock is represented by a project-specific process based on available SBS production data (Wildnauer und Schreiber 2022) and literature information on SEBS composition. As SEBS additionally requires hydrogenation of the polybutadiene block, this approach is considered a proxy and may underestimate the additional material and energy requirements associated with SEBS production.

1.7.6 Transportation

Data on the origin of raw materials, manufacturing locations, and associated transport routes were limited. Therefore, assumptions were introduced to close the identified data gaps and to establish a conservative and consistent transport scenario across the cable life cycle, considering that raw materials, manufacturing, installation, and end-of-life treatment may take place at different locations across Europe.

Transportation is considered at the main interfaces between the individual life-cycle processes. This includes the supply of raw materials to the cable manufacturing site, transportation of the manufactured cable to the installation site, transportation of the decommissioned cable to the shredding facility, and subsequent transportation of the separated material fractions to their respective recycling facilities.

Road freight is assumed for the transport of raw materials as well as for terrestrial transport during end-of-life treatment. These transport processes are modelled using the ecoinvent dataset “transport, freight, lorry 16–32 metric ton, EURO5 | transport, freight, lorry 16–32 metric ton, EURO5 | APOS, U – RER”. In contrast, due to the size and mass of HVDC submarine cables, the manufactured cable is assumed to be loaded at a coastal manufacturing or load-out location and transported to the installation area by vessel.

Marine operations required for cable laying and recovery are treated separately from transportation. Cable-laying vessel activities are included in the installation stage, while the corresponding recovery operations are assigned to the end-of-life stage. This distinction allows transport between locations to be separated from the operational effort required to install or recover the cable and avoids double counting of vessel activities.

The transport modes, distances, and corresponding modelling assumptions are summarized in Table 5.

Table 5: Raw materials origins, distances, and transportation

Transport process	Transported material/product	Mode	Distance
Transportation of HVDC raw materials	Raw materials and components to manufacturing	Lorry, 16–32 t, EURO 5	1,000 km
Transportation of manufactured cable to installation site	Finished HVDC submarine cable	Included in installation stage	200 km
Transportation of decommissioned cable to shredding	Recovered cable to shredding facility	Lorry, 16–32 t, EURO 5	300 km
Transportation of shredded cable to material recycling	Separated material fractions to recycling facilities	Lorry, 16–32 t, EURO 5	100 km

1.7.7 Manufacturing

Energy data (electricity) is partially disaggregated for the different manufacturing processes and is provided as part of the same dataset from VTT and Maillefer (Table 6). Energy values are specified for generic manufacturing, water cooling, and air compression. Inputs and outputs related to extrusion and wire drawing is included in the ecoinvent datasets as upstream emissions.

Table 6: Manufacturing inventory applied in the LCA of the benchmark Inventory (the values are per FU)

Flow	Generic Manufacturing	Units
Inputs		
Electricity	1.29E-08	MWh
Nitrogen	1.57E-07	kg
Water	1.86E-06	kg
Outputs		
Waste	1.11E-12	t
Methane	1.28E-11	t

In addition, several auxiliary flows, including water and nitrogen consumption as well as waste generation, are included in the inventory. HVDC cables are typically transported wound on cable drums or spools; however, the production and use of these transport components are excluded from the scope of the present model.

For the NEWGEN cable, the available manufacturing inventory is limited to electricity consumption associated with the manufacturing technology. The corresponding values are presented in Table 7 per functional unit, assuming an 80% load.

Table 7: Manufacturing inventory applied in the LCA of the NEWGEN Inventory (the values are per FU)

Flow	Manufacturing Lab scale	Manufacturing Pilot scale	Units
Electricity	2.96E-09	2.48E-09	MWh

The initial inventory was based on lab-scale data and was subsequently adjusted using pilot-scale measurements. The pilot-scale value reflects the improved energy efficiency achieved at a larger production volume and is therefore considered more representative of the manufacturing process at an advanced development stage.

1.7.8 Installation

The cable-laying phase covers the offshore installation of 1 km of submarine cable. Identical installation conditions are assumed for the benchmark and NEWGEN cable designs. Due to the absence of a specific dataset for cable-laying vessels, the dataset *diesel, burned in fishing vessel* was selected as a proxy to represent marine fuel combustion and the associated vessel emissions. The inventory is presented in Table 8.

Table 8: Inventory for the laying of 1 km of submarine cable (the values are per FU)

Flow	Generic Manufacturing	Units	Comments
Diesel, burned in fishing vessel	3.69766E-06	MJ	Proxy for fuel combustion by the cable-laying vessel; based on 537 L/km and 38 MJ/L

1.7.9 Operation and Maintenance

The operation and maintenance (O&M) stage accounts for repair and replacement activities resulting from cable failures over the assumed 25-year service life. The failure assumptions are based on the reliability assessment provided by the University of Bologna.

The reliability model differentiates between internal failures originating within the cable system and external failures resulting from external events. External failure rates are assumed to be identical for both cable systems, whereas internal failure rates vary according to cable design and reliability characteristics.

For the baseline assessment, a constant annual failure rate is assumed over the service life. The expected lifetime failure frequency is calculated as:

$$r_{replacment} = h_r \cdot lifetime$$

Table 9: Replacement factor of Benchmark and NEWGEN cables (Lauria u. a. 2016)

Flow	Internal failure rate	External failure rate	Replacement factor over 25 years	Comments
Benchmark HVDC cable	5.025E-5	0.001114	0.00116425	Includes external failures and the cable-specific internal failure contribution
NEWGEN HVDC cable	3.943E-20	0.001114	0.001114	Dominated by the common external failure rate; internal contribution is negligible

Table 9 shows the replacement factors of benchmark and NEWGEN cable. This factor is applied to the raw materials, manufacturing, transportation, installation, and end-of-life treatment associated with the replaced cable section. A 28-day vessel operation is assumed for each repair event, based on indicative durations for vessel mobilization and demobilization, repair activities, and weather-related delays reported for offshore cable repair operations (Sharples 2011). Cable jointing is assumed to take place on board the repair vessel during this period, and the associated energy demand is therefore represented through vessel fuel consumption. A fuel consumption of 17.3 m³/day (17,300 L/day) is applied, based on the reported economic-speed consumption of the Seaway Aimery, a vessel designed for cable installation, repair, and maintenance activities (Seaway7 2023). In the LCA model, “diesel burned in fishing vessel” is used as a proxy for the energy consumption of the repair operation. The cable-joint material inventory includes steel, bitumen, silicone, aluminium, lead, and copper.

Steel contributes to the largest share of mass, which covers the outer housing of the joint. It was modelled using “market for steel, low-alloyed | steel, low-alloyed | APOS, U – GLO”.

Bitumen will be used as a filling and waterproofing material inside the casing. This was modelled using market for bitumen seal | bitumen seal | APOS, U – GLO.

Silicone is used for the pre-moulded joint insulation, this was modelled using “market for silicone product | silicone product | APOS, U – RER” as a proxy.

Aluminium contributes mainly to the connector and associated hardware. This was modelled using “market for aluminium, wrought alloy | aluminium, wrought alloy | APOS, U – GLO”.

Lead makes up around 30 kg, used to rebuild the metallic sheath at the joint. This was modelled using “market for lead | lead | APOS, U – GLO”.

Copper is used for bonding and contacting components. This was modelled using “market for copper, cathode | copper, cathode | APOS, U – GLO”.

Each repair event includes two HVDC submarine cable joints at the end of the cable section. The cable joint is modelled equally for both the NEWGEN and XLPE benchmark cables in the openLCA model. Table 10 shows the cable joint inventory per joint.

Table 10: Cable joints installation inventory per joint

Flow	Materials used for cable joints	Units
aluminium, wrought alloy	40	kg
bitumen seal	100	kg
copper, cathode	15	kg
lead	30	kg
silicone product	90	kg

1.7.10 Use phase

The use phase accounts for the electricity losses associated with transmitting electricity through 1 km of cable. As the functional unit is defined as 1 MWh of electricity delivered at the receiving end, only the additional electricity required to compensate for transmission losses is included in the life-cycle inventory. The transmitted electricity itself is not treated as an input to the cable system.

Two operating scenarios are assessed as part of the sensitivity analysis.

In the baseline common-load scenario, both cable systems operate at the same current of 1,960 A and at an operating voltage of 525 kV. This represents a like-for-like comparison under identical electrical loading conditions. Under this scenario, the benchmark XLPE cable shows slightly lower transmission losses than the NEWGEN PP cable.

In the cable-specific ampacity sensitivity scenario, each cable operates at 80% of its own current-carrying capacity. The respective ampacity is defined based on a maximum conductor temperature of 70°C. Since the two cable designs have different current-carrying capacities, the

resulting operating currents, transmitted power and absolute transmission losses also differ. This scenario therefore reflects the performance of each cable relative to its own design capability.

For both scenarios, the corresponding transmission losses are converted into the additional electricity demand required per functional unit and included in the use-phase inventory. The applied transmission parameters are presented in Table 11.

Table 11: Transmission losses for the benchmark and NEWGEN cable designs

Scenario	Parameter	Benchmark XLPE	NEWGEN PP	Unit
80% common load — baseline	Current	1,960	1,960	A
	Input power	1,029	1,029	MW
	Transmission losses	31.99	32.77	W/m
80% cable-specific ampacity — sensitivity	Input power	1,149.08	1,031.53	MW
	Transmission losses	41.1	33.0	W/m

The common-load scenario compares both cables under the same electrical load, whereas the cable-specific ampacity scenario compares their performance at the same relative utilization of their respective current-carrying capacity.

1.7.11 End of life

The end-of-life phase considers the treatment of the cable after the assumed operational lifetime. Two scenarios were assessed to represent worst and the best-case scenario:

- **Subsea abandonment:** the decommissioned cable remains on the seabed.
- **Cable recovery and recycling:** the cable is recovered and transferred to subsequent treatment and recycling processes.

The end-of-life phase considers the treatment of the cable after the assumed 25-year service life. Two alternative scenarios are assessed to reflect different decommissioning strategies:

Subsea abandonment: the decommissioned cable remains on the seabed, and no recovery or recycling activities are performed.

Cable recovery and recycling: the cable is recovered from the seabed and transported for subsequent treatment, material separation and recycling.

The following sections describe the modelling assumptions and inventories applied to both scenarios.

Scenario 1 – Subsea abandonment

In the subsea abandonment scenario, the decommissioned cable is assumed to remain on the seabed. No recovery, transportation, dismantling or recycling activities are included.

The continued occupation of the seabed by the cable is included in the inventory. Potential long-term degradation, including possible releases of metals or other substances to the marine environment, is not quantified because sufficiently reliable data on degradation and leaching rates are not available.

The seabed occupation is assumed to be the same for the benchmark and NEWGEN cable systems, as the same cable footprint and abandonment period are applied. The occupied area is calculated from the cable outer diameter and length:

$$A_{occupation} = D_{outer} * L$$

where $A_{occupation}$ is the seabed occupation aream², D_{outer} is the outer diameter of the cable m, and L is the cable length [m]. As the NEWGEN and benchmark cables are assumed to have the same seabed occupation area, the same occupation area is applied to both cable types. Table 12 lists for the subsea abandonment scenario per Functional Unit.

Table 12: Inventory for the subsea abandonment scenario per FU

Flow	Type	Amounts	Units
Occupation, sea and ocean	Input	9.26E-07	m²·a

Scenario 2 – Cable recovery and recycling

In the second scenario, the cable is recovered from the seabed after the assumed operational lifetime and transferred for subsequent treatment and recycling. This includes:

- recovery of the cable from the seabed;
- transport of the recovered cable to the treatment facility;
- separation and treatment of the cable components;
- recycling of recoverable material fractions;
- treatment or disposal of non-recyclable fractions.

The corresponding modelling assumptions and inventories for cable recovery, treatment and recycling are described in the following sections.

Cable recovery

The recovery stage represents the removal of 1 km of cable from the seabed. Due to the absence of a specific dataset for cable recovery vessels, diesel burned in a fishing vessel is used as a proxy for vessel operation, as shown in Table 13. The same recovery process is assumed for the benchmark and NEWGEN cable designs.

Table 13: Inventory for cable recovery per FU(Intertek Energy & Water Consultancy Services 2020)

Flow	Amounts	Units	Comments
Diesel, burned in fishing vessel	7.39532E-06	MJ	Proxy for cable recovery vessel. Fuel demand is assumed to be twice the cable installation demand due to the lower recovery rate.

Note: Cable recovery is assumed to require twice the vessel operating time of cable installation, based on the available data on submarine cable installation and recovery rates. Accordingly, the vessel fuel consumption for cable recovery is assumed to be twice the fuel demand of the installation stage.

Cable shredding and separation

After recovery, the decommissioned cable is assumed to be shredded and separated into its main material fractions. A material loss of 5% is assumed during the shredding process, while the remaining 95% is transferred to subsequent treatment. The electricity required for shredding and separation is included in the inventory.

The separated aluminium, lead, steel and polymer fractions are then sent to the corresponding downstream treatment processes. For the polymer fraction, the baseline scenario assumes a 50/50 split between recycling and incineration, representing the two alternative end-of-life routes applied in the project model. Table 14 shows the inventory for cable shredding per functional unit of both cables.

Table 14: Inventory for cable shredding per FU of both cables

Flow	Amount NEWGEN	Unit
electricity, high voltage	1.85063E-06	kWh
Aluminium scrap for recycling	2.16522E-09	t
Steel scrap for recycling	5.88549E-09	t
Polymer fraction (50% recycled, 50% incinerated)	1.81131E-09	t
Lead scrap for recycling	3.51006E-09	t

The following sections describe the downstream recycling and incineration processes applied to the separated material fractions.

Downstream treatment processes

The separated material fractions are treated using adapted ecoinvent 3.9 APOS processes. The same end-of-life scenarios are applied to both the benchmark XLPE and NEWGEN PP cable systems to ensure a consistent comparison. Differences in the results therefore arise from the material composition and quantities of the respective cable designs rather than from different treatment assumptions.

Aluminium recycling. The recovered aluminium fraction is modelled using two ecoinvent processes representing the preparation of post-consumer aluminium scrap and its subsequent treatment at a refiner. Together, these processes represent scrap preparation followed by secondary aluminium production.

Steel recycling. The recovered steel fraction is represented by the ecoinvent process “steel production, electric, low-alloyed”, using unsorted iron scrap as an input. Electric steel production is used as a proxy for recycling the recovered steel fraction. Transport between the shredding and recycling facilities is not included.

Polymer treatment. For both cable systems, a comprehensive end-of-life scenario was considered: in which 50 per cent of the separated polymer fraction is sent for recycling, whilst the remaining 50 per cent is incinerated. The incinerated share is modelled by using "treatment of waste wire plastic, municipal incineration with fly ash extraction" as a proxy for the thermal treatment of cable insulation and jacketing materials. The modelling method for the recycling portion follows the approach described by (Boss und Landberg 2021), in which the recovered polymers are processed into recycled plastic materials suitable for specific applications, without replacing virgin insulation-grade polymers. This scenario reflects a more realistic end-of-life scenario: due to contaminants, limitations in material separation and the cross-linking properties of cross-linked polyethylene (XLPE), only a portion of the polymer components can actually be recovered. This modelling approach is applicable to both XLPE/PE and PP-based cable systems, whilst retaining their respective material compositions in the inventory.

Lead recycling. The recovered lead fraction is represented using an adapted version of the ecoinvent aluminium scrap refining process. Aluminium-specific inputs and outputs are replaced with lead-related flows, and the recovered lead is credited as an avoided product. The ecoinvent dataset “market for lead | lead | APOS, U – GLO” is used as the provider for the substituted lead product. Transport between the shredding and lead recycling facilities is not included.

Table 15 presents the downstream treatment processes for different material fractions in cables

Table 15: Overview of downstream treatment processes

Material fraction	Treatment route	Dataset / proxy used	Main modelling adaptation
Aluminium scrap	Recycling	treatment of aluminium scrap, post-consumer, by collecting, sorting,	Two ecoinvent processes are combined to represent preparation

Material fraction	Treatment route	Dataset / proxy used	Main modelling adaptation
		cleaning, pressing + treatment of aluminium scrap, post-consumer, prepared for recycling, at refiner	and subsequent recycling of aluminium scrap.
Steel scrap	Recycling	steel production, electric, low-alloyed | iron scrap, unsorted	Electric steel production is used as a proxy for recycling of the separated steel fraction. Transport from shredding to the recycling facility is currently excluded.
XLPE/PE	Incineration	treatment of waste wire plastic, municipal incineration with fly ash extraction	Used as a proxy for incineration of the separated cable polymer fraction.
XLPE/PE	Recycling	Adapted recycling process based on Boss & Landberg	1 kg shredded XLPE/PE is combined with 1.4592 kg virgin HDPE. The process additionally requires 0.24145 kWh low-voltage electricity and 0.00014 m³ water.
XLPE/PE	Recycling – substitution	Adapted recycling process	2.4592 kg plastic granulate is modelled as an avoided product. The process also generates 0.0272 kg of a residual waste-plastic flow.*
NEWGEN PP-based insulation	Recycling	Separate NEWGEN treatment model	PP is assumed to be mechanically recyclable without the addition of virgin polymer.
Lead	Recycling	Adapted recycling process: “treatment of aluminium scrap, new, at refiner | aluminium scrap, new | APOS, U - RER”	The recovered lead fraction is modelled as an avoided product output, with “market for lead | lead | APOS, U – GLO” used as the proxy dataset for the avoided production of primary lead.

The recycling process includes the addition of virgin HDPE. Consequently, the mass of the resulting plastic granulate exceeds the mass of the incoming XLPE/PE waste fraction. The applied input and output ratios are based on the underlying source data and are scaled proportionally to the amount of XLPE/PE treated.

1.8 Data quality

Data quality was evaluated in terms of geographical, technological and temporal representativeness. The qualitative criteria used for the assessment are summarized in Table 16.

Table 16 Criteria for the qualitative assessment of data quality.

Quality level	Geographical	Technological	Temporal
Very good	Study region directly represented	Same process and technology	< 3 years
Good	Broader region including the study area	Same process, similar technology	< 6 years
Satisfactory	Comparable production conditions	Similar process or partly specified technology	< 10 years
Poor	Limited geographical comparability	Related process or product	< 15 years
Very poor	Unknown or substantially different region	Significantly different technology or scale	Unknown or > 15 years

The assessment covers primary data provided by NEWGEN project partners and secondary data, mainly sourced from ecoinvent 3.9 APOS. Table 17 presents an indicative evaluation of the main inventory categories.

Table 17 Data quality assessment of the benchmark and NEWGEN LCA models.

Data category	Geographical	Technological	Temporal	Main consideration
Cable composition and materials	Satisfactory	Very good	Good–Very good	Project-specific data (2021–2024)
Manufacturing	Good	Satisfactory	Good–Very good	Pilot-scale production data
Background material processes	Good–Satisfactory	Good–Satisfactory	Good	Generic datasets and selected proxies
Transport and installation	Satisfactory	Satisfactory	Satisfactory-Good	Assumed distances and vessel proxy
Use phase	Satisfactory	Good	Satisfactory	Updated electrical and thermal model
Operation and maintenance	Not rated	Satisfactory	Good	Modelled reliability and repair activities
End-of-life	Satisfactory	Satisfactory	N/A	Prospective treatment and recovery scenarios

Primary data cover the period 2021–2024, corresponding to good to very good temporal representativeness relative to the assessment year 2026. The project-specific cable inventories provide a reliable basis for the comparison, while pilot-scale production data and selected background proxies introduce additional uncertainty.

Overall, the available data are considered suitable for the intended comparative LCA. The main limitations concern industrial-scale production, long-term reliability and prospective end-of-life treatment. These aspects should be considered when interpreting the results.

1.9 Data gaps and simplification

This part summarizes the main modelling assumptions and data gaps of the current benchmark LCA model:

- Both cable systems share the same general architecture, with the main differences related to insulation composition, additives and material quantities.

- Inventories are developed for 1 km of cable and normalized to 1 MWh of electricity delivered over a 25-year reference service life.
- The baseline comparison uses a common input power of 1,029 MW. The corresponding transmission losses are 31.99 W/m for the benchmark and 32.77 W/m for NEWGEN. Alternative operating conditions are examined in the sensitivity analysis.
- NEWGEN insulation production is modelled using available pilot-scale data, as industrial-scale production data are not yet available.
- Missing production data are supplemented with ecoinvent 3.9 APOS datasets. Proxy processes are used where necessary, including wire drawing for conductor prefabrication and German medium-voltage electricity where process-specific data are unavailable.
- The same installation assumptions are applied to both systems, with marine diesel combustion used as a proxy for cable-laying vessel operation.
- O&M accounts for cable failures, repairs and replacement of damaged sections. External failure rates are assumed to be identical, while internal failure rates are cable specific.
- End-of-life modelling includes subsea abandonment and cable recovery with subsequent treatment and recycling. The recovery route assumes 5% material loss during shredding, with additional scenarios for polymer recycling and incineration. Adapted background processes are used where specific recycling datasets are unavailable, particularly for lead.

1.10 Model implementation in the openLCA software

openLCA is the main software tool used to perform the LCA in this study. In accordance with the defined system boundaries, the analysis is divided into several modelling stages covering both the benchmark HVDC cable and the NEWGEN cable. This chapter provides an overview of the modelling approach and the individual life cycle stages considered in the assessment.

Figure 3 presents the model graph for the production stage of the benchmark HVDC cable, developed in openLCA 2.7.0.



Figure 3: Model graph of openLCA model of benchmark HVDC cable production

Figure 4 shows the model graph for the production of the NEWGEN HVDC cable in openLCA. The model follows the same overall LCA stage structure as the benchmark cable, while reflecting the differences in the manufacturing process and insulation composition of the NEWGEN cable.

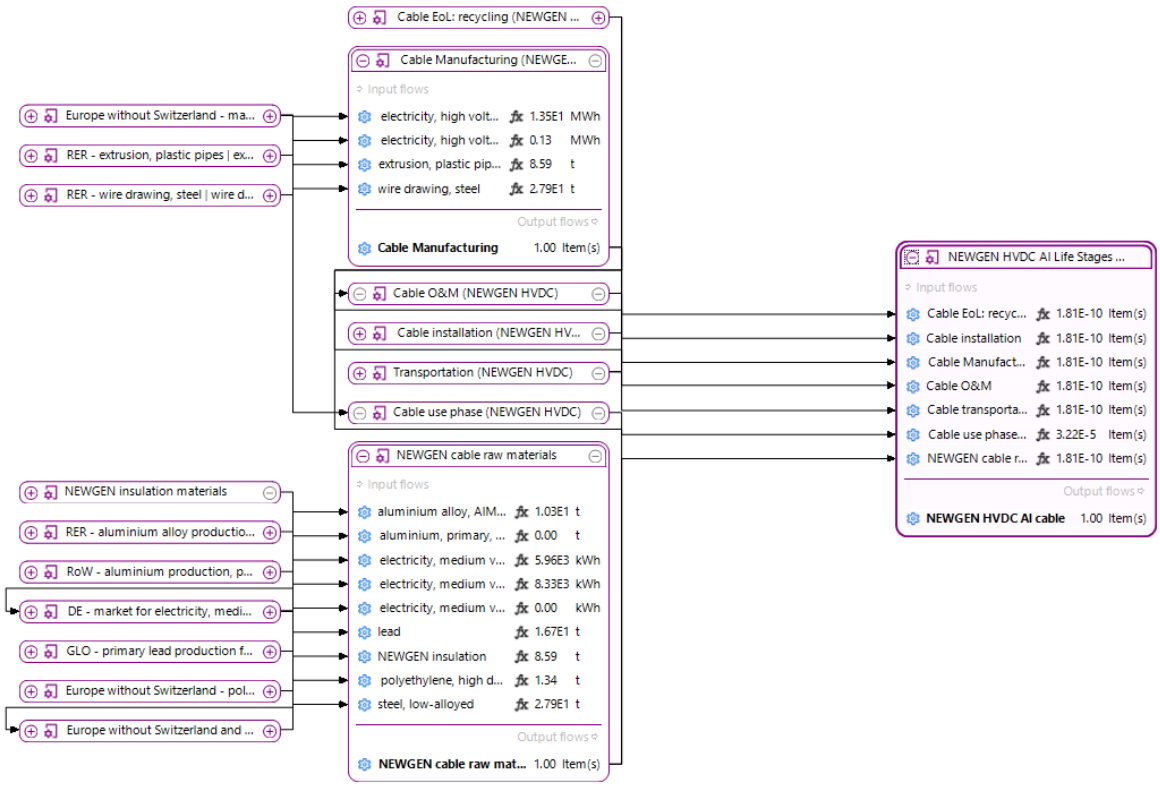


Figure 4: Model graph of openLCA model of benchmark HVDC cable production

1.11 Baseline Life Cycle Impact Assessment results – Benchmark HVDC cable

This section presents the life-cycle environmental impacts of the benchmark XLPE-insulated cable, expressed per functional unit of 1 MWh of electricity delivered over a distance of 1 km, based on a reference service life of 25 years and the common baseline input power of 1,029 MW. The results are calculated with the Environmental Footprint (EF 3.1) method and are reported in Table 18.

Table 18: Environmental impact assessment of the benchmark HVDC cable

Name	Impact assessment result	Unit
Acidification - 2017	5.52E-05	mol H+ equivalents
Climate change - 2017	1.09E-02	kg CO2 Equivalents
Climate change-Biogenic - 2017	2.59E-05	kg CO2-Equivalents
Climate change-Fossil - 2017	1.09E-02	kg CO2 Equivalents
Climate change-Land use and land use change - 2017	3.11E-05	kg CO2-Equivalents
Ecotoxicity, freshwater - 2017	3.13E-02	CTUe
Ecotoxicity, freshwater_inorganics - 2017	2.97E-02	CTUe
Ecotoxicity, freshwater_organics - 2017	1.61E-03	CTUe
EF-particulate Matter - 2017	2.03E-10	disease incidence
Eutrophication marine - 2017	1.13E-05	kg N equivalents
Eutrophication, freshwater - 2017	1.03E-05	kg P equivalents
Eutrophication, terrestrial - 2107	8.87E-05	mol N equivalents
Human toxicity, cancer - 2018	3.78E-12	CTUh
Human toxicity, cancer_inorganics - 2018	2.24E-12	CTUh
Human toxicity, cancer_organics - 2018	1.55E-12	CTUh
Human toxicity, non-cancer - 2018	1.07E-10	CTUh
Human toxicity, non-cancer_inorganics - 2018	1.05E-10	CTUh

Name	Impact assessment result	Unit
Human toxicity, non-cancer_organics - 2018	1.84E-12	CTUh
Ionising radiation, human health - 2017	7.09E-03	kBq U235 equivalents
Land use - 2017	4.39E-02	dimensionless (pt)
Ozone depletion - 2017	1.96E-10	kg CFC11 equivalents
Photochemical ozone formation - human health - 2017	2.83E-05	kg NMVOC equivalents
Resource use, fossils - 2017	2.57E-01	MJ
Resource use, minerals and metals - 2017	1.56E-08	kg Sb equivalents
Water use - 2017	-7.21E-02	m3-world equivalents

To keep the interpretation tractable, the detailed impact assessment will focus on the most relevant impact categories.

1.11.1 Raw materials

Figure 5 shows the contribution of processes to the key impact categories under EF 3.1 for the cable raw materials stage. The impact is dominated by three materials: lead makes the largest contribution to Acidification (~48%), Ecotoxicity freshwater (~90%), Eutrophication freshwater (~42%), and Resource use minerals & metals (~98%); aluminum conductor leads Climate change (~55%), Particulate matter (~58%), and Resource use fossils (~43%); and steel also makes a visible contribution across most categories. The polymer fraction - PE-LD granulate, recycled PE-HD, carbon black, and the peroxide crosslinker — is significant only in Resource use fossils.

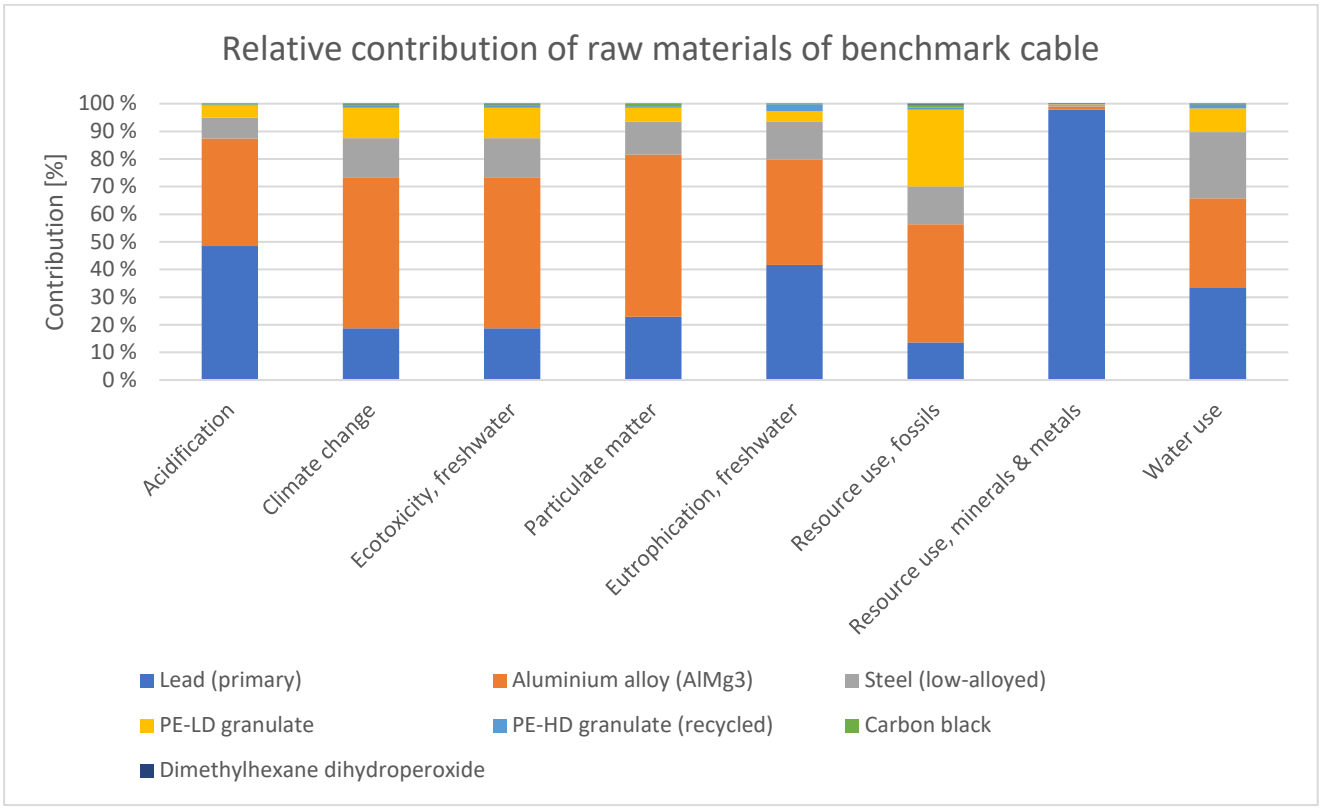


Figure 5: Contribution of raw materials to key EF 3.1 impact categories — benchmark (XLPE) cable

1.11.2 Manufacturing

Figure 6 shows the relative contribution of subprocesses to the key EF 3.1 impact categories for the cable manufacturing phase. Electricity consumption contributes dominantly across most categories, leading Climate change, Acidification, Eutrophication freshwater (~80%), Resource use fossils, and Water use. Wire drawing for steel armoring is the second-largest contributor throughout, and leads Ecotoxicity freshwater (~55%) and Resource use minerals & metals (~70%), driven by metal emissions associated with the wire drawing process. Extrusion of insulation materials makes a visible contribution only to Particulate matter (~10%). Nitrogen, hazardous waste incineration, and water only make negligible contributions across these categories.

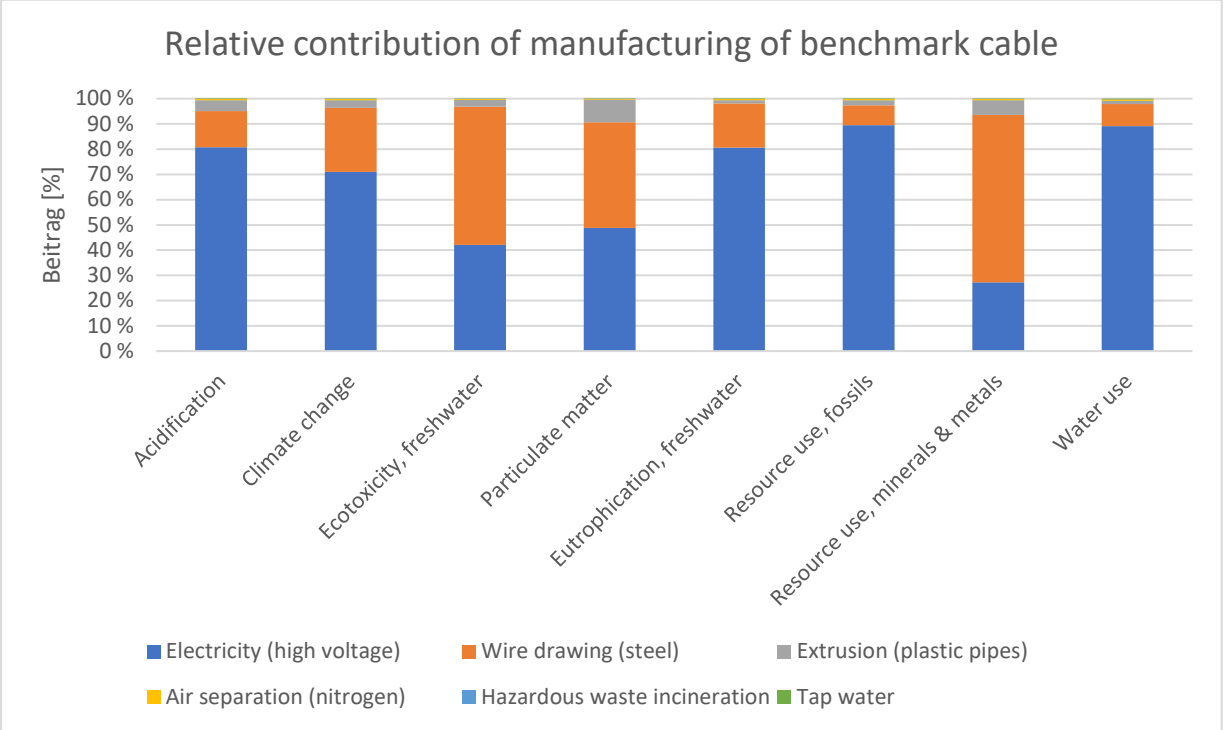


Figure 6: Contribution of cable manufacturing to key EF 3.1 impact categories - benchmark (XLPE) cable

1.11.3 Transportation

All four transport processes are modelled using the same freight process “transport, freight, lorry 16-32 metric ton, EURO5 | transport, freight, lorry 16-32 metric ton, EURO5 | APOS, U” so the impact contribution of each process is directly proportional to its transport distance, and results are reported as total results for the phase as a whole without further disaggregation by processes.

Table 19 presents the characterized LCIA results for the transportation stage across the key EF 3.1 impact categories. Climate change totals and resource use, fossils are both consistent with the phase being driven predominantly by diesel fuel combustion in freight transport.

Table 19: Impact assessment results of transportation processes

Name	Impact assessment result	Unit
Acidification - 2017	1.27E-08	mol H+ equivalents
Climate change - 2017	3.89E-06	kg CO2 Equivalents
Ecotoxicity, freshwater - 2017	2.69E-05	CTUe
EF-particulate Matter - 2017	3.14E-13	disease incidence
Eutrophication, freshwater - 2017	2.80E-10	kg P equivalents
Resource use, fossils - 2017	5.54E-05	MJ
Resource use, minerals and metals - 2017	1.19E-11	kg Sb equivalents

1.11.4 Installation, Use, Operation and Maintenance

Table 20 shows the impact assessment results of installation and use phase per functional unit. The installation phase only comprises the diesel used for laying of the table. The use phase comprises only the electrical energy required to compensate transmission losses over the cable's operating lifetime. Unlike installation, transportation, the use phase is the primary locus of differentiation between the PP and XLPE cable variants, since its magnitude scales directly with each cable's respective transmission loss per functional unit.

For Operation and Maintenance, Climate change and resource use, fossils are caused by the marine diesel consumed by the repair vessel over the assumed number of repair events.

Table 20: Impact assessment results of Installation, Use, Operation and Maintenance

Impact categories	Installation	O&M	Use phase	Unit
Acidification - 2017	1.36E-08	3.64E-07	5.45E-05	mol H+ equivalents
Climate change - 2017	4.24E-07	1.21E-05	0.01086	kg CO2 Equivalents
Ecotoxicity, freshwater - 2017	2.66E-06	9.83E-05	0.03027	CTUe
EF-particulate Matter - 2017	1.03E-13	2.78E-12	1.98E-10	disease incidence
Eutrophication, freshwater - 2017	4.96E-12	6.30E-10	1.03E-05	kg P equivalents
Eutrophication, terrestrial - 2107	3.63E-08	9.66E-07	8.73E-05	mol N equivalents
Resource use, fossils - 2017	5.55E-06	0.00016	0.25624	MJ

1.11.5 End of life: recycling

Figure 7 presents the contribution of subprocesses to Climate Change for the benchmark cable recycling scenario. Recycling of aluminum components makes the largest avoided burden credit, followed by recycling of steel scrap, which indicates the high greenhouse gas intensity of virgin aluminum and steel production. Lead scrap recycling and electricity consumption for shredding remain negligible contribution compare to other subprocesses. Both the incineration and the recycling of the polymer fraction generate emissions that increase the climate change impact. In addition, diesel consumption during the recovery of the benchmark cable makes a substantial contribution to climate change. Overall, the avoided burden derived from metal recycling outweighs the burden associated with polymer fraction processing and recycling.

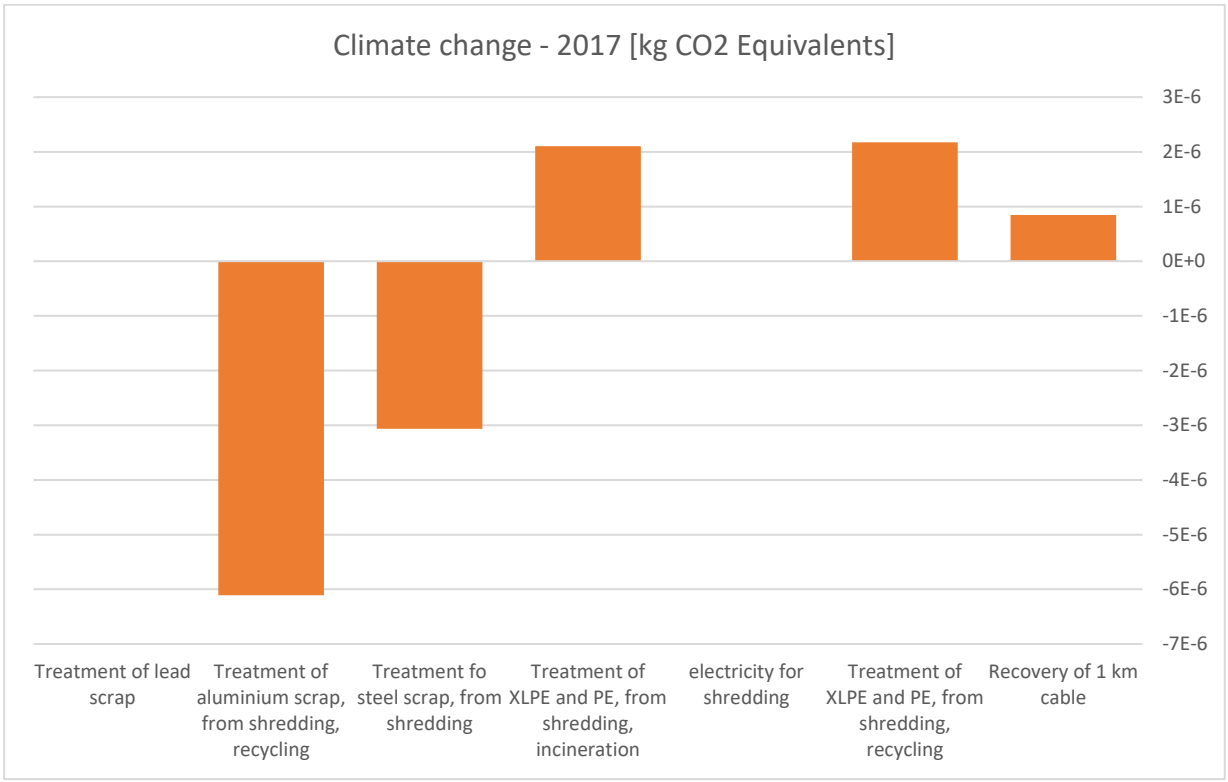


Figure 7: Climate change contribution of individual end-of-life sub-processes - benchmark (XLPE) cable recycling scenario

Figure 8 shows contribution of subprocesses to Resource use, fossils for the benchmark cable recycling scenario. Recycling of polymer fraction makes the largest contribution to this impact, in which the process mixes Polyethylene high density granulate for making polyethylene granulate. Therefore, the contribution of using polyethylene granulates makes the recycling of polymer contribution. Recycling of steel scrap and Aluminum scrap generate avoided burden credit of this impact, while lead scrap recycling and electricity consumption contribute negligible credit. Recovery of 1 km cable and XLPE/PE incineration added smaller positive contributions. Overall, metal recycling is beneficial to this impact, whilst polymer recycling and incineration partially offsets those benefits.

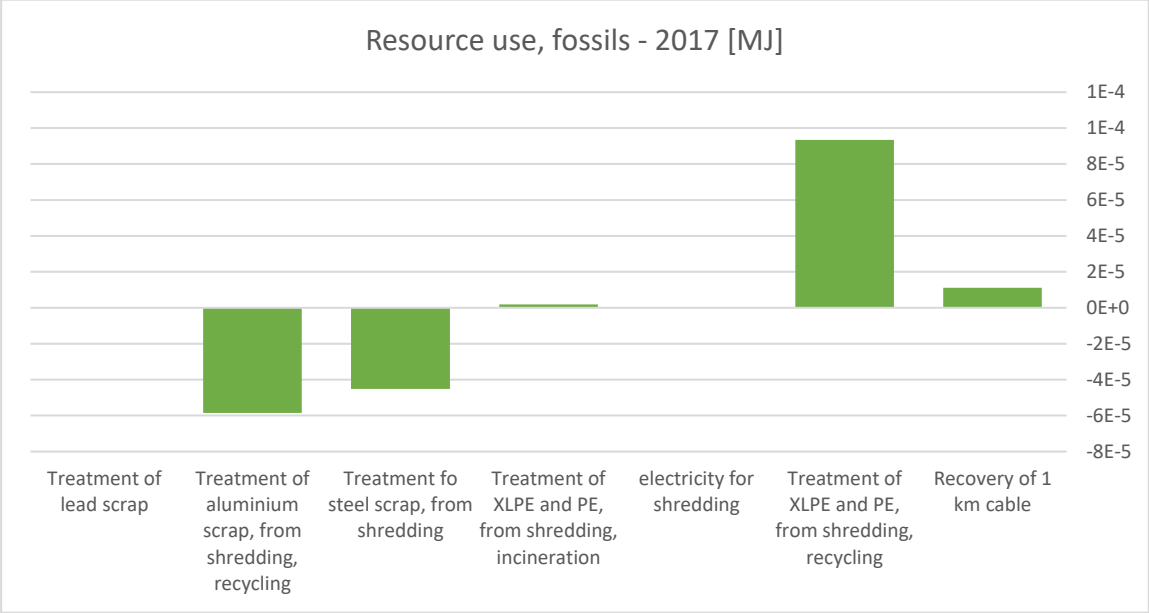


Figure 8: Resource use, fossils contribution of individual end-of-life sub-processes - benchmark (XLPE) cable recycling scenario.

Figure 9 shows the contribution of sub-processes to Resource use, minerals and metals for the benchmark cable recycling scenario. This impact is overwhelmingly contributed by aluminum scrap recycling, which generates a large positive contribution. This reflects metal consumed in the aluminum recycling process by making secondary aluminum. Treatment of steel scrap generates avoided burden, while all other sub-processes — lead scrap recycling, Polymer incineration, Polymer recycling, electricity for shredding, and recovery of 1 km cable — are negligible.

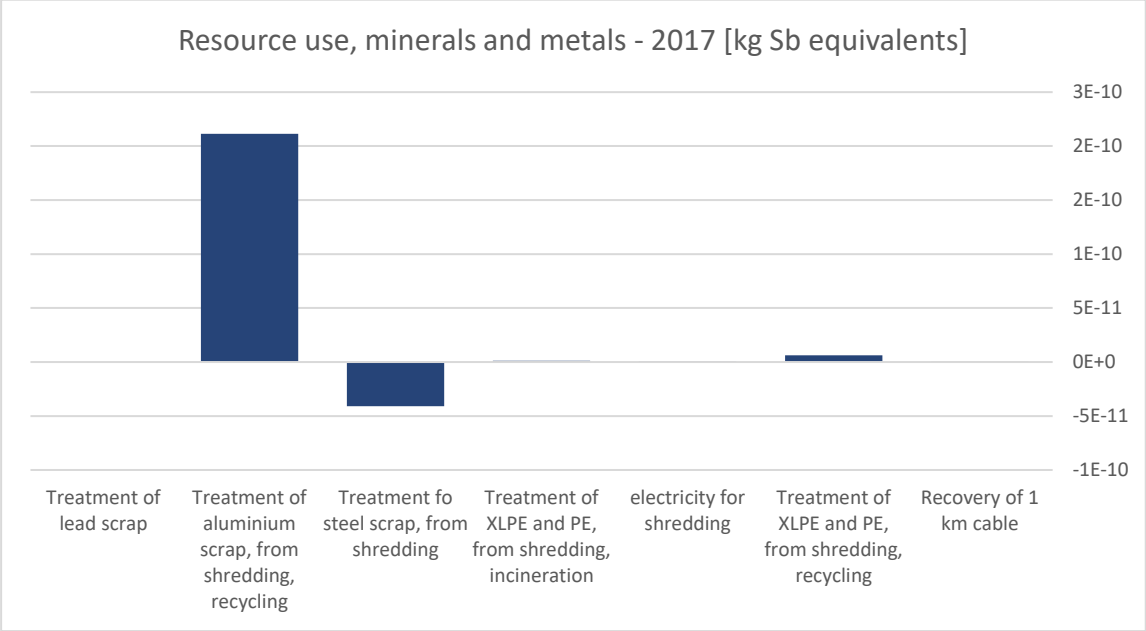


Figure 9: Resource use, minerals and metals contribution of individual end-of-life sub-processes - benchmark (XLPE) cable recycling scenario

1.12 Baseline Life Cycle Impact Assessment results – NEWGEN HVDC cable

This section presents the life-cycle environmental impacts of the NEWGEN HVDC cable, expressed per functional unit of 1 MWh of electricity delivered over a distance of 1 km, based on a reference service life of 25 years and the common baseline input power of 1,029 MW. Table 19 presents the total environmental impacts across the life-cycle stages included in the system boundary.

Table 21 Environmental impact assessment of the NEWGEN HVDC cable

Name	Impact assessment result	Unit
Acidification - 2017	5.6466E-05	mol H+ equivalents
Climate change - 2017	0.01116811	kg CO2 Equivalents
Climate change-Biogenic - 2017	2.6566E-05	kg CO2-Equivalents
Climate change-Fossil - 2017	0.01110972	kg CO2 Equivalents
Climate change-Land use and land use change - 2017	3.1823E-05	kg CO2-Equivalents
Ecotoxicity, freshwater - 2017	0.03208595	CTUe

Name	Impact assessment result	Unit
Ecotoxicity, freshwater_inorganics - 2017	0.03042655	CTUe
Ecotoxicity, freshwater_organics - 2017	0.0016594	CTUe
EF-particulate Matter - 2017	2.0763E-10	disease incidence
Eutrophication marine - 2017	1.1565E-05	kg N equivalents
Eutrophication, freshwater - 2017	1.0541E-05	kg P equivalents
Eutrophication, terrestrial - 2107	9.0752E-05	mol N equivalents
Human toxicity, cancer - 2018	3.871E-12	CTUh
Human toxicity, cancer_inorganics - 2018	2.287E-12	CTUh
Human toxicity, cancer_organics - 2018	1.584E-12	CTUh
Human toxicity, non-cancer - 2018	1.093E-10	CTUh
Human toxicity, non-cancer_inorganics - 2018	1.0741E-10	CTUh
Human toxicity, non-cancer_organics - 2018	1.882E-12	CTUh
Ionising radiation, human health - 2017	0.00726381	kBq U235 equivalents
Land use - 2017	0.04497681	dimensionless (pt)
Ozone depletion - 2017	2.0119E-10	kg CFC11 equivalents
Photochemical ozone formation - human health - 2017	2.9003E-05	kg NMVOC equivalents
Resource use, fossils - 2017	0.26309502	MJ
Resource use, minerals and metals - 2017	1.5824E-08	kg Sb equivalents
Water use - 2017	-0.07388026	m3-world equivalents

1.12.1 Raw materials

Figure 8 shows the contribution of the sub-processes to the key impact categories of the EF 3.1 method. For Resource use, minerals & metals, Ecotoxicity, freshwater, and Acidification, the primary lead jacketing makes the leading contribution. The aluminum alloy conductor makes the

largest contribution to Climate change, Particulate matter, Eutrophication, freshwater, and Resource use, fossils, driven primarily by the energy intensity of aluminum production. The NEWGEN insulation material also contributes substantially to Resource use, fossils.

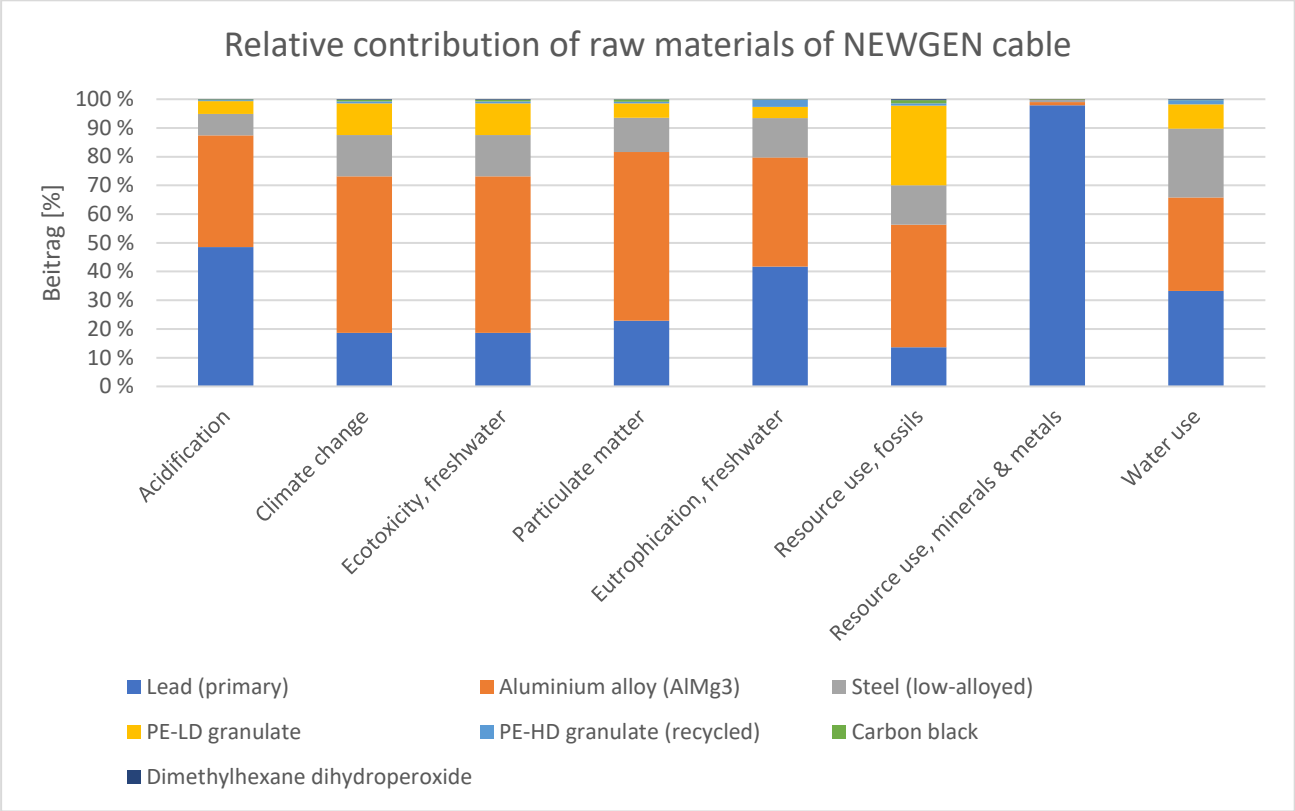


Figure 10: Contribution of raw materials to key EF 3.1 impact categories — NEWGEN cable

1.12.2 Cable manufacturing

Figure 11 shows that wire drawing for steel armoring makes the leading contribution to Ecotoxicity, freshwater, Particulate matter and Resource use, minerals & metals. Electricity, used for lead extrusion and conductor wire drawing, makes the largest contribution to Climate change, Eutrophication, freshwater, Climate Change, Resource use, fossils and Water use. For Acidification, wire drawing of steel contributes only marginally more than electricity consumption. For Particulate matter, the extrusion process of insulation materials also makes a substantial contribution.

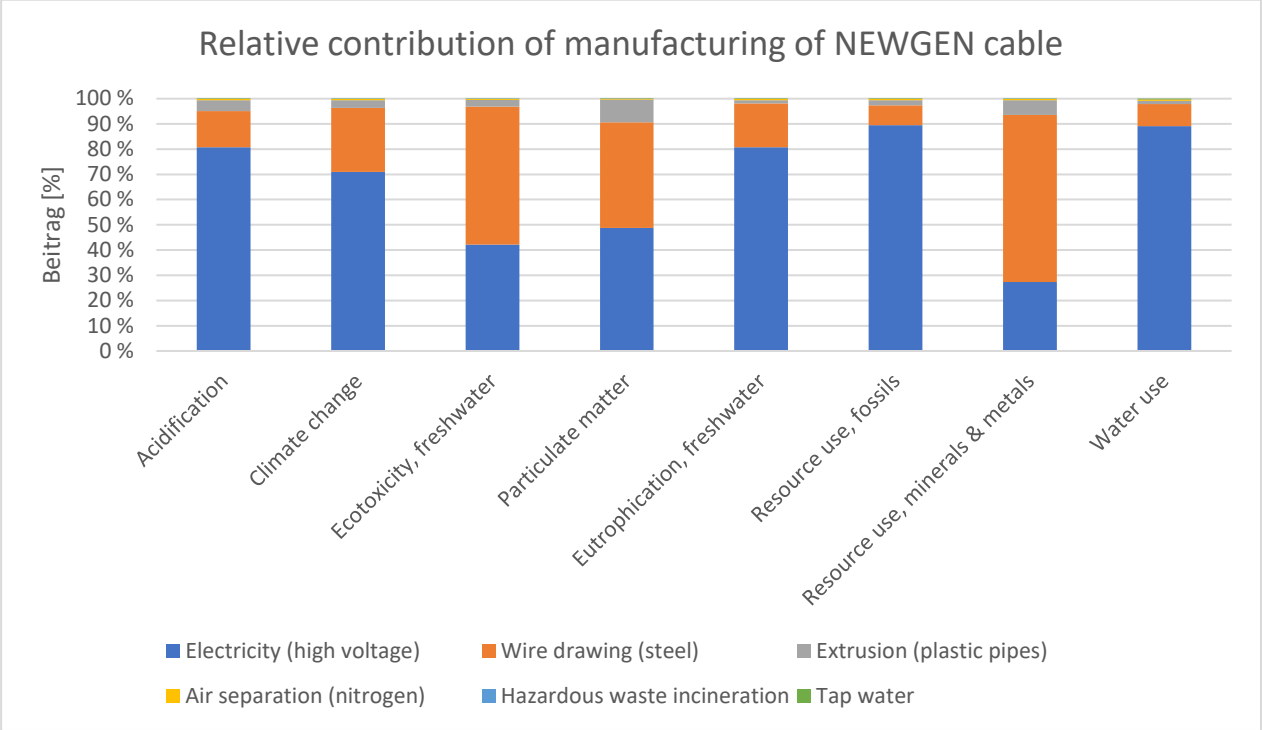


Figure 11: Contribution of cable manufacturing to key EF 3.1 impact categories — NEWGEN cable

1.12.3 Transportation

Table 22 presents the characterized LCIA results for the transportation stage across the key EF 3.1 impact categories. All four transport processes are modelled using the same freight process, "transport, freight, lorry 16–32 metric ton, EURO5 | APOS, U". The transport distances are identical to those assumed for the benchmark cable. As the NEWGEN cable has a slightly lower mass than the benchmark cable, its transportation-related impact is correspondingly slightly lower across all categories.

Table 22: Impact assessment results of transportation processes of NEWGEN cable

Name	Impact assessment result	Unit
Acidification - 2017	1.39E-08	mol H+ equivalents
Climate change - 2017	4.26E-06	kg CO2 Equivalents
Ecotoxicity, freshwater - 2017	2.94E-05	CTUe
EF-particulate Matter - 2017	3.44E-13	disease incidence
Eutrophication, freshwater - 2017	3.06E-10	kg P equivalents

Resource use, fossils - 2017	6.06E-05	MJ
Resource use, minerals and metals - 2017	1.30E-11	kg Sb equivalents

1.12.4 Installation, Use, Operation and Maintenance

Table 23 lists the results of the LCIA for NEWGEN cables during the installation, operation and maintenance (O&M), and use phases. As with the reference cable, the installation phase includes only the marine diesel consumed by the laying vessel; the operation and maintenance phase include vessel fuel and replacement material inventory associated with maintenance; and the use phase includes the electrical energy required to compensate for transmission losses throughout the operational lifespan. Across these three phases, the differences for each impact category span several orders of magnitude. Because the NEWGEN cable has a lower internal failure rate for its insulation than the benchmark cable, the resulting overall operational and maintenance impact is slightly lower.

Table 23: Impact assessment results of transportation processes of NEWGEN cable

Impact categories	Installation (NEWGEN HVDC)	O&M (NEWGEN HVDC)	Use phase (NEWGEN HVDC)	Unit
Acidification - 2017	1.36E-08	3.48E-07	5.59E-05	mol H+ equivalents
Climate change - 2017	4.24E-07	1.14E-05	1.11E-02	kg CO2 Equivalents
Ecotoxicity, freshwater - 2017	2.66E-06	9.44E-05	3.10E-02	CTUe
EF-particulate Matter - 2017	1.03E-13	2.66E-12	2.03E-10	disease incidence
Eutrophication, freshwater - 2017	4.96E-12	5.42E-10	1.05E-05	kg P equivalents
Eutrophication, terrestrial - 2107	3.63E-08	9.23E-07	8.95E-05	mol N equivalents
Resource use, fossils - 2017	5.55E-06	1.50E-04	2.63E-01	MJ

1.12.5 End of life: recycling

Figure 12 illustrates the contribution to climate change made by the sub-processes at the end-of-life stage of NEWGEN cable. The overall trend is broadly consistent with that of the baseline cable: emissions reductions from aluminum scrap recycling are the largest, followed by those from lead and steel scrap, reflecting the fact that these materials have replaced the production of

virgin metals. The incineration of plastic components is the largest source of Climate Change, primarily due to the carbon dioxide released during combustion, whilst the electricity consumption required for the shredding of 1 km of cable makes a relatively minor contribution. The recycling yield for the plastic components is close to zero, indicating that this differs from the cross-linked polyethylene (XLPE)/polyethylene (PE) recycling process in the baseline case—which requires blending with virgin high-density polyethylene (HDPE).

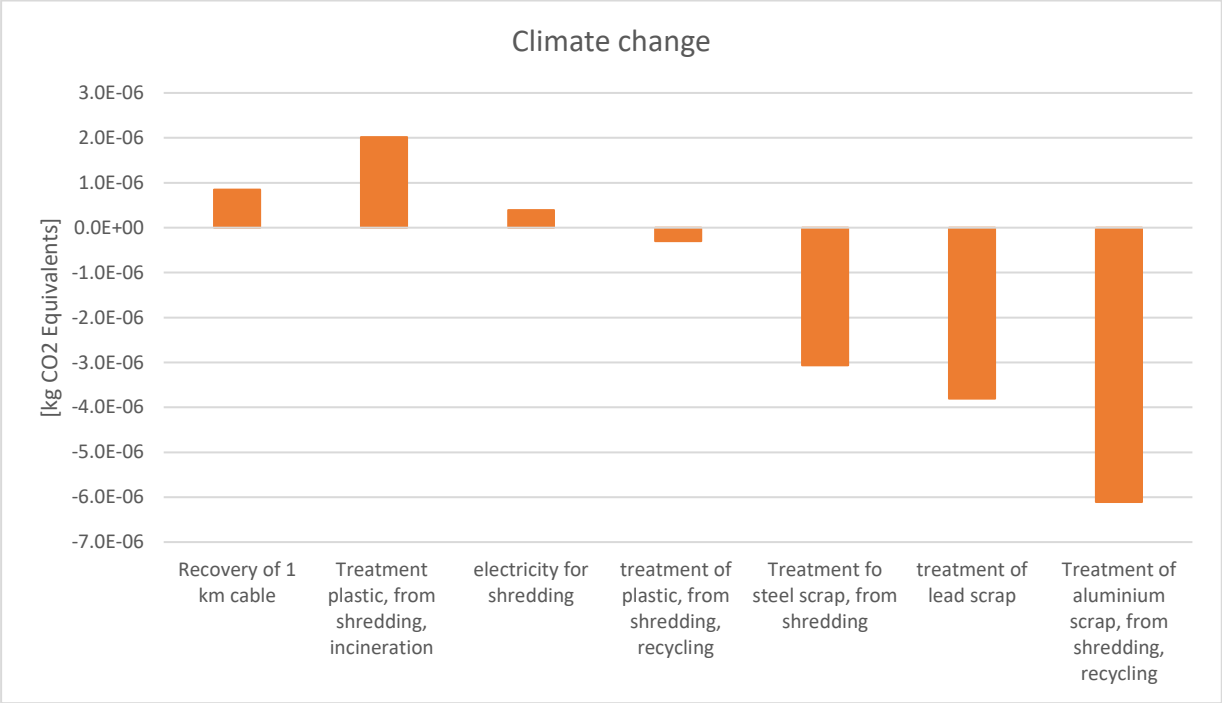


Figure 12: Climate change contribution of end-of-life sub-processes — NEWGEN cable recycling.

Figure 13 shows the contribution of sub-processes to Resource use, fossils for the NEWGEN (PP) cable recycling process. The NEWGEN cable recycling process generates a net negative (beneficial) result in this impact. Aluminum scrap recycling generates the largest avoided-burden credit, followed by steel scrap and lead scrap recycling, all reflecting displaced virgin metal production. Electricity for shredding and recovery of 1 km cable are the only positive visible burdens. Critically, plastic incineration and plastic recycling both contribute near-zero values.

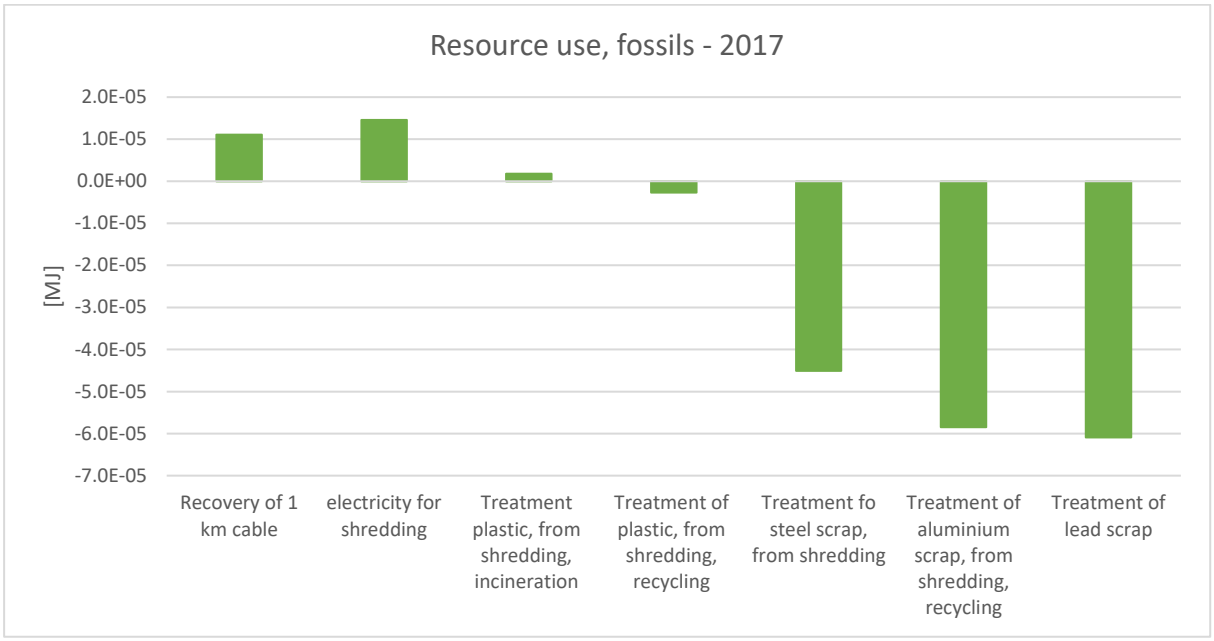


Figure 13: Resource use, fossils contribution of individual end-of-life sub-processes — NEWGEN cable recycling process.

Figure 14 shows the contribution of sub-processes to Resource use, minerals and metals for the NEWGEN cable recycling process. This impact category is overwhelmingly dominated by a single process: treatment of lead scrap, which generates a large avoided-burden credit, reflecting the displaced virgin lead production and its associated mineral-resource depletion. Aluminum scrap recycling is the only process which makes a positive contribution, representing the mineral resources consumed in the secondary aluminum production chain. All remaining sub-processes — recovery of 1 km cable, plastic incineration, plastic recycling, electricity for shredding, and steel scrap treatment — contribute negligibly to this impact category. The dominant role played by lead recycling in these results is consistent with findings from the raw material production stage: in the ecoinvent dataset, primary lead production is a resource-intensive process.

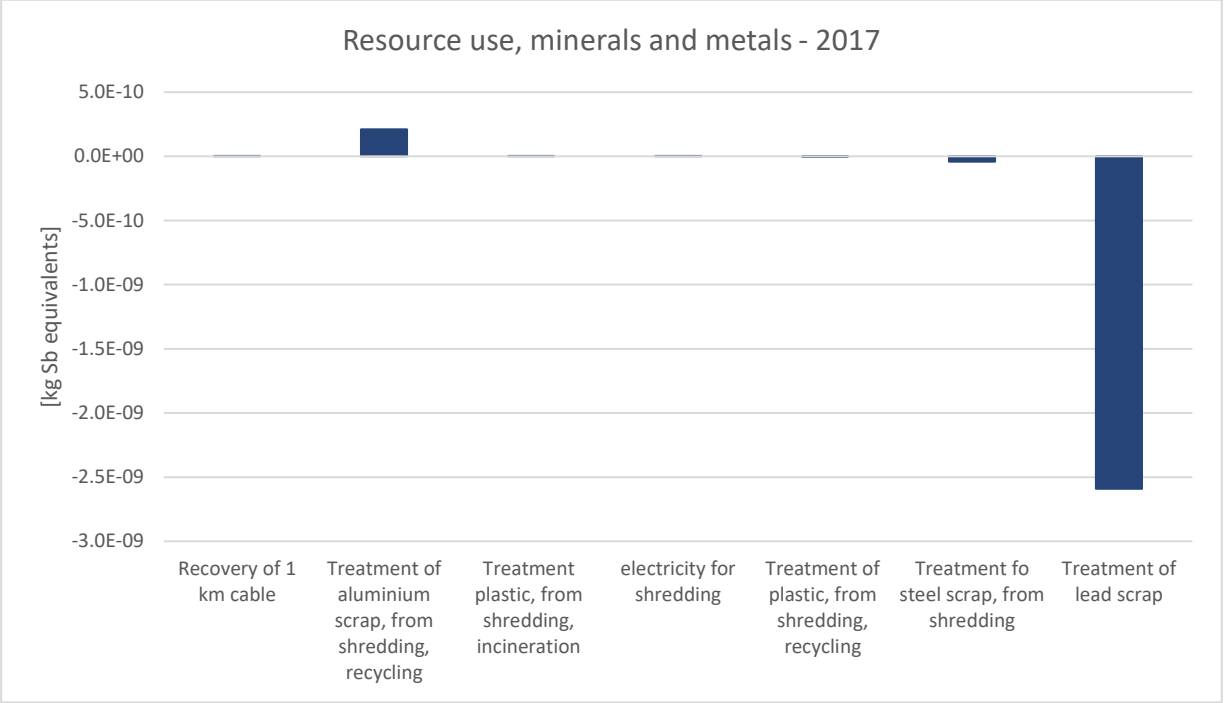


Figure 14: Resource use, minerals and metals contribution of individual end-of-life sub-processes — NEWGEN cable recycling process

1.13 LCIA comparison and Sensitivity Analysis

This chapter concludes a quantitative comparison between the NEWGEN HDVC cable and the benchmark HDVC cable. As mentioned, both conductors are made from the same material — aluminum alloy — so the two designs differ only in their insulation materials and associated additives. The NEWGEN cable uses polypropylene (PP) insulation with its corresponding additives, whereas the benchmark cable uses XLPE insulation crosslinked with the peroxide 2,5-dimethylhexane-2,5-dihydrop.

In addition to differences in insulation materials, these two cables also differ in two aspects that affect their LCIA impacts. First, during the operation and Maintenance phase, the different thermal properties of the two insulation materials result in variations in electricity transmission losses between the two insulation materials. Second, the two cables have different failure rates, with the NEWGEN cable having a slightly lower failure rate than the reference cable, which affects the impact of the operations and maintenance activities.

A sensitivity analysis will be performed in order to evaluate different scenarios including different loading conditions, alternative NEWGEN additive formulations, and different end-of-life scenarios — namely cable recycling and in-situ abandonment.

1.13.1 Comparison between the benchmark cables and the NEWGEN cable at 80% load with the same current

In this comparison, both cables are assessed under the same operating current of 1960 A, corresponding to 80% of the loading condition. Since the transmission voltage is identical (525 kV), an equal current means both cables deliver the same power, and therefore the same quantity of electricity delivered per unit of time. This condition ensures that the two cable systems provide

equivalent service, which is a prerequisite for a meaningful comparison with the functional unit defined as 1 MWh delivered at the receiving end over 1 km. Based on this, any differences between these two cables in terms of environmental impact reflect differences in their material composition and transmission losses, rather than differences in the amount of energy they carry.

Figure 15 presents the overall life cycle comparison between the benchmark (XLPE) and NEWGEN (PP) HVDC cables at 80% load with the same current, with results across the EF 3.1 impact categories.

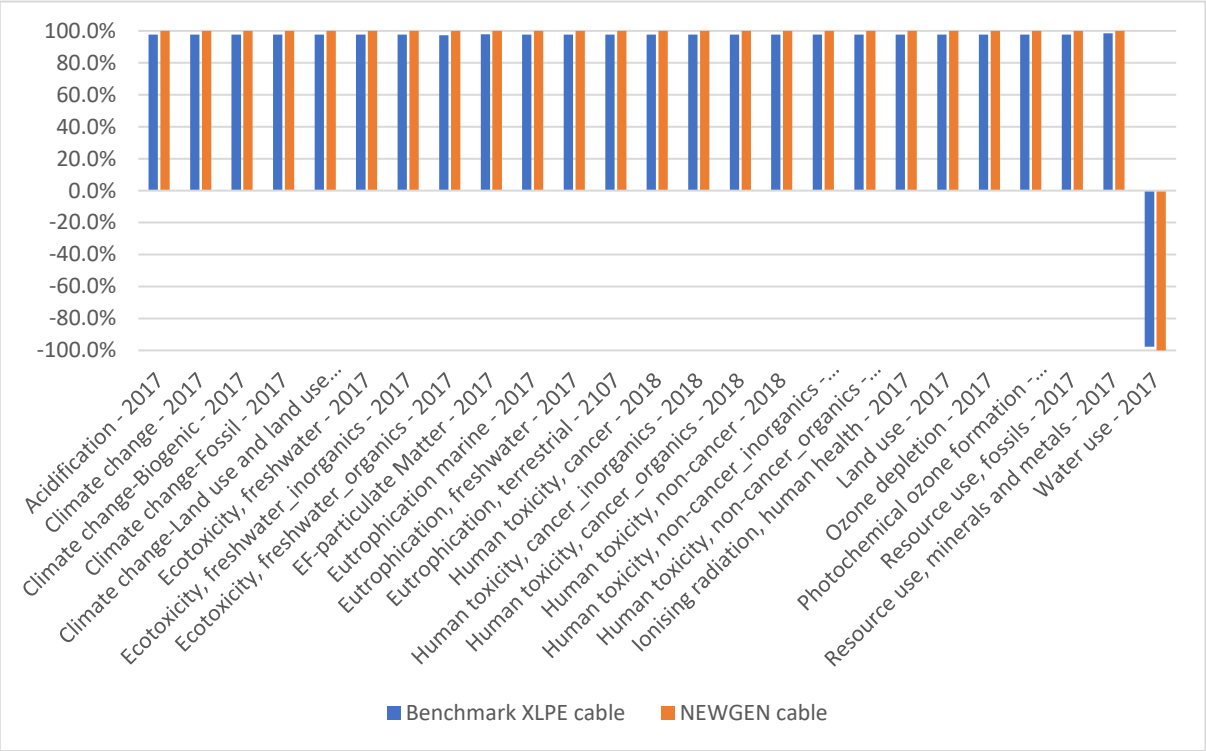


Figure 15: Overall LCIA relative result comparison - benchmark vs NEWGEN HVDC cable (80% load)

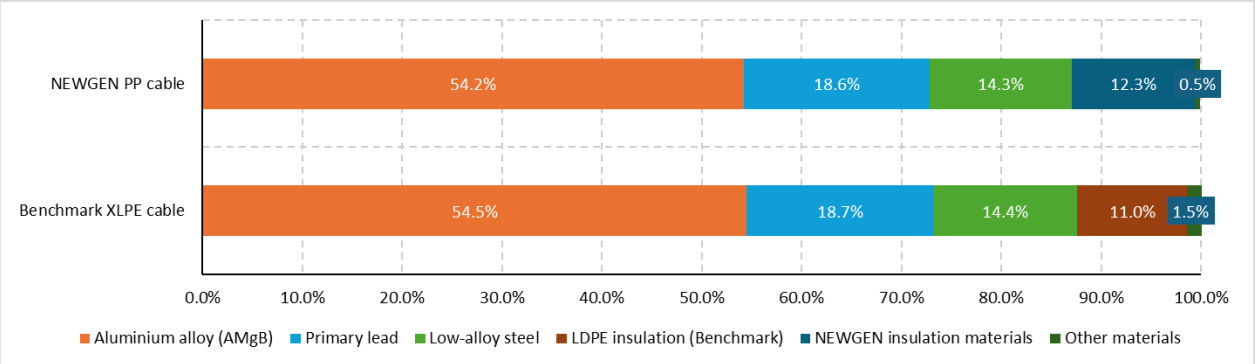


Figure 16: Contribution of raw materials to the climate change impact of the benchmark cable and the NEWGEN cable

Figure 16 compares the relative contributions of the raw materials to the climate change impact of both cable systems. The contribution pattern of both cables is nearly identical, with Aluminum raw materials accounting for about 54% of the impact, followed by Lead sheath (approx. 19%) and steel armoring (approx. 14%). The main difference lies in the insulation material: The insulation material contributes 11.0% in the benchmark cable, while the insulation material contributes 12.3% in the NEWGEN cable. The remaining material components account for less than 2% in both systems. The climate change impacts of the raw materials are almost equal, at 2.95E-05 kg CO_2 eq per FU for the NEWGEN cable and 2.94E-05 kg CO_2 eq per FU for the benchmark cable.

Figure 17 shows the relative contributions of the life-cycle stages to the impact category resource use, minerals and metals. For both cables, the use phase accounts for the largest contributor (55.6% for the benchmark cable and 56.2% for the NEWGEN cable), followed by raw materials (43.3% and 42.8%, respectively). The contribution from the use phase stems from the electricity required to compensate for transmission losses, while its supply chain involves the consumption of metals and minerals. In terms of raw materials, this impact primarily comes from primary lead. For both systems, all other life cycle phases combined account for approximately 1%. Therefore, the contribution patterns of these two cables are nearly identical.



Figure 17: Contribution of life-cycle stages to resource use, minerals and metals for the benchmark XLPE cable and the NEWGEN PP cable

1.13.2 Comparison between benchmark and NEWGEN cable at the same conductor temperature

Figure 18 presents the overall life cycle comparison between the benchmark and NEWGEN HVDC cables at 80% load, where the conductor operates at approximately 50 °C (derived from the 70 °C maximum temperature at full load). Results are normalized to the benchmark cable (100%) across the EF 3.1 impact categories.

The NEWGEN cable achieves a consistently lower environmental impact than the benchmark across all reported categories except water use, reaching approximately 85–90% of the benchmark's impact in every category. This reduction is uniform across impact categories of different physical nature. The underlying driver is that, at the same conductor temperature (50 °C at 80% load, derived from the 70 °C maximum), the NEWGEN cable operates at a lower current than the benchmark — a consequence of PP's higher thermal resistivity, which causes the conductor to reach a given temperature at a lower current(International Electrotechnical Commission 2023). This lower current results in lower delivered power, and correspondingly lower transmission losses ($P_{Joule} = I^2R$), which propagate through the functional unit normalisation to yield a lower environmental impact per MWh delivered across all categories.

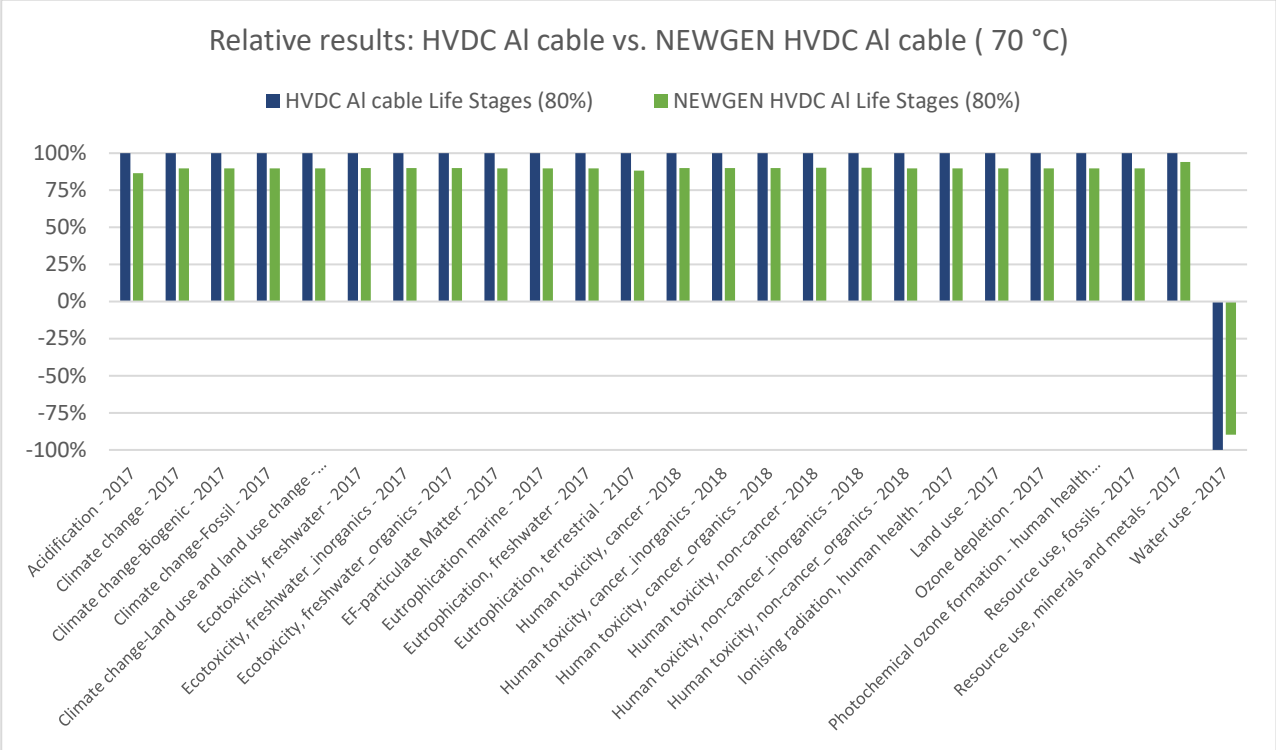


Figure 18: Relative life cycle impact comparison — benchmark vs NEWGEN cable at 80% load (T_cond = 70 °C)

1.13.3 Sensitivity analysis of NEWGEN additives

To assess whether the choice of additive influences the overall life cycle results, three additive alternatives are assessed: PE-g-MAH(x), PP-g-MAH(x), and SEBS-g-MAH. Each additive was used solely to replace the additive component in the NEWGEN insulation material, whilst retaining the PP base polymer and all other model parameters. The baseline formulation uses PP-g-MAH(x) as the additive.

Figure 19 presents the relative environmental impact of the NEWGEN insulation material produced using three different additive formulations — PE-g-MAH, PP-g-MAH (baseline), and SEBS-g-MAH across the key EF 3.1 impact categories. This result isolates the insulation material production itself from the whole model, thereby revealing more visible differences. Ecotoxicity, freshwater shows that PE-g-MAH reaches only approximately 57% of the baseline, while SEBS-g-MAH was at approximately 67% — both have significantly lower impact lower than PP-g-MAH. Climate change and Eutrophication, freshwater also show notable differences, with PE-g-MAH at approximately 89% of the baseline. For Particulate matter, Resource use fossils, and Resource use minerals & metals, the three formulations are more closely aligned (90–100%). Water use shows a notable difference in the negative direction, with PE-g-MAH generating a larger water credit than the baseline.

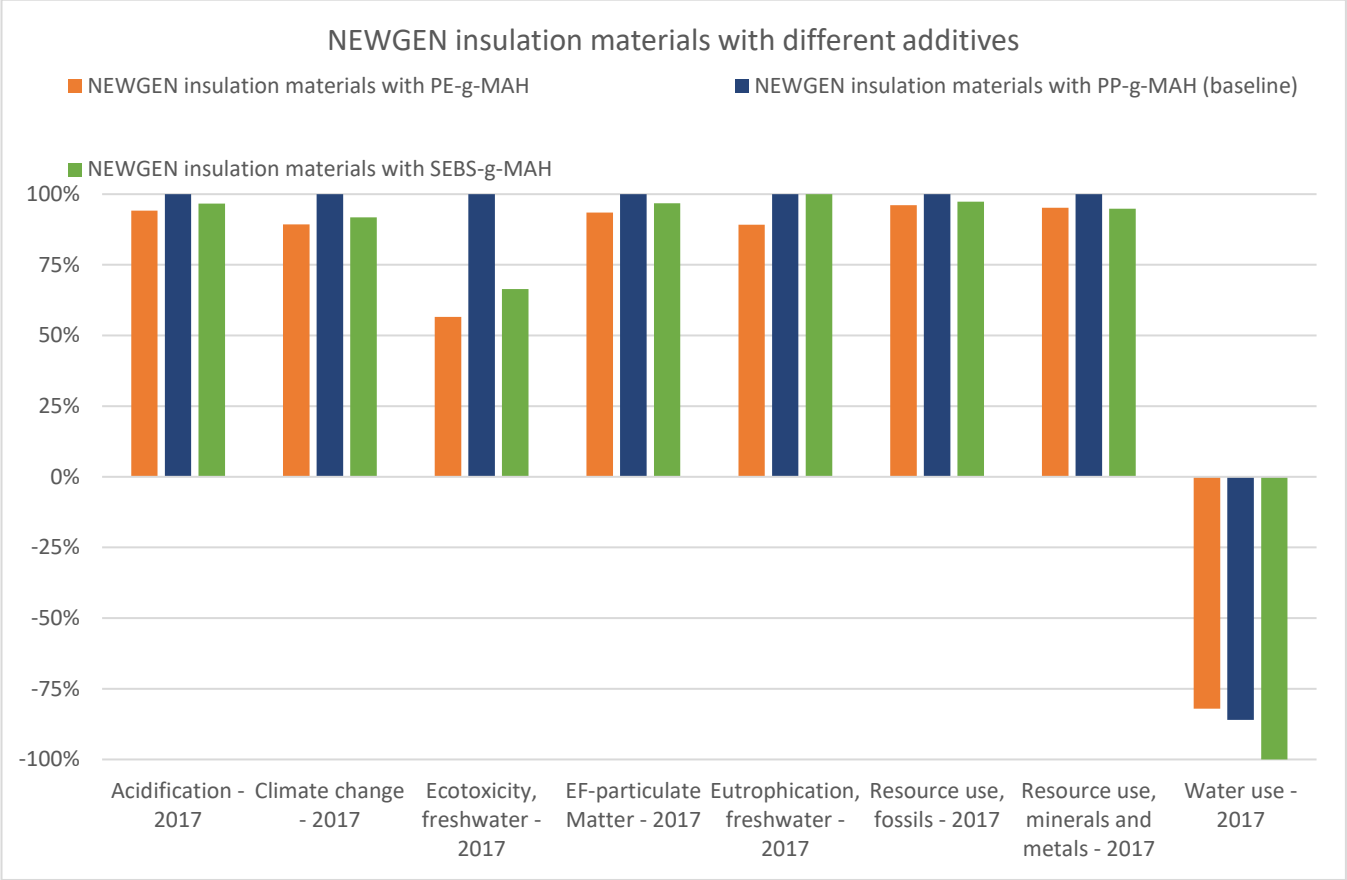


Figure 19: Relative impact results of NEWGEN cable with 3 insulation additives

1.13.4 Sensitivity analysis of end-of-life scenarios

The baseline scenario assumes that cables are recycled at the end of life, with the recycled cable materials replacing virgin materials production. To assess the sensitivity of the life-cycle analysis results to this scenario, an alternative scenario—the in-situ abandonment scenario—was also assessed; in this scenario, the cables are left on the seabed. All other model parameters remain consistent with those of the baseline scenario.

Figure 20 presents the relative LCIA of both the benchmark and NEWGEN cables under two end-of-life scenarios — in-situ abandonment and recycling across the key EF 3.1 impact categories. Across most categories all four results cluster tightly near 100%, confirming that the end-of-life scenario choice has minimal influence on the overall life cycle result for either cable.

One impact category departs from this pattern. Resource use, minerals and metals shows a visible difference: the recycling for both cables are notably lower than the abandonment scenarios, reflecting the avoided-burden credit from recovered metals — particularly lead — which is the dominant driver of this category.

The choice between recycling and abandonment affects Resource use, minerals and metals meaningfully for both cables, but does not alter the PP-vs-XLPE comparison in any category.

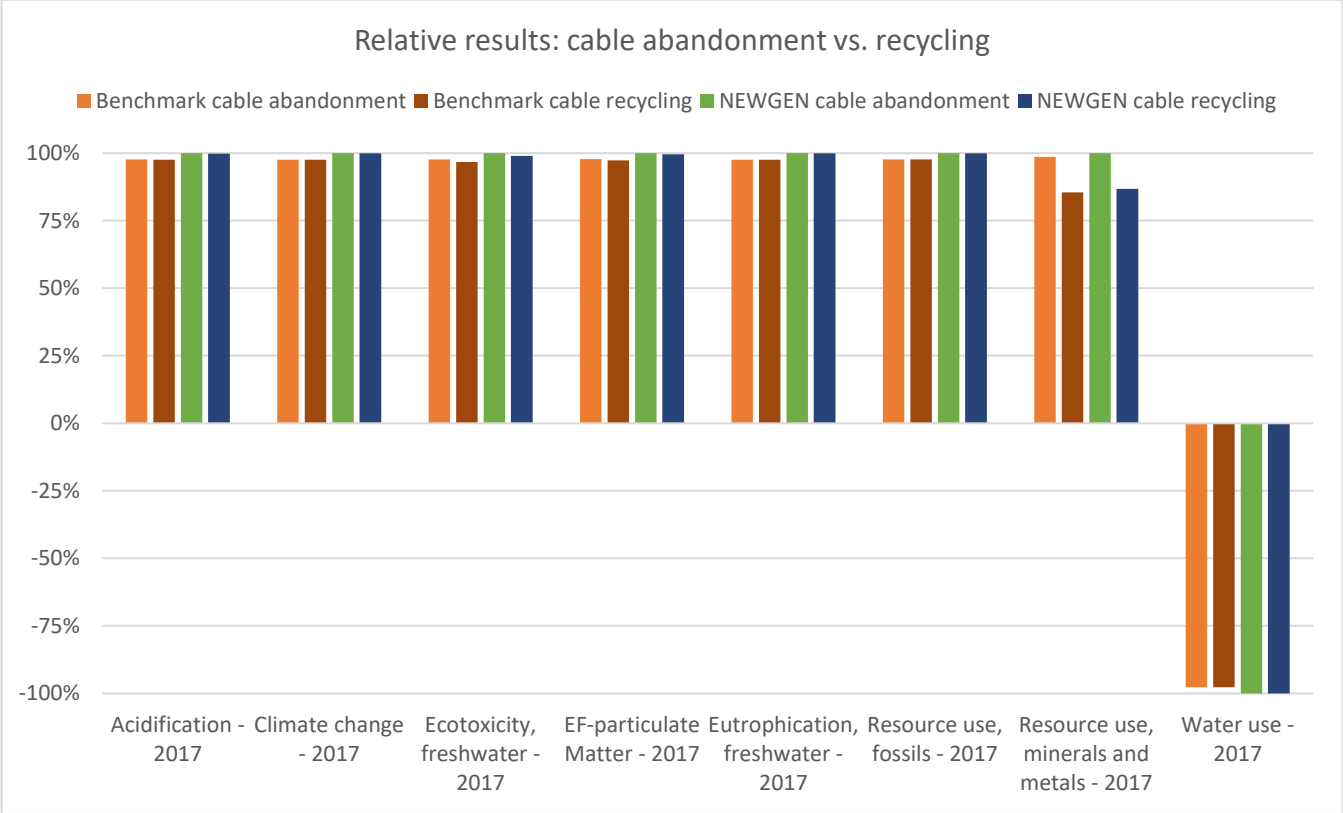


Figure 20: LCIA results of different end of life scenarios of cables

1.13.5 Sensitivity to Lifetime of cables

In the baseline scenario, the service life of the cable is assumed to be 25 years, which is consistent with the typical minimum durability guarantee for submarine cables (Ardelean und Minnebo 2015). However, in the engineering literature, the technical design life of high-voltage direct current (HVDC) cables is typically set at 40 years; Studies estimating the insulation lifetime of HVDC cables adopt a design lifetime of 40 years, with a design failure probability of 1% (Mazzanti 2023). To account for this uncertainty, this paper conducts a sensitivity analysis comparing two service life scenarios (25 years and 40 years).

Figure 21 presents the relative life cycle impact of both the benchmark and NEWGEN cables under two assumed operating lifetimes — 25 years and 40 years.

Across most categories， the results for these four scenarios are very similar, and for both cables, the 25-year lifespan scenario shows slightly higher impacts than the 40-year lifespan scenario. This is consistent with the expectation that the shorter the operational lifespan, the fewer megawatt-hours (MWh) the cable transmits over its lifecycle; consequently, fixed burdens (raw materials, manufacturing, transportation, and end-of-life disposal) must be amortized over a smaller amount of transmitted energy, thereby increasing its contribution per functional unit. However, this effect is minor because the use phase (transmission losses)—whose magnitude is proportional to operating time and, consequently, to the energy transmitted—dominates the overall impact; thus, the results per functional unit are largely unaffected by service life.

Resource use, minerals and metals is the one category where the lifetime assumption produces a clearly visible difference: the 40-year scenarios are notably lower than the 25-year scenarios. This is because this category is dominated by the fixed metal component (lead, aluminum, steel)

of the cable, which does not scale with operating time — a longer lifetime spreads this fixed burden over more delivered energy, reducing the per-FU impact substantially.

For both types of cables, across all categories, a 40-year service life results in a lower environmental impact than a 25-year service life. This is because a longer service life spreads environmental burdens (raw materials, manufacturing, transportation, and end-of-life disposal) over a greater total energy supply, thereby reducing the environmental impacts per functional unit. The effect is most pronounced in Resource use, minerals and metals, the result for a 40-year service life is approximately 85% of that for a 25-year service life.

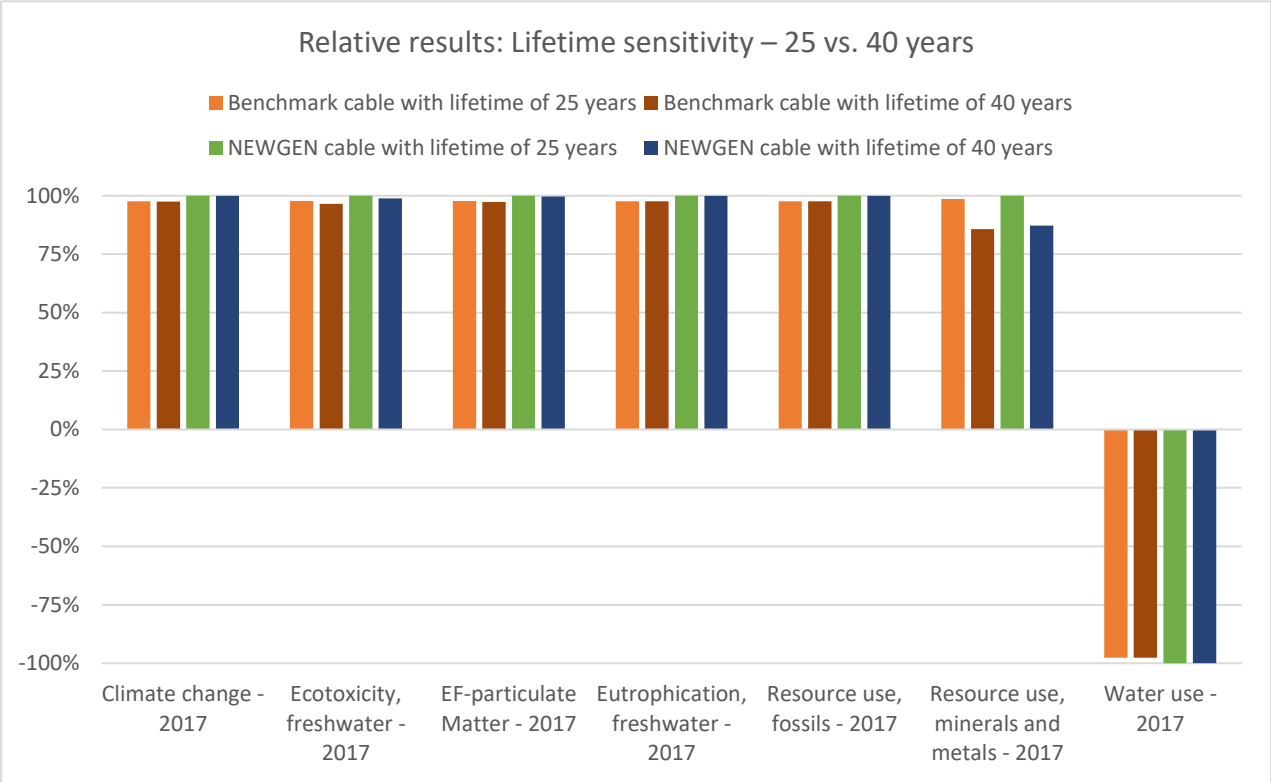


Figure 21: Relative LCA results of different polymer end of life treatment scenarios of the benchmark cable

1.14 Interpretation

This life cycle assessment shows some findings from the comparison between the NEWGEN and benchmark HVDC cables.

First off, the use phase, which is basically the electrical energy needed to cover transmission losses over the operating lifetime, leads the total life cycle impact across almost every EF 3.1 category. Other phases else, like installation, transport, and O&M, contributes far less. Under the baseline comparison (80% load, I = 1960 A, U = 525 kV), the impact of the use phase exceeds installation by four to five orders of magnitude in every impact. This backs up the pattern consistently seen in transmission-cable LCA literature, where operational losses make up the vast majority of total impact. In practical terms, the comparison between the two cables comes down almost entirely to what happens during the use phase.

Under the baseline comparison (80% load, I = 1960 A, U = 525 kV), the NEWGEN cable shows a consistently higher impact than the benchmark — about 2.3–2.4% higher across most categories, which correspond to difference in use-phase losses carrying over proportionally through all impact categories. Third, there's one impact category that stands out from this trend: Resource use, minerals and metals shows an increase of just 1.52%. That's because this category is dominated by the lead and aluminium content common to both cables. Since that metal component doesn't scale with insulation material or operational losses, this shared metal component dilutes the difference in the impacts between the two cables. Finally, water use gives a net negative (credit) result for both cables. That reflects the AWARE characterization and background water-balance modelling in the electricity and metal-production datasets rather than actual physical water savings.

At the raw materials stage, three metals account for the vast majority of the environmental impact: Aluminium conductor, lead (sheath) and Steel (armour). The polymer fraction (LDPE/PP insulation, HDPE sheath, carbon black, and peroxide crosslinker for the benchmark) is significant only in Resource use fossils and is negligible in all other categories.

During the manufacturing stage, the wire-drawing process for steel armour, as well as the electricity consumption associated with lead extrusion and conductor production drawing, are the primary contributing factors, whilst insulation extrusion makes a significant contribution to particulate matter emissions.

The use phase is affected by a single process only, which is the electricity consumption required to compensate for transmission losses. The transport, installation, operation and maintenance, and end-of-life account for only a small fraction of the total life-cycle impact. Within each category, the impact of the use phase is four to five orders of magnitude higher than that of the installation phase, whilst the operation and maintenance phase fall somewhere in between. As all four phases are influenced by common logistical factors (diesel used for vessel operation and freight transport) rather than differences in the composition of the insulation materials, their impact on both types of cable is almost identical.

Under temperature-matched conditions, the currents in these two cables are not the same. Because PP has a higher thermal resistivity than XLPE, the NEWGEN cable can reach any given temperature at a lower current: under a common upper limit of 70 °C, the current in the NEWGEN cable is approximately 2,456 A, while that in the reference cable is 2,736 A. As a result, the NEWGEN cable has lower absolute losses per meter (approximately 55.5 W/m, compared to 69 W/m for the reference cable), but its output power is also lower, since $P = U \cdot I$. Therefore, the higher losses in the reference cable are due to a heavier load under the same thermal conditions, rather than lower efficiency per unit current.

Under current-matched conditions, the comparison examines only efficiency under identical operating conditions; however, the NEWGEN cable’s higher thermal resistivity increases the conductor temperature and resistance, thereby increasing Joule losses—which is precisely the source of the approximately 2.4% disadvantage reported in this study. Under “matched temperature” conditions, the comparison measures power transmission capacity under thermal constraints; the benchmark cable can carry a higher current at the same temperature; although it transmits more power, this manifests as higher absolute losses. Neither benchmark is incorrect; they simply provide solutions to different design challenges. Only the “matched current” benchmark is compatible with the functional units used in this study, because the functional unit expressed as “1 MWh transmitted per kilometer” requires that the two cable systems provide the same service before their loads can be compared.

Three sensitivity analyses were performed to test the robustness of the baseline comparison.

NEWGEN additives scenario: PP-g-MAH vs PE-g-MAH vs SEBS-g-MAH: but these differences do not extend to the cable level. This additive constitutes a very small proportion of the insulation compound, which itself accounts for a negligible portion of the cable's overall environmental impact compared to the aluminum conductor, lead sheath, steel armor, and in-service losses—the primary contributors to the cable's total environmental impact. Therefore, the selection of additives should be based on technical standards (processability, adhesion, space charge suppression, and long-term electrical durability) rather than environmental considerations. In either case, PE-g-MAH is the more environmentally friendly choice.

End-of-life scenario*:* recycling versus in-situ abandonment. For the benchmark cable and the NEWGEN cable, abandonment yields slightly higher impact than recycling in most categories, the difference being most visible in Resource use, minerals and metals: the recycling for both cables are notably lower than the abandonment scenarios, reflecting the avoided-burden credit from recovered metals. The in-situ abandonment scenario involves only a single flow—seabed occupation (occupation of the seabed)—and does not involve material recovery or processing, nor does it generate offsetting credits. Therefore, the uncertainty in modeling this scenario is extremely low; however, correspondingly, the scope of environmental impacts it covers is relatively limited. In contrast, the recycling scenario involves multiple interacting sub-processes: cable recovery, shredding (electricity consumption), material sorting, and differentiated treatment of the various components—with each stage generating either an environmental burden or credits for avoiding such burdens. This greater complexity leads to correspondingly greater modeling uncertainty, as the results depend on assumptions regarding recycling rates, substitution rates, the quality of the recycled materials produced, and whether the recycled materials actually substitute for virgin production. However, the results show that, for both types of cables, the choice of end-of-life scenario has only a negligible impact on their overall life-cycle impact, with the sole exception of the "Resource Use, minerals and metals" category, in which the emission reduction benefits from metal recycling reduce emissions in the recycling scenario to approximately 85% of those in the disposal scenario. Across all categories, the relative rankings of the two cable designs remained unchanged. This indicates that, within the scope of this study, decisions regarding the end-of-life phase are not a key factor influencing the comparison results—however, it should be noted that, due to the narrow scope of the disposal scenario, it does not account for the potential long-term ecological impacts of leaving materials on the seabed (e.g., exposure to electromagnetic fields, habitat alteration, or the eventual degradation of materials), which fall outside the scope of the EF 3.1 impact category and are therefore not covered by this assessment.

Operating lifetime (25 versus 40 years). Overall, the 40-year lifetime yields a lower impact than the 25-year lifetime across all categories for both cables, because the longer operating period amortizes the fixed burdens — raw materials, manufacturing, transportation and end-of-life — over more delivered energy, reducing their contribution per functional unit. The effect is most presented in Resource use minerals & metals, where the fixed metal content dominates and the result of the 40-year case reaches approximately 85% of the 25-year. The relative position of the two cables is preserved under both lifetime assumptions.

1.15 Limitations and Conclusions

Under benchmark comparison conditions (80% load, matched current of 1,960 A and 525 kV, with recycling after end-of-life), the environmental impacts of the benchmark cable are approximately 2.3–2.4% lower than those of the NEWGEN PP cable in most aspects of EF 3.1 impact categories. This difference is consistent across all categories and can be traced to the use phase—which accounts for the dominant share of the overall impact—where the discrepancy is driven by differences in transmission losses between the two designs. The smallest difference

(1.52%) is observed in the Resource use, minerals, and metals category, reflecting the similar metal content shared by both cable types.

This ranking remains stable across all three sensitivity analyses (additive formulation, end-of-life scenarios, and operational lifespan), and there are no reversals in category rankings under any scenario. However, the ranking is somewhat sensitive to the choice of comparison benchmark: if matched conductor temperature rather than matched current is used as the benchmark, the results are reversed, and the magnitude of the difference is small regardless of the benchmark used.

The margin is narrow enough that it should be read as approximate parity with a slight edge to the benchmark, rather than as a decisive result. Furthermore, this comparison does not cover characteristics outside the scope of the EF 3.1 classification that may influence material selection—particularly the recyclability of polypropylene (PP) as a thermoplastic. As shown in this study, PP avoids the burden of blending with virgin high-density polyethylene (HDPE) present in the cross-linked polyethylene (XLPE) recycling process, while also eliminating the peroxide cross-linking and degassing steps required for XLPE.

Parts of the inventory rest on estimates rather than measured data. The cable joint material inventory (approximately 575 kg per joint) is an estimate; no kilogram-level breakdown is publicly available for 525 kV HVDC repair joints. The load factor is likewise an assumption, as no duty-cycle data exists for a link of this voltage class.

The insulation internal failure rate provided by the University of Bologna is derived for a 40-year service life, whereas this study also assesses a 25-year lifetime scenario. Applying a rate derived for one service period to a shorter one introduces uncertainty, particularly given that the PP failure rate follows a decreasing hazard function ($\beta < 1$), for which the instantaneous rate varies with service age.

Finally, the actual failure rate depends on cable length, route characteristics, burial depth, and local marine activity. Since the functional unit is defined in kilometers, these route-related factors cannot be accounted for in the current model; therefore, the failure rate is applied uniformly along the entire length of the cable.

2. Material Circularity Indicator Assessment (MCI)

To complement the environmental assessment, a supplementary circularity analysis was conducted for the benchmark XLPE and NEWGEN PP cable systems. The assessment focuses on material consumption and recovery, providing an additional perspective on resource efficiency within the overall LCSA framework.

2.1 Methodology and scope

The assessment was conducted using the GreenDelta Circularity Package (2026) for openLCA, applying the Material Circularity Indicator (MCI). The package extends the ecoinvent 3.12 Cut-off database with dedicated flows for tracking material inputs, recovery and waste throughout the supply chain. As no additional circularity flows were assigned to the foreground cable processes, the analysis relies on the available background data and provides a screening-level assessment rather than a direct measure of the cables' physical recyclability.

The indicator considers virgin material consumption, material recovery, recycling-related losses and product utility (Ellen MacArthur Foundation & Granta Design, 2019).

$$MCI = 1 - LFI \cdot F(X)$$

where LFI represents the Linear Flow Index and F(X) accounts for the relative lifetime and utility of the product.

The Linear Flow Index (LFI) is calculated as:

$$LFI = \frac{V + M}{2M + \frac{W_f + W_c}{2}}$$

where:

- M = total material input;
- V = virgin material input;
- W= M−R_{recov} non-recovered material;
- W_f = waste from feedstock production for the next life cycl
- W_c = waste from recycling processes

The utility factor accounts for the relative lifetime and use of the product:

$$X = \frac{L}{L_{av}} \cdot \frac{U}{U_{av}}$$

where L and U represent product lifetime and number of uses, respectively, while the subscript av denotes the corresponding industry averages. The correction factor is defined as F(X)=0.9/X.

Both cable systems were considered using the functional unit of 1 MWh delivered and a reference period of 25 years. Product and reference lifetimes were both assumed to be 25 years, with identical utility assumptions (X = 1).

The calculation uses circularity flows from the linked background datasets, including upstream material flows associated with electricity consumption during operation. The NEWGEN results were estimated by scaling the benchmark circularity inventory according to the difference in use-phase electricity consumption, while keeping the remaining life-cycle contributions unchanged.

2.2 Circularity results and interpretation

The circularity results for both cable systems are presented in Table 24, including the main material-flow indicators used to calculate the MCI. The benchmark results were obtained directly from the Circularity Package, while the NEWGEN values represent an indicative estimate based on the approach described above.

Table 24 Circularity assessment results for the benchmark and NEWGEN cable systems.

Circularity indicator	Unit	Benchmark	NEWGEN (estimated)
Total material input (M)	kg/FU	3.363×10^{-3}	3.442×10^{-3}
Virgin material input (V)	kg/FU	2.967×10^{-3}	3.036×10^{-3}
Recycled material input	kg/FU	3.139×10^{-5}	3.213×10^{-5}
Recovered material (Rrecov)	kg/FU	3.277×10^{-3}	3.357×10^{-3}
Waste from feedstock production (Wf)	kg/FU	4.489×10^{-8}	4.533×10^{-8}
Waste from recycling processes (Wc)	kg/FU	4.846×10^{-8}	4.923×10^{-8}
Material Circularity Indicator (MCI)	–	**0.5915**	**0.5920**

The benchmark cable achieves an MCI of 0.5915, while the estimated value for NEWGEN is 0.5920. On the MCI scale of 0 to 1, where higher values indicate greater material circularity, these results suggest a similar circularity profile for both modelled product systems.

Virgin materials account for approximately 88% of the total material input in the benchmark model. At the same time, the calculation includes substantial recovered material flows originating from the background supply chains. The contribution analysis shows that the use phase accounts for approximately 95.6% of total material input and 99.9% of recovered material, mainly through upstream processes associated with electricity supply.

The marginal difference between the two MCI values is primarily driven by the adjusted use-phase electricity consumption. As the assessment was intended to provide an overall perspective on circularity at the product-system level, the results mainly reflect material flows captured by the background database rather than the physical recyclability of individual cable components.

2.3 Conclusion and recommendation

The screening-level assessment indicates nearly identical MCI values for both cable systems, with results largely driven by background material flows associated with electricity supply.

A more comprehensive, material-level circularity assessment is recommended once additional data on recycled content and actual end-of-life recovery rates become available. This would allow foreground-specific circularity flows to be incorporated and differences between the two cable technologies to be examined in greater detail.

3. Life Cycle Costing

In this section, the life cycle costing (LCC) of the benchmark and NEWGEN HVDC cable systems is presented. As explained in the LCA, the NEWGEN concept is a cable system that utilizes PP insulation with space-charge-control additives as a new technology. The LCC analysis compares the cost of the reference and the innovative HVDC cable system over their lifetime, considering the acquisition, operating and maintaining, reliability-related costs, maintenance, repair and replacement, and end-of-life costs.

In addition, the timing of life-cycle costs is assessed by allocating expenditures to the years in which they occur and discounting future costs to present value.

3.1 Goal of Life Costing

The purpose of the LCC study is to provide a comparative economic assessment of the benchmark and NEWGEN HVDC cable systems over their life cycle. The study identifies the main differences in cost between the two cable concepts and evaluates the impacts of technical performance on the LCC, especially transmission losses and reliability-related O&M.

The assessment is intended as a comparative technology-level analysis and not as a complete project-level estimate of costs for an HVDC infrastructure project. The study aims to identify and compare the main cost drivers and explaining the differences in detail.

3.2 Functional unit and reference period

The functional unit used in the LCC is the same as the one used in the LCA assessment. It implies that 1 MWh of electricity transferred through the HVDC cable system during the reference period of 25 years is under consideration. The same period is considered for the NEWGEN and benchmark cables.

3.3 Scope of the Life Cycle Costing

The LCC assessment employs a prospective comparative approach: the economic performance of the benchmark and NEWGEN HVDC cable is compared with regard to a 25-year service life. The system boundary of the assessment comprises raw materials, cable manufacturing, transportation, installation, use-phase electricity losses, operation and maintenance, and end-of-life activities.

The timing of costs is explicitly considered by allocating expenditures to the years in which they occur and discounting future costs to present value. Reliability-related O&M is modelled using constant annual failure rates over the 25-year reference period, with cable-specific failure rates applied to the benchmark and NEWGEN systems.

3.4 System boundaries and cost components

The system boundaries of the LCC follow those applied to the LCA in order to establish a consistent comparison between the benchmark and NEWGEN cable systems. The assessment comprises the supply of raw materials, cable manufacturing, transportation, installation, use-phase electricity losses, operation and maintenance, and end-of-life treatment. Costs and

revenues are thus allocated to the corresponding life cycle stages, which are subsequently assessed based on the same functional basis for both cable concepts.

The assessment focuses on cost components directly represented in the cable life-cycle model and should not be interpreted as a complete project-level cost estimate for an HVDC infrastructure project.

3.5 Limitations of the study

The LCC is intended to provide a comparison and outlook on the benchmark and the NEWGEN cable systems, and it should not be considered as an in-depth analysis of the investment or project financing. The same modeling assumptions and unit prices were used for comparable materials and activities for the two cable systems whenever possible.

The prices are based on publicly available market information, industry partner information, and project-specific assumptions. Therefore, the prices should be considered indicative values. The prices of materials, electricity, fuel, and scrap metal can vary significantly over time. In the time-dependent analysis of LCC, the change in costs is calculated using a general inflation assumption, which represents nominal costs. The costs are discounted separately to calculate the present values. Thus, specific future prices are not assumed.

The following simplifying assumptions are applied:

- Taxes, VAT, financing costs and company overheads are excluded.
- Common price assumptions are used for equivalent materials and activities. NEWGEN costs may rely on commercial proxies, experimental data and current market information.
- The assessment does not cover the full CAPEX and OPEX of an HVDC project. Infrastructure-level costs are excluded unless stated otherwise.
- End-of-life modelling includes recovery, shredding and scrap revenues; downstream recycling costs are excluded.
- Reliability-related O&M is modelled using constant annual failure rates over the reference period. No age-dependent increase in failure probability is assumed.
- Economic losses from supply interruptions, downtime and lost transmission capacity are excluded unless included in the O&M model.

3.6 Cost inventory

The LCC inventory includes material costs, costs of production and energy, costs of operation and maintenance, and costs of end-of-life phase-out. To the extent possible, analogous price assumptions were used for the comparison of the benchmark and NEWGEN cable systems. Cable-specific prices were used when the material or technological differences between the compared cables are significant.

Table 25 Generic material prices.

Material	Unit price	Source
Conductor aluminum	1,300 $/t	Public data
Jacketing PE	1.5 €/kg	Maillefer
Metal jacketing	516 €/t	Eurofer
Steel wire	620 €/t	MEPS

The same unit prices were applied to both systems for common material items, which are indicated in the benchmark and NEWGEN designs, whereas the corresponding material quantities differ according to the respective cable configuration.

Table 26 Benchmark insulation prices.

Material	Unit price	Source
Peroxide insulation	4,000 €/t	Maillefer
Peroxide SC XLPE	6,000 €/t	Maillefer

The benchmark cable utilizes peroxide cross-linked XLPE insulation. The given industrial project partner provided the prices for the main insulation and semi conductive XLPE materials.

Meanwhile, the NEWGEN insulation system is based on a PP formulation, and thus, the different price inventory should be applied in comparison with the XLPE-based benchmark insulation. The prices of the principal polymer components were collected from the freely available market information and project data.

Table 27 NEWGEN insulation prices.

Material	Unit price	Source
PP random copolymer, Moplen RP210G	1,366 $/t	Plas.com
Thermoplastic polyolefin elastomer, Hifax CA 7441 A	2,465 $/t	Plastic-price.com
Propylene-based elastomer, Vistamaxx 6102FL	2,135 $/t	Plastic-price.com

In addition to the main polymer components, the NEWGEN insulation contains a PP-g-MAH additive, which was specifically developed as part of the project. Since this is an experimental material and not a commercial one, its price was estimated based on the price of the input materials used to produce it. In particular, the current project uses a PP maleic anhydride-based additive.

The prices used for this material were compared to the available information regarding the European market and were found to be in a reasonable range for the given market. For the case of ODCB, the price used was conservatively selected above the market value.

Table 28 NEWGEN PP-g-MAH additive precursor prices.

Material	Unit price	Source
Acetone	1.08 €/kg	European market / Eurostat COMEXT
Liquid nitrogen	0.13 €/kg	European bulk industrial gas market
Maleic anhydride	1.26 €/kg	European market data
o-Dichlorobenzene (ODCB)	2.04 €/kg	Price assumption, validated against European market data
PP granulate	1.41 €/kg	European polymer market data

The manufacturing costs are calculated from the specific demands of energy and auxiliary materials of the corresponding production process. A common electricity price was assumed for both cable systems, whereas prices for auxiliary materials and waste treatment were based on publicly available market and fee data.

Table 29 Manufacturing costs.

Material	Unit price	Source
Electricity	276 €/MWh	Benchmark & NEWGEN
Liquid nitrogen	0.13 €/kg	Benchmark
Water	1.75 €/kg	Benchmark
Hazardous waste treatment	3,850 €/t	Benchmark

Transportation costs were modelled using publicly available freight price data. The same transport price assumptions were applied to the benchmark and NEWGEN cable systems.

Table 30 Transportation cost.

Material	Unit price	Source
Container transport	119.76 $ / 40-ft container	40-ft container payload: 28.8 t
Lorry transport	0.20 €/t·km	Road freight

Installation costs are based on the diesel consumption related to cable installation activities. The same diesel price assumption was applied to both cable systems.

Table 31 Installation cost.

Material	Unit price	Source
Diesel	1.78 €/kg	Benchmark & NEWGEN

Operation and maintenance costs include the materials required for cable joint repair or replacement activities as well as diesel consumption associated with maintenance operations. Material prices were derived from publicly available commodity market data and supplier information.

Table 32 Operation and maintenance costs

Material	Unit price	Application	Source
Aluminium	2.77 €/kg	Cable joint	LME / Trading Economics
Bitumen	0.52 €/kg	Cable joint	Argus Media
Copper	12.12 €/kg	Cable joint	London Metal Exchange
Lead	1.59 €/kg	Cable joint	London Metal Exchange
Silicone	20.00 €/kg	Cable joint	Lindemann Silikon
Steel	0.71 €/kg	Cable joint	EUROMETAL / Fastmarkets
Diesel	1.78 €/kg	O&M activities	European Commission, Weekly Oil Bulletin

Use-phase costs are based on the electricity losses occurring during cable operation. The same electricity price assumption is applied to both the benchmark and NEWGEN cable systems, while differences in use-phase costs result from the respective cable losses.

Table 33 Use phase cost

Cost parameter	Unit price	Applied to	Source
Electricity	90 €/MWh	Benchmark & NEWGEN	IEA, Electricity 2026 – Prices

IEA reports an average EU wholesale electricity price of about USD 95/MWh in 2025, with 2026 futures at roughly the same level.

A simplified economic approach was applied on the end-of-life stage. The costs for cable recovery from the sea and subsequent shredding were considered directly. The revenues from the recovered materials were calculated using the corresponding scrap market values and modelled as negative costs, thus reducing the total life cycle costs.

No downstream costs for cable recycling were considered. The market value of the recovered scrap was assumed to represent the economic value of the material delivered to the recycling market. The material losses during the shredding process and the corresponding recycling shares are accounted for separately in the openLCA model.

Table 34 End of life stage costs

Type	Cost parameter / material	Unit price / revenue	Application	Source
Cost	Diesel	1.78 €/kg	Cable recovery from seabed	European Commission, Weekly Oil Bulletin
Cost	Electricity	276 €/MWh	Cable shredding	Eurostat, *Electricity price statistics*
Revenue	Aluminium scrap	600 $/t	Sale of recovered aluminium	ScrapMonster, European scrap prices
Revenue	Lead scrap	441 $/t	Sale of recovered lead	Market price assumption
Revenue	Plastic scrap	467 €/t	Sale of recyclable plastic fraction	European Environment Agency
Revenue	Steel scrap	130 $/t	Sale of recovered steel	ScrapMonster, European scrap prices

The revenue generated from recovered materials is entered in the LCC model with a negative sign. Consequently, higher material recovery rates increase the end-of-life credit, whereas recovery and shredding activities contribute positively to the end-of-life costs.

The source for the lead scrap value of 441 $/t should be added once the corresponding market reference used in the model is identified.

3.7 LCC Calculation Approach

Baseline life-cycle cost contributions were first calculated without considering the timing of cost occurrence, allowing the main economic drivers and differences between the benchmark and NEWGEN cable systems to be identified.

The LCC model was implemented in openLCA by extending the product-system structure developed for the environmental LCA with cost and revenue data. Material costs were derived from material quantities and unit prices, while manufacturing costs were primarily based on process energy demand and electricity prices. Use-phase costs represent the economic value of transmission losses, and end-of-life costs include treatment and recovery activities, with revenues from recovered materials accounted for as negative costs. Cable inventories were modelled on a 1 km basis and scaled to the functional unit according to the general calculation methodology.

The baseline calculations and subsequent parameter analyses were carried out in openLCA. Results were exported to Microsoft Excel for aggregation, comparison and graphical presentation.

3.8 Baseline LCC Results

The baseline LCC was calculated using a common input power of 1,029 MW for both cable systems, allowing the benchmark XLPE and NEWGEN PP cables to be compared under identical operating conditions.

At this input power, the calculated transmission losses are approximately 31.99 W/m for the benchmark XLPE cable and 32.77 W/m for the NEWGEN PP cable, corresponding to about 2.4% higher losses for NEWGEN. These losses directly affect the electricity-loss costs and therefore the use-phase contribution to the LCC.

The baseline results represent the economic comparison before applying time-dependent financial effects such as inflation and discounting.

3.9 Undiscounted baseline results

Table 35 presents the undiscounted LCC results by life cycle stage. Values are expressed per functional unit. The percentage contributions indicate the relative importance of each stage within the respective cable system.

Table 35. Undiscounted baseline LCC results for the benchmark and NEWGEN cable systems

Life cycle stage	Benchmark [EUR/FU]	Contribution	NEWGEN [EUR/FU]	Contribution	Difference
Raw materials	1.693E−5	0.60%	8.864E−6	0.31%	−47.6%
Manufacturing	3.570E−6	0.13%	4.227E−6	0.15%	+18.4%
Transportation	1.796E−6	0.06%	1.572E−6	0.05%	−12.5%
Installation	2.121E−7	0.007%	2.121E−7	0.007%	0.0%
Use phase	2.798E−3	98.90%	2.867E−3	99.25%	+2.5%
O&M	6.284E−6	0.22%	6.018E−6	0.21%	−4.2%
End-of-life	2.330E−6	0.08%	7.989E−7	0.03%	−65.7%
Total LCC	**2.829E−3**	**100%**	**2.888E−3**	**100%**	**+2.1%**

The baseline results show a slightly higher total life-cycle cost for the NEWGEN cable under the selected operating condition. The total LCC is approximately 0.00283 EUR/FU for the benchmark and 0.00289 EUR/FU for NEWGEN, corresponding to an increase of approximately 2.1%.

The result is strongly dominated by the use phase, which accounts for approximately 98.9% of the benchmark LCC and 99.3% of the NEWGEN LCC. At the common input power of 1,029 MW, transmission losses are 31.99 W/m for the benchmark and 32.77 W/m for NEWGEN. This approximately 2.4% difference results in a use-phase cost around 2.5% higher for NEWGEN and largely determines the overall LCC difference.

The remaining life-cycle stages contribute only a small share of total costs but show larger relative differences between the two cable designs. Compared with the benchmark, NEWGEN has approximately 47.6% lower raw-material costs, 18.4% higher manufacturing costs, 12.5% lower transportation costs, 4.2% lower O&M costs, and 65.7% lower end-of-life costs. Installation costs are effectively identical.

Excluding the use phase, the combined cost of the remaining stages is approximately 30.3% lower for NEWGEN. However, these stages represent only about 1.1% of the benchmark LCC and 0.8% of the NEWGEN LCC, limiting their influence on the total result.

3.10 Temporal modelling and discounting

In order to integrate the timing of life-cycle costs, the baseline LCC was spread out over To account for the timing of life-cycle costs, the baseline LCC was distributed over the 25-year reference period. Raw material, manufacturing, transportation and installation costs were allocated to Year 0. Use-phase and O&M costs were distributed over Years 1–25, while end-of-life costs were allocated to Year 25.

The same time-value assumptions were applied to both the benchmark and the NEWGEN cable system. Baseline costs were expressed in reference-year prices. For future years, costs were escalated using an annual inflation rate of 2%, corresponding to the symmetric medium-term inflation target of the European Central Bank (ECB, 2026). Future nominal costs were subsequently discounted to present value using a nominal discount rate of 6%.

The combination of a 2% inflation rate and a 6% nominal discount rate corresponds to an effective real discount rate of approximately 3.92%.

$$r_{real} = \frac{1 + 0.06}{1 + 0.02} - 1 = 3.92\%$$

This value is close to the 4% real financial discount rate specified by the European Commission as an indicative benchmark for public investment operations under its cost-benefit framework (EC, 2014). It is used here as a reference assumption rather than as a cable-sector-specific requirement.

For a cost expressed in reference-year prices, the annual present-value adjustment factor applied in the model was therefore:

$$DF_t = \left(\frac{1 + 0.02}{1 + 0.06}\right)^t$$

where *t* represents the year of the 25-year reference period. Future costs are first escalated according to the assumed 2% inflation rate and subsequently discounted to present value using the 6% nominal discount rate. Costs occurring in Year 0 are not adjusted, while future use-phase, O&M and end-of-life contributions progressively decrease in present-value terms.

Table 36 Time-dependent LCC Parameters

Parameter	Value
Reference period	25 years
Inflation rate	2.0%
Nominal discount rate	6.0%
Effective real discount rate	3.92%

3.11 Time-dependent LCC results

Table 37 compares the undiscounted baseline LCC with the discounted life-cycle cost over the 25-year reference period. A constant annual failure rate is applied throughout the service life, consistent with the available reliability data.

Table 37 Time-dependent LCC results represented in EUR/FU

Metric, EUR/FU	Benchmark	NEWGEN	NEWGEN vs Benchmark
Undiscounted baseline LCC	2.829×10^{-3}	2.888×10^{-3}	+2.1%
Discounted LCC – constant reliability	1.790×10^{-3}	1.825×10^{-3}	+2.0%

Discounting reduces the cumulative 25-year LCC by approximately 36.8% for both cable systems, while having almost no effect on their relative difference. After discounting, the NEWGEN cable remains approximately 2.0% higher in LCC than the benchmark.

Figure 22 shows the annual discounted LCC contributions of the two cable systems over the 25-year reference period. Raw material, manufacturing, transportation, and installation costs occur

in Year 0, while use-phase and O&M costs are distributed over Years 1–25. End-of-life costs are allocated to Year 25. A constant annual failure rate is assumed throughout the service life. Future costs progressively decrease in present-value terms due to discounting.

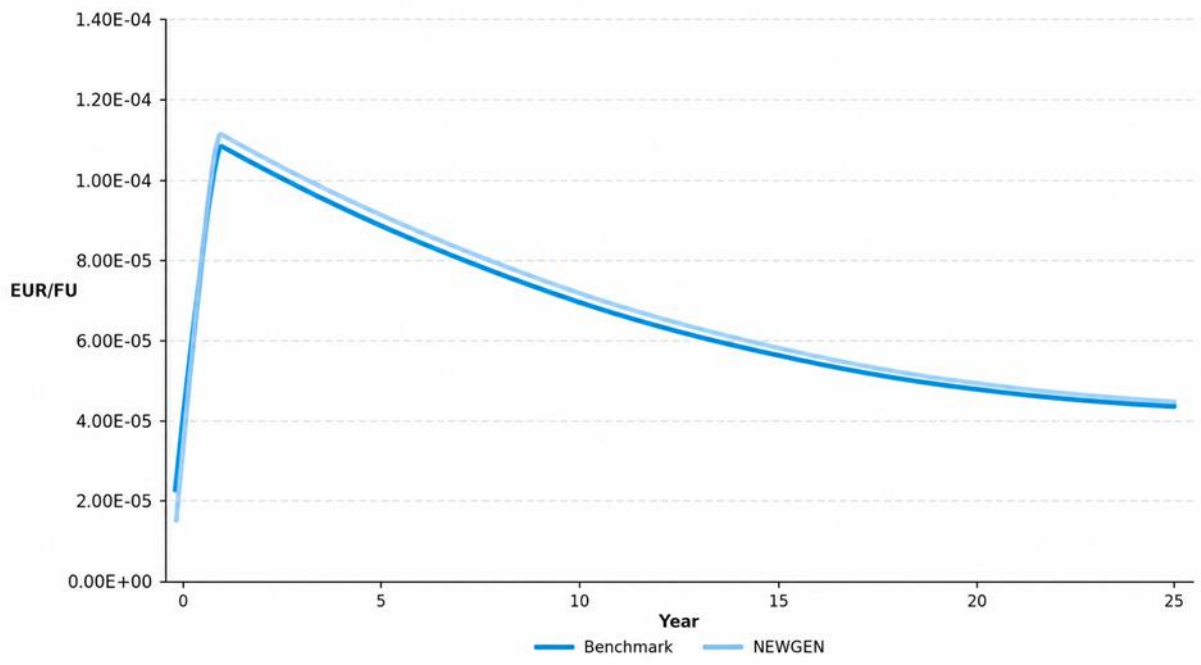


Figure 22 Annual present-value-adjusted LCC over the 25-year reference period

In Year 0, the NEWGEN cable shows lower costs than the benchmark due to its lower combined upfront life-cycle costs. From Year 1 onward, however, its annual discounted costs are slightly higher, mainly due to the higher electricity-loss costs during operation. The similar development of both curves indicates that discounting affects the two cable systems in a comparable way and therefore has little influence on their relative difference. Overall, the discounted 25-year LCC of NEWGEN remains approximately 2.0% higher than that of the benchmark.

3.12 Conclusion and recommendations

Under the applied cost inventory, transmission-loss-related use-phase costs remain the dominant economic driver. Reliability-related O&M represents only a small share of the total LCC and is modelled using constant annual failure rates over the reference period.

Further sensitivity analysis should therefore focus primarily on operating conditions and electricity prices, as these parameters directly influence the dominant use-phase contribution. More detailed age-dependent reliability modelling could be considered in future assessments if corresponding failure data become available.

Overall, the NEWGEN concept shows a slightly higher modelled LCC under the assessed operating conditions. This result is primarily driven by the assumed transmission losses at the common input power of 1,029 MW and should therefore be interpreted in relation to the selected operating conditions rather than as a general cost disadvantage independent of cable loading and thermal constraints.

4. Social Life Cycle Assessment

This section provides the step-by-step application of the approach called Social Life Cycle Assessment (S-LCA) to the benchmark and NEWGEN HVDC cable system. In addition to the environmental and economic impact analyses, the potential social risks related to the material sourcing, manufacturing, transport, installation, operation and maintenance, and end-of-life process were assessed.

4.1 Goal of S-LCA

The aim of the S-LCA is to evaluate whether the NEWGEN cable may lead to a significant change in the potential social risk compared to the benchmark one. The main emphasis is put on the differences deriving from the introduction of a new material concept replacing the conventional insulation with the NEWGEN PP-based one.

Particular attention is paid to the determination of life-cycle stages, materials, and upstream economic activities driving the social-risk potential of both cables under study. The comparison is made to identify the re-location of social risks rather than the extent to which they affect selected suppliers or production sites.

As the analysis was performed based only on PSILCA data, and no additional information was provided on the social performance of particular sites and suppliers involved in the cable manufacturing process, these results are to be seen as indicative only. They are to help identify potential areas of concern in the supply chains of both cables under comparison.

4.2 Functional unit and reference period

The S-LCA uses the same functional unit as the environmental LCA and LCC: 1 MWh of electricity delivered via the HVDC cable system over a reference service life of 25 years. Material and activity inventories that were initially drawn up for 1 km of cable are normalized using the same technical assumptions to ensure that the benchmark and NEWGEN systems can be compared.

Electricity transmission during operation is not a distinct social inventory. Nevertheless, the common functional unit is retained to guarantee that the environmental, economic and social assessments are comparable.

4.3 Scope of the S-LCA

The S-LCA provides a screening-level assessment of potential social risks associated with the life cycles of the benchmark and NEWGEN cable systems, including the supply chains. It covers issues of relevance to raw materials, manufacturing, transportation, installation, operation and maintenance, and end-of-life. Labour, human rights, resource-related and governance aspects are considered. Electricity transmission associated with operation is not modelled as a separate social inventory.

Rather than assessing individual companies or suppliers, the analysis aims to identify potential social-risk hotspots and complement the environmental LCA and LCC results.

4.4 System boundaries

The system scope is divided into the key life-cycle stages: material extraction and processing, manufacturing, transport and distribution, installation, operation and maintenance (O&M), and end-of-life treatment, including recycling.

Electricity distribution during the period of use is not considered since the scope of the S-LCA is focused on material and service related supply-chains, whereas the electricity supply itself is not in the focus of this study. The O&M of the electrical power transmission facility is included in the system boundary; however, the materials related to the maintenance and replacement of the cables including transportation, manufacturing and end-of-life treatment where relevant are included.

The same system scope is applied for the NEWGEN and the benchmark cable system, in order to allow a meaningful comparison.

4.5 Limitations of the study

The assessment is based primarily on PSILCA country-sector data, reflecting potential social risks rather than actual conditions at production sites or suppliers. The resolution of the assessment, in terms of both geographical and sectoral detail, may limit the extent to which information specific to a particular production site or supplier can be incorporated: in cases where this information is not available, allocations are made on the basis of representative country-sector activities or, more generally, economic sectors.

The contribution of a process is determined by both the economic activity embodied in the model and the social-risk intensity of a corresponding PSILCA sector. A high contribution should not necessarily be associated with a particularly large physical material or energy input. Moreover, a significant share of "No data" in a number of indicators constrains the interpretation of those social themes.

The results are primarily intended to facilitate comparative assessment and identification of hotspots. More detailed conclusions about individual suppliers or production sites would require primary social data and more detailed sourcing information.

4.6 Data source and modelling approach

The S-LCA was modelled using the Developer version of PSILCA 4.0. Foreground activities were related to PSILCA country-sector processes via monetary inputs, mainly based on the economic data from the LCC. Physical material quantities were converted to monetary values using the corresponding unit prices, and transport, installation, O&M and end-of-life activities were modelled using the corresponding cost assumptions.

Each input was related to an appropriate PSILCA country-sector process according to the activity type and available geographical information. In the absence of a particular sector or sourcing location, the closest representative activity was selected. The foreground model was structured according to the life-cycle stages, thus allowing the identification of social-risk contributions at a stage and upstream supply-chain level using the contribution tree within PSILCA.

4.7 Selection of social indicators

The social impact indicators were chosen based on the UNEP Guidelines for Social Life Cycle Assessment of Products and Organizations (2020) and Methodological Sheets for S-LCA Subcategories (2021). The indicators were selected according to the research question and scope, their relevance to the HVDC cable supply chain, and the availability of supporting data in the PSILCA database, rather than aiming to cover all available subcategories (Table 38).

The chosen indicators fell under the categories of labour and human rights, occupational health and safety, and access to material resources and governance. This choice was made because these topics were most relevant to the analysed HVDC cable supply chains, covering metal, polymer, and chemical production, as well as transportation and other processes. Additionally, selecting the most relevant indicators helped to limit the scope of the study and avoid redundancy between different categories and topics. It also facilitated the identification of potential improvement areas and performance gaps in the two HVDC cable variants.

Table 38: Selected social indicators for the S-LCA assessment

Stakeholder	UNEP subcategory	PSILCA indicator(s)	Relevance for the cable study
Workers	**Child labour**	Children in employment, total	Relevant for upstream raw-material and industrial supply chains
Workers	**Forced labour**	Frequency of forced labour	Captures potential human-rights risks associated with global sourcing
Workers	**Fair salary**	Sector average wage, per month / Living wage, per month	Indicates potential risks related to adequate remuneration in supplying sectors
Workers	**Health and safety**	Rate of fatal accidents at workplace	Particularly relevant for mining, metal production, manufacturing and logistics
Workers	**Freedom of association and collective bargaining**	Trade union density	Reflects workers' ability to organise and protect labour rights
Local community	**Access to material resources**	Extraction of ores	Relevant to the upstream extraction of metals used in the cable systems
Value chain actors	**Corruption**	Public sector corruption	Provides a sourcing-related governance indicator for global supply chains

4.8 Inventory modelling and dataset selection

Material inputs from the foreground inventory were allocated to corresponding representative PSILCA country-sector activities on the basis of their economic classification and available sourcing data. Metal mineral inputs were related to respective basic-metal and fabricated-metal sectors, whereas polymer and chemical inputs were represented by plastics and chemical

manufacturing sectors. Representative country-sector activities were selected on the basis of available sourcing data; in the absence of such data, generic geographical datasets were used.

The NEWGEN insulation was modelled separately, with polymer inputs and precursor chemicals apportioned to respective PSILCA sectors. By doing so, the differences between the conventional and the novel design were preserved, thus enabling a separate assessment of their impact on the social risk indicators.

Table 39: Mapping of cable inventory inputs to PSILCA activities

Material/component	PSILCA activity	Geography	Cable system
Aluminium conductor	Manufacture of basic metals	Norway	Both
Lead jacketing	Manufacture of basic metals	Sweden	Both
Steel wire	Manufacture of fabricated metal products	Sweden	Both
PE jacketing	Manufacture of rubber and plastic products	Sweden	Both
XLPE insulation material	Manufacture of rubber and plastic products	Sweden	Benchmark
SC XLPE material	Manufacture of rubber and plastic products	Sweden	Benchmark
PP-based insulation components	Manufacture of rubber and plastic products	Sweden	NEWGEN
Insulation additive precursors	Manufacture of chemicals and chemical products	Sweden	NEWGEN

4.9 Software model implementation

Separate S-LCA models were developed for the benchmark and NEWGEN cable systems using a common structure. Each model consists of a master process combining six life-cycle stages: raw material extraction, manufacturing, transportation, installation, operation and maintenance (O&M), and recycling. These stages are represented by individual foreground processes linked to the relevant PSILCA country-sector activities through monetary inputs (Figure 23). The underlying inventories reflect the material composition and process requirements of each cable system.

The O&M stage also accounts for additional materials and activities associated with cable replacement following failures. The master process aggregates the contributions from all stages to calculate the total social-risk results per functional unit, while allowing individual life-cycle stages and upstream sectors to be examined separately in the hotspot analysis.

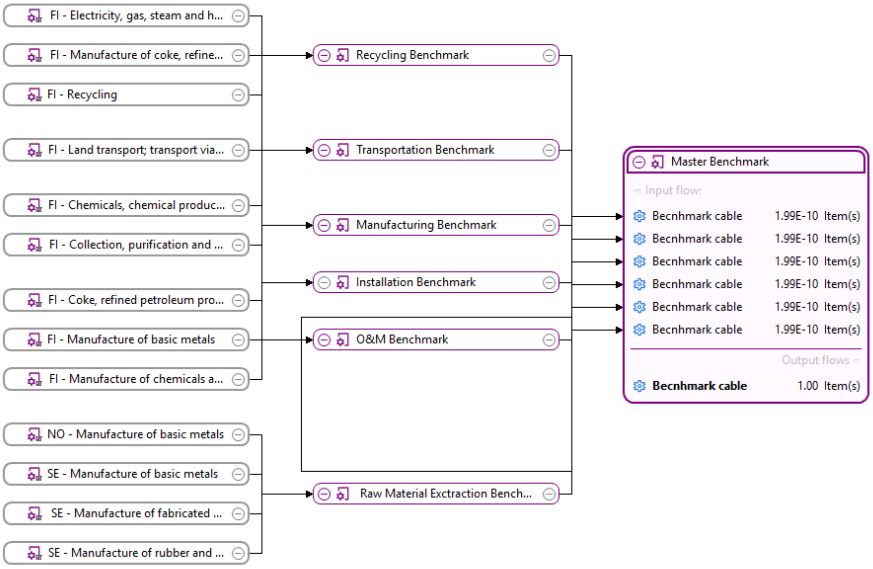


Figure 23: S-LCA model for benchmark cable built in openLCA

4.10 S-LCA hotspot analysis

To provide an initial overview of the benchmark cable's social-risk profile, the distribution of embodied worker-hour activity across PSILCA risk levels was examined for the selected indicators. Figure r shows the share of activity associated with very low, low, medium, high and very high risk, together with the share for which no risk data are available. This provides a general indication of the risk patterns before examining individual life-cycle stages and upstream sectors in more detail.

Hotspot analysis for Benchmark and NEWGEN model

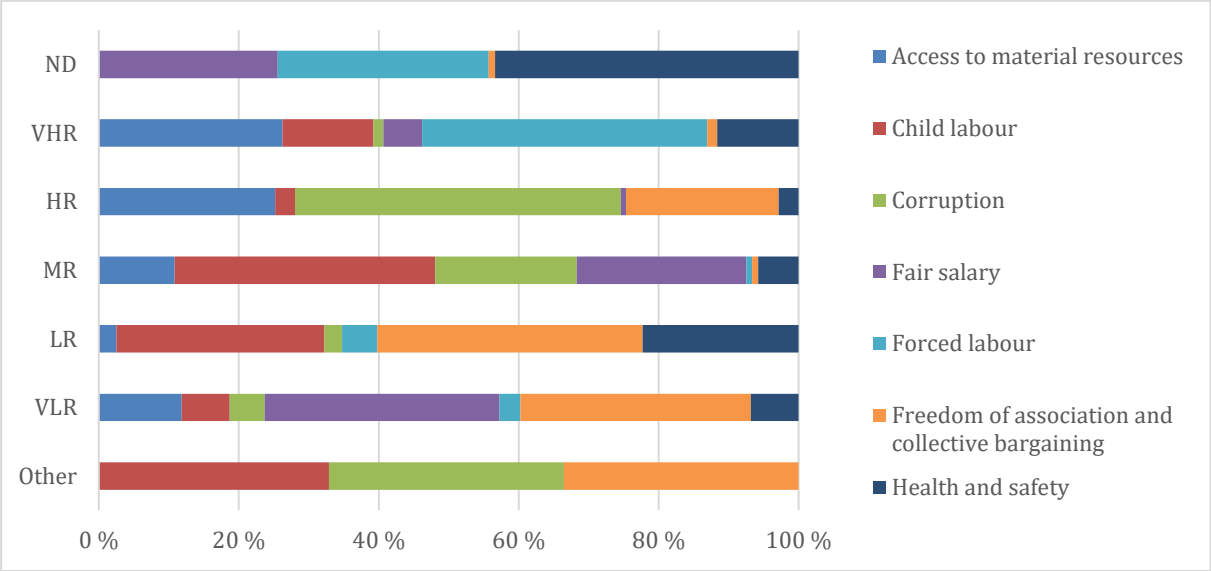


Figure 24 . Average risk-level distribution across selected social indicators for the benchmark and NEWGEN cables, based on embodied worker-hours.

Figure 24 presents the average distribution of risk levels across the selected social indicators for the benchmark and NEWGEN cables, based on embodied worker-hours.

The selected indicators show different risk patterns. For child labour, most of the activity falls into the medium- and low-risk classes (45% and 24%), although a noticeable share (19%) is classified as very high risk. Fair salary is concentrated mainly in the very-low- and medium-risk classes (34% and 29%), while 28% of the activity has no available risk data.

A clearer high-risk signal appears for forced labour, where 59% of the activity is classified as very high risk. At the same time, 33% falls into the no-data category, so this result should be interpreted with some caution. Freedom of association and collective bargaining shows a more balanced profile, with similar shares in very low, low and high risk (33%, 30% and 30%).

For health and safety, the main limitation is data availability: 48% of the activity is classified as no data. The remaining activity is spread across several risk levels, with the largest shares at low risk (18%) and very high risk (17%).

The strongest concentration of higher risks is found for access to material resources. About 35% of the activity is classified as high risk and 38% as very high risk. Corruption also shows a strong high-risk profile, with 64% of the activity in the high-risk class and another 24% at medium risk.

In the end, the benchmark results identify forced labour, access to material resources and corruption as the most pronounced risk areas. A comparison with the corresponding NEWGEN results reveals nearly identical social-risk profiles across all assessed indicators. Differences are generally limited to minor shifts of approximately 1–2 percentage points between individual risk levels, without substantially changing the overall distribution or the identified risk hotspots.

To understand where these risks originate within the cable life cycle, we further examined the selected social themes using representative underlying PSILCA indicators and their contribution trees.

The risk patterns in Table 40 are expressed as the share of embodied worker-hour activity assigned to the PSILCA risk classes: VLR – very low risk, LR – low risk, MR – medium risk, HR – high risk and VHR – very high risk. No data represents activity for which no corresponding risk information is available. The life-cycle contributions, in contrast, show which stages contribute most strongly to the weighted result of the respective underlying indicator.

Table 40 Summary of social-risk hotspots for the selected indicators

Social theme	Main risk pattern	Main life-cycle hotspots	Interpretation
Child labour	45% MR, 24% LR, 19% VHR	O&M 65.2%, Recycling 12.8%, Manufacturing 9.9%, Raw materials 7.5%	Based on *Children in employment, total*, the result is strongly concentrated in O&M, with secondary contributions from recycling and manufacturing.
Forced labour	59% VHR, 33% no data	O&M 69.4%, Recycling 11.8%, Manufacturing 9.6%	*Frequency of forced labour* shows one of the clearest O&M-dominated profiles.
Fair salary	34% VLR, 29% MR, 28% no data	*Sector average wage*: Raw materials 41.3%, O&M 33.1%. *Living wage*: Raw materials 75.2%	Wage-related risks are considerably more dependent on raw-material production than most other themes.
Freedom of association and collective bargaining	33% VLR, 30% LR, 30% HR	Raw materials 42.4%, Recycling 27.1%, O&M 21.0%	Based on *Trade union density*, the contribution is distributed mainly between raw materials, recycling and O&M.
Health and safety	48% no data, 17% VHR, 18% LR	O&M 69.1%, Recycling 11.9%, Manufacturing 9.6%	For *Rate of fatal accidents at workplace*, O&M is the dominant life-cycle hotspot. The overall theme should nevertheless be interpreted with caution because of the high no-data share.
Access to material resources	35% HR, 38% VHR	O&M 43.3%, Raw materials 31.1%, Recycling 13.3%, Manufacturing 8.3%	*Extraction of ores* is influenced by both O&M-related supply chains and direct material production.
Corruption	64% HR, 24% MR	O&M 68.5%, Recycling 12.0%, Manufacturing 9.6%	*Public sector corruption* is predominantly associated with upstream activities connected to O&M.

The stage-level results show two broad patterns. Child labour, forced labour, fatal workplace accidents and public-sector corruption are mainly associated with O&M, which accounts for around 65–70% of the respective indicator results. Fair salary and trade union density, in contrast,

are more strongly influenced by raw-material production. Access to material resources lies between these two groups, with substantial contributions from both O&M and raw materials.

The high O&M contribution is largely linked to Manufacture of coke, refined petroleum products and nuclear fuels – FI, which is used in the model to represent fuel- and petroleum-related inputs for maintenance and replacement activities. Depending on the indicator, this process contributes roughly 63–68% of the total result. However, this does not mean that the corresponding social risks are concentrated in Finland.

The main country-sector hotspots can be identified in the supply chain as following upstream contributions:

- **Russia:** Mining, trade, electricity supply, chemicals, petroleum refining, iron and steel, machinery and transport repeatedly emerge as upstream contributors to forced labour, health and safety, corruption and access to material resources.
- **China:** Raw chemical materials; Steel processing; Non-ferrous metal smelting; Metal products; Electrical machinery and equipment. Their overall contribution is smaller, but several of these sectors appear in high- and very-high-risk classes.
- **Sweden and Norway:** Manufacture of rubber and plastic products – SE; Manufacture of fabricated metal products – SE; Manufacture of basic metals – SE and NO. These sectors are especially important for wage-related indicators and trade union density, where raw-material production plays a larger role.
- **Finland:** Manufacture of coke, refined petroleum products and nuclear fuels; Recycling; Electricity, gas, steam and hot water supply. These processes enter through O&M, recycling and manufacturing and act as links to wider upstream supply chains.

The benchmark and NEWGEN cables show very similar social-risk profiles, with differences in the distribution of risk levels generally limited to 1–2 percentage points across the assessed indicators. This suggests that changes in cable composition have only a minor effect on the overall social-risk distribution under the modelled conditions.

Hotspot analysis for Benchmark USA model

An additional hypothetical USA benchmark scenario was introduced to explore how an alternative supply chain could influence the social-risk profile of the cable system. The same risk-level analysis was applied to assess potential changes in social risks and identify the main contributing life-cycle stages and upstream country-sector activities. Figure 25 presents the distribution of embodied worker-hour activity across the selected social indicators for this scenario.

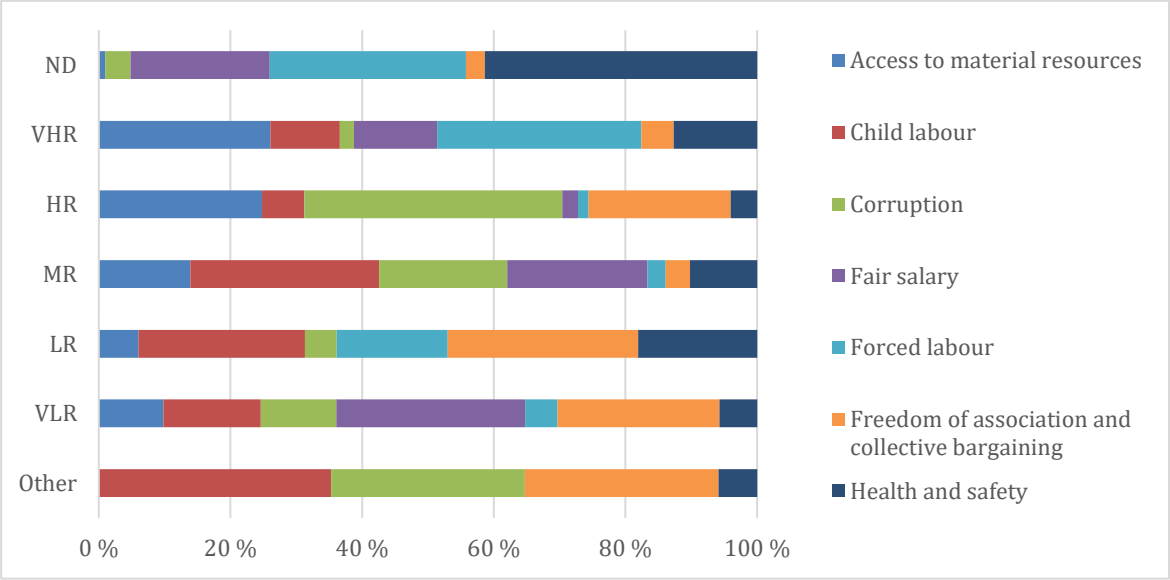


Figure 25 . Risk-level distribution of selected social indicators for the NEWGEN cable based on embodied worker-hour activity variable

The selected indicators show different risk patterns. Child labour is mainly concentrated in the medium- (31%) and low-risk (21%) classes, followed by very low (18%) and very high risk (15%). Forced labour shows a more pronounced high-risk profile, with 44% of the activity classified as very high risk and 31% having no available risk data.

Fair salary has a more mixed distribution, with 35% very low risk, 23% medium risk and 22% no data. Freedom of association and collective bargaining is relatively evenly distributed between very low (30%), high (27%) and low risk (24%).

For health and safety, data availability remains an important limitation, with 43% of the activity classified as no data. The largest remaining shares are associated with very high (18%) and low risk (15%).

Access to material resources shows the strongest concentration in the upper risk classes, with 37% very high risk and 31% high risk. Corruption is similarly dominated by the high-risk category (49%), followed by medium risk (21%).

Overall, forced labour, access to material resources and corruption remain the most pronounced risk areas, while the substantial no-data shares for forced labour and health and safety introduce additional uncertainty. To investigate the origin of these risks, the selected social themes were further examined using representative underlying PSILCA indicators and their contribution trees.

The risk-level distributions describe the share of embodied worker-hour activity assigned to each PSILCA risk class. The life-cycle contributions presented in Table 41, in contrast, refer to the medium-risk results of the corresponding underlying indicators.

Table 41 Summary of social-risk patterns and main life-cycle hotspots for the NEWGEN cable

Social theme	Main risk pattern	Main life-cycle hotspots	Interpretation
Child labour	31% MR, 21% LR, 18% VLR, 15% VHR	Recycling 33.8%, Manufacturing 26.0%, Raw materials 19.7%, O&M 8.4%	Based on Children in employment, total, the medium-risk result is mainly driven by recycling and manufacturing, with additional contributions from raw-material production.
Forced labour	44% VHR, 31% no data	Recycling 37.1%, Manufacturing 30.4%, Raw materials 14.1%, Installation 8.1%, Transportation 6.7%, O&M 3.6%	Frequency of forced labour shows a strong concentration in recycling and manufacturing, with a relatively small O&M contribution.
Fair salary	35% VLR, 23% MR, 22% no data	Sector average wage: Raw materials 46.4%, O&M 24.8%, Recycling 16.1%, Manufacturing 8.8%. Living wage: Raw materials 60.7%, O&M 30.6%	Both wage-related indicators are primarily material-driven, although sector-average wage shows more pronounced contributions from recycling and manufacturing.
Freedom of association and collective bargaining	30% VLR, 27% HR, 24% LR	O&M 34.7%, Raw materials 29.6%, Recycling 18.8%, Manufacturing 11.7%	The medium-risk result is distributed across several stages, with O&M and raw-material production representing the largest contributors.
Health and safety	43% no data, 18% VHR, 15% LR	Recycling 34.6%, Manufacturing 27.9%, Raw materials 13.1%, O&M 10.2%	Based on Rate of fatal accidents at workplace, recycling and manufacturing dominate the medium-risk result. The high no-data share remains an important limitation.
Access to material resources	37% VHR, 31% HR, 15% MR	Raw materials 49.5%, Recycling 21.2%, Manufacturing 13.1%, O&M 9.8%	Extraction of ores is predominantly driven by raw-material production, particularly plastics and metal-related supply chains.
Corruption	49% HR, 21% MR, 14% VLR	Raw materials 26.9%, Recycling 26.0%, Manufacturing 21.5%, O&M 17.7%	Based on Active involvement of enterprises in corruption and bribery, the medium-risk result is distributed across four main stages without a single dominant contributor.

The stage-level results show that child labour, forced labour and fatal workplace accidents are primarily associated with recycling and manufacturing, which together account for approximately 60–68% of their respective medium-risk contributions. These results are mainly linked to Finnish recycling activities and upstream petroleum-related and electricity supply processes.

Raw-material production plays a greater role in wage-related indicators and access to material resources, contributing 60.7% to Living wage, 49.5% to Extraction of ores and 46.4% to Sector average wage. Freedom of association and corruption show a more distributed contribution across life-cycle stages.

In the hypothetical US benchmark scenario, O&M-related contributions are mainly linked to Manufacture of other plastic products – US and Mining and oil and gas field machinery manufacturing – US, particularly for freedom of association and wage-related indicators. However, O&M is not the dominant contributor to most medium-risk results.

Further upstream analysis shows that potential social risks extend beyond the countries represented by the immediate background processes. The main country-sector hotspots identified in the supply chains include:

- **Russia**: Russian energy extraction, electricity supply, chemicals, petroleum refining, metals, machinery, trade and transport recur as upstream contributors to several social-risk indicators. Wholesale and retail trade is particularly relevant for child labour, while energy extraction contributes substantially to forced labour and fatal workplace accidents.

- **Sweden and Norway**: Manufacture of rubber and plastic products – SE; Manufacture of fabricated metal products – SE; Manufacture of basic metals – SE and NO. These activities are particularly important for wage-related indicators and Extraction of ores, reflecting the contribution of plastics and metal-related supply chains.

- **United States**: Manufacture of other plastic products; Mining and oil and gas field machinery manufacturing; Manufacture of chemical products. These processes mainly enter through the US-specific O&M stage and contribute particularly to fair salary and freedom of association.

- **China**: Raw chemical materials; Steel processing; Non-ferrous metal smelting; Metal products; Electrical machinery and equipment. Their contributions are particularly visible in the upstream results for freedom of association and collective bargaining.

- **Finland**: Recycling; Manufacture of coke, refined petroleum products and nuclear fuels; Electricity, gas, steam and hot water supply. These processes account for substantial contributions within recycling and manufacturing and connect the corresponding life-cycle stages to wider international supply chains.

Further upstream analysis suggests that the contributions associated with Finnish recycling and electricity supply are linked to significant social-risk contributions from Russian energy, trade and industrial sectors, particularly in relation to child labour, forced labour and fatal workplace accidents.

With respect to access to material resources, Russian energy extraction emerges as an important upstream contributor alongside Swedish rubber, plastics and metal-related activities. Corruption shows a wider geographical and sectoral spread, encompassing Russian agriculture, trade, electricity supply, manufacturing and recycling, as well as Ukrainian trade-related activities.

In summary, the hypothetical USA benchmark scenario identifies recycling, manufacturing and raw-material production as the main medium-risk hotspots, while O&M plays a smaller role for most indicators. Upstream contributions extend to Russian energy and industrial sectors, Scandinavian material supply chains and US manufacturing. These results reflect potential risks within the modelled PSILCA supply chains rather than verified sourcing relationships.

4.11 Comparison of selected indicators and normalized results

To complement the hotspot analysis, the three cable systems were compared using selected social indicators and aggregated normalized results. The benchmark serves as the reference case, with its score set to 100 for each indicator.

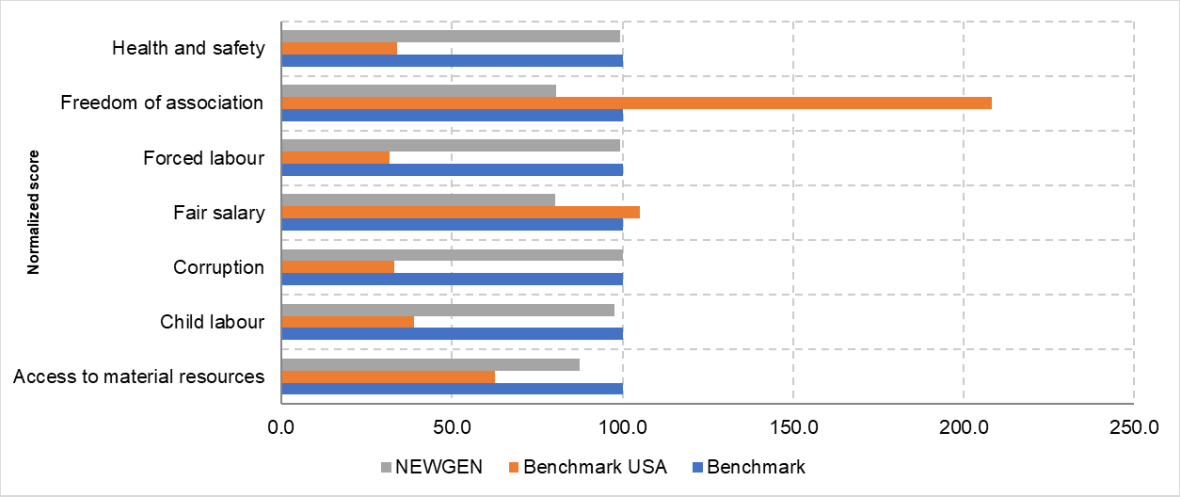


Figure 26 Aggregated normalized social-impact scores for the three cable systems (Benchmark = 100).

NEWGEN remains close to the benchmark across most indicators (Figure 26), with the largest differences observed for fair salary and freedom of association (both around 80, relative to the benchmark value of 100) and access to material resources (87). Child labour, forced labour, corruption and health and safety show only minor changes.

The hypothetical USA benchmark scenario exhibits a different profile, with considerably lower normalized results for forced labour (32), corruption (33), health and safety (34), child labour (39) and access to material resources (62). In contrast, fair salary reaches approximately 105 and freedom of association 209. Thus, the USA scenario shifts the distribution of potential social risks rather than reducing the results consistently across all indicators.

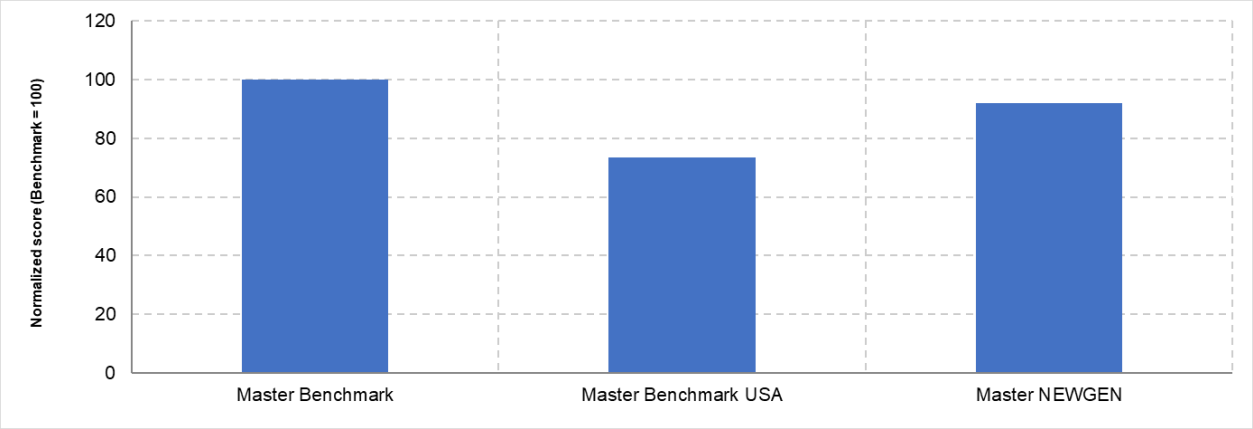


Figure 27. Aggregated normalized social-impact scores for the three cable systems (Benchmark = 100).

The aggregated results (Figure 27) show normalized scores of approximately 100 for the benchmark, 92 for NEWGEN and 73 for the USA benchmark. This corresponds to an overall reduction of approximately 8% for NEWGEN and 27% for the USA benchmark relative to the reference case.

Although the USA benchmark shows a pronounced increase in freedom of association, its substantially lower scores across several other indicators result in the lowest aggregated normalized score under the applied assessment method.

4.12 Conclusion and recommendations

The S-LCA indicates similar social-risk profiles for the benchmark and NEWGEN cable systems, with differences in risk-level distributions generally limited to 1–2 percentage points. Forced labour, access to material resources and corruption stand out among the assessed indicators, while data gaps limit the interpretation of some wage- and health-and-safety-related results.

The main hotspots are also largely shared between the two systems. O&M-related upstream supply chains, particularly petroleum-related activities, contribute substantially to several indicators, while wage-related risks are more strongly associated with metal, plastic and insulation supply chains. NEWGEN's higher relative O&M contribution mainly reflects scaling to the functional unit rather than increased fuel consumption per kilometre.

The additional hypothetical USA benchmark scenario demonstrates the influence of geographical and supply-chain assumptions. Its main medium-risk contributions shift towards recycling, manufacturing and raw-material production, although Russian energy and industrial sectors remain recurring upstream hotspots.

In the aggregated normalized comparison, NEWGEN reaches approximately 92 and the USA benchmark 73, relative to the benchmark value of 100. However, individual indicators follow different patterns: freedom of association in the USA scenario, for example, increases to approximately 209. These findings highlight the importance of considering individual social-risk indicators alongside aggregated results.

For further development of the assessment, priority should be given to:

- Obtaining more specific information on the origin and suppliers of metals, polymers, insulation materials and fuels, including US-specific supply chains.
- Replacing generic country-sector proxies with supplier- or technology-specific data, particularly for the identified upstream hotspots.
- Collecting primary information on labour conditions, recycling and O&M activities to address the identified data gaps.
- Further investigating the composition and sourcing of the NEWGEN insulation supply chain, particularly its contribution to wage- and resource-related indicators.

The identified hotspots and normalized results reflect potential social risks within the modelled PSILCA supply chains rather than verified conditions at individual suppliers or production sites. They nevertheless provide a useful basis for prioritizing further data collection and targeted supply-chain due diligence.

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6. Funding statement

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7. Appendices

Annex table 1 Overall LCIA results of different end of life scenarios of benchmark cables and NEWGEN cables

Impact categories	Benchmark cable abandonment	Benchmark cable recycling	NEWGEN cable abandonment	NEWGEN cable recycling	Unit
Acidification - 2017	5.52E-05	5.52E-05	5.66E-05	5.65E-05	mol H+ equivalents
Climate change - 2017	1.09E-02	1.09E-02	1.12E-02	1.12E-02	kg CO2 Equivalents
Climate change-Biogenic - 2017	2.59E-05	2.59E-05	2.66E-05	2.66E-05	kg CO2-Equivalents
Climate change-Fossil - 2017	1.09E-02	1.09E-02	1.11E-02	1.11E-02	kg CO2 Equivalents
Climate change-Land use and land use change - 2017	3.11E-05	3.11E-05	3.18E-05	3.18E-05	kg CO2-Equivalents
Ecotoxicity, freshwater - 2017	3.17E-02	3.14E-02	3.24E-02	3.21E-02	CTUe
Ecotoxicity, freshwater_inorganics - 2017	3.00E-02	2.97E-02	3.07E-02	3.04E-02	CTUe
Ecotoxicity, freshwater_organics - 2017	1.63E-03	1.61E-03	1.68E-03	1.66E-03	CTUe
EF-particulate Matter - 2017	2.04E-10	2.03E-10	2.09E-10	2.08E-10	disease incidence
Eutrophication marine - 2017	1.13E-05	1.13E-05	1.16E-05	1.16E-05	kg N equivalents
Eutrophication, freshwater - 2017	1.03E-05	1.03E-05	1.05E-05	1.05E-05	kg P equivalents
Eutrophication, terrestrial - 2107	8.88E-05	8.87E-05	9.08E-05	9.08E-05	mol N equivalents
Human toxicity, cancer - 2018	3.97E-12	3.78E-12	4.06E-12	3.87E-12	CTUh
Human toxicity, cancer_inorganics - 2018	2.41E-12	2.24E-12	2.47E-12	2.29E-12	CTUh
Human toxicity, cancer_organics - 2018	1.56E-12	1.55E-12	1.59E-12	1.58E-12	CTUh
Human toxicity, non-cancer - 2018	1.09E-10	1.07E-10	1.12E-10	1.09E-10	CTUh
Human toxicity, non-cancer_inorganics - 2018	1.07E-10	1.05E-10	1.10E-10	1.07E-10	CTUh
Human toxicity, non-cancer_organics - 2018	1.84E-12	1.84E-12	1.89E-12	1.88E-12	CTUh
Ionising radiation, human health - 2017	7.09E-03	7.09E-03	7.26E-03	7.26E-03	kBq U235 equivalents
Land use - 2017	4.40E-02	4.39E-02	4.50E-02	4.50E-02	dimensionless (pt)
Ozone depletion - 2017	1.97E-10	1.96E-10	2.02E-10	2.01E-10	kg CFC11 equivalents
Photochemical ozone formation - human health - 2017	2.84E-05	2.84E-05	2.90E-05	2.90E-05	kg NMVOC equivalents
Resource use, fossils - 2017	2.57E-01	2.57E-01	2.63E-01	2.63E-01	MJ

Resource use, minerals and metals - 2017	1.80E-08	1.56E-08	1.82E-08	1.58E-08	kg Sb equivalents
Water use - 2017	-7.21E-02	-7.21E-02	-7.39E-02	-7.39E-02	m3-world equivalents

Annex table 2 Overall LCIA results for the benchmark and NEWGEN cables under 25-year and 40-year lifetime scenarios.

Impact categories	Benchmark cable with lifetime of 25 years	Benchmark cable with lifetime of 40 years	NEWGEN cable with lifetime of 25 years	NEWGEN cable with lifetime of 40 years	Unit
Acidification - 2017	5.52E-05	5.51E-05	5.65E-05	5.64E-05	mol H+ equivalents
Climate change - 2017	1.09E-02	1.09E-02	1.12E-02	1.12E-02	kg CO2 Equivalents
Climate change-Biogenic - 2017	2.59E-05	2.59E-05	2.66E-05	2.65E-05	kg CO2-Equivalents
Climate change-Fossil - 2017	1.09E-02	1.08E-02	1.11E-02	1.11E-02	kg CO2 Equivalents
Climate change-Land use and land use change - 2017	3.11E-05	3.10E-05	3.18E-05	3.18E-05	kg CO2-Equivalents
Ecotoxicity, freshwater - 2017	3.14E-02	3.10E-02	3.21E-02	3.17E-02	CTUe
Ecotoxicity, freshwater_inorganics - 2017	2.97E-02	2.94E-02	3.04E-02	3.01E-02	CTUe
Ecotoxicity, freshwater_organics - 2017	1.61E-03	1.61E-03	1.66E-03	1.65E-03	CTUe
EF-particulate Matter - 2017	2.03E-10	2.02E-10	2.08E-10	2.07E-10	disease incidence
Eutrophication marine - 2017	1.13E-05	1.13E-05	1.16E-05	1.16E-05	kg N equivalents
Eutrophication, freshwater - 2017	1.03E-05	1.03E-05	1.05E-05	1.05E-05	kg P equivalents
Eutrophication, terrestrial - 2107	8.87E-05	8.85E-05	9.08E-05	9.06E-05	mol N equivalents
Human toxicity, cancer - 2018	3.78E-12	3.74E-12	3.87E-12	3.83E-12	CTUh
Human toxicity, cancer_inorganics - 2018	2.24E-12	2.20E-12	2.29E-12	2.25E-12	CTUh
Human toxicity, cancer_organics - 2018	1.55E-12	1.54E-12	1.58E-12	1.57E-12	CTUh
Human toxicity, non-cancer - 2018	1.07E-10	1.05E-10	1.09E-10	1.08E-10	CTUh

Human toxicity, non-cancer_inorganics - 2018	1.05E-10	1.03E-10	1.07E-10	1.06E-10	CTUh
Human toxicity, non-cancer_organics - 2018	1.84E-12	1.83E-12	1.88E-12	1.87E-12	CTUh
Ionising radiation, human health - 2017	7.09E-03	7.09E-03	7.26E-03	7.26E-03	kBq U235 equivalents
Land use - 2017	4.39E-02	4.39E-02	4.50E-02	4.49E-02	dimensionless (pt)
Ozone depletion - 2017	1.96E-10	1.96E-10	2.01E-10	2.01E-10	kg CFC11 equivalents
Photochemical ozone formation - human health - 2017	2.84E-05	2.83E-05	2.90E-05	2.90E-05	kg NMVOC equivalents
Resource use, fossils - 2017	2.57E-01	2.57E-01	2.63E-01	2.63E-01	MJ
Resource use, minerals and metals - 2017	1.56E-08	1.36E-08	1.58E-08	1.38E-08	kg Sb equivalents
Water use - 2017	-7.21E-02	-7.21E-02	-7.39E-02	-7.39E-02	m3-world equivalents

Annex table 3 LCIA results for the NEWGEN insulation material with alternative additive formulations

Impact categories	NEWGEN insulation materials with PE-g-MAH	NEWGEN insulation materials with PP-g-MAH (baseline)	NEWGEN insulation materials with SEBS-g-MAH	Unit
Acidification - 2017	7.67E-03	8.14E-03	7.87E-03	mol H+ equivalents
Climate change - 2017	2.01E+00	2.26E+00	2.07E+00	kg CO2 Equivalents
Climate change-Biogenic - 2017	3.51E-03	3.64E-03	5.10E-03	kg CO2-Equivalents
Climate change-Fossil - 2017	2.01E+00	2.25E+00	2.06E+00	kg CO2 Equivalents
Climate change-Land use and land use change - 2017	8.40E-04	8.70E-04	8.70E-04	kg CO2-Equivalents
Ecotoxicity, freshwater - 2017	7.28E+00	1.29E+01	8.54E+00	CTUe
Ecotoxicity, freshwater_inorganics - 2017	6.93E+00	8.32E+00	8.18E+00	CTUe
Ecotoxicity, freshwater_organics - 2017	3.55E-01	4.54E+00	3.65E-01	CTUe

EF-particulate Matter - 2017	9.32E-08	9.97E-08	9.64E-08	disease incidence
Eutrophication marine - 2017	1.40E-03	1.49E-03	1.46E-03	kg N equivalents
Eutrophication, freshwater - 2017	3.30E-04	3.70E-04	3.70E-04	kg P equivalents
Eutrophication, terrestrial - 2107	1.42E-02	1.52E-02	1.46E-02	mol N equivalents
Human toxicity, cancer - 2018	5.53E-10	9.33E-10	6.51E-10	CTUh
Human toxicity, cancer_inorganics - 2018	3.61E-10	3.85E-10	4.00E-10	CTUh
Human toxicity, cancer_organics - 2018	1.92E-10	5.48E-10	2.51E-10	CTUh
Human toxicity, non-cancer - 2018	1.31E-08	1.43E-08	1.53E-08	CTUh
Human toxicity, non-cancer_inorganics - 2018	1.18E-08	1.26E-08	1.40E-08	CTUh
Human toxicity, non-cancer_organics - 2018	1.32E-09	1.72E-09	1.33E-09	CTUh
Ionising radiation, human health - 2017	1.45E-01	1.49E-01	1.53E-01	kBq U235 equivalents
Land use - 2017	3.62E+00	3.64E+00	3.73E+00	dimensionless (pt)
Ozone depletion - 2017	2.12E-08	2.83E-08	2.31E-08	kg CFC11 equivalents
Photochemical ozone formation - human health - 2017	7.72E-03	8.29E-03	7.90E-03	kg NMVOC equivalents
Resource use, fossils - 2017	7.34E+01	7.63E+01	7.43E+01	MJ
Resource use, minerals and metals - 2017	1.37E-05	1.44E-05	1.37E-05	kg Sb equivalents
Water use - 2017	-2.65E+00	-2.78E+00	-3.23E+00	m3-world equivalents

Annex table 4 LCIA results of the benchmark cable and the NEWGEN cable at the same conductor temperature

Impact categories	HVDC Al cable Life Stages (80%) 70 °C	NEWGEN HVDC Al Life Stages (80%) 70 °C	Unit
Acidification - 2017	1.10E-04	9.50E-05	mol H+ equivalents
Climate change - 2017	2.10E-02	1.89E-02	kg CO2 Equivalents
Climate change-Biogenic - 2017	5.00E-05	4.48E-05	kg CO2-Equivalents
Climate change-Fossil - 2017	2.09E-02	1.88E-02	kg CO2 Equivalents
Climate change-Land use and land use change - 2017	5.99E-05	5.37E-05	kg CO2-Equivalents
Ecotoxicity, freshwater - 2017	5.94E-02	5.35E-02	CTUe

Ecotoxicity, freshwater_inorganics - 2017	5.63E-02	5.07E-02	CTUe
Ecotoxicity, freshwater_organics - 2017	3.10E-03	2.79E-03	CTUe
EF-particulate Matter - 2017	3.87E-10	3.48E-10	disease incidence
Eutrophication marine - 2017	2.17E-05	1.95E-05	kg N equivalents
Eutrophication, freshwater - 2017	1.99E-05	1.78E-05	kg P equivalents
Eutrophication, terrestrial - 2107	1.70E-04	1.50E-04	mol N equivalents
Human toxicity, cancer - 2018	7.18E-12	6.46E-12	CTUh
Human toxicity, cancer_inorganics - 2018	4.22E-12	3.80E-12	CTUh
Human toxicity, cancer_organics - 2018	2.95E-12	2.65E-12	CTUh
Human toxicity, non-cancer - 2018	2.01E-10	1.81E-10	CTUh
Human toxicity, non-cancer_inorganics - 2018	1.98E-10	1.78E-10	CTUh
Human toxicity, non-cancer_organics - 2018	3.53E-12	3.17E-12	CTUh
Ionising radiation, human health - 2017	1.37E-02	1.23E-02	kBq U235 equivalents
Land use - 2017	8.46E-02	7.59E-02	dimensionless (pt)
Ozone depletion - 2017	3.79E-10	3.40E-10	kg CFC11 equivalents
Photochemical ozone formation - human health - 2017	5.43E-05	4.88E-05	kg NMVOC equivalents
Resource use, fossils - 2017	4.96E-01	4.44E-01	MJ
Resource use, minerals and metals - 2017	2.43E-08	2.29E-08	kg Sb equivalents
Water use - 2017	-1.39E-01	-1.25E-01	m3-world equivalents

Annex table 5 PSILCA 4 S-LCA indicator results for the benchmark cable per functional unit.

Name	Category	Impact assessment result	Unit
Access to electricity	Social Impacts Weighting Method	1.48E-06	AE med risk hours
Access to internet	Social Impacts Weighting Method	5.07E-06	AI med risk hours
Active involvement of enterprises in corruption and bribery	Social Impacts Weighting Method	1.90E-04	AC med risk hours
Animal protection	Social Impacts Weighting Method	2.07E-04	AN med risk hours
Asylum seekers rate	Social Impacts Weighting Method	2.44E-05	AS med risk hours

Biodiversity & Habitat	Social Impacts Weighting Method	2.74E-04	BH med risk hours
Certified environmental management systems	Social Impacts Weighting Method	0.001161867	CE med risk hours
Child marriage, female	Social Impacts Weighting Method	5.98E-06	CM med risk hours
Child marriage, male	Social Impacts Weighting Method	2.13E-06	CM med risk hours
Children in employment, female	Social Impacts Weighting Method	4.39E-04	CE med risk hours
Children in employment, male	Social Impacts Weighting Method	4.56E-04	CE med risk hours
Children in employment, total	Social Impacts Weighting Method	4.56E-04	CE med risk hours
Contribution to economic development	Social Impacts Weighting Method	1.47E-04	CD med risk hours
Data protection and privacy	Social Impacts Weighting Method	3.46E-06	DP med risk hours
Ecosystem services	Social Impacts Weighting Method	2.29E-04	EC med risk hours
Embodied agricultural area footprint	Social Impacts Weighting Method	3.53E-06	EA med risk hours
Embodied CO2 footprint	Social Impacts Weighting Method	3.44E-04	EC med risk hours
Embodied CO2-eq footprint	Social Impacts Weighting Method	3.41E-04	EC med risk hours
Embodied forest area footprint	Social Impacts Weighting Method	3.40E-06	EF med risk hours
Embodied value added total	Social Impacts Weighting Method	8.37E-05	EV med risk hours
Embodied water footprint	Social Impacts Weighting Method	2.08E-04	EW med risk hours
Emigration rate	Social Impacts Weighting Method	1.37E-05	EM med risk hours
Evidence of violations of laws and employment regulations	Social Impacts Weighting Method	2.18E-05	EV med risk hours
Extraction of biomass (related to area)	Social Impacts Weighting Method	7.50E-05	EB med risk hours
Extraction of biomass (related to population)	Social Impacts Weighting Method	3.86E-04	EB med risk hours
Extraction of fossil fuels	Social Impacts Weighting Method	0.001973557	EF med risk hours
Extraction of industrial and construction minerals	Social Impacts Weighting Method	4.45E-04	EI med risk hours
Extraction of ores	Social Impacts Weighting Method	3.60E-04	EO med risk hours
Female genital mutilation 0-14	Social Impacts Weighting Method	3.63E-06	FGM med risk hours

Female genital mutilation 15-49	Social Impacts Weighting Method	4.49E-06	FGM med risk hours
Female with account at a financial institution	Social Impacts Weighting Method	2.03E-05	FF med risk hours
Food insecurity	Social Impacts Weighting Method	1.31E-05	FI med risk hours
Freedom of association and collective bargaining	Social Impacts Weighting Method	2.85E-04	FA med risk hours
Freedom of the press	Social Impacts Weighting Method	0.002012239	FP med risk hours
Frequency of forced labour	Social Impacts Weighting Method	0.001959775	FL med risk hours
Gender inequalities	Social Impacts Weighting Method	6.27E-06	GI med risk hours
Gender wage gap	Social Impacts Weighting Method	2.99E-04	GW med risk hours
Global freedom scores	Social Impacts Weighting Method	0.002045993	GF med risk hours
Global Peace Index	Social Impacts Weighting Method	0.001972242	GP med risk hours
Global Terrorism Index	Social Impacts Weighting Method	2.18E-04	GT med risk hours
Goods produced by forced labour	Social Impacts Weighting Method	6.11E-05	GF med risk hours
Health expenditure, domestic general government	Social Impacts Weighting Method	7.06E-06	HE med risk hours
Health expenditure, external resources	Social Impacts Weighting Method	2.35E-06	HE med risk hours
Health expenditure, out-of-pocket	Social Impacts Weighting Method	5.74E-05	HE med risk hours
Health expenditure, total	Social Impacts Weighting Method	4.36E-05	HE med risk hours
Homicides	Social Impacts Weighting Method	2.15E-04	HO med risk hours
Household air pollution attributable DALYs, female	Social Impacts Weighting Method	5.07E-06	HA med risk hours
Household air pollution attributable DALYs, male	Social Impacts Weighting Method	2.06E-04	HA med risk hours
Illiteracy rate, female	Social Impacts Weighting Method	1.75E-05	I med risk hours
Illiteracy rate, male	Social Impacts Weighting Method	4.47E-06	I med risk hours
Illiteracy rate, total	Social Impacts Weighting Method	1.46E-05	I med risk hours
Immigration rate	Social Impacts Weighting Method	1.99E-05	IM med risk hours
Indigenous People Rights Protection Index	Social Impacts Weighting Method	2.39E-05	IP med risk hours
Informal employment, female	Social Impacts Weighting Method	3.29E-05	IE med risk hours
Informal employment, male	Social Impacts Weighting Method	2.56E-05	IE med risk hours

Informal employment, total	Social Impacts Weighting Method	3.24E-05	IE med risk hours
Internally displaced people	Social Impacts Weighting Method	5.07E-05	ID med risk hours
International Migrant Stock	Social Impacts Weighting Method	3.15E-04	IS med risk hours
International migrant workers in the sector	Social Impacts Weighting Method	1.53E-04	IW med risk hours
Internet freedom scores	Social Impacts Weighting Method	0.001999707	IF med risk hours
Labour productivity	Social Impacts Weighting Method	6.34E-06	LP med risk hours
Level of industrial water use (related to renewable water resources)	Social Impacts Weighting Method	6.02E-05	IW med risk hours
Level of industrial water use (related to total withdrawal)	Social Impacts Weighting Method	0.00215655	IW med risk hours
Life expectancy at birth	Social Impacts Weighting Method	2.67E-05	LE med risk hours
Living wage, per month	Social Impacts Weighting Method	1.74E-04	LW med risk hours
Mean years of schooling, female	Social Impacts Weighting Method	1.32E-05	S med risk hours
Mean years of schooling, male	Social Impacts Weighting Method	1.32E-05	S med risk hours
Mean years of schooling, total	Social Impacts Weighting Method	2.06E-05	S med risk hours
Men in the sectoral labour force	Social Impacts Weighting Method	6.33E-05	M med risk hours
Minimum wage, per month	Social Impacts Weighting Method	5.60E-06	MW med risk hours
Net migration rate	Social Impacts Weighting Method	1.52E-04	NM med risk hours
number of strikes	Social Impacts Weighting Method	4.48E-05	NS med risk hours
Number of threatened species	Social Impacts Weighting Method	3.78E-04	NT med risk hours
Online Consumer Protection Legislation	Social Impacts Weighting Method	5.31E-06	OC med risk hours
Paid maternity leave	Social Impacts Weighting Method	1.98E-04	PM med risk hours
Political stability and absence of violence	Social Impacts Weighting Method	0.001967054	PS med risk hours
Pollution level of the country	Social Impacts Weighting Method	8.44E-05	PL med risk hours
Population below national poverty line	Social Impacts Weighting Method	6.36E-06	PP med risk hours
Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Social Impacts Weighting Method	9.13E-04	AC med risk hours

Presence of indigenous population	Social Impacts Weighting Method	2.24E-05	PI med risk hours
Presence of sufficient safety measures	Social Impacts Weighting Method	2.63E-05	SS med risk hours
Public expenditure on education	Social Impacts Weighting Method	2.06E-04	PE med risk hours
Public sector corruption	Social Impacts Weighting Method	1.98E-04	PC med risk hours
R&D expenditures	Social Impacts Weighting Method	7.39E-06	RD med risk hours
Rate of fatal accidents at workplace	Social Impacts Weighting Method	0.00141252	FA med risk hours
Rate of non-fatal accidents at workplace	Social Impacts Weighting Method	3.71E-05	NA med risk hours
Rate of researchers	Social Impacts Weighting Method	6.15E-06	RR med risk hours
Safe access to Drinking water coverage	Social Impacts Weighting Method	2.32E-05	DW med risk hours
Sanitation coverage	Social Impacts Weighting Method	0.002068556	SC med risk hours
Sector average wage, per month	Social Impacts Weighting Method	3.82E-04	SA med risk hours
Social Protection Expenditures	Social Impacts Weighting Method	5.09E-06	SR med risk hours
Social responsibility along the supply chain	Social Impacts Weighting Method	3.98E-04	SS med risk hours
State of democracy	Social Impacts Weighting Method	9.28E-06	SD med risk hours
Trade union density	Social Impacts Weighting Method	1.93E-05	TU med risk hours
Trafficking in persons	Social Impacts Weighting Method	0.001996976	TP med risk hours
Under-five mortality rate	Social Impacts Weighting Method	6.24E-06	UM med risk hours
Unemployment rate in the country	Social Impacts Weighting Method	3.73E-05	UR med risk hours
Violations of mandatory health and safety standards	Social Impacts Weighting Method	7.24E-05	VS med risk hours
Waste management	Social Impacts Weighting Method	0.001955218	WM med risk hours
Weekly hours of work per employee female	Social Impacts Weighting Method	1.21E-05	WH med risk hours
Weekly hours of work per employee male	Social Impacts Weighting Method	6.22E-06	WH med risk hours
Women in the sectoral labour force	Social Impacts Weighting Method	0.001048462	W med risk hours
Youth illiteracy rate, female	Social Impacts Weighting Method	4.29E-06	YI med risk hours

Youth illiteracy rate, male	Social Impacts Weighting Method	5.80E-06	YI med risk hours
Youth illiteracy rate, total	Social Impacts Weighting Method	4.05E-06	YI med risk hours
Youth unemployment	Social Impacts Weighting Method	6.29E-06	YU med risk hours

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Name	Category	Impact assessment result	Unit
Access to electricity	Social Impacts Weighting Method	1.36E-06	AE med risk hours
Access to internet	Social Impacts Weighting Method	5.94E-06	AI med risk hours
Active involvement of enterprises in corruption and bribery	Social Impacts Weighting Method	9.77E-05	AC med risk hours
Animal protection	Social Impacts Weighting Method	8.46E-05	AN med risk hours
Asylum seekers rate	Social Impacts Weighting Method	2.40E-05	AS med risk hours
Biodiversity & Habitat	Social Impacts Weighting Method	1.82E-04	BH med risk hours
Certified environmental management systems	Social Impacts Weighting Method	4.41E-04	CE med risk hours
Child marriage, female	Social Impacts Weighting Method	6.85E-06	CM med risk hours
Child marriage, male	Social Impacts Weighting Method	2.48E-06	CM med risk hours
Children in employment, female	Social Impacts Weighting Method	1.66E-04	CE med risk hours
Children in employment, male	Social Impacts Weighting Method	1.73E-04	CE med risk hours
Children in employment, total	Social Impacts Weighting Method	1.73E-04	CE med risk hours
Contribution to economic development	Social Impacts Weighting Method	5.60E-05	CD med risk hours
Data protection and privacy	Social Impacts Weighting Method	3.65E-06	DP med risk hours
Ecosystem services	Social Impacts Weighting Method	1.08E-04	EC med risk hours
Embodied agricultural area footprint	Social Impacts Weighting Method	2.48E-06	EA med risk hours
Embodied CO2 footprint	Social Impacts Weighting Method	1.66E-04	EC med risk hours
Embodied CO2-eq footprint	Social Impacts Weighting Method	1.61E-04	EC med risk hours
Embodied forest area footprint	Social Impacts Weighting Method	1.21E-06	EF med risk hours

Embodied value added total	Social Impacts Weighting Method	3.31E-05	EV med risk hours
Embodied water footprint	Social Impacts Weighting Method	9.77E-05	EW med risk hours
Emigration rate	Social Impacts Weighting Method	1.28E-05	EM med risk hours
Evidence of violations of laws and employment regulations	Social Impacts Weighting Method	4.16E-05	EV med risk hours
Extraction of biomass (related to area)	Social Impacts Weighting Method	7.39E-05	EB med risk hours
Extraction of biomass (related to population)	Social Impacts Weighting Method	2.92E-04	EB med risk hours
Extraction of fossil fuels	Social Impacts Weighting Method	7.07E-04	EF med risk hours
Extraction of industrial and construction minerals	Social Impacts Weighting Method	3.84E-04	EI med risk hours
Extraction of ores	Social Impacts Weighting Method	2.26E-04	EO med risk hours
Female genital mutilation 0-14	Social Impacts Weighting Method	2.70E-06	FGM med risk hours
Female genital mutilation 15-49	Social Impacts Weighting Method	4.17E-06	FGM med risk hours
Female with account at a financial institution	Social Impacts Weighting Method	2.13E-05	FF med risk hours
Food insecurity	Social Impacts Weighting Method	1.78E-05	FI med risk hours
Freedom of association and collective bargaining	Social Impacts Weighting Method	2.11E-04	FA med risk hours
Freedom of the press	Social Impacts Weighting Method	7.18E-04	FP med risk hours
Frequency of forced labour	Social Impacts Weighting Method	6.22E-04	FL med risk hours
Gender inequalities	Social Impacts Weighting Method	6.36E-06	GI med risk hours
Gender wage gap	Social Impacts Weighting Method	1.64E-04	GW med risk hours
Global freedom scores	Social Impacts Weighting Method	7.32E-04	GF med risk hours
Global Peace Index	Social Impacts Weighting Method	7.12E-04	GP med risk hours
Global Terrorism Index	Social Impacts Weighting Method	1.10E-04	GT med risk hours
Goods produced by forced labour	Social Impacts Weighting Method	6.48E-05	GF med risk hours
Health expenditure, domestic general government	Social Impacts Weighting Method	7.44E-06	HE med risk hours
Health expenditure, external resources	Social Impacts Weighting Method	2.21E-06	HE med risk hours

Health expenditure, out-of-pocket	Social Impacts Weighting Method	4.23E-05	HE med risk hours
Health expenditure, total	Social Impacts Weighting Method	3.79E-05	HE med risk hours
Homicides	Social Impacts Weighting Method	1.11E-04	HO med risk hours
Household air pollution attributable DALYs, female	Social Impacts Weighting Method	4.56E-06	HA med risk hours
Household air pollution attributable DALYs, male	Social Impacts Weighting Method	7.56E-05	HA med risk hours
Illiteracy rate, female	Social Impacts Weighting Method	2.30E-05	I med risk hours
Illiteracy rate, male	Social Impacts Weighting Method	5.42E-06	I med risk hours
Illiteracy rate, total	Social Impacts Weighting Method	1.98E-05	I med risk hours
Immigration rate	Social Impacts Weighting Method	1.87E-05	IM med risk hours
Indigenous People Rights Protection Index	Social Impacts Weighting Method	1.58E-05	IP med risk hours
Informal employment, female	Social Impacts Weighting Method	3.89E-05	IE med risk hours
Informal employment, male	Social Impacts Weighting Method	2.60E-05	IE med risk hours
Informal employment, total	Social Impacts Weighting Method	3.79E-05	IE med risk hours
Internally displaced people	Social Impacts Weighting Method	4.21E-05	ID med risk hours
International Migrant Stock	Social Impacts Weighting Method	1.85E-04	IS med risk hours
International migrant workers in the sector	Social Impacts Weighting Method	2.01E-04	IW med risk hours
Internet freedom scores	Social Impacts Weighting Method	6.98E-04	IF med risk hours
Labour productivity	Social Impacts Weighting Method	5.87E-06	LP med risk hours
Level of industrial water use (related to renewable water resources)	Social Impacts Weighting Method	1.09E-04	IW med risk hours
Level of industrial water use (related to total withdrawal)	Social Impacts Weighting Method	8.64E-04	IW med risk hours
Life expectancy at birth	Social Impacts Weighting Method	1.38E-05	LE med risk hours
Living wage, per month	Social Impacts Weighting Method	2.16E-04	LW med risk hours
Mean years of schooling, female	Social Impacts Weighting Method	1.73E-05	S med risk hours
Mean years of schooling, male	Social Impacts Weighting Method	1.73E-05	S med risk hours
Mean years of schooling, total	Social Impacts Weighting Method	2.88E-05	S med risk hours

Men in the sectoral labour force	Social Impacts Weighting Method	4.43E-05	M med risk hours
Minimum wage, per month	Social Impacts Weighting Method	4.54E-06	MW med risk hours
Net migration rate	Social Impacts Weighting Method	1.44E-04	NM med risk hours
number of strikes	Social Impacts Weighting Method	5.24E-05	NS med risk hours
Number of threatened species	Social Impacts Weighting Method	1.66E-04	NT med risk hours
Online Consumer Protection Legislation	Social Impacts Weighting Method	8.02E-06	OC med risk hours
Paid maternity leave	Social Impacts Weighting Method	6.56E-05	PM med risk hours
Political stability and absence of violence	Social Impacts Weighting Method	6.34E-04	PS med risk hours
Pollution level of the country	Social Impacts Weighting Method	9.99E-05	PL med risk hours
Population below national poverty line	Social Impacts Weighting Method	7.38E-06	PP med risk hours
Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Social Impacts Weighting Method	2.55E-04	AC med risk hours
Presence of indigenous population	Social Impacts Weighting Method	1.01E-05	PI med risk hours
Presence of sufficient safety measures	Social Impacts Weighting Method	2.31E-05	SS med risk hours
Public expenditure on education	Social Impacts Weighting Method	7.71E-05	PE med risk hours
Public sector corruption	Social Impacts Weighting Method	6.66E-05	PC med risk hours
R&D expenditures	Social Impacts Weighting Method	5.66E-06	RD med risk hours
Rate of fatal accidents at workplace	Social Impacts Weighting Method	4.85E-04	FA med risk hours
Rate of non-fatal accidents at workplace	Social Impacts Weighting Method	9.99E-05	NA med risk hours
Rate of researchers	Social Impacts Weighting Method	7.70E-06	RR med risk hours
Safe access to Drinking water coverage	Social Impacts Weighting Method	1.43E-05	DW med risk hours
Sanitation coverage	Social Impacts Weighting Method	7.83E-04	SC med risk hours
Sector average wage, per month	Social Impacts Weighting Method	3.40E-04	SA med risk hours
Social Protection Expenditures	Social Impacts Weighting Method	5.88E-06	SR med risk hours

Social responsibility along the supply chain	Social Impacts Weighting Method	1.57E-04	SS med risk hours
State of democracy	Social Impacts Weighting Method	7.10E-06	SD med risk hours
Trade union density	Social Impacts Weighting Method	4.02E-05	TU med risk hours
Trafficking in persons	Social Impacts Weighting Method	6.96E-04	TP med risk hours
Under-five mortality rate	Social Impacts Weighting Method	6.07E-06	UM med risk hours
Unemployment rate in the country	Social Impacts Weighting Method	4.91E-05	UR med risk hours
Violations of mandatory health and safety standards	Social Impacts Weighting Method	1.64E-04	VS med risk hours
Waste management	Social Impacts Weighting Method	6.19E-04	WM med risk hours
Weekly hours of work per employee female	Social Impacts Weighting Method	6.35E-06	WH med risk hours
Weekly hours of work per employee male	Social Impacts Weighting Method	4.51E-06	WH med risk hours
Women in the sectoral labour force	Social Impacts Weighting Method	3.99E-04	W med risk hours
Youth illiteracy rate, female	Social Impacts Weighting Method	5.03E-06	YI med risk hours
Youth illiteracy rate, male	Social Impacts Weighting Method	5.54E-06	YI med risk hours
Youth illiteracy rate, total	Social Impacts Weighting Method	4.96E-06	YI med risk hours
Youth unemployment	Social Impacts Weighting Method	8.73E-06	YU med risk hours

Annex table 7 PSILCA 4 S-LCA indicator results for the NEWGEN cable per functional unit.

Name	Category	Impact assessment result	Unit
Access to electricity	Social Impacts Weighting Method	1.18E-06	AE med risk hours
Access to internet	Social Impacts Weighting Method	3.67E-06	AI med risk hours
Active involvement of enterprises in corruption and bribery	Social Impacts Weighting Method	1.59E-04	AC med risk hours
Animal protection	Social Impacts Weighting Method	1.84E-04	AN med risk hours
Asylum seekers rate	Social Impacts Weighting Method	1.64E-05	AS med risk hours
Biodiversity & Habitat	Social Impacts Weighting Method	2.29E-04	BH med risk hours

Certified environmental management systems	Social Impacts Weighting Method	0.001023388	CE med risk hours
Child marriage, female	Social Impacts Weighting Method	4.48E-06	CM med risk hours
Child marriage, male	Social Impacts Weighting Method	1.57E-06	CM med risk hours
Children in employment, female	Social Impacts Weighting Method	3.88E-04	CE med risk hours
Children in employment, male	Social Impacts Weighting Method	4.03E-04	CE med risk hours
Children in employment, total	Social Impacts Weighting Method	4.03E-04	CE med risk hours
Contribution to economic development	Social Impacts Weighting Method	1.31E-04	CD med risk hours
Data protection and privacy	Social Impacts Weighting Method	2.50E-06	DP med risk hours
Ecosystem services	Social Impacts Weighting Method	1.99E-04	EC med risk hours
Embodied agricultural area footprint	Social Impacts Weighting Method	2.53E-06	EA med risk hours
Embodied CO2 footprint	Social Impacts Weighting Method	2.92E-04	EC med risk hours
Embodied CO2-eq footprint	Social Impacts Weighting Method	2.90E-04	EC med risk hours
Embodied forest area footprint	Social Impacts Weighting Method	2.99E-06	EF med risk hours
Embodied value added total	Social Impacts Weighting Method	7.36E-05	EV med risk hours
Embodied water footprint	Social Impacts Weighting Method	1.79E-04	EW med risk hours
Emigration rate	Social Impacts Weighting Method	9.83E-06	EM med risk hours
Evidence of violations of laws and employment regulations	Social Impacts Weighting Method	1.56E-05	EV med risk hours
Extraction of biomass (related to area)	Social Impacts Weighting Method	5.42E-05	EB med risk hours
Extraction of biomass (related to population)	Social Impacts Weighting Method	3.05E-04	EB med risk hours
Extraction of fossil fuels	Social Impacts Weighting Method	0.001764924	EF med risk hours
Extraction of industrial and construction minerals	Social Impacts Weighting Method	3.45E-04	EI med risk hours
Extraction of ores	Social Impacts Weighting Method	2.85E-04	EO med risk hours
Female genital mutilation 0-14	Social Impacts Weighting Method	2.94E-06	FGM med risk hours
Female genital mutilation 15-49	Social Impacts Weighting Method	3.58E-06	FGM med risk hours

Female with account at a financial institution	Social Impacts Weighting Method	1.49E-05	FF med risk hours
Food insecurity	Social Impacts Weighting Method	9.06E-06	FI med risk hours
Freedom of association and collective bargaining	Social Impacts Weighting Method	2.36E-04	FA med risk hours
Freedom of the press	Social Impacts Weighting Method	0.00178718	FP med risk hours
Frequency of forced labour	Social Impacts Weighting Method	0.00175525	FL med risk hours
Gender inequalities	Social Impacts Weighting Method	4.83E-06	GI med risk hours
Gender wage gap	Social Impacts Weighting Method	2.40E-04	GW med risk hours
Global freedom scores	Social Impacts Weighting Method	0.00181266	GF med risk hours
Global Peace Index	Social Impacts Weighting Method	0.001763782	GP med risk hours
Global Terrorism Index	Social Impacts Weighting Method	1.90E-04	GT med risk hours
Goods produced by forced labour	Social Impacts Weighting Method	4.24E-05	GF med risk hours
Health expenditure, domestic general government	Social Impacts Weighting Method	5.36E-06	HE med risk hours
Health expenditure, external resources	Social Impacts Weighting Method	1.79E-06	HE med risk hours
Health expenditure, out-of-pocket	Social Impacts Weighting Method	4.67E-05	HE med risk hours
Health expenditure, total	Social Impacts Weighting Method	3.44E-05	HE med risk hours
Homicides	Social Impacts Weighting Method	1.89E-04	HO med risk hours
Household air pollution attributable DALYs, female	Social Impacts Weighting Method	3.97E-06	HA med risk hours
Household air pollution attributable DALYs, male	Social Impacts Weighting Method	1.82E-04	HA med risk hours
Illiteracy rate, female	Social Impacts Weighting Method	1.22E-05	I med risk hours
Illiteracy rate, male	Social Impacts Weighting Method	3.20E-06	I med risk hours
Illiteracy rate, total	Social Impacts Weighting Method	1.01E-05	I med risk hours
Immigration rate	Social Impacts Weighting Method	1.42E-05	IM med risk hours
Indigenous People Rights Protection Index	Social Impacts Weighting Method	2.08E-05	IP med risk hours
Informal employment, female	Social Impacts Weighting Method	2.36E-05	IE med risk hours
Informal employment, male	Social Impacts Weighting Method	1.89E-05	IE med risk hours
Informal employment, total	Social Impacts Weighting Method	2.33E-05	IE med risk hours

Internally displaced people	Social Impacts Weighting Method	4.27E-05	ID med risk hours
International Migrant Stock	Social Impacts Weighting Method	2.51E-04	IS med risk hours
International migrant workers in the sector	Social Impacts Weighting Method	1.00E-04	IW med risk hours
Internet freedom scores	Social Impacts Weighting Method	0.001778728	IF med risk hours
Labour productivity	Social Impacts Weighting Method	4.91E-06	LP med risk hours
Level of industrial water use (related to renewable water resources)	Social Impacts Weighting Method	4.53E-05	IW med risk hours
Level of industrial water use (related to total withdrawal)	Social Impacts Weighting Method	0.001888479	IW med risk hours
Life expectancy at birth	Social Impacts Weighting Method	2.29E-05	LE med risk hours
Living wage, per month	Social Impacts Weighting Method	1.21E-04	LW med risk hours
Mean years of schooling, female	Social Impacts Weighting Method	9.58E-06	S med risk hours
Mean years of schooling, male	Social Impacts Weighting Method	9.58E-06	S med risk hours
Mean years of schooling, total	Social Impacts Weighting Method	1.42E-05	S med risk hours
Men in the sectoral labour force	Social Impacts Weighting Method	5.17E-05	M med risk hours
Minimum wage, per month	Social Impacts Weighting Method	4.49E-06	MW med risk hours
Net migration rate	Social Impacts Weighting Method	1.05E-04	NM med risk hours
number of strikes	Social Impacts Weighting Method	3.14E-05	NS med risk hours
Number of threatened species	Social Impacts Weighting Method	3.28E-04	NT med risk hours
Online Consumer Protection Legislation	Social Impacts Weighting Method	3.61E-06	OC med risk hours
Paid maternity leave	Social Impacts Weighting Method	1.77E-04	PM med risk hours
Political stability and absence of violence	Social Impacts Weighting Method	0.001759872	PS med risk hours
Pollution level of the country	Social Impacts Weighting Method	6.18E-05	PL med risk hours
Population below national poverty line	Social Impacts Weighting Method	5.04E-06	PP med risk hours
Presence of anti-competitive behaviour or violation of anti-trust and monopoly legislation	Social Impacts Weighting Method	8.31E-04	AC med risk hours
Presence of indigenous population	Social Impacts Weighting Method	1.95E-05	PI med risk hours

Presence of sufficient safety measures	Social Impacts Weighting Method	1.88E-05	SS med risk hours
Public expenditure on education	Social Impacts Weighting Method	1.82E-04	PE med risk hours
Public sector corruption	Social Impacts Weighting Method	1.77E-04	PC med risk hours
R&D expenditures	Social Impacts Weighting Method	6.03E-06	RD med risk hours
Rate of fatal accidents at workplace	Social Impacts Weighting Method	0.001266698	FA med risk hours
Rate of non-fatal accidents at workplace	Social Impacts Weighting Method	2.66E-05	NA med risk hours
Rate of researchers	Social Impacts Weighting Method	4.76E-06	RR med risk hours
Safe access to Drinking water coverage	Social Impacts Weighting Method	2.02E-05	DW med risk hours
Sanitation coverage	Social Impacts Weighting Method	0.001833157	SC med risk hours
Sector average wage, per month	Social Impacts Weighting Method	2.91E-04	SA med risk hours
Social Protection Expenditures	Social Impacts Weighting Method	3.66E-06	SR med risk hours
Social responsibility along the supply chain	Social Impacts Weighting Method	3.50E-04	SS med risk hours
State of democracy	Social Impacts Weighting Method	7.39E-06	SD med risk hours
Trade union density	Social Impacts Weighting Method	1.40E-05	TU med risk hours
Trafficking in persons	Social Impacts Weighting Method	0.001776724	TP med risk hours
Under-five mortality rate	Social Impacts Weighting Method	4.82E-06	UM med risk hours
Unemployment rate in the country	Social Impacts Weighting Method	2.66E-05	UR med risk hours
Violations of mandatory health and safety standards	Social Impacts Weighting Method	4.96E-05	VS med risk hours
Waste management	Social Impacts Weighting Method	0.001751729	WM med risk hours
Weekly hours of work per employee female	Social Impacts Weighting Method	1.01E-05	WH med risk hours
Weekly hours of work per employee male	Social Impacts Weighting Method	4.88E-06	WH med risk hours
Women in the sectoral labour force	Social Impacts Weighting Method	9.34E-04	W med risk hours
Youth illiteracy rate, female	Social Impacts Weighting Method	3.12E-06	YI med risk hours
Youth illiteracy rate, male	Social Impacts Weighting Method	4.49E-06	YI med risk hours

Youth illiteracy rate, total	Social Impacts Weighting Method	2.92E-06	YI med risk hours
Youth unemployment	Social Impacts Weighting Method	4.71E-06	YU med risk hours