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SCAPE
POWERING E-MOBILITY

D8.8 - Environmental assessment of materials and processes

SWITCHING-CELL-ARRAY-BASED POWER ELECTRONICS CONVERSION FOR FUTURE ELECTRIC VEHICLES

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Executive Summary

This report provides the results of the environmental impact evaluation of the integrated inverter/on-board-charger power converter (IIOBC) for electric vehicles currently under development in SCAPE project. The assessment is performed following the Life Cycle Assessment (LCA) methodology from the cradle-to-grave approach, including material extraction, manufacturing of components, assembly, and end-of-life through recycling of electronic components. The analysis is focused on materials; therefore, the use phase is excluded and will be further assessed in Task 8.5.2. The Life Cycle Inventory for the manufacturing of the IIOBC has been built based on primary data provided by project partners on converter composition and with the support of the environmental databases Ecoinvent and GaBi Professional. The outputs of this analysis will feed Task 8.5.3 on ecodesign, allowing to identify significant aspects influencing the environmental performance of the converter and providing recommendations for reducing its environmental effects. Impact analysis is provided at IIOBC level, as well as at detail for sublevels in the IIOBC electrical structure; i.e., the Converter Legs (CLs), the High-Voltage Switching Cells (HVSCs), and the CL controller boards. The impact categories assessed correspond to Global Warming Potential, Abiotic Depletion-elements, Acidification, Eutrophication, Primary Energy Demand, and Human Toxicity Potential. The obtained results show a dominant impact associated to the manufacturing of components. In particular, the CL control board, CL printed-circuit board and HVSCs components are identified as the main contributors to environmental impacts.

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List of Figures

List of Tables

List of Acronyms and Abbreviations

AP	Acidification Potential
ADPe	Abiotic Depletion Potential - elements
CL	Converter leg
EP	Eutrophication Potential
EV	Electric Vehicle
GWP	Global Warming Potential
HVSC	High-Voltage Switching Cell
HTP	Human Toxicity Potential
IIOBC	Integrated Inverter/On-Board Charger
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
PCB	Printed Circuit Board
PED	Primary Energy Demand
SC	Switching cell
WP	Work Packages

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Contents

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1. Introduction

This report corresponds to the deliverable "D8.8 Environmental assessment of materials and processes" and consists of the environmental impact assessment of the materials and manufacturing processes required for the proposed power converters in the SCAPE project.

This environmental analysis follows the guidelines and recommendations of the ISO standards 14040/44:2006 on Life Cycle Assessment (LCA) and covers the evaluation of the following life cycle aspects: resource extraction, manufacturing of converter components, assembly, and recycling of electronic components. The construction of the Life Cycle Inventory (LCI) is based on a detailed analysis and processing of data provided in close collaboration with project partners.

In the scope of Task 8.5.2, the resultant inventory from this deliverable will be updated at the end of the project with data related to the final design of the electric vehicle (EV) Integrated Inverter/On-Board Charger power converter (IIOBC) and extended to include the EV auxiliary DC-DC converter for the assessment of the full EV power-conversion system. Moreover, this second LCA study will consider the full lifecycle, including the use phase.

In addition, the outputs of this preliminary analysis will feed the application of the ecodesign approach defined in Task 8.5.3, aiming to support the decision-making regarding design in work package (WP) 3, WP4 and WP6. It will allow selecting the most appropriate materials for the manufacturing of the proposed IIOBC and to quantify and understand its environmental effects.

1.1. Structure of the system under study

The EV power-conversion system proposed in SCAPE is composed of two power converters: the IIOBC and the auxiliary dc-dc converter. The present LCA study, which is of a preliminary nature due to the early development stage of the project, focuses on the IIOBC. Figure 1 shows the structure of the converter.

The power converter design concept proposed by SCAPE follows a modular and scalable approach., where the basic building-block is the switching cell (SC). The SCs allow building the converter legs (CLs) following multilevel structures, providing superior scalability capabilities to the converter, allowing to adapt the converter voltage rating to the battery voltage by changing the CL number of levels. This is performed without the need to change the SC components, contrary to the conventional non-multilevel deign approach. Finally, the converter is built from a combination of CLs and passive components.

The SC main component is a power silicon-carbide (SiC) metal-oxide semiconductor field-effect transistor (MOSFET), which behaves as a controlled switch, and enables the basic working principle of the power converters; i.e., transferring energy between the converter input and output by switching tens-of-thousand times per second the power switches and using the passive components elements (inductors and capacitors) as energy buffers.

The SC also includes:

- An auxiliary power SiC MOSFET in series with the main switch, which allows isolating the SC from the rest of the CL circuit in case the SC fails.
- The ancillary circuit to drive the power MOSFETs, detect the SC failure, and the communication drives to share information between the CL local control and the SC.
- The necessary power supplies to feed the ancillary circuits.

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- A shunt resistor for current measurement purposes.

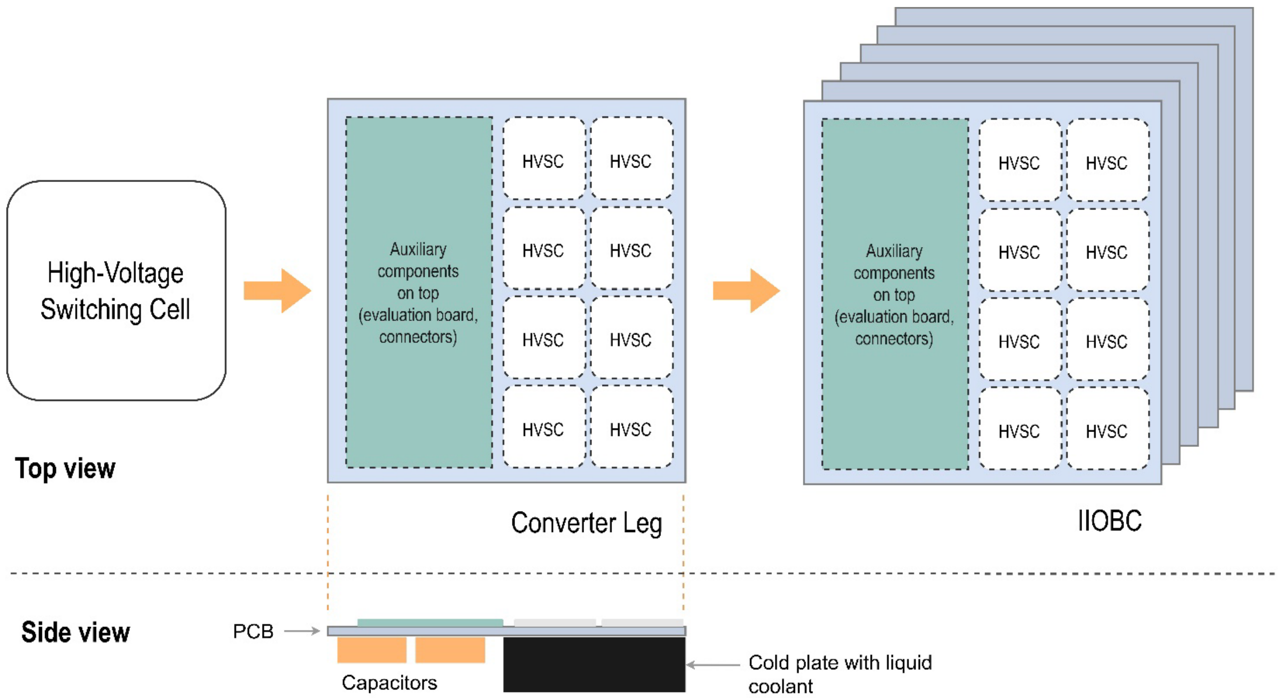

Figure 1 – IIOBC structure (source: IREC)

SCAPE also aims at implementing the CLs hardware with the state-of-the-art chip-embedding technology, which consists of embedding the power semiconductor chips inside the CL printed-circuit board (PCB), as shown in **Figure 2** this allows increasing the converter power density by reducing the overall losses heatsinking requirements, enabling 3D structures in the PCB, reducing the passive-component size thanks to increased switching frequency, and reducing the amount of material use from the power semiconductors.

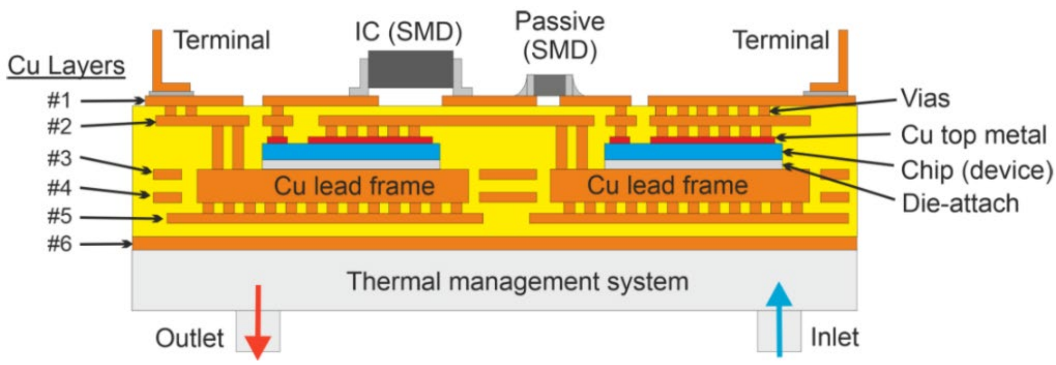

Figure 2 – Cross section of a PCB featuring chip embedding (source: CSIC)

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2. Assessment methodology

The methodology followed for the development of this Task 8.5.1 on environmental assessment is linked to the ecodesign approach defined in Task 8.5.3 for the manufacturing of the proposed EV power-conversion system (see Figure 3). The ecodesign approach is based on the requirements and recommendations of ISO 14006:2020 on *Environmental management systems – Guidelines for incorporating ecodesign,* which integrates the Life Cycle approach for evaluating environmental impacts. This evaluation serves as a base for further use in the application of the hotspots analysis method, aimed to identify critical aspects influencing the environmental performance of the system. Refinement of this first evaluation will be performed in the frame of the Task 8.5.2, consisting of the full LCA analysis of the final power-conversion system.

This environmental analysis is performed following the guidelines of ISO 14040 and ISO 14044 standards on LCA studies (ISO, 2006a, 2006b). LCA methodology is a recognized tool for addressing the environmental aspects and potential environmental impacts of a product or system throughout their life cycle.

Under these standards, LCA studies consist of four main steps:

a) Goal and scope definition. It includes the goal of the study detailing the intended application and use of results, definition of system boundaries, limitations and functional unit for quantification and reference for comparability of LCA results.

b) LCI analysis. It consists of the collection of data and calculations for quantifying inputs and outputs of a product or system in the form of inventory.

c) Impact assessment. It is aimed at associating data from the LCI with specific impact indicators to evaluate their significance and provide information for the interpretation phase.

d) Interpretation phase. Results from the inventory analysis and impact assessment are summarized and discussed to provide conclusions and recommendations for supporting decision-making in accordance with the goal and scope defined. These remarks are used to feed the mentioned ecodesign approach in Task 8.5.3.

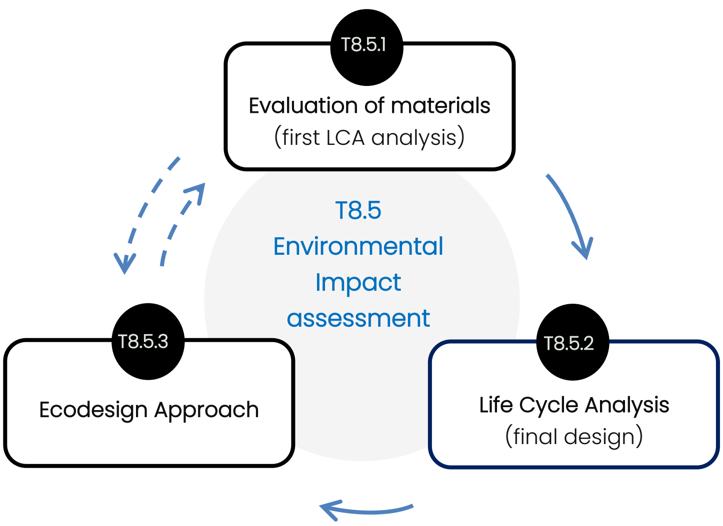

Figure 3 - Assessment approach and relation among tasks (source: IREC)

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3. General considerations for the LCA

The following points should be considered when interpretating results:

- The environmental analysis presented in this study covers the available developments in design until November 2023, and it is focused on the IIOBC.
- Data and results for the thermal management solution require further adjustments since the final design is under development.
- Due to confidentiality issues, the characterization of the shunt resistor, the SiC MOSFETs and the chip embedding process present uncertainties.
- Information obtained from suppliers on components characteristics (mass, dimensions) may be subject to uncertainties due to discrepancies between suppliers' datasheets and official material declarations, or by the absence of the latest.
- This first LCA analysis is part of an iterative process, further adjustments will be made for improving accuracy and confidence in results.

4. Environmental assessment (LCA) of the IIOBC

This section provides details on the application of the LCA methodology and the corresponding results for the current design developments of the IIOBC. Table 1 summarizes the converter parts included in the LCA analysis at this first phase of the project and the corresponding partners in charge of their development and data provision.

Table 1 – Converter parts included in the LCA study and collaboration in data gathering.

Part	WP	Project partner	Description of data provided
High-Voltage Switching Cells (HVSCs)	WP3	UPC	Bill of materials (BoM) for the manufacturing of the HVSCs including manufacturer and supplier part number, quantities, and description of components.
Thermal management	WP4	Deep Concept	Composition and mass characteristics of preliminary version of the thermal management solution (cold plate with liquid coolant) for converter legs.
Chip embedding (CE)	WP4	CSIC	Dimensions and mass characteristics of embedded components (shunt resistor and SiC MOSFETs). There are some restrictions in specific information of components and CE process due to confidentiality.
Converter leg (CL)	WP6	IREC	Details on dimensions and auxiliary components of the CLs. Support on classification of components and identification of LCI datasets.

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4.1. Goal and scope definition

This study aims to assess the environmental impacts related to the production of the IIOBC developed in the frame of the SCAPE project, with a focus on SCs and CLs as main innovations (see Figure 1).

The scope is defined from the cradle-to-grave approach comprising raw materials extraction, manufacturing of components, assembly of the IIOBC and the end-of-life stage. The use phase and transportation are excluded from the analysis as the focus of this task is on materials analysis. The considered IIOBC parts and the corresponding system boundaries for the evaluation are shown in Figure 4. Housing, cables, heat exchanger, pipelines connecting the coldplate with the heat exchanger, as well as other auxiliary components are not included in the scope of this evaluation. It should be noted that inductors, which are typically required in EV on-board chargers, are not included in the study, given the fact that the IIOBC employs the EV electrical machine windings as inductors.

End-of-life consists of recycling treatment of electronics for metals recovery in copper smelter.

The functional unit is defined as 1 unit of 6-phase converter (IIOBC) for EV application and rated at 100 kW and 800 V dc.

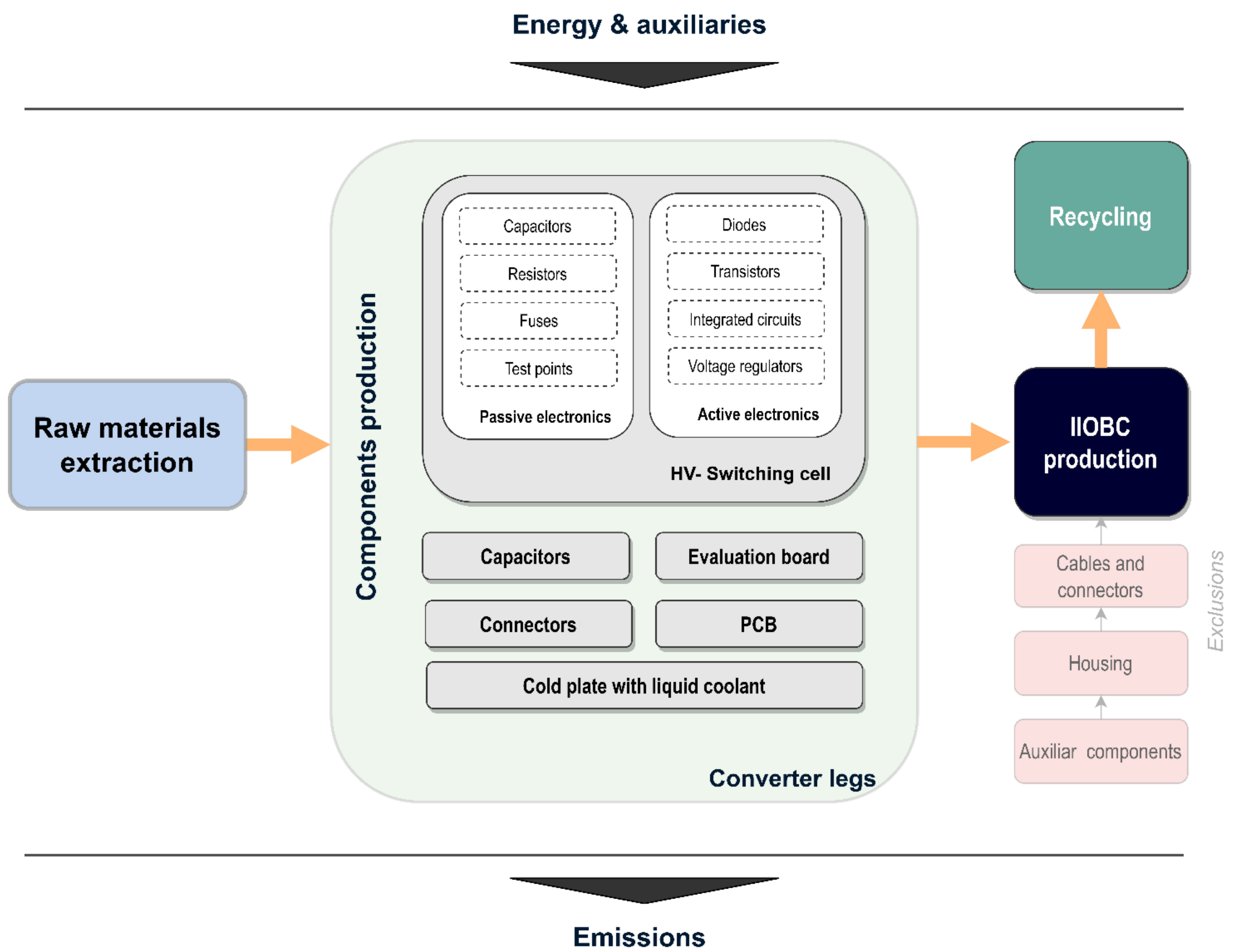

Figure 4 - System boundaries for the LCA study (source: IREC)

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4.2. Life Cycle Inventory

The LCI is built from primary data provided by project partners (see **Table 1**), as well as from secondary data from scientific literature and the recognized environmental databases Gabi Professional and Ecoinvent 3.9.1.

Information on the IIOBC design and data collected from project partners were analyzed, resulting in a total of 93 different components. The processing of data followed the next criteria:

- The study considers the parts physical characteristics (mass and dimensions) and mounting type as identified in the datasheets, material declarations and information available in suppliers and manufacturers webpages. DigiKey (www.digikey.es) and Mouser Electronics (www.mouser.es) were used as suppliers' references for the search.
- The categorization of components is done in accordance with common classification criteria for electronics in LCA, especially considering the Electronics Database structure followed for modelling in GaBi -Sphera software (Sphera, 2020). This categorization comprises: Passive electronics (capacitors, resistors, coils), active electronics (diodes, ICs, transistors), other components (FR4 substrates, assembly lines, solder pastes).
- Once all components are classified, corresponding environmental datasets on production of electronic components were identified in Ecoivent 3.9.1 and GaBi professional databases, ensuring compatibility with one or more of the following criteria: component function, material type, dimensions, mass, and mounting type.
- Due to the high variety of components with specific characteristics, aggregation of components with similar characteristics has been necessary to match datasets specifications.
- Lastly, the scaling factor by component is calculated based on mass/dimensions defined in the project and datasets.

4.2.1. IIOBC

The IIOBC consists of 6 units of CL with a total mass of 5.34 kg. Each CL is composed of eight HVSCs, a thermal management system, an evaluation board, connectors, capacitors, and a PCB for mounting all the components in the CL.

The LCI for producing the CL and HVSC, as well as end-of-life considerations are described in next sub-sections.

4.2.2. Converter leg

A summary of the required inputs for manufacturing a unit of CL is provided in **Table 2.** Details and assumptions for the construction of the LCI and the modelling in the LCA software are described as following:

- **High-Voltage Switching cells:** mass for 8 units of HVSCs with the characteristics described in sub section 4.2.3.
- **Cold plate with liquid cooling:** thermal management solution composed of: a) heatsink fabricated in aluminum with a mass estimation of 96g (12g per SC); b) plastic housing manufactured through additive manufacturing using epoxy resin material. Mass estimated in 448g (56g per SC). Energy consumption for additive manufacture (SLA printing)

estimated from literature in 0.01437 kWh/g of epoxy resin (Ulkir, 2023); c) liquid coolant composed of deionized water with 40% ethylene glycol. Mass estimation is based on an effective volume of 16,41 cm3 of liquid coolant inside the cold plate and a density of 1.115 g/cm^3 for the coolant mix at 20°C (REMPEC, 2020). A 200% volume increase of liquid coolant is assumed considering the extra flow volume in pipelines and heat exchanger. For both heatsink and housing production a yield of 95% is assumed.

- **Evaluation Board:** FPGA Evaluation board assumed to be conformed of 50% passive and 50% active electronic components from Ecoinvent 3.9.1.
- **Capacitors:** corresponding mass for 12 film capacitors.
- **Connectors:** two pieces of female-on-board connectors made of a phosphor bronze alloy type C510 (contact material) and PTB-polybutylene terephthalate (insulation). A composition of 15% contact material and 85% insulation is assumed.
- **FR4 substrates:** PCB area calculated in 0.0162 m2 (12.0 x 13.5 cm) and modelled as an 8-layer rigid FR4 with chem-elec AuNi finish and 3.26 kg/m^2 density.
- **Assembly lines:** auxiliaries and energy consumption for the mounting of components onto the PCB area through surface mount technology and using a Pb-free solder paste. It is assumed that 100% of components are surface mounted. The same considerations are assumed for the 3 components embedded into the PCB (shunt resistor, 1 piece; SiC MOSFETs, 2 pieces), given that the stated assembly data is the most similar to chip-embedding among available datasets.

Table 2 -LCI for producing a unit of Converter Leg of the IIOBC

Category	Text	Model code	Quantity	Unit
Electronics	High-Voltage Switching Cells	HVSC	34.14	g
Thermal management	Cold plate with liquid coolant:	CL_TM	578.33	g
	• Liquid coolant	TM_Liq	34.33	g
	• Aluminum heatsink	TM_HS	96.00	g
	• Housing	TM_H	448.00	g
	• Energy consumption for additive manufacture of housing	TM_H	6.76	kWh
Electronics	Evaluation board	CL_EB	101.00	g
Passive electronics (large)	Capacitors	L_PE_C	84.00	g
Other components	Connectors	CL_C	40.00	g
	FR4 substrates	CL_PCB	52.81	g
	Assembly lines	CL_A	0.0162	m^2
		Total mass per CL	890,29	g

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4.2.3. High-Voltage Switching Cells

The developed HVSCs consist of a group of passive (capacitors, resistors, fuses, and test points) and active electronic components (diodes, transistors, integrated circuits, and voltage regulators), accounting for a total of 123 pieces and total mass of 4.267g per SC.

Disaggregation of the LCI per type of component is provided in Table 3 in terms of mass. Specifications and assumptions are detailed as following:

Passive electronics

- **Capacitors:** total mass for two types of capacitors according to material composition: ceramic (31 pieces with size dimensions 0603) and tantalum capacitors (2 pieces).
- **Resistors:** a total of 44 resistors grouped into 4 categories: a) thick film chip resistor with 0603 dimensions (40 pieces); b) thick film chip resistor with 1210 dimensions (2 pieces), size 1206 is assumed for the LCA model due to availability of datasets; c) trimming Potentiometer (1 piece); d) shunt resistor (1 piece), the dataset for resistor production-metal film type from Ecoinvent was chosen by similarity in composition (CuMnNi-manganin). Total mass of resistor is estimated based on reference dimensions provided by CISC and an average density of 2,84 mg/mm^3 among the rest of resistors. Packaging is considered in calculations as it represents less than 2% of mass.
- **Fuses:** corresponding mass for 1 fuse chip size 0402.
- **Test points:** mass for 10 pieces of test points classified into two groups according to size and material composition: a) test points size 0603 made of aluminum wrought alloy. Auxiliaries and energy use for manufacturing is adapted from the bronze casting process of Ecoinvent to RoW: casting, aluminum; b) test points fabricated in a phosphor bronze alloy type C510 (main material) and Nylon as insulation material with a contribution of 25% and 75% to total mass respectively. Data on the production process for the alloy was obtained through and adaptation to the dataset process for aluminum alloy production, AlMg3 from Ecoinvent, proven compatibility with bronze alloy processing. Auxiliaries and energy consumption for the casting process are considered. The insulation material was assumed to be Nylon 6, glass filled. A 95% yield efficiency is assumed for the manufacturing of both test point types.

Active electronics

- **Diodes:** a total amount of 17 pieces of diodes are classified into three groups according to type and function. a) Light Emitting Diodes (5 pieces); b) power diodes (4 pieces); c) signal diodes (8 pieces).
- **Transistors:** transistors consist of 3 pieces of power MOSFETs for surface mounting and 2 pieces of bare-chip SiC MOSFETs. The inventory to produce the bare chip transistor is based on adaptations of processes and data from the Ecoinvent dataset for transistor production, surface-mounted excluding epoxy resin encapsulation. Mass is calculated in 7.48mg considering a volume of 3.6 mm^3 and an average density of 2.08 mg/mm^3 estimated from information of the two 30 V MOSFETs considered in the design.
- **Integrated circuits:** mass for 10 pieces of Integrated Circuits logic type.

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- **Voltage regulator:** comprising a total of 3 pieces of voltage regulators modelled as transistors (signal type) based on composition similarity.

Table 3 -LCI for producing a unit High-Voltage Switching Cell

Category	Text	Model code	Quantity	Unit
Passive electronics				
Capacitors	Ceramic capacitor	S_PE_C1	165.10	mg
	Tantalum capacitor	S_PE_C2	144.00	mg
	Total		309.10	mg
Resistors	Chip resistor 0603	S_PE_R1	80.00	mg
	Chip resistor 1210	S_PE_R2	32.00	mg
	Trimming Potentiometer	S_PE_R3	120.30	mg
	Shunt resistor	S_PE_R4	146.59	mg
	Total		378.89	mg
Fuses	Fuse chip	S_PE_F1	4.70	mg
	Total		4.70	mg
Test points	Test points 0603	S_PE_T1	37.80	mg
	Test points (Phosphor Bronze 510)	S_PE_T2	264.40	mg
	Total		302.20	mg
		Total passive electronics	994,89	mg
Active electronics				
Diodes	Light Emitting Diode	S_PE_D1	41.00	mg
	Power diode	S_PE_D2	59.74	mg
	Signal diode	S_PE_D3	21.53	mg
	Total		122.27	mg
Transistors	Transistor (Power MOSFET)	S_AE_T1	413.04	mg
	Transistor (bare chip)	S_AE_T2	14.95	mg
	Total		427.99	mg
Integrated circuits	Logic type ICs	S_AE_IC1	2435.42	mg
	Total		2435.42	mg
Voltage regulators	Voltage regulator	S_AE_VR1	286.72	mg
	Total		286.72	mg
		Total active electronics	3272.40	mg
		Total mass per HVSC	**4267.29**	**mg**

4.2.4. End-of-life

According to the WEEE European Directive 2012/19/EU (European Commission, 2012), power converters are classified as electric and electronic equipment. Under this consideration, end-of-life is assumed to consist of 100% recycling of electronic components accounting for a total mass of 1.87 kg excluding the thermal management solution. Data and processes for recycling are based on Ecoinvent treatment of electronics for metals recovery in copper smelter, comprising reception and processing for obtaining metal co-products from electric and electronic waste for further production of secondary metals such as gold. These additional processes are not included in the

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assessment. 95% efficiency in the recycling process is assumed. The assessment in this stage is focused on the impacts of recycling, credits from this process are not accounted and will be further analyzed in detail in Task 8.5.2.

4.3. Impact Assessment

The assessment was conducted using the mid-point approach through the CML2001 and Primary Energy Demand methods. Calculations were performed with the support of the LCA for experts (former GaBi) software.

The environmental impact categories used in this study are: Global Warming Potential (GWP), Abiotic Depletion-elements (ADPe), Acidification Potential (AP), Eutrophication Potential (EP), Primary Energy Demand (renewable and non-renewable, PED) and Human Toxicity Potential (HTP). These categories encompass relevant aspects for evaluating the environmental risks of electronic products and EV components such as climate change, resource depletion, energy demand, effects on land and water ecosystems, and harm caused to human health (Benveniste et al., 2022; Ghodrat et al., 2017; Kabus et al., 2020).

Details on impact categories and methods chosen are provided in Table 4.

Table 4 -Impact categories used in the study.

Impact category	Method	Unit	Description
Global Warming Potential (**GWP,** 100 years), excl. biogenic carbon	CML 2001-Aug 2016 (Guinée et al., 2002)	kg CO2 eq	Climate change indicator related to emissions of greenhouse gases to air. Characterization factors developed by the Intergovernmental Panel on Climate Change (IPCC) and expressed as Global Warming Potential for time horizon 100 years, excluding biogenic carbon emissions.
Abiotic Depletion Potential- elements (**ADPe**)	CML 2001-Aug 2016 (Guinée et al., 2002)	kg Sb eq	Measure the depletion of mineral resources. This indicator is related to extraction of minerals resources based on concentration reserves and rate of de-accumulation.
Acidification Potential (**AP**)	CML 2001-Aug 2016 (Guinée et al., 2002)	kg SO2 eq	Assesses the impact of acidifying substances on soil, groundwater, surface water, organisms, ecosystems, and materials.
Eutrophication Potential (**EP**)	CML 2001-Aug 2016 (Guinée et al., 2002)	kg PO4 3-eq	Includes all impacts due to excessive levels of macronutrients in the environment caused by emissions of nutrients to air, water, and soil.
Primary Energy Demand, renewable and non-renewable, (**PED**)	PED, net calorific value (Kupfer et al., 2020)	MJ	Quantifies direct and indirect energy resource demand from both renewable and non-renewable sources.
Human Toxicity Potential (**HTP**)	CML 2001-Aug 2016 (Guinée et al., 2002)	1,4-DCB eq	Measures effects of toxic substances on the human environment.

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4.4. Results

Results of the environmental impact assessment for the production of the proposed IIOBC and end-of-life treatment through recycling are listed by impact category in Table 5. Graphical representation of the modeling process in the LCA software for the most relevant parts of the converter is provided in the Annexes section.

Under the system boundaries defined in this study, the major contribution to overall impacts is related to the production phase of the converter. The manufacture of the IIOBC comprises the impacts associated with the extraction and processing of materials for the manufacture of converter elements, including additional processes for their assembly. On the other hand, recycling presents a minimum influence of less than 1% in all impact categories. This low contribution of recycling is attributed to the low-impact processes of the treatment, corresponding to reception and processing of electronic waste, and in which complementary processing of metal co-products for obtaining refined secondary metals is out of the system of analysis.

Converter manufacturing generates a total of 944 kg CO_2 eq. in the GWP indicator. Concerning ADPe, the production phase accounts for 0.26 kg Sb eq., representing the impact by the extraction of resources that leads to depletion of mineral reserves. Indicators measuring effects on air, land, and water, as well as the impact on human health by the emission of toxic substances show absolute values of 5.46 kg SO2 eq., 3.34 kg Phosphate eq. and 3,149.41 kg DCB eq. for AP, EP and HTP indicators, respectively. Lastly, PED from renewable and non-renewable resources accounts for 15,883 MJ.

As a reference for comparison, based on the work developed by Kabus et al. (2020) on a LCA study of two charging systems for EVs, we obtained an estimation of 580 kg CO_2 eq to produce an AC-DC converter that is part of an on-board charging system with power up to 22 kW. However, this estimation is based on aggregated data provided in the study and can present deviation from original results or uncertainty degree of data due to the limitations in the LCI considered for the study.

Table 5 – LCA results for the production and end-of-life management of the proposed IIOBC

Impact category	Unit	Total	IIOBC production	End-of-life
Global Warming Potential (GWP 100 years)	kg CO2 eq.	944.05	944.01	3.32E-02
Abiotic Depletion. elements (ADPe)	kg Sb eq.	0.26	0.26	9.06E-08
Acidification Potential (AP)	kg SO2 eq.	5.46	5.46	6.78E-05
Eutrophication Potential (EP)	kg Phosphate eq.	3.34	3.34	1.44E-05
Primary energy demand from ren. and non ren. resources. net cal. Value (PED)	MJ	15,883.23	15,883.00	2.24E-01
Human Toxicity Potential (HTP)	kg DCB eq.	3,149.60	3,149.41	1.96E-01

Analysis at CL level is given in detail in Table 6 in terms of absolute values by impact category and by component for the manufacturing phase. Moreover, normalization of results is provided in Figure 5 for a more consistent analysis at component level. From the results, it is observed that the evaluation board acts as the major contributor in all impact categories. It is influenced by its significant share in mass among the electronic components conforming the CL. Impact contribution is followed by the effect of HVSCs and PCB production.

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Concerning the PCB (FR4 substrate), the high impacts are in general associated to the environmental and energy intensive processes required for the extraction and processing of copper, which constitutes 89% of its material resources inventory (non-renewable elements). However, there is a reduced impact in the HTP indicator. Although copper is identified as potentially toxic for human health, there are other elements such as arsenic, cadmium, chromium, lead, and mercury that are ranked as priority metallic elements with high degree of toxicity that induce multiple damages to health, even at lower exposure levels (Tchounwou et al., 2014).

Based on the previous explanation for the HTP indicator, apart from the dominant contribution of the evaluation board, the production of the group of components that conform the HVSCs is of relevance for this indicator. This is due to the significant presence of the previously mentioned high toxic elements, which accounts for 33% of HVSCs composition. For the ADPe category, both evaluation board and HVSCs show high impact due to the variety of mineral resources used in the manufacture of their diverse electronic components.

Table 6 – LCA results for the production of one unit of CL.

Impact category	Unit	Total impact	Results by component						
			Evaluation board	Connectors	Thermal management	HV- SCs	Capacitors	Assembly	FR4 substrate
GWP 100 years	kg CO2 eq.	157.42	64,92	0,17	5,41	33,92	3,96	1,26	47,78
ADPe	kg Sb eq.	4.35E-02	2,26E-02	5,14E-05	2,48E-05	1,42E-02	3,23E-04	7,87E-04	5,49E-03
AP	kg SO2 eq.	0.911	0,385	0,003	0,016	0,283	0,034	0,011	0,179
EP	kg Phosphate eq.	0.556	0,321	0,001	0,013	0,182	0,014	0,007	0,018
PED	MJ	2648.66	1104,21	4,51	144,50	572,14	71,83	21,32	730,15
HTP	kg DCB eq.	525.20	292,88	4,10	6,78	174,17	29,45	8,50	9,32

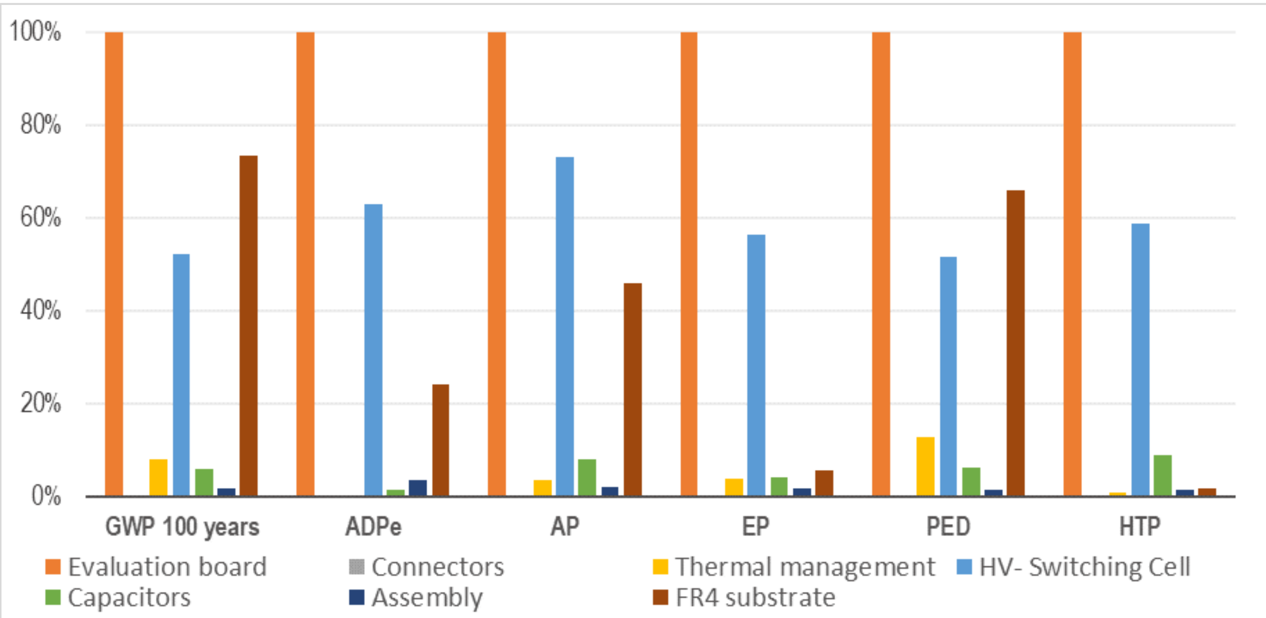

Figure 5 – Normalized LCA results by CL component (source: IREC)

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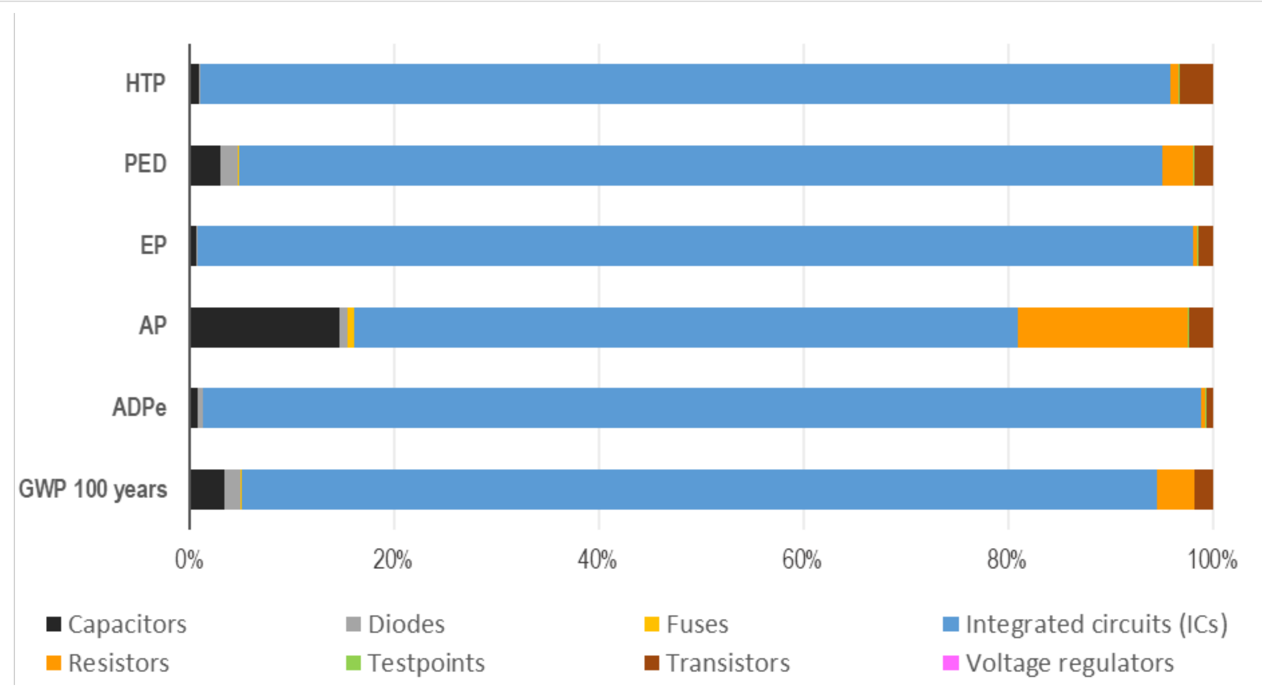
The impacts associated with one unit of HVSC are presented in **Figure 6**. In general, one unit of HVSC generates 4.24 kg CO2 eq. as a measure of the GWP indicator. Moreover, results show active electronics (diodes, ICs, transistors, and voltage regulators) as the dominant contributor in all impact categories. This is mainly due to the influence of integrated circuits, which represents around 57% of the SC mass. Both resistors and capacitors present an average contribution of 4% among impact categories, but higher for AP due to the emission of inorganic pollutants such as sulphur dioxide, nitrogen dioxide and ammonia.



Impact category	Capacitors	Diodes	Fuses	Integrated circuits (ICs)	Resistors	Testpoints	Transistors	Voltage regulators
GWP 100 years	3,48%	1,58%	0,15%	89,36%	3,60%	0,06%	1,77%	0,000001%
ADPe	0,80%	0,58%	0,02%	97,39%	0,49%	0,03%	0,69%	0,0000004%
AP	14,70%	0,78%	0,69%	64,74%	16,65%	0,12%	2,32%	0,000002%
EP	0,69%	0,18%	0,02%	97,12%	0,47%	0,05%	1,47%	0,000001%
PED	3,01%	1,81%	0,12%	90,07%	3,07%	0,05%	1,87%	0,000001%
HTP	0,95%	0,10%	0,02%	94,78%	0,73%	0,21%	3,21%	0,000002%

Figure 6 – LCA results for one unit of High-Voltage Switching Cell (source: IREC)

Results for the production of the thermal management solution present a similar behavior among impact categories, with slightly higher contribution in the GWP and PED indicators (see **Figure 5**). In general, and for these two indicators, as observed in **Figure 7** the production of plastic housing is the largest contributor. This is due to the associated impacts of the epoxy resin and the energy consumption for additive manufacturing. In particular, AP, ADPe, ET and HTP indicators are mainly influenced by the epoxy resin material.

Impacts from connectors and assembly of components through surface mounting are negligible, as they represent an average of less than 2% of impact among categories.

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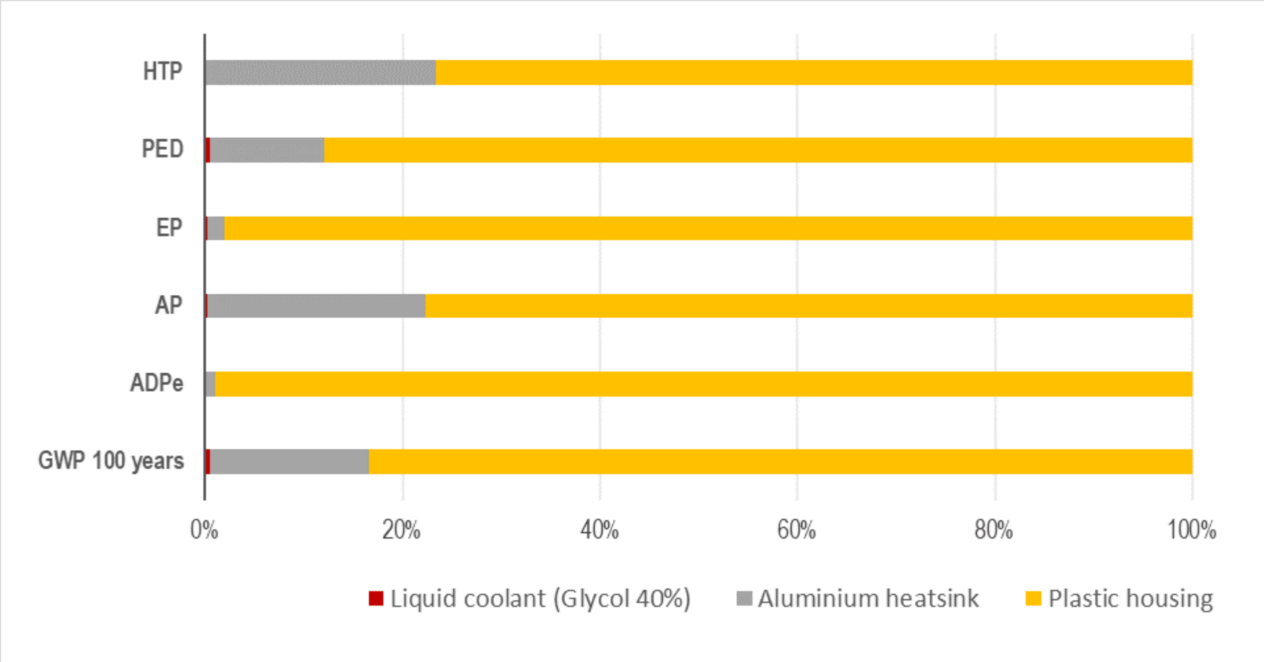

Impact category	Liquid coolant (Glycol 40%)	Aluminium heatsink	Plastic housing
GWP 100 years	0,43%	16,14%	83,43%
ADPe	0,002%	1,04%	98,96%
AP	0,27%	22,06%	77,67%
EP	0,20%	1,72%	98,08%
PED	0,47%	11,59%	87,95%
HTP	0,09%	23,27%	76,64%

Figure 7 – LCA results for one unit of thermal management solution (source: IREC)

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5. Conclusions

This deliverable shows the LCA analysis of current design developments for the IIOBC proposed in SCAPE as part of a novel approach for modular and scalable EV power-conversion system. The analysis was performed from the cradle to grave approach, considering recycling as treatment alternative at the end-of-life.

This evaluation is part of a wider strategy framed in Task 8.5.3 on ecodesign, in which LCA is a fundamental part for identifying the aspects with significant contribution to the environmental performance of the converter. Therefore, providing basis for recommending strategies aimed at reducing negative environmental effects.

In general, evaluation board is the highest contributor to impact. However, further analysis in detail of its life cycle inventory is required for increasing accuracy on results since it was modeled using general datasets for the production of passive and active electronics. Similarly, the thermal management solution (cold plate with liquid coolant) must be re-evaluated once the final design is available in order to reduce its environmental impact.

HVSCs were identified as significant contributors to CL impacts, mainly because of the intensive processes related to mineral resource extraction and processing. Although the inventory and analysis were performed in detail, it is recommended to perform an uncertainty analysis for confidence in results.

For the components and processes involved in the chip embedding process, confidentiality in data provision restricts the proper application of the LCA. Further alternatives for modeling this process must be explored in the frame of Task 8.5.2 on LCA of the final power-conversion system prototype. In addition, credits from the avoided use or virgin materials due to recycling will be studied in this final evaluation.

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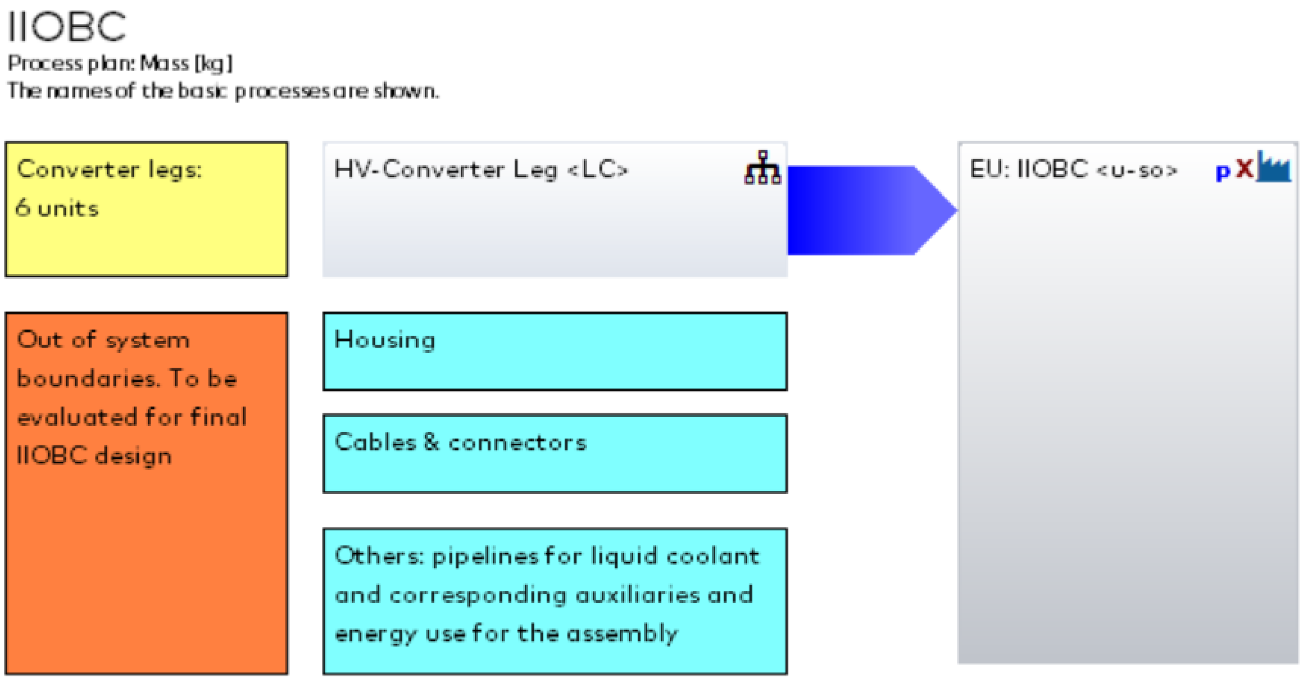
7. Annexes

This section provides graphical representation of the most relevant models developed for the calculations of environmental impact of the different converter parts. These diagrams represent the flow of resources according to the specifications and assumptions described in section 4.2 – Life Cycle Inventory (LCI) and were built using the LCA software for experts (former GaBi).

Diagrams are grouped into main parts: IIOBC, Converter Leg and High-Voltage Switching Cell.

7.1. Model of the IIOBC



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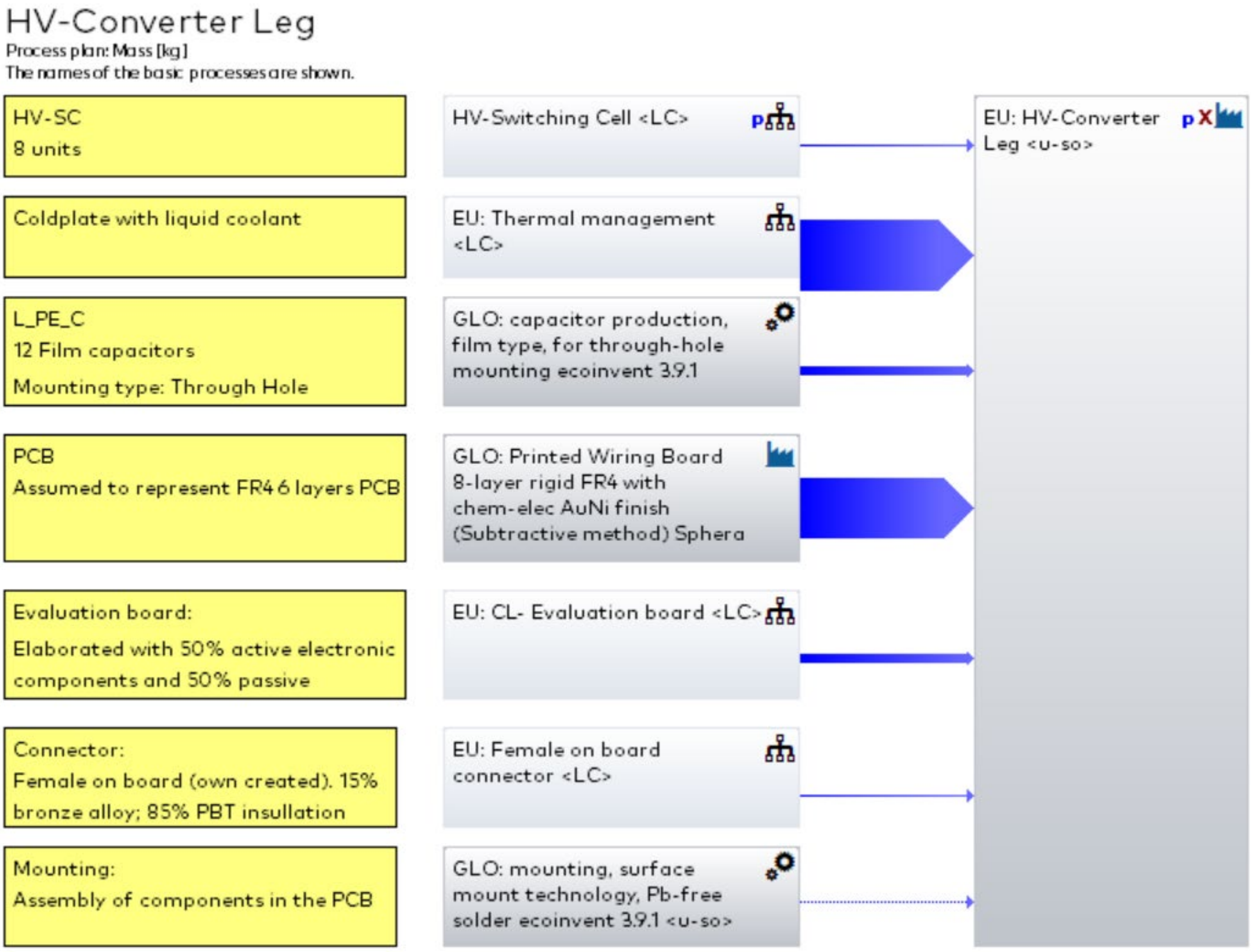
7.2. Model of the Converter Leg and its components



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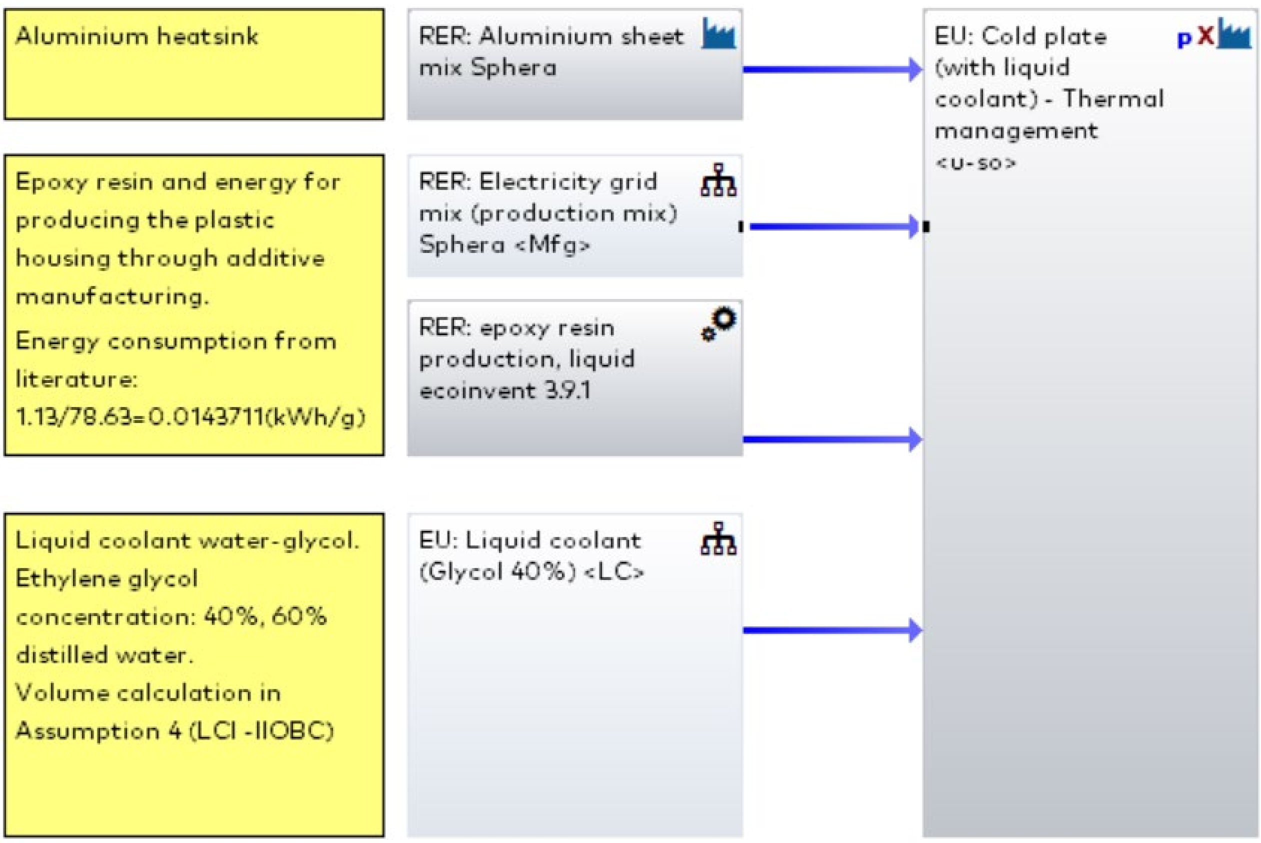
Thermal management
Process plan:Reference quantities
The names of the basic processes are shown.



Liquid coolant (Glycol 40%)
Process plan:Reference quantities
The names of the basic processes are shown.

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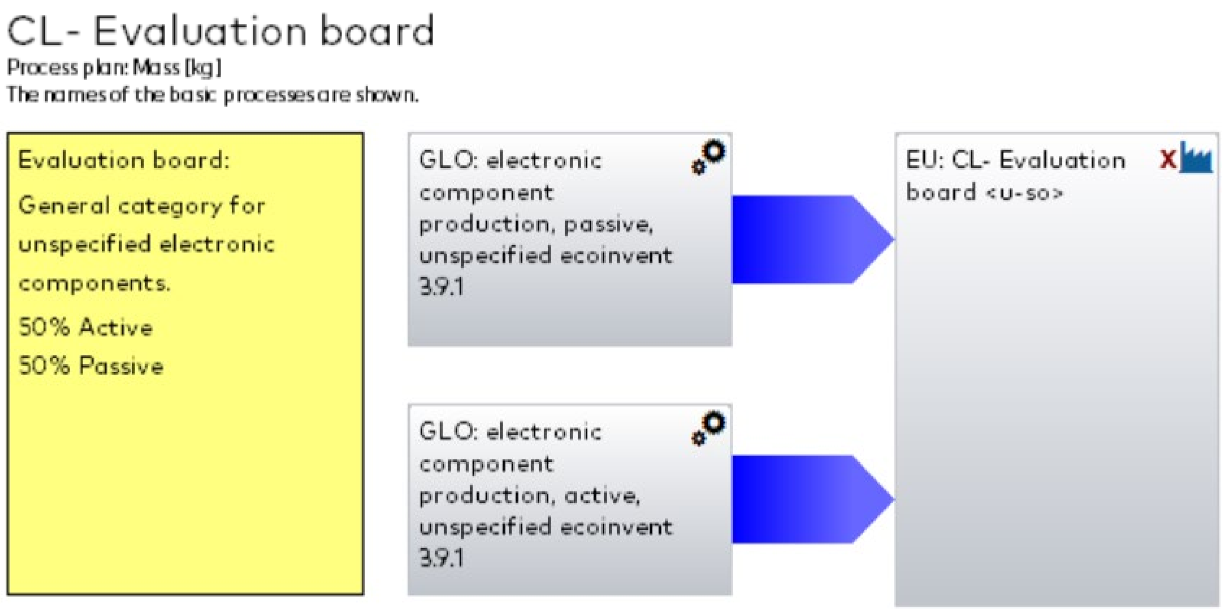

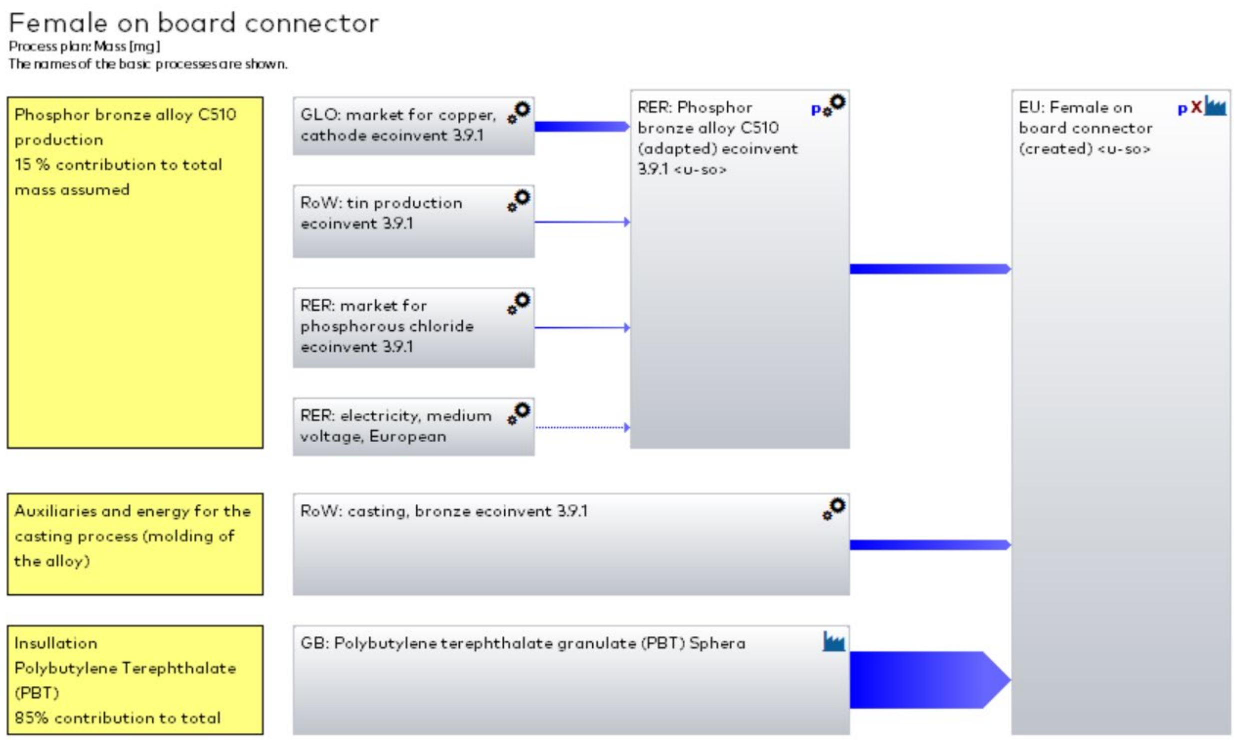

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7.3. Model of a High-Voltage Switching Cell and its components

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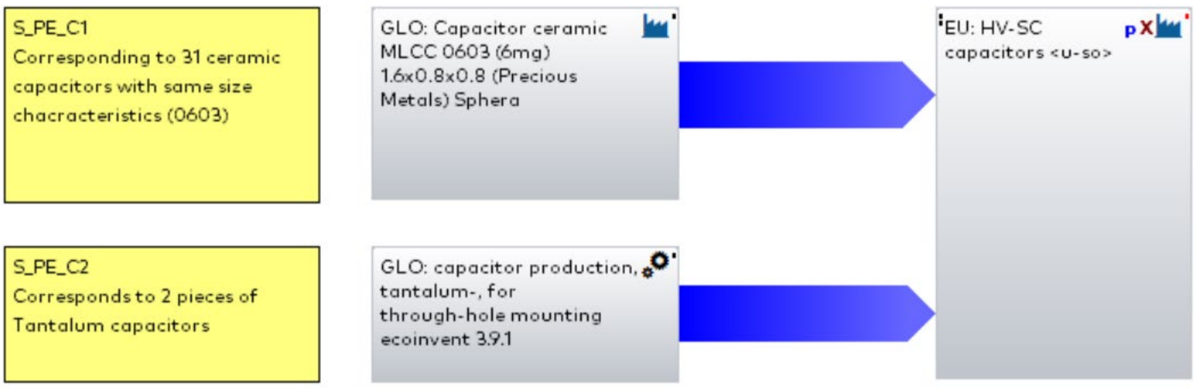
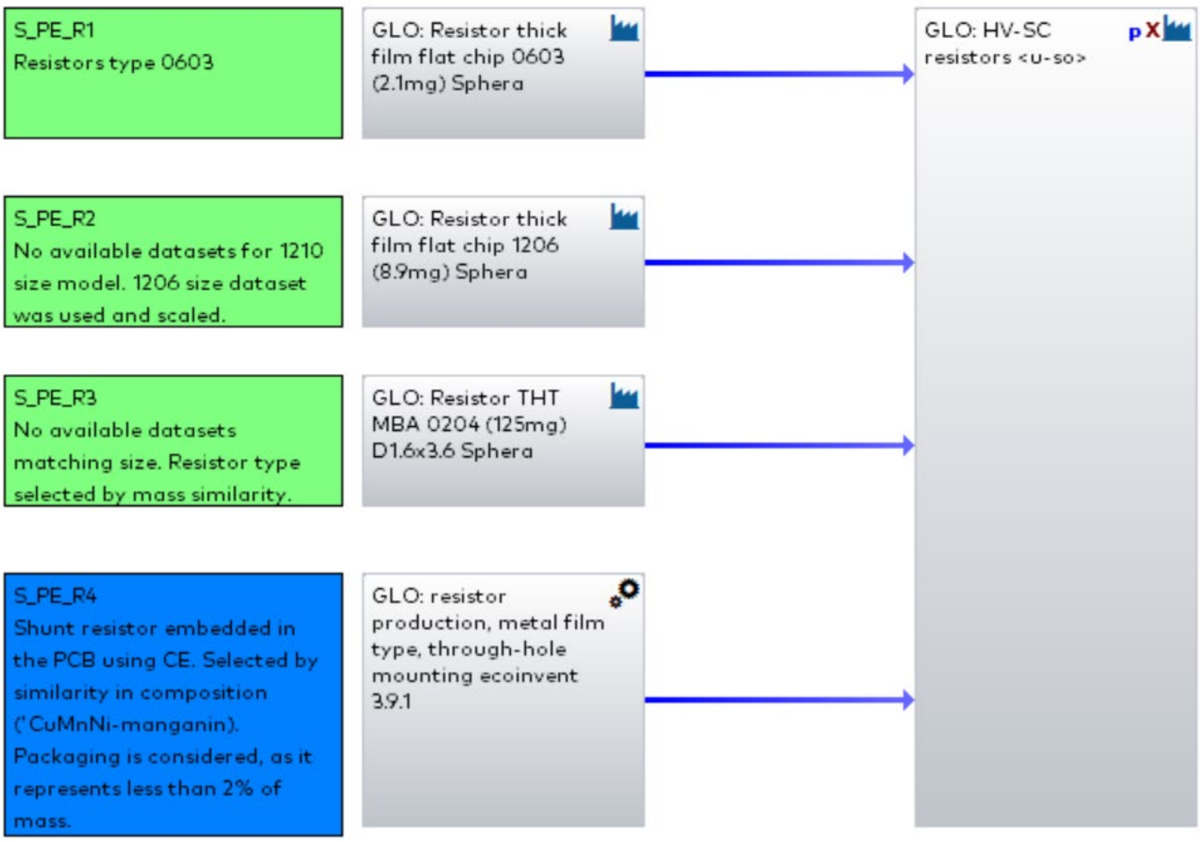
HV-SC capacitors

Process plan: Mass [kg]
The names of the basic processes are shown.



HV-SC Resistors

Process plan:Reference quantities
The names of the basic processes are shown.



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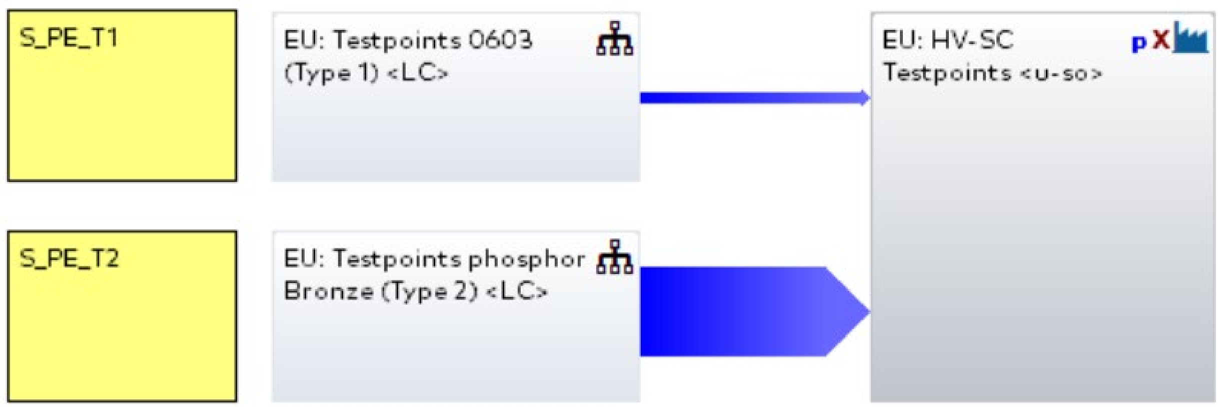
HV-SC Testpoints

Process plan: Mass [kg]
The names of the basic processes are shown.



Testpoints 0603 (Type 1)

Process plan: Mass [kg]
The names of the basic processes are shown.

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Testpoints phosphor Bronze (Type 2)

Process plan: Mass [mg]
The names of the basic processes are shown.

HV-SC Diodes

Process plan: Mass [kg]
The names of the basic processes are shown.

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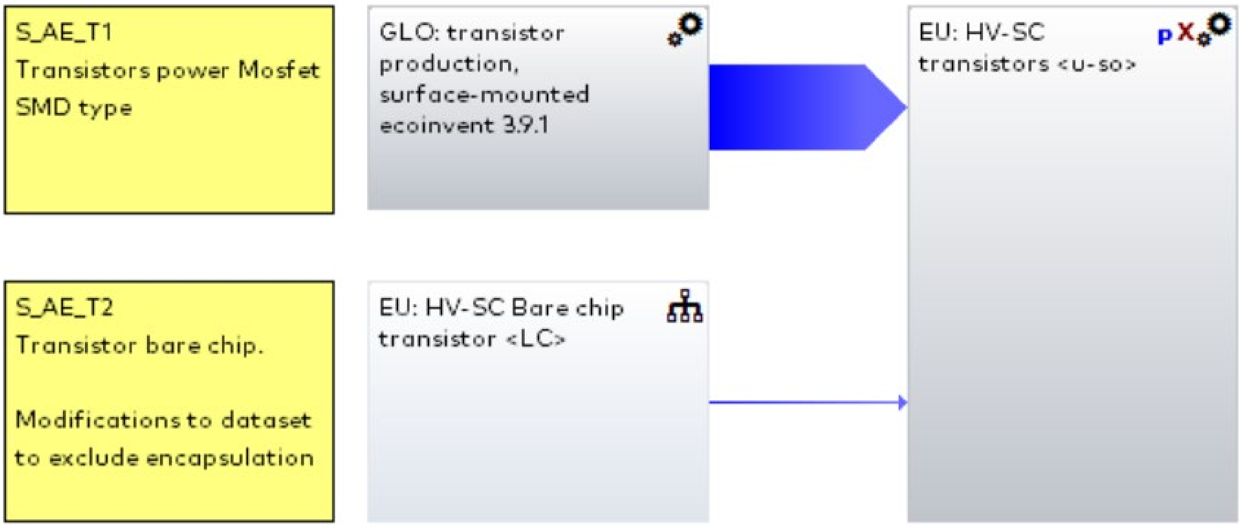
HV-SC Transistors

Process plan: Mass [kg]
The names of the basic processes are shown.



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