



SCAPE
POWERING E-MOBILITY

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D8.9 – LCA report on the proposed integrated and scalable power converters

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

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Executive Summary

This report looks at the environmental footprint of the Integrated Inverter Charger (IIC) technology developed in the SCAPE project and is an extension and refinement of the deliverable D8.8. 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. The evolution of the project is analysed by measuring the emissions of the early mock-up to the final IIC prototype. This IIC is designed to function as a power inverter and as an onboard charger, however, due to the lack of environmental assessments on onboard chargers, the results from the IIC are compared to two commercial inverters, one modelled as part of this project with data from one partner, and the other from literature. The assessment is performed following the Life Cycle Assessment (LCA) methodology from the cradle-to-grave approach. Although 16 different emissions have been estimated, there has been a focus on greenhouse gas emissions, finding that the IIC designed in SCAPE presents a lower footprint than commercial inverters, both from the case modelled in this study and from literature values. Although limitations of this study should be considered, the presented results show a promising projection for this technology, as we believe TRL of SCAPE's IIC still has room for improvement regarding its environmental performance.



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List of Acronyms and Abbreviations

AB – Advisory Board	LCI – Life Cycle Inventory
AC – Acidification	LCIA – Life Cycle Impact Assessment
CC – Climate Change – total	LU – Land Use
CE – Human toxicity, cancer – total	MOSFET – Metal-oxide semiconductor field-effect transistor
CL – Converter Leg	NCE – Human toxicity, non-cancer – total
CRM – Critical Raw Material	OA – Open Access
DES – Dissemination and Exploitation Strategy	OD – Ozone depletion
EB – Executive Board	OEM – Original Equipment Manufacturer
EC – European Commission	PC – Project Coordinator
ECF – Ecotoxicity, freshwater – total	PCB – Printed Circuit Board
EEE – Electrical and Electronic Equipment	PM – Particulate matter
EF – Eutrophication, freshwater	POF – Photochemical ozone formation, human health
EIB – Exploitation and Innovation Board	REE – Rare Earth Elements
EM – Eutrophication, marine	RUF – Resource use, fossils
EoL – End-of-Life	RUM – Resource use, mineral and metals
ET – Eutrophication, terrestrial	SC – Switching Cell
EV – Electric Vehicle	SiC – Silicon Carbide
GA – General Assembly	SRM – Strategic Raw Materials
GHG – Greenhouse Gas	TM – Thermal Management
IIC – Integrated Inverter Charger	TRL – Technology Readiness Level
IPR – Intellectual Property Rights	WEEE – Waste of Electrical and Electronic Equipment
IR – Ionizing radiation, human health	WP – Work Packages
LCA – Life Cycle Assessment	WU – Water use



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1. Introduction

This report corresponds to the deliverable “D8.9 LCA report on the proposed integrated and scalable power converters” and consists of the environmental impact assessment of the entire lifecycle for the proposed power converters in the SCAPE project, also referred to as Integrated Inverter Charger (IIC).

The analysis carried and this report follow the guidelines and recommendations of the ISO standards 14040/44:2006 on Life Cycle Assessment (LCA), depicted in **Figure 1**, and covers the evaluation of the following life cycle aspects: resource extraction, manufacturing of converter components, assembly, use and the End of Life 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 previous deliverable is updated with data related to the SCAPE’s final design of the electric vehicle (EV) IIC and compared with the initial mock-up and with a commercial alternative. It should be highlighted that, although SCAPE is developing the converter to behave as an inverter and an onboard charger, we have only considered as an inverter. This is mainly because of comparability reasons, as we have not found any article estimating the environmental impact of onboard chargers or an inventory with their components, but only inverters. Because LCA has a comparative nature – it’s aim is to see if the footprint of an alternative is higher or lower than another – we treated the developed IIC from SCAPE only as an inverter. Nevertheless, all the components forming the IIC have been considered

In addition, the outputs of this preliminary analysis will feed the application of the eco-design 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 IIC and to quantify and understand its environmental effects.

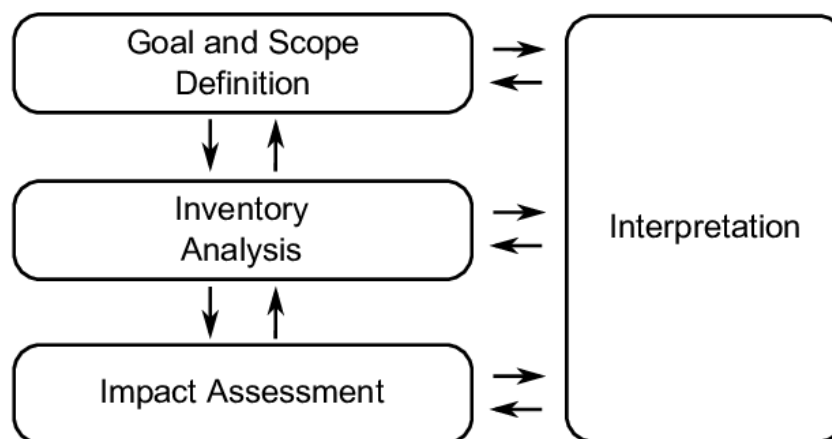


Figure 1 – Life Cycle Assessment phases

1.1. Structure of the system under study

The EV power-conversion system proposed in SCAPE is composed of two power converters: the inverter and the auxiliary dc-dc converter. The present LCA study focuses on the inverter, although to differentiate to the inverters to which SCAPE IIC is compared, it is referred as converter or IIC.

Figure 2 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, allowing 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 design 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.
- A shunt resistor for current measurement purposes.

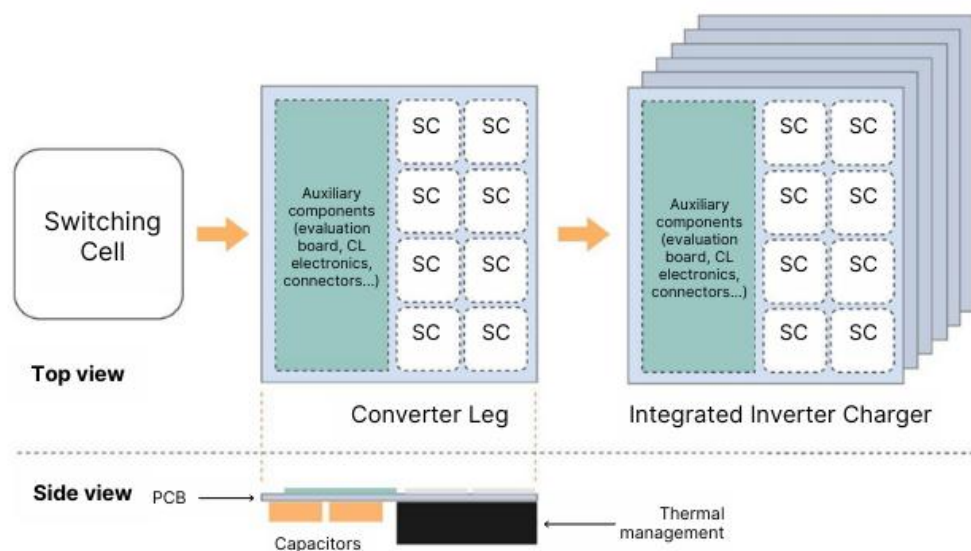


Figure 2 – Schematic of the electronics of the assessed inverter. Its modularity and scalability are shown from left to right, where 8 SC are required for 1 CL and 6 CL for 1 IIC (source: IREC).

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 3 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.

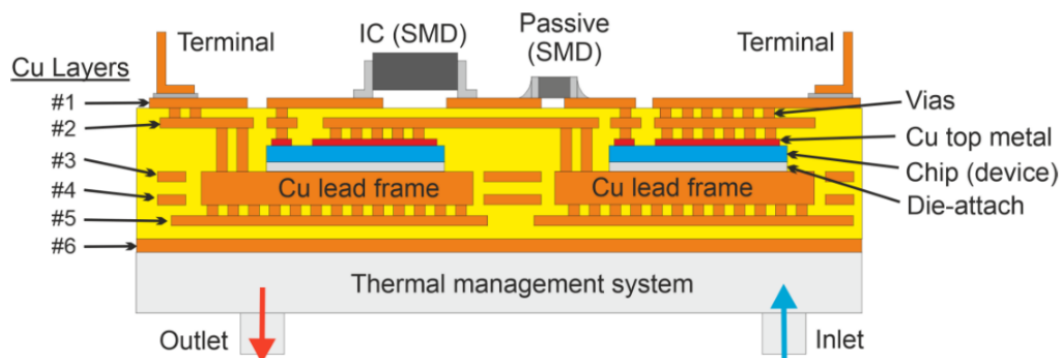


Figure 3 – Cross section of a PCB featuring chip embedding (source: CSIC)

2. Goal and Scope

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

The objective of this project is to estimate the environmental footprint of a newly designed integrated inverter-charger (IIC) converter for EVs and to compare it with the current state-of-the-art. More in detail we compare the results obtained from the SCAPE design with a commercial inverter from AVL and an EV inverter found in literature. The scope is defined from the cradle-to-grave approach comprising raw materials extraction, manufacturing components, assembly of the IIC, use, transport and the end-of-life stage. Additionally, housing and thermal management are considered and included in the assessment. The rest of auxiliary components required for a commercial inverter to function are excluded from the analysis.

The functional unit is defined as 1 unit of 6-phase IIC for EV application and rated at 100 kW, however, for comparability purposes, this is defined in the model as the total electricity converted by the IIC through its entire lifetime, measured in kWh. The system boundaries and the functional unit are depicted in **Figure 4**.

The foreground data for the IIC are collected from SCAPE project partners, with remaining gaps completed using peer-reviewed literature. For the background LCI modelling, two databases are employed: ecoinvent v3.10 [1] and Sphera. Although using a single database would be preferable to ensure full methodological consistency within the study, these two databases are used because each one presents advantages over the other in specific points. Sphera own specific datasets on electronic components such as diodes, capacitors and transistors, that ecoinvent does not and they are very useful for this study. On the other hand, ecoinvent datasets are widely used in other studies, which, for comparability purposes, becomes the preferred database for the rest of the activities. Thus, Sphera is used only for electronic components whereas ecoinvent is used for the rest of the activities.

The modelling is performed using LCA for Experts (formerly GaBi), and the impact categories assessed correspond to the Environmental Footprint 3.1 method, following the recommendations of the European Union [2].



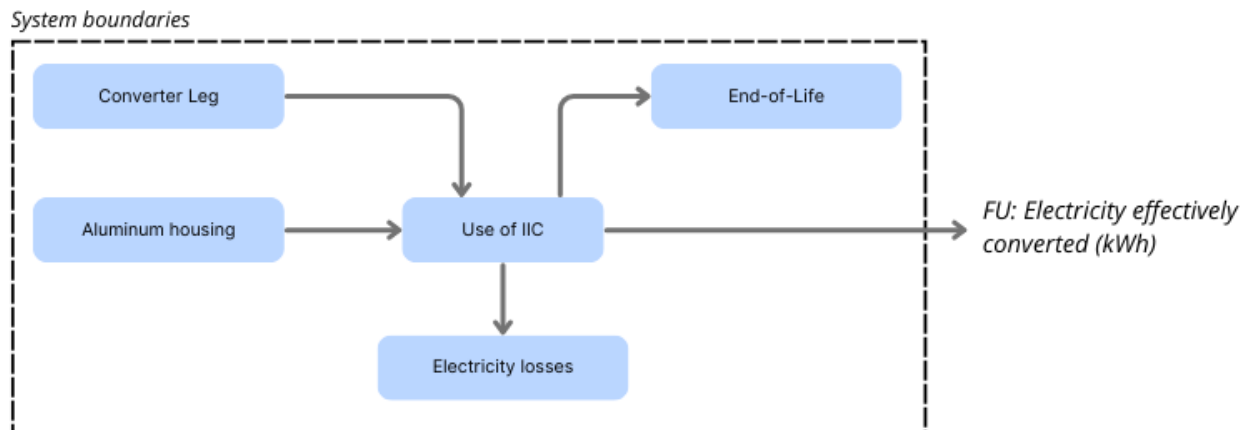


Figure 4 – System boundaries and functional unit considered in this study. Phases of the study are depicted in three columns, from left to right: manufacturing – including raw material extraction –, use phase and end-of-life.

3. Life Cycle Inventory

The inventory is built from primary data provided by project partners as well as from secondary data from scientific literature and the recognized environmental databases Gabi Professional and ecoinvent 3.9.1. We have built upon previous deliverable work, expanding and refining the data collection. The specifics for each alternative (Mock-up, SCAPE's final converter and commercial inverter) are described in independent sections.

Manufacturing. All the elements constituting the converter have been considered, except for the board connectors and the fuse. This converter is formed by six Converter Legs (CL) protected by an aluminium casing. Each CL is formed by a printed circuit board (PCB), eight Switching Cells (SC), an evaluation board, auxiliary electronic elements, capacitors and female connectors. Additionally, one set of thermal management is considered for each CL. There is a different level of details between the parts forming the converter. SCs are the novelty respect current converter technologies and thus, higher detail is gathered for this section. Whereas housing and thermal management have been modelled through estimation with a lower degree of certainty.

The study considers the physical characteristics (mass and dimensions) of each element (resistor, capacitor, transistor...) and mounting type as identified in the data sheets, 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. Due to the high number of electronic elements (133), the use of datasets from Sphera database has been prioritized, ensuring compatibility with one or more of the following criteria: component function, material type, dimensions, mass, and mounting type. The scaling factor by component is calculated based on mass/dimensions defined in the project and datasets, depending on the available data of the element.

For those elements that did not match the description of the datasets, the material declaration of the element has been used to model it from scratch. 41 elements have been modelled, using the quantities and types of materials from material declarations and energy requirements based on the type of element and the materials used in the element itself. To estimate this value, we have used the energy requirements from ecoinvent "*resistor production, auxiliaries and energy use*" as a generic element. If the element was made with silicon, the process "*silicon, electronics grade*" was added to the previous process. In both cases, the scaling was done according to the element's weight and

material. We have used energy inputs from ecoinvent because their inputs are open to view whereas Sphera datasets are not. For those elements containing silicon carbide, insights from [3] have been used, where energy requirements for manufacturing silicon carbide elements are described in kWh/cm², scaling this value to the area in which the material is used. This area is an approximation considering the packing area of the element (e.g. transistor) and is subject to considerable uncertainty. The processes for these energy inputs are “Medium voltage electricity” and “heat for district or industrial use, other than natural gas”, following ecoinvent inventories for electronics, using one country or another depending to where the manufacturing sites of the element’s company are (mostly China or U.S

These countries’ selections are then used to estimate the transport distances of each element to France, which is chosen arbitrarily as a destination country where the IIC would be assembled. This assemblage is considered only as the soldering of electronics on the PCB, the remaining tasks needed for the full configuration of the converter are not considered, as it is not seen as a sensible part for the assessment [4]. Further, some elements that are needed for the proper functioning of the converter are not included in the analysis and considered as cut-off due to the early stages of technology and, thus, the lack of precise definition of these. These elements include, among others, the cables and connectors between CL, pump and tubes for the thermal management outside the CL.

Transport. In this study transport is considered between manufacturing and use; and between use and recycling. It is assumed that the vehicles used for transportation would be trucks and ships, depending on the countries involved. Market activities were generally avoided because information about who the supplier of the different electronic elements was available, and thus, the location of the manufacturing site was searched online and assumed. The distance of transport has been estimated considering the main manufacturing centres of all the companies listed in WP3 HV-SC BOM V1.02 which can be summarized in 6 countries: China, USA, Germany, Japan, Italy and Switzerland. For those countries outside Europe, 3 transport processes are modelled truck-ship-truck, whereas for European countries, the elements are transported only by truck. Distances are averages between countries and the webpage searates [5] is used to estimate the distance by ship to France

Use stage. After transporting the elements and assembling the SCAPE’s final converter, the converter is ready to be used. We use key performance indicators from the project, and we consider that the converter will last 16.000h, or 600.000km, with an efficiency of 95,65% for the mock-up, 97.5% for the Chip embedding and between 84 and 98% for the commercial version. Following the reasoning from [4], and for later comparability purposes, a consumption of 16 kWh/100km is considered and losses throughout its lifetime are estimated with **Equation 1**. The electricity mix selected to power the converter is the average European mix, no maintenance is considered, and the emissions from this stage will be exclusively from electricity losses. The efficiency of the battery is not considered, but the efficiency of the grid, as well as their infrastructure, are implicitly taken into account by using the low voltage datasets.

Equation 1 – Energy losses estimations, as per [4]

$$\text{Energy losses} = EV \text{ consumption per km} \cdot N \text{ km} \cdot (1 - \text{efficiency})$$

EoL. Although the End-of-Life (EoL) stage is not considered a key stage in the environmental impacts of Electrical and Electronic Equipment (EEE) [6], due to the modular ambition of the project, authors believe it is appropriate to estimate the potential recycling has, so it can be compared with other EoL



strategies in future research. According to EU regulation, 95% of the average vehicle weight must be recovered and 85% of the average vehicle weight must be recycled per year by the state members [7]. Nevertheless, knowing the difficulties of recycling Rare Earth Elements and the economic unfeasibility of retrieving metals and other elements in very low quantities in electronics, it is argued that the converter studied in this article may not follow these percentages. Recycling rates from [8], based on [9] are used and depicted in **Table 1**. Further, the only metals considered in this process are economically feasible to recycle major metals (iron, copper and aluminium) and precious metals (gold, silver and palladium) like in [10].

Table 1 – End-of-life recycling rates for economically viable metals. These are approximations from [8] based on [9].

Recycling Rate	
Copper	50%
Aluminium	60%
Gold	75%
Silver	40%
Palladium	60%

It has been assumed that the recycling process happens in Europe and therefore considers the transport of the converter to Belgium, as the biggest electronic recycler (Umicore) has a recycling and refining site in this country (Haboken) [11]. This company (or any other) would use different sorts of techniques to separate the materials before sending them to pyro, biohydro, hydrometallurgical recycling [12]. Some of these techniques are crushing, shredding, air classifying, separating with magnets and eddy currents... Even if the whole process was transparent and the exact processes applied to the converter recycling were known, which does not happen, there would still be missing datasets to model these processes. For that reason, only some basic stages of the recycling process that are present in the ecoinvent datasets are considered. In a nutshell, the recycling process considered is as follows: Disassembly of the converter from the EV, transport by truck to the recycling facility in Belgium, disassembly of the housing, thermal management and electronics. Aluminium and copper from thermal management and housing are smelted in different processes, while electronics are shredded and smelted to extract valuable materials. These smelting processes have an efficiency attached [8], and the slags and wastes from these processes are considered to be transported by ship and landfilled in Ghana or India [13]. Recycling is modelled in a way that the material recovered from the recycling process avoids primary production, which can lead, in some impact categories, to negative emissions.

3.1. Mock-up

In the LCA developed in deliverable D8.8, the hotspot was the Evaluation Board. This was mainly because of the low resolution there was in the modelling, which used general datasets of passive and active electronics at a 50/50 weight ratio. Knowing this was an issue, we have modelled all the electronics considering an element resolution, not only for the Switching Cell, but for all the electronics embedded in the IIC. The specific components forming the mock-up are:

Housing. The project did not define the housing, but we have made some rough estimations to consider it:

- Defined as a cubic case of 500 x 200 x 600mm with 5mm thickness
- Considered a density of Aluminium 6063: 2.69g/cm³



- Aluminium case of 8.3kg

Thermal management. For the mock-up a thermal management formed by copper S-shaped tubes embedded in a block of aluminium in contact with the CL. This design follows the measures from WP7. On top of that, we estimated the volume inside the tubes to calculate the amount of cooling liquid required.

- Aluminium weight: 1.5kg
- Copper weight: 440g
- Liquid coolant (Glycol 40%): 116g

Female on board connection.

- Considering a weight distribution of 15% bronze and 85% PBT insulation
- Total weight of 40g

PCB. A "Printed Wiring Board 8-layer rigid FR4 with chem-elec AuNi finish" is considered with the "Pb-free soldering required" as Sphera processes for 740cm². This PCB is considered to hold all the electronics considered in the converter with the only exception of the Evaluation Board, which has its own PCB.

Converter Capacitors. 12 Film capacitors with a total weight of 84g are modelled through the process "capacitor production, film type, for through-hole mounting".

Switching Cell. Following the Bill of Materials (BOM) of the High Voltage Switching Cell defined in WP3 Task 3.1 in its version V0.7. The electronic elements are grouped according to their type (resistor, capacitor, transistor...). Individual groups are created with the aim of identifying hotspots in later stages. However, for those element types with only one or two elements were grouped together into "Other electronics". Also, there is a fuse considered in the BOM, but it is ignored because there is no similar dataset and the low weight it represents (1.6mg).

- Capacitors: 13 different capacitors from the BOM, 288 units per CL. In the model they are converted into two types: "Capacitor ceramic MLCC 0603 (6mg) 1.6x0.8x0.8 (Precious Metals)" and "Capacitor ceramic MLCC 1210 (50mg) 3,2x2,5x1,6 (Base Metals)". Dividing the weight of the real element by the dataset weight, we estimate the amount of dataset units required to represent each element. Considering the previously mentioned datasets, we considered 384,5 and 16,9 units respectively for the CL.
- Diodes: 13 different diodes from the BOM, 136 units per CL. In the model they are converted into several types: "Diode power DO214/219 (93mg) 4.3x3.6x2.3 (...)" ; "Diode signal SOD123/323/523 (1.59mg) 0.8x0.75x1.6 with Au-Bondwire; (...)" ; "Diode signal SOD123/323/523 (9.26mg) 2.4x1.6x1 with Au-Bondwire (...)" ; "LED SMD high-efficiency with lens max 0.5A (59mg) Au bondwire 3.5x3.5x2.0 (...)" . Following the same reasoning as with capacitors, the quantities for each diode dataset are: 0,8, 26,1, 3,9, and 15. Four of them are modelled from their material declarations and energy requirements are estimated from their weight and the ecoinvet proxy "resistor production, auxiliaries and energy use" for electricity and heat requirements, identified from the manufacturers code: BAS316,115 (16 units), MM3Z15VTIG (8), RB520S30TIG (16), RFN1LAM6STR (8).



- Resistors: 26 different resistors from the BOM, 408 units per CL. In the model they are converted into several types: “Resistor flat chip 1206 (8.9mg)” and “Resistor thick film flat chip 0603 (2.1mg)” with 46,2 and 417,8 units respectively. Two resistors of them are modelled from their material declarations and energy requirements following the same criteria previously stated: 3313J-1-103E (8 units) and BVS-Z-R0002-1.0 (8).
- Test points: All the test points are manually created following the material and energy requirements for the elements from the company Keystone Electronics, 5001, 5003 and 5011 and from TE Connectivity, RCU-0C. The quantity for each element is 8, 8, 8, 48 and 240 respectively.
- Voltage regulators: There are only two elements with a total of 8 units each per CL. One is modelled through the process “Transistor signal SOT23 8 leads (18mg) 1.4x3x2” with 28,7 units and the other (TLE4285G) one is modelled from scratch.
- Transistors: 5 different transistors from the BOM, 40 units per CL. In the model they are converted into “Transistor DPAK TO252 (290mg) 6.6x6.2x2.2”; “Transistor power THT/SMD SOT93/TO218 7 leads (4.80g) (...)”; with 11,7 and 21,5 units each. Additional electricity requirements are attached to the last type of transistors, since they are elements with 17.7mm² SiC devices embedded and the process from Sphera does not represent it accurately. Then, two transistors are modelled from scratch: NTMS4920NR2G (8 units) and SI2307CDS-TI-GE3 (8).
- Integrated circuits: 6 different integrated circuits from the BOM, 48 units per CL. Only one integrated circuit is modelled from datasets: “IC SO 20 (530mg) 12.8x7.5 mm CMOS logic (90nm node)” with 31,2 units. The rest are modelled from scratch: MAX660MX/NOPB, MIC2776L, REF3325AIDCKT, SN74LVC1G175DCKR, TPSM265R1SILR; 8 units each.
- Other electronics: It considers Amplifier, digital isolator, configurable multifunction gate, comparator and sensor. All these items are built from scratch with the following manufacturers codes INA181A4IDBVR, MAX2244ICAEE+, SN74LVC1G99DCUR, TLV3201AIDBVT, TMP05BKSZ-500RL7; 8 units each and 16 units of SN74LVC1G58DCKR.

Evaluation Board. The information to build this component comes from the MAX R 10 10M08 Eval Kit Board, facilitated by project partners. Unlike the Switching Cell, which different groups are modelled together, the Evaluation Board is all modelled in one process. The inputs considered are the following:

- Capacitors: 6 different capacitors from the BOM, 61 units. They are modelled with the processes from Sphera: “Capacitor ceramic MLCC 0603 (6mg) 1.6x0.8x0.8 (Precious Metals)” and “Capacitor Al-capacitor SMD (300mg) D6.3x5.4”; with 16,6 and 0,7 units respectively.
- Clock Oscillator: From Sphera, the process “IC QFN 24 (61.6 mg) 4x6 mm CMOS logic (14 nm node)” is used for 1 unit.
- Connector: A proxy from these elements is created using the weight of the elements, using copper and epoxy resin in a 4:1 weight ratio.
- Converter: The process “IC TQFP 32 (146mg) 5x5 mm MPU generic (130 nm node)” is used with an equivalent of 0,25 units.
- Diode: The process “LED SMD high efficiency with lens max 0.5A (59mg) Au bondwire 3.5x3.5x2.0; (...)” is used with an equivalent of 2,85 units.



- Gate Array: The process "IC QFP 32 (184mg) 7×7 mm CMOS logic (90 nm node)" with an equivalent of 1 unit.
- Resistor: It is divided into the process "Resistor thick film flat chip 0603 (2.1mg)" with 40,1 units and two resistors built from scratch with the manufacturers code 3362P-1-103TLF (1 unit), LTR10EVHFLR100 (2).
- Switch: Two Sphera processes are used: "Key switch Dip (79mg) 11.39×4.5×1.5" (1 unit) and "Key switch tact (242mg) 6.2×6.3×1.8" (2 units).
- Voltage references, Amplifier and Ferrites: These elements are created from scratch using the same criteria as expressed previously. Their manufacturing numbers are: MCP1525T-I/TT (1 unit), LM2902DR2 (2) and BLM18AG601SN1D (2)
- PCB: Modelled with the Sphera processes "Printed Wiring Board 8-layer rigid FR4 with chem-elec AuNi finish" and "Pb-free soldering required" with a total area of 67,5cm².

Converter Leg Electronics. Here, all the remaining electronics embedded in the Converter Leg that are not considered in the Switching Cell are considered. Following the same criteria for grouping elements for Switching the electronics have been grouped into the following groups:

- Amplifiers: 4 different amplifiers from the BOM, 5 units per CL. Two of them are modelled using the processes "IC SO 20 (530mg) 12.8×7.5 mm CMOS logic (90nm node) (...)" and "IC TSSOP 8 (23mg) 3×3 mm DRAM (57 nm node)" with 1 and 12 units respectively. The remaining two elements were modelled from scratch considering the manufacturing codes AD8565AKSZ-REEL7 (1 unit) and LT6370IMS8#PBF (1 unit).
- Capacitors: 13 different capacitors from the BOM, 98 units per CL. In the model they are converted into: "Capacitor ceramic MLCC 0603 (6mg) 1.6×0.8×0.8 (Precious Metals)"; "Capacitor ceramic MLCC 1210 (50mg) 3.2×2.5×1.6 (Base metals)"; "Capacitor tantal SMD Y (25mg) 3.2×1.6×1.6; technology mix; production mix, at plant; (25mg) 3.2×1.6×1.6 (en)"; "Capacitor ceramic MLCC 2220 (450mg) 5.7×5×2.5 (Precious Metals)". Quantities are respectively 28,9, 54,2, 4,3 and 306,7.
- Connectors: 2 different connectors are modelled from scratch following the material declarations and energy requirements for the Würth Electronics element with numbering 691321100002 (2 units), 691321100003 (2).
- Sensors: 3 different sensors are included in the BOM, one high accuracy current sensor, modelled with the process "IC SO 20 (530mg) 12.8×7.5 mm CMOS logic (90nm node)" with an equivalent quantity of 2,5 and two temperature sensors that are built from scratch from the manufacturer numbering TMP05BKSZ-500RL7 (7 units).
- Inductors: 3 different inductors are present in the BOM, all of which are built from scratch for the manufacturer numbering 744025100 (3 units), 744032001 (2) and NR5040T3R3N (1).
- Converter: 3 different converters are present in the BOM, the closest process found is "inverter production, 0.5kW" and using the weight from the BOM elements and the process, we estimate an equivalent quantity of 0,0123 pieces of this process.
- Resistors: 13 different resistors from the BOM with a total of 70 units per CL. In the model they are converted into: "Resistor flat chip 0603 (1.9mg)"; "Resistor thick film flat chip 0603 (2.1mg)"; "Resistor thick film flat chip 1206 (8.9mg)" with 5,3, 21,2 and 55,5 units respectively.



- Other electronics: as in the Switching cell, there are several elements that are grouped into a bigger cluster. Here, it is considered receiver, transceiver, diode, test points, line splitters, voltage regulator, nuts and bolts. The first two mentioned items are modelled with the processes “Connector RJ45/8P8C ethernet 8-pin plug (2.4g) (gold-plated)” and “IC SO 8 (76mg) 4.9x3.9 mm CMOS logic (90 nm node) (...)” with an equivalent quantity of 1,4 and 1,3 respectively. The rest of the elements are built from scratch following manufacturers codes Keystone electronics 5001 (9 units) and 5003 (17 units), TE Connectivity RCU-0C (8 units), MM5Z3V3T1G (20 units), SN74AHCT1G125DBVR (2 units), SN74AHCT541PWR (2 units), TPS7A3901DSCT (3 units). Moreover, 212g of chromium steel is used as bolts and 37g to represent the required nuts.

A very relevant part of the modelling has to do with estimating the electricity losses. From the SCAPE project, we have used the KPIs to define the SCAPE’s final efficiency of the product at 97,5%. From communications with the partners, and more specifically, from Schweizer, we know that the chip embedding technology applied in the SCAPE’s final version can reduce switching losses at 65% and conduction losses at 20%. Knowing this, we assume that all the losses are equally shared in the Mock-up and reduced by 65% and 20% for the SCAPE’s final version. With these assumptions we present the **equations 2-5** to determine the efficiency of the Mock-up. Where L is Losses as a value from 0-1; F refers to the last version of the converter, P means Mock-up, S refers to the switching (losses) and C to the conduction (losses).

Equation 2 – SCAPE’s final efficiency of the IIC as per KPIs of the project

$$2,5\% = L_F = L_F^S + L_F^C$$

Equation 3 – Assumption of equal Switching and Conduction in the Mock-up

$$L_P^S = L_P^C$$

Equation 4 – Equivalence between switching losses in the Mock-up and the SCAPE’s final IIC considering chip embedding efficiency improvements

$$L_P^S = \frac{L_F^S}{1 - 0,65}$$

Equation 5 – Equivalence between conduction losses in the Mock-up and the SCAPE’s final IIC considering chip embedding efficiency improvements

$$L_P^C = \frac{L_F^C}{1 - 0,2}$$

The result of applying these equations is that the Mock-up efficiency reaches 95,65%, with conduction and switching losses of 2,175% each. However, efficiency is approximately 96% to convey the idea that this is not an exact measured number but an approximation. SCAPE’s final electricity requirements are estimated following equation 1, reaching 3.840 kWh of lost electricity.

3.2. IIC – SCAPE’s final IIC

SCAPE’s final IIC is the evolution of the Mock-up, which represents the base of this IIC, although with some changes in the physical components described below.

Thermal Management. Two approaches have been considered as per indications of the project partners for this component.



1. This part of the IIC has been redesigned and is made of a case of epoxy resin where the refrigerant flows and an aluminium plaque that transfers the heat from the SC to the refrigerant. The weight of the epoxy resin is estimated approximately at 90g and the aluminium at 280g. Moreover, it is considered that this thermal management unit is used to cool two CL, which affects the SCAPE's final number of this component to consider in the IIC.
2. Elimination of the thermal management. As per calculations of WP6, it is estimated that the cooling system of the motor could be used to cool the converter without affecting its original goal.

PCB. A proposed optimization of the design proposed by SCAPE experts in the subject considers that is possible to decrease the dimensions of 310 x 125 mm, which results in an area of the PCB to 387.5 cm². The height in its maximum point is 15mm and the gap between the PCB and the internal side of the housing in all directions is marked at 15mm.

Housing. Considering the optimization of the PCB and the thermal management options, the housing has been updated and two options are considered, as depicted in **Figure 5**. Before, however, there are some considerations that both options have in common. The internal space of the housing measures 330 x 145mm, leaving 10mm of margin in all directions with the PCB measures. The thickness of the casing is 5mm and the density of the aluminium used to estimate the weight is 2.690 kg/m³.

1. The converter is compacted into one block built as the union of three equal configurations, each formed by two CL and one Thermal management between those CL. This block is protected with a rectangular cube, with a total height of 210mm. Total weight is 3.77kg.
2. The converter is mounted around the motor, using its thermal management. Thus, a rectangular box without the bottom wall is modelled as housing, leaving the converter in direct contact with the motor cooling system. Thus, each of the six converter Leg needs independent housing, with a height of 30mm. Total weight is 6,16 kg.

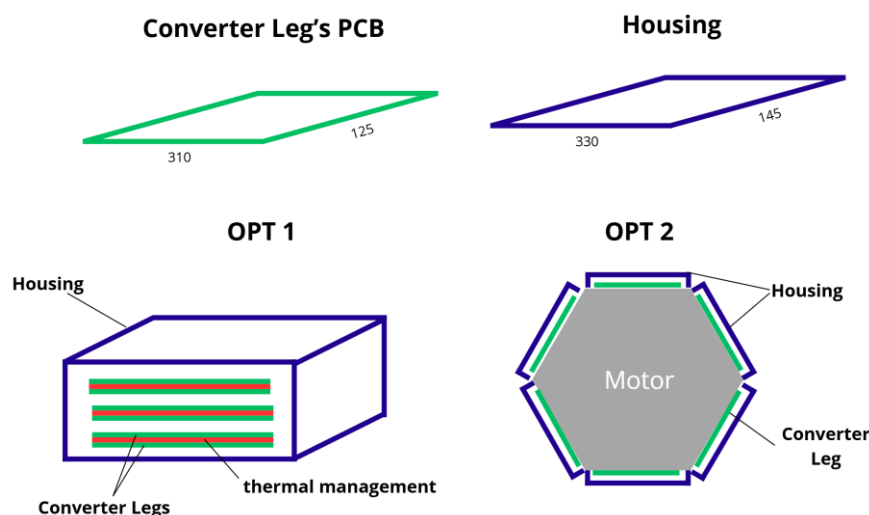


Figure 5 – Conceptual configurations for SCAPE's final IIC for the two designs. Housing is represented in Blue, Converter Legs in green and thermal management in red.

Converter Leg electronics. 26,3 "Capacitor film-capacitor boxed RM15 (3.2g) 17.7x10x16.5; technology mix; production mix, at plant; (3.2g)" are substituted with 307 "Capacitor ceramic MLCC 2220 (450mg)

5.7x5x2.5 (Precious Metals)” due to the change of 12 capacitors with the manufacturers code MKPI848S55050JK2A to B58035U5106M001.

Switching cell. Following the Bill of Materials (BOM) of the High Voltage Switching Cell defined in WP3 Task 3.1 in its version V1.02, elements present changes in the SC quantity as described below:

- Change of quantity. There are elements that are affected in the number of times they are used.
 - The capacitors represented by the process “Capacitor ceramic MLCC 0603 (6mg) 1.6x0.8x0.8 (Precious Metals)” increase by 6,4 units.
 - The resistors represented by “Resistor thick film flat chip 0603 (2.1mg)” decrease 2,4 units.
 - The test point modelled from scratch “RCU-0C” are reduced in 1 unit.
- Elimination of elements from V0.7. Some elements are erased to be substituted for others that fit best according to technical requirements. It is possible that these elements are represented by the same Sphera process as other elements a that are added or changed in quantity.
 - Diodes represented by “Diode signal SOD123/323/523 (9.26mg) 2.4x1.6x1” are reduced by 1,1 units
 - The resistors represented by “Resistor thick film flat chip 0603 (2.1mg)” decrease 2,9 units.
 - The resistors represented by “Resistor film flat chip 1206 (8.9mg)” decrease 3,6 units.
 - The resistors represented by “Resistor THT MBA 0204 (125mg) D1.6x3.6” decrease 1,6 units.
 - Two elements modelled from scratch are reduced by 1 unit: Voltage regulator “NCP781BMN150TAG” and Amplifier “INA281A3IDBVR”.
- Addition of elements in V1.02. Some elements are added because they are considered better choices for the overall IIC because of technical reasons. Those elements added are:
 - Resistors represented by “Resistor thick film flat chip 0603 (2.1mg)” increase 3,5 units.
 - Resistors represented by “Resistor flat chip 1206 (8.9mg)” increase 5,8 units.
 - Capacitors represented by “Capacitor ceramic MLCC 1210 (50mg) 3,2x2,5x1,6 (Base Metals)” increase by 2,1 units.
 - Capacitors represented by “Capacitor ceramic MLCC 0603 (6mg) 1.6x0.8x0.8 (Precious Metals)” increase by 1 unit
 - Capacitors represented by “Diode signal SOD123/323/523 (9.26mg) 2.4x1.6x1 with Au-Bondwire” increased by 0,5.
 - A set of elements modelled from scratch are introduced with one unit each: Amplifier “INA181A4IDBVR”, Digital isolator “MAX2244ICAEE+”, integrated circuit “REF3325AIDCKT” and Comparator “TLV3201AIDBVT”.
- Chip embedding transistors. The most important change in the SC however is the embedding of the transistors “C3M0015065K” and “UJ4SC075006K4S” by in the PCB. This action in made to



increase the efficiency of the IIC. Although the embedding of the transistors includes new manufacturing stages, it removes others, and after careful consideration with the partners involved in this section, the manufacturing is modelled with the same process used in the mock-up. An important change however, is the recalculation of the SiC area of the “UJ4SC075006K4S” transistor to Si, moving from 20mm² to 100mm². This change also has affected the energy intensity of the manufacturing process [4].

- After careful consideration with the partners involved in the technical part, the iFuse is changed from using SiC to Si. This is justified because it is understood that, in the commercial version of SCAPE's IIC, this part will be changed to a more economic version of the same device. This has implications in the energy intake for its manufacture and in the area needed for the device. Also important to highlight is the fact that, despite this change we assume no consequences affecting the efficiency.

The efficiency of the SCAPE's final IIC is set to meet the projects KPIs at 97,5%, which considering equation 1 leads to losses equal to 2.400 kWh.

3.3. Inverter from AVL

Finally, a commercial EV inverter from the project partner AVL is assessed. The inverter has been disassembled at AVL's facilities and a BOM has been prepared by them together with a document visually showing each part of the inverter. Because of confidentiality reasons we will not detail at the same level as the previous inverters.

Housing. Aluminium casing is provided for the whole inverter and for the EMC filter. Both are modelled considering the material requirements and deep drawing and machine casting as manufacturing techniques for different sections of the component. Other elements included in the housing like gaskets are also included here.

Electronics: Several PCBs are present in this inverter filled with different electronics. These have been counted and identified one by one through the images provided by AVL and a dataset has been assigned accordingly. This applies to the EMC Filter, Control Board, Gate Board and ETAS Board.

DC Link. We have modelled this component with the dataset “Capacitor film-capacitor boxed RM27.5 (20.4g) 31x21x31”, scaling it to the component weight.

LEM AC Sensor. For this component there is no dataset that fits this description and thus, it has been built from scratch. Also, we were unable to find detailed data from the manufacturer to build the component from scratch with rigorous data, we had to make assumptions of the composition of the inverter based on general knowledge of this kind of inverter. We assume that this component is a Hall-Effect inverter with a weight share of 60% ferrite (magnetic core) and 40% active electronics.

Power Module. We followed PELCA LCI documentation for Power Module FS820R08A6P2B [14] and built the component from scratch. The main difference is that the one used in our project uses SiC. We substitute the silicone in the PELCA product by SiC and include the energy requirements for SiC as per [4] considering an area estimated by our partners for the specific Power module used by AVL with the reference FS03MRI2A6MAILB, resulting in 663mm³ per power module. **Other items.** Connectors, temperature sensors, cables, bolts and screws have been modelled according from scratch knowing the total weight and the material used (facilitated in the BOM). Except for cables for which datasets the dataset “Cable 3 wire (EN15804 A1-A3)” has been used.



Finally, the efficiency of this inverter is set as a calculation considering the efficiency ranges given for this inverter and the time, we estimate the inverter spends at these efficiencies. Considering **Figure 6**, we consider that the studied inverter is for an EV type Sedan where spends 70% of the time with a current between 0-30A and 30% of the time above that range. We know that the efficiency of the inverter depends on the torque and the speed needed from the motor, but for the sake of simplicity we consider current as the main factor to define the efficiency. Having said this, although the efficiency range given is between 94-97,5%, we believe that 94% is only given at very sporadic moments and therefore is not considered. Thus, we estimate the final efficiency as if 70% of the time the inverter is used at maximum efficiency (97,5%) and 30% of the time at medium efficiency (96%), with a resulting average value of 97,05% and total losses of 2.832 kWh.

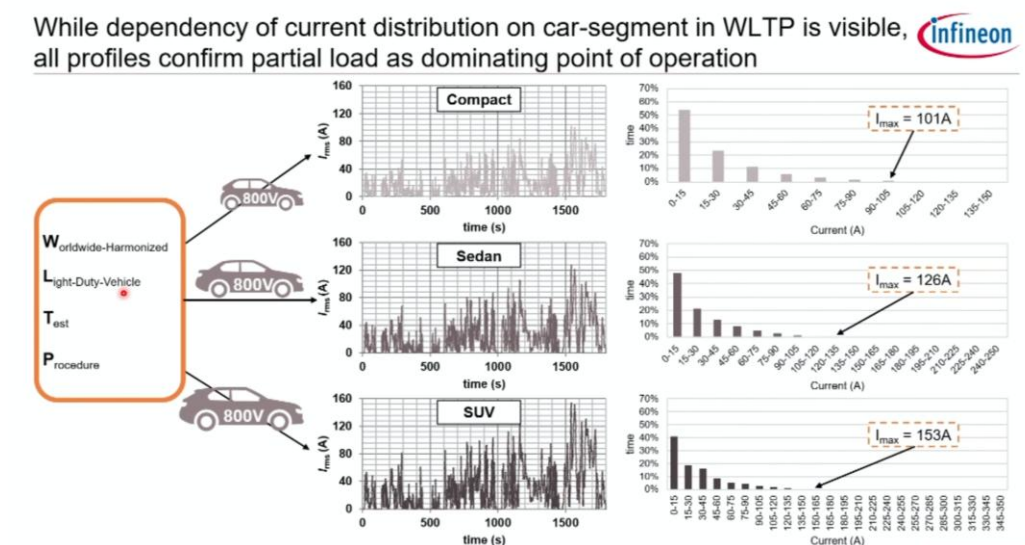


Figure 6 – Time of an EV at different currents estimated by Infineon [15].

4. Life Cycle Impact Assessment

It is important to mention that the Impact categories assessed, and the underlying methods have changed from the last deliverable to this one. In the deliverable “D8.8 Environmental assessment of materials and processes”, six impact categories were defined and assessed considering that they were the most relevant to this project. These were Climate Change, Abiotic Depletion-elements, Acidification, Eutrophication, Primary Energy Demand (renewable and non-renewable) and Human Toxicity; and the methodologies behind the calculation of the results were based on CML 2001 [16], [17]. However, after careful consideration and having in mind that this is a European project, we conclude that we should follow recommendations from the European Commission [18] and the Joint Research Center [19], where a set of impact categories and LCIA calculation methods are defined under the framework of the Environmental Footprint 3.1. These impact categories and methods used for estimating the SCAPE’s final environmental footprint are depicted and described in **Table 2**. The emissions for all the impact categories depicted are estimated, although in this we have focused on Climate Change because we consider the IIC assessed as part of the energy transition, which aims to tackle Greenhouse gas (GHG) emissions.

Calculations are performed using LCA for experts (former GaBi) software. We used their database for electronic components coupled with ecoinvent for general processes, as described in section 2.

Table 2 –Impact categories used in the study as defined per EF 3.1, references for the underlying methods can be found in [2].

Impact category	Underlying LCIA method	Unit	Description
Acidification (AC)	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)	mol H+eq	The increase in acidity of soil and water bodies due to the deposition of acidifying substances
Climate Change – total (CC)	Bern model – Global warming potential (GWP) over a 100-year time horizon based on IPCC 2021 (Forster et al., 2021).	kg CO ₂ eq	The total radiative forcing from greenhouse gas emissions, calculated as Global Warming Potential over a 100-year horizon
Ecotoxicity, freshwater – total (ECF)	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), adapted as in Saouter et al. (2018)	CTUe	The potential toxic impact on freshwater organisms due to the release of harmful substances into the environment.
Eutrophication, freshwater (EF)	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe 2008.	kg Peq	The enrichment of freshwater ecosystems with nutrients (phosphorus), leading to excessive algae growth and oxygen depletion.
Eutrophication, marine (EM)	EUTREND model (Struijs et al., 2009) as implemented in ReCiPe 2008	kg Neq	The enrichment of marine ecosystems with nitrogen, potentially leading to "dead zones" and loss of aquatic life.
Eutrophication, terrestrial (ET)	Accumulated Exceedance (Seppälä et al. 2006, Posch et al., 2008)	mol Neq	The impact of excessive nutrients (nitrogen) on land, leading to shifts in species composition and loss of biodiversity.
Human toxicity, cancer – total (CE)	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), as in Saouter et al. (2018)	CTUh	The potential impact on human health via the environment due to the intake of substances that may cause cancer.
Human toxicity, non-cancer – total (NCE)	Based on USEtox2.1 model (Fantke et al. 2017, Rosenbaum et al. 2008), as in Saouter et al. (2018)	CTUh	The potential impact on human health due to the intake of substances that may cause non-cancerous effects (e.g., organ damage).
Ionising radiation, human health (IR)	Human health effect model as developed by Dreicer et al. (1995) and published in Frischknecht et al. (2000).	kBq U235	The impact of radioactive releases on human health, specifically related to the exposure to the U235 radionuclide.
Land Use (LU)	Soil quality index based on LANCA model (De Laurentiis et al. 2019) and on the LANCA CF version 2.5 (Horn and Maier, 2018)	Dimension less (pt)	The impact on land quality (soil organic matter, erosion, etc.) based on the area of land occupied and the intensity of its use.
Ozone depletion (OD)	EDIP model based on the ODPs of the World Meteorological Organisation (WMO) over an infinite time horizon (WMO 2014 + integrations)	kg CFC-11eq	The degradation of the stratospheric ozone layer, which filters UV radiation, caused by emissions of substances like CFCs
Particulate matter (PM)	PM model (Fantke et al., 2016 in UNEP 2016)	Disease incidence	The potential health impacts (e.g., respiratory diseases) caused by the inhalation of fine particles and their precursors.
Photochemical ozone formation, human health (POF)	LOTOS-EUROS model (Van Zelm et al., 2008) as applied in ReCiPe 2008.	kg NMVOCeq	The formation of ground-level ozone (smog) through the reaction of volatile organic compounds (VOCs) and NO _x under sunlight.
Resource use, fossils (RUF)	van Oers et al., 2002 as in CML 2002 method, v.4.8	MJ	The depletion of non-renewable fossil energy resources (coal, oil, gas) based on their energy content.
Resource use, mineral and metals (RUM)	van Oers et al., 2002 as in CML 2002 method, v.4.8	kg Sbeq	The depletion of non-renewable abiotic resources based on their scarcity and remaining reserves.



Water use (WU)	Available WATER REmaining (AWARE) model (Boulay et al., 2018; UNEP 2016)	m3 world eq. deprived water	The relative amount of water used in a specific watershed, weighted by the scarcity of water in that region (AWARE method).
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5. Interpretation

5.1. Results

Results for all the alternatives are shown in **Table 3**. The most notable thing is the significant decrease in all impact categories between SCAPE mock-up and Chip embedding (CE) models. The evolution of the IIC has brought a significant decrease in emissions, mainly driven by the efficiency improvement, but also relevant for embedded emissions. Considering the values from the table, we can see that the two version of SCAPE's final IIC present the lowest values for all impact categories. However, the configuration where the IIC is cased independently presents the lowest value for 15 of the 16 impact categories assessed. Graphs showing the contribution of each section for each alternative studied are shown in **Figures A1-A3**, visible in the Annexes.

Table 3 – Results for all impact categories for the assessed alternatives. TM refers to Thermal Management. Highlighted in green, the lowest value for each for each impact category.

Impact category	unit	mock-up	CE- IIC with Motor	CE – IIC Independent	Commercial inverter
Acidification	Mole H+ eq	13,66	9,40	9,09	10,00
Climate Change - total	kg CO2 eq	2287,79	1447,14	1375,28	1748,67
Ecotoxicity, freshwater - total	CTUe	12488,70	5902,89	5736,80	9222,35
Eutrophication, freshwater	kg P eq	1,52	0,91	0,91	1,19
Eutrophication, marine	kg N eq	2,06	1,34	1,29	1,63
Eutrophication, terrestrial	Mole N eq	19,571521	12,95	12,34	15,78
Human toxicity, cancer - total	CTUh	1,09E-05	9,24E-07	8,72E-07	1,29E-06
Human toxicity, non-cancer - total	CTUh	1,27E-03	2,41E-05	2,38E-05	3,85E-05
Ionising radiation, human health	kBq U235 eq	1007,9618	592,51	592,68	697,42
Land Use	-	8418,8727	5048,20	5029,06	6081,70
Ozone depletion	kg CFC-11 eq	2,83E-05	1,79E-05	1,80E-05	2,90E-05
Particulate matter	Disease inc	8,39E-05	6,21E-05	5,74E-05	6,22E-05
Photochemical ozone formation, human health	kg NMVOC eq	6,29	4,15	3,98	4,84
Resource use, fossils	MJ	47680,715	28974,25	28341,08	34522,07
Resource use, mineral and metals	kg Sb eq	6,37E-02	3,37E-02	3,37E-02	6,44E-02
Water use	m3 world eq	1317,0012	810,84	800,24	975,69

In **Figure 7**, the contribution for GHG emissions of each major part of the converter can be seen for all converter alternatives. When considering the average EU electricity mix, the main contributor of GHG emissions are the electricity losses. Looking at this graph, it becomes obvious that the emissions



reduction between the Mock-up and the SCAPE's final version is mainly due to efficiency improvements, although there are also important reductions in thermal management and the converter footprint. Housing, on the other hand, presents an increase in emissions. SCAPE's two final alternatives show similar results, although the one that is independent from the motor shows a slightly smaller GHG footprint. This means that the emissions from thermal management are smaller than the extra aluminium required for having each Converter Leg cased independently.

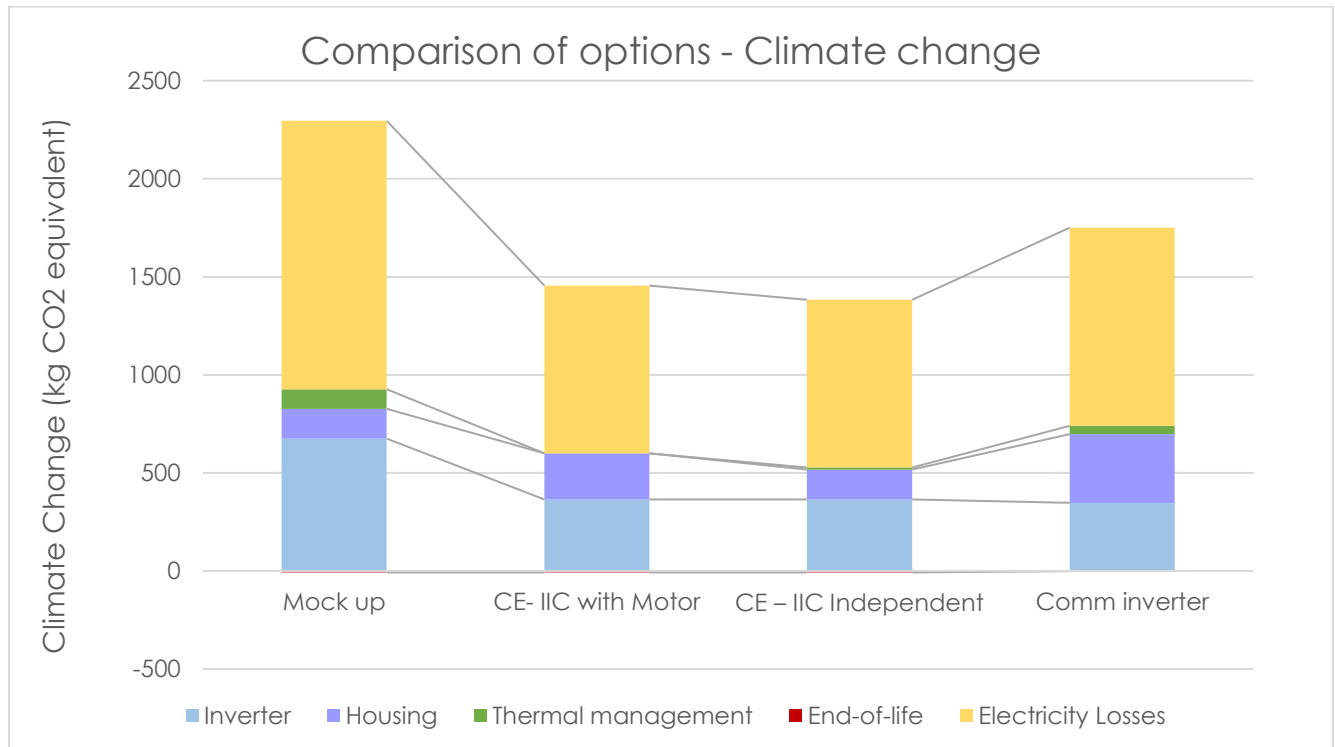


Figure 7 – Total GHG emissions for the three alternatives represented in this study. CE means Chip Embedding, referring to the last version of the SCAPE's converter.

When comparing the SCAPE's final version with the commercial inverter, we see that although the footprint is almost the same, the share of emissions for section is very different. A deeper view is projected in **Figure 8**, where the embedded emissions of SCAPE's final versions and the commercial inverter are zoomed in. In this graph we see the total emissions are very similar in all three alternatives reaching around 350kg of CO2 emissions. Thermal management present significant differences if we consider their total share of emissions, since one SCAPE's alternative uses the engine's thermal management, this value can be considered zero, and the remaining SCAPE's design emits one fourth of the commercial. This difference comes mainly from the different use of materials. Whereas the commercial device uses exclusively aluminium, SCAPE's thermal management minimizes the use of this material, using it only as heatsink and utilizes epoxy resin for the overall container of the cooling liquid. The component that sets the difference regarding GHG emissions is housing. Commercial inverter's housing doubles the emissions of the Independently arranged SCAPE converter and emit more than 100 additional kg of CO2 equivalent for the arrangement around the motor. Considering that the outer measures of the commercial inverter's housing, its area doubles SCAPE's final PCB design. Although the design of SCAPE's housing estimated is just an approximation, the area considerations make that the results estimated are proportionate to their material requirements. Nevertheless, seeing the high impact that this part of the inverter has in the overall footprint in commercial option, representing more than 15% of the total emissions for 7 impact categories, and

20% for Climate Change, we believe that it is worth to invest time to design a realistic housing for the IIC, increasing the accuracy of the LCA conclusions.

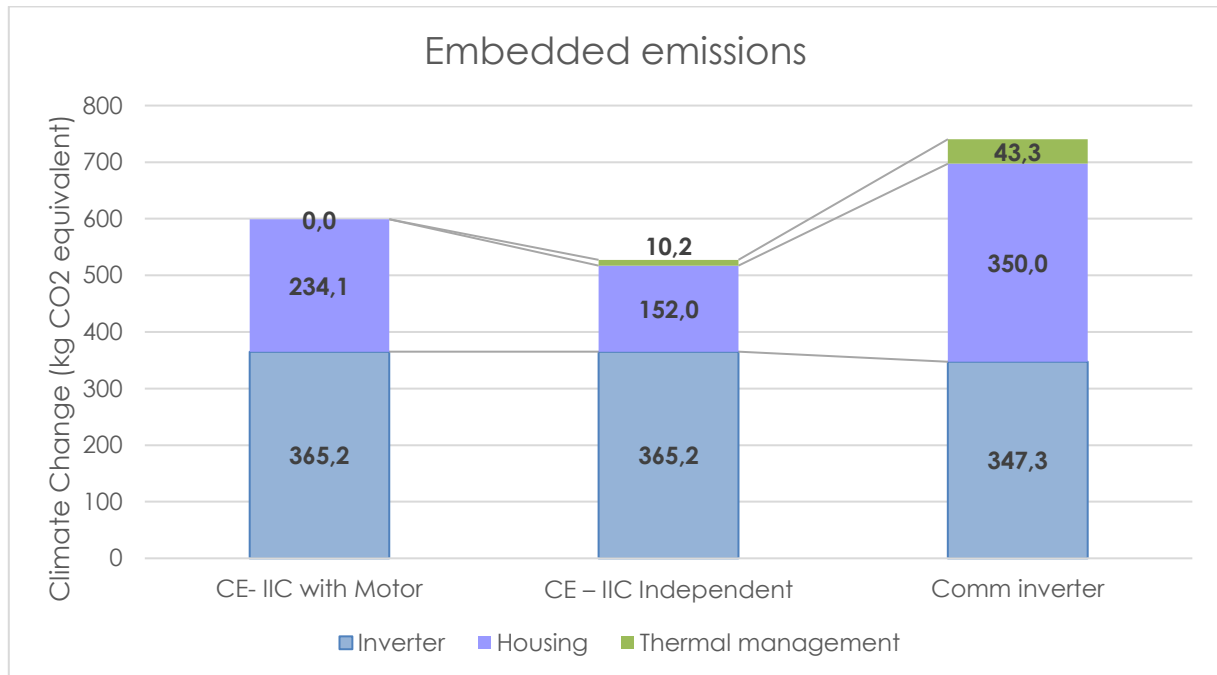


Figure 8 – Embedded GHG emissions shares for SCAPE’s final IIC and commercial inverter.

Again, we zoom in into the converter components of both alternatives, as depicted in **Figure 9**. Due to the different configuration of these two converters, the division of components is very different, having only in common the thermal management and connectors. However, the concentration of GHG emissions is very similar in both arrangements, in the case of the SCAPE’s device, emissions are concentrated in two components: Switching Cell and PCB, reach 75% of total GHG emissions. For the commercial device, three components: Control Board, Gate board and Power module reach 70% of GHG emissions. After this analysis we went a layer deeper to see exactly which electronic components the ones are emitting the most in both cases, and the answer is the same. For both alternatives, PCBs and elements with the presence of Si or SiC are the highest emitting parts. The minimization of these two components will be the key to reducing the embedded emissions. This, however, is easier said than done, and in the case of SiC and Si components, it could even be counterproductive, since the use of these materials is driven because of the increase of efficiency in the overall converter, which we already know is the main GHG contributor.

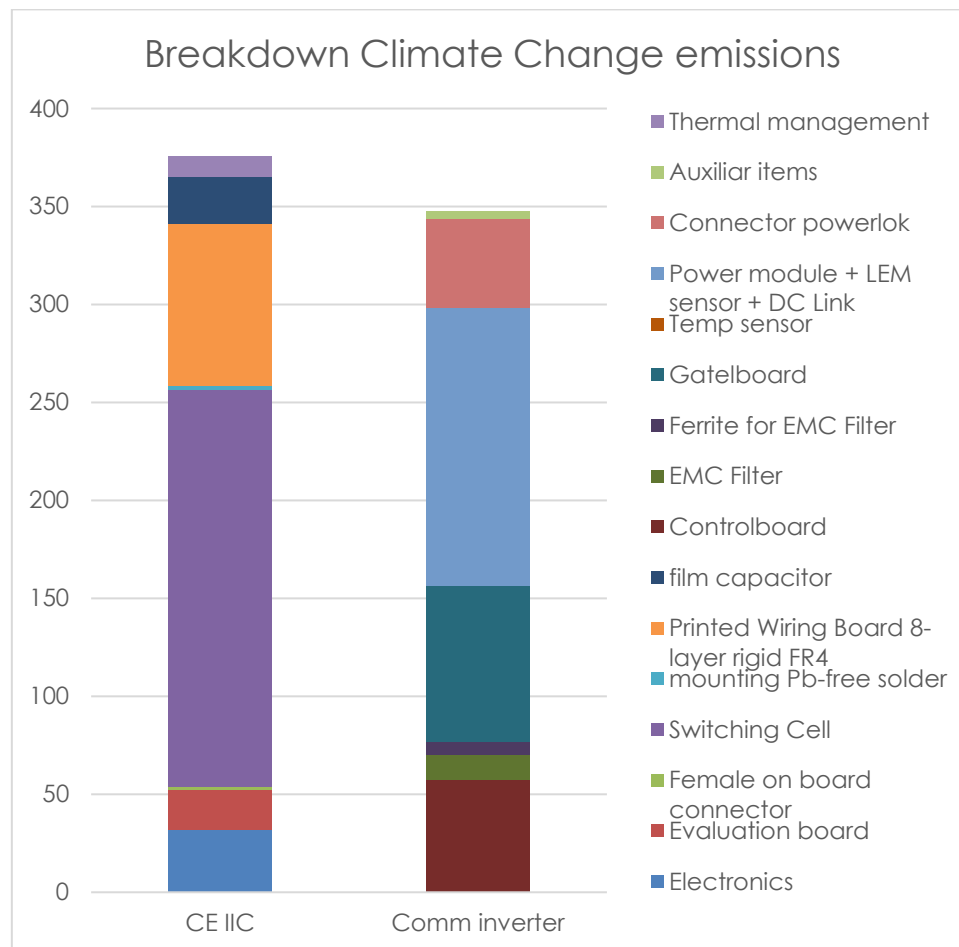


Figure 9 – Breakdown of the GHG emissions share from the components forming the converters for the SCAPE's final converters and the commercial alternative.

5.1.1. Critical Raw Material list

Driven by strategic security for the EU, we have extracted the total use of materials for each IIC alternative. Then, we filtered to match the EU CRM and SRM list [20] and finally compared the SCAPE's final IIC versus the commercial alternative. In **Table 4** each CRM and SRM are listed and the percentage shown represents the division between SCAPE's materiality and the one from the commercial inverter. These results do not represent 100% the reality, since they are extracted from datasets that may not contain the exact same materials as the real converters, these results should be considered as an approximation. Since the difference between the two SCAPE's design originate in the housing and thermal management, many materials present the same value. Also, there are comments regarding some materials, as they may not fit exactly the description of the EU list. In **Table A 1**, in the Annexes, the exact amount for each alternative can be found.

These results do not show a clear winner or loser. SCAPE alternatives contain a much higher concentration of platinum group metals, cobalt, helium, graphite, nickel and some Heavy REE, whereas it also sees major reductions in other materials such as Aluminium (caused by the underestimation of the housing), antimony, boron, feldspar, gallium and manganese. For some positions, a zero was output from the model, but since many elements are modelled with datasets, we cannot be certain that those materials are not used in the real case and we have written "-" instead.

Table 4 – Percentages of the CRM according to the EU list [20] within the chip embedding compared to those of the commercial inverter. Results are color coded for clearer visualization. In green results below 80%, in yellow between 80% and 250% and in red those above 250%. REE means Rare Earth Elements.

SCAPE's final IIC compared to the commercial inverter			
CRM	CE- IIC with Motor	CE – IIC Independent	Comments
Antimony	4,5%	4,5%	
Arsenic	38,5%	38,5%	
Bauxite	102,5%	91,1%	
Alumina	-	-	
Aluminium	56,0%	37,3%	
Baryte	-	-	
Beryllium	-	-	
Bismuth	-	-	
Boron	3,6%	3,6%	do not discriminate metallirgy grade
Cobalt	253,5%	253,4%	
Coking coal	-	-	
Copper	54,1%	54,1%	
Feldspar	2,0%	1,7%	
Fluorspar	60,7%	45,2%	
Gallium	107,7%	107,7%	
Germanium	-	-	
Hafnium	41,0%	40,8%	
Helium	2309,3%	2309,2%	
Lithium	162,6%	161,1%	do not discriminate battery grade
Magnesium	43,2%	43,0%	do not discriminate magnesium metal
Manganese	3,9%	3,8%	do not discriminate battery grade
Graphite	9327,1%	9315,2%	do not discriminate battery grade
Nickel	297,5%	297,4%	do not discriminate battery grade
Niobium	77,8%	77,8%	
Phosphate rock	-	-	
Phosphorus	137,8%	136,9%	
Silicon	37,3%	37,4%	do not discriminate metal
Strontium	36,0%	34,6%	
Tantalum	19,9%	19,9%	
Titanium	45,1%	44,8%	do not discriminate metal
Tungsten	-	-	
Vanadium	88,0%	78,5%	
Platinum group metals			
ruthenium	3022,5%	3022,5%	
rhodium	2142,9%	2142,9%	
palladium	1729,7%	1729,7%	
osmium	3024,0%	3024,0%	
iridium	3021,8%	3021,8%	
platinum	2262,2%	2262,2%	
Heavy REE			
Europium	34,6%	34,9%	
Gadolinium	35,9%	36,0%	



Terbium	71,2%	71,3%	also Rare earths for magnets
Dysprosium	85,5%	77,0%	also Rare earths for magnets
Holmium	289,9%	269,8%	
Erbium	87,4%	78,7%	
Thulium	500,4%	468,3%	
Ytterbium	86,6%	77,9%	
Lutetium	358,8%	334,8%	
Scandium	36,4%	36,2%	
Yttrium	37,3%	41,1%	
Light REE			
Lanthanum	34,5%	34,8%	
Cerium	33,8%	34,1%	
Praseodymium	34,4%	34,5%	also Rare earths for magnets
Neodymium	38,0%	37,6%	also Rare earths for magnets
Promethium	-	-	
Samarium	44,7%	45,2%	

5.2. LCA comparison with literature

As a verification process, we compare our LCA results with those of literature. We used the work from [4], which explores the environmental impact of a Volkswagen ID.3 150kW inverter. The characteristics of each study are depicted in **Table 5** for transparency purposes regarding the suitability of the comparison cases. A summary of the results for the climate change category is shown in **Table 6**, differentiating between absolute and relative results. Total results refer to the impacts from the production, use and disposal of the inverter, whilst relative results refer to the impact per kWh delivered by the inverter. To make a fair comparison, we matched the electricity mixes from both studies, re-estimating the impacts for SCAPE's inverter using the Global mix. The embedded emissions for the SCAPE's inverter consider the inverter, the housing and the EoL. When comparing the GHG emissions, it is important to consider the lifetime of both inverters since this factor is directly linked to the total electricity losses, which affects directly to the relative emissions estimated.

Total emissions in absolute terms are very similar in the two cases, with values going around 1.400 kg of CO₂ equivalent. Total relative emissions (total emissions divided by the total kWh by the lifetime of the device in kWh) show a different picture, with SCAPE's study emitting half of the total emissions from the literature. If we want to disregard emissions from efficiency losses and focus only on the embedded emissions, we see that the total CO₂ footprint from SCAPE's alternative is 1.5 times higher than the literature case. However, if we consider the lifetime of each alternative can include the lifetime in the equation, we see that those emissions from the SCAPE converter are 25% lower than those from the literature.

Besides the lifetime of the inverters, there are other characteristics that should be considered. First, the different working power each inverter presents, with the value from literature being 1,5 times higher than the studied inverter. Second, the maturity of technology, on the one hand, we have an inverter from industry that has been already deployed in the market (TRL 9) and on the other hand, a IIC being developed and tested as a Mock-up (TRL 5-6). From second point, the low Technology Readiness Level of SCAPE's IIC might be an advantage, since there is room for improvement and many changes will happen before SCAPE's final deployment, changing its environmental performance for better or



worse. In any case, these are promising results that show the great potential that the work that is being carried out at SCAPE.

Table 5 – Conditions and assumptions of the compared studies. *In the compared study, it is explicitly stated to have a scope gate-to-gate; however, the material needs – and therefore, the whole supply chain – are considered in the assessment. Having this in mind, the scope is considered cradle-to-gate.

	Own study	Literature [4]
Databases	Ecoinvent Sphera	Ecoinvent
Electricity mix geographic boundary	Global	Global
Electricity mix year database	2020	2017
Scope study	cradle-to-grave	cradle-to-gate*
Inverter power (kW)	100	150
Inverter efficiency	97,5%	97%
Lifetime in km	600.000	300.000
Lifetime in kWh	96.000	48.000
Electricity losses in kWh	2.400	1.440

Table 6 – Results comparison between compared studies. Absolute emissions refer to the total footprint of the inverter including the electricity losses. Relative emissions refer to the footprint per kWh that enters the inverter.

		Own study	Literature [4]	Own/ literature
Embedded emissions + electricity losses	Total emissions (kg CO2 eq)	1.375	1.434	0,96
	Relative emissions (g CO2 eq/kWh)	14,3	14,9	0,96
Embedded emissions	Total emissions (kg CO2 eq)	519,8	708	0,73
	Relative emissions (g CO2 eq/kWh)	5,4	7,4	0,73
	Percentage of the embedded emissions over the total footprint	37,8%	24,7%	1,53

5.3. Sensibility analysis – electricity

GHG emissions from electricity losses are equally – if not more – important than those embedded in the electronic parts of the converter. Using average datasets from Global or European electricity may not be the most accurate assumption if it is considered that a vehicle will mostly be used – and therefore charged – in one country. This is why a sensitivity analysis is performed to see how the results change – considering SCAPE's last converter's version at 97,5% efficiency – when supplying electricity from specific countries, namely, Germany, Spain, France, Italy and Türkiye. Results for Global mix are included, as they were used in the previous section of this report and authors believe this can provide a perspective on the performance outside Europe. Additionally, as the electricity mix will change with the energy transition, it is considered relevant to include an analysis where the future electricity mixes are included. Using the national plans for 2030 from the previously mentioned countries, their electricity mixes are modelled [21], [22]. Furthermore, to account for the real electricity generation, in this analysis, the efficiencies from the transmission and distribution infrastructure from each country (extracted from ecoinvent processes) are considered. Similarly, distribution and transmission network infrastructure are considered with the same values as in ecoinvent. Authors are aware that this may not be true, since the penetration of renewables will require the reinforcement of

these networks to different degrees, but the uncertainty of these calculations makes it unfeasible to consider in this study.

In **Figure 9** we can see the embedded and use stage GHG emissions of the IIC and considering different countries and regions. The first noticeable thing is that using the EU-mix under or overvalues the use stage emissions depending on the country or region. For Spain and France, their mix is less pollutant, resulting in lower emissions, whereas for Global, Germany, Italy and Türkiye, using the EU-mix underrepresents the emissions from this stage. If we look at the future, what we see is a different picture, with all the countries mentioned presenting lower emissions than the EU-mix. Considering that the IIC treated in this report is projected to be deployed in the future (no less than in 5 years), we believe that the emissions to consider for the use stage should be those from each specific country in the future. However, the reader should be aware of the uncertainty linked to future mixes, which are based in each country predictions, announcements and desires. All the results for the combination of all impact categories and IICs alternatives are shown in **Table A2**, in the Annexes.

The second important finding is that when comparing embedded and use stage emissions, the difference between both gets reduced with time. While in the present, emissions derived from losses are significantly higher than those embedded – except for France –, in 2030, Germany, Italy and Türkiye present similar levels of emissions for both stages and, in France and Spain, usage emissions are lower. As electricity generation from renewable sources increases, the significance of electricity losses, and consequently, the impact of emissions related to efficiency will decline, whilst the importance of embedded emissions will grow. On the other hand, it could be argued that as time passes and the electricity mix gets greener, the embedded emissions in electronics will also decrease, especially in energy-intensive IICs using semiconductors. China, for example, plans to peak its emissions by 2030 and become carbon-neutral before 2060 [23]. This means that, in the long term, manufacturing emissions will be cut by the increasing share of renewables in the electricity mix of semiconductor manufacturing countries like China. Having this in mind, to reduce the environmental footprint of the studied IIC, both usage and manufacturing stages should be optimized. The former could be done through efficiency improvements or by reducing the use of the EV. For the latter, reducing the embedded emissions can be accomplished through strategies to extend the components and IIC's lifespan and enhance the recovery of components: Monitoring the health status of sensible components while being used and implementing a design that enables modularity and repairability and sourcing these elements at countries or factories fed with renewable energy. The first two options are already being implemented in the SCAPE project, although they are not being accounted in this analysis.

Further research should be carried out to refine the estimations on the future embedded footprint and decarbonized scenarios through advanced LCA-packages like premise [24], timex-package [25] or fossil-free ecoinvent [26], improving the accuracy of calculations in the future tense.



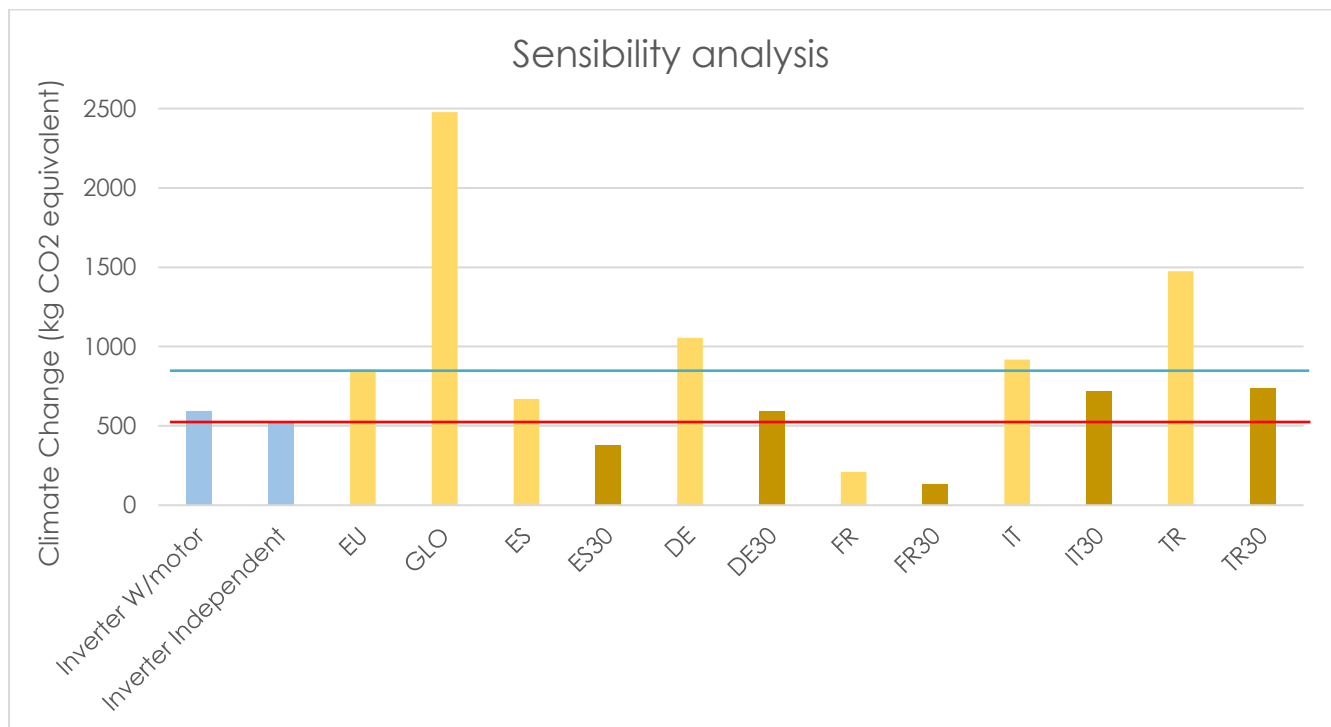


Figure 10 – Results for the emissions of different countries and regions considering 98% efficiency. Bars are coloured differently for easier differentiation: blue for embedded emissions; light yellow for current electricity mixes; dark yellow for future electricity mixes. Two horizontal lines are included to clearly identify which type of emissions are higher or lower than the embedded emissions (red line) and for the EU-mix (blue line).

5.4. Limitations of these results

Considering the results previously presented, we believe it is important also to devote some lines to describe the limitations of this research. There are limitations that apply to the general field of sustainability of electronics and others that are specific about this project.

LCA and electronics. The methodology behind LCA is purely model based, which means that it is based entirely on the data with which the model is fed. Here, we highlight the most important factors that affect the accuracy of the presented results based on the work from [27]. Technological developments in electronics are fast paced and are subject to secrecy in their supply chain and manufacturing processes, both because of the competition between manufacturers. Whereas gathering inventory data is a time-consuming process that requires expertise on a topic that lacks transparency. This leads to an important lag between the available LCA datasets and reality, quickly outdated datasets representativeness. Datasets may rely on products that are already outdated when they are sent to the LCA practitioners, ensuring that there is no problem if there is a data leak to their competitors. All this jeopardizes the representativeness of the datasets used. This not only affects the materials of the electronic components, but more importantly, the manufacturing processes. Energy requirements and the use of high-purity chemicals and materials are best kept secrets of companies, which are very reluctant to share this information. This fact adds another limitation layer, since the datasets available do not usually refer to high-purity chemicals but to those that are more common.

SCAPE. First, although the SCAPE project research at using one single converter as inverter and onboard charger, we have only considered the converter to behave as an inverter. This can be relevant when comparing different options. However, since the lifetime of the SCAPE's inverter is

greater than the compared cases, we multiplied the embedded footprint of those inverters to make the lifetime equal in both cases. Thus, the comparisons in this study look at SCAPE's converter against two inverters instead of comparing the SCAPE's converter against an inverter and an onboard charger. Second, estimating the area for SiC sections in manufactured elements (transistors and integrated circuits). As previously shown, the hotspot in the switching cell comes from the transistors and the integrated circuits because of the presence of Si and SiC parts in these elements. The energy intensity of these materials drastically increases emissions. Using the commercial number of the different elements (i.e., transistors, integrated circuits), we identified the material declarations and the data sheets of each element and used that information to build these elements in the LCA model. However, the area for the SiC chip was never clear, as the datasheets showed the dimensions of the converter from the outside, with the packaging covering the semiconductor area. Thus, we had to approximate the area to consider this manufacturing requirement in our estimations, which will most likely lead to an overestimation of the impacts. Third, when comparing converters (i.e., SCAPE's version and the commercial converter) the TRL should be kept in mind. Whereas the commercial device is a mature and already commercially available converter, SCAPE's version is still in a development stage. This affects the uncertainty of the results in two ways: The potential improvement of the converter, because it is still in development, this converter will suffer modifications that will improve or worsen its environmental footprint for the components already considered; and, the completeness of the device may be affected, meaning that SCAPE's converter may require additional components to work under realistic conditions.

Chip embedding. Emissions from SCAPE's last developed IIC are estimated without considering two key parts. First the Shunt resistor, which, as explained in WP6, is a key component embedded in the PCB, like the two mentioned chip embedding transistors (section 3.2). Due to lack of information regarding this element, its change has been ignored and the same element considered in the mock-up has been used in SCAPE's final version. Second and more importantly, the different stages of the manufacturing process of chip embedding have not been considered, largely due to uncertainties in the energy requirements both in lab and factory-scale. We believe that the first limitation mentioned here has a very limited impact on the overall calculations, especially since the efficiency used considers the improvements brought by the overall chip embedding technology, of which the shunt resistor is part of. However, the manufacturing limitation is certainly of higher importance, especially because of what we just mentioned. We are considering the advantages of chip embedding technology, but not including the manufacturing stage, which could bring emissions to a higher level, especially bearing in mind that the current total GHG emissions between the commercial and SCAPE's IIC is not very distant.

6. Conclusions

After evaluating the environmental footprint of the technology developed in the SCAPE project and compared it with commercial alternatives from project partners and from literature, we believe the current technology has a promising future, although further research is needed.

The evolution of the IIC's design (mock-up and final design) has derived in the decrease of emissions as a side-effect of the reduction of the thermal management material use, the increase of efficiency due to the chip embedding technology and because of the refinement of the inventory. When comparing the results from SCAPE's final design against the commercial version of one of our partners, we see lower emissions for the sixteen assessed impact categories in SCAPE's IIC. When



focusing on greenhouse gas (GHG) emissions, we see that total values are similar for SCAPE's and commercial inverters. However, the casing estimated for SCAPE's represents less than half the converter electronics GHG emissions, whereas for the commercial device, the GHG emissions from the housing equal those from the inverter electronics. On the other hand, GHG emissions from the two design alternatives from the SCAPE's IIC are lower than those of the commercial alternative. For both alternatives we see that most GHG emissions come mainly from the PCB and from elements with semiconductors, i.e.: transistors and integrated circuits.

We have projected future electricity mixes to see how the weight between embedded and use emissions would vary over time. It becomes clear that, for most countries – except for France –, electricity losses will still be the major source of emissions. Nevertheless, the gap between embedded and use-stage emissions will narrow with time, with some countries – Spain – already projecting to have higher embedded than use stage emissions. For this reason, it is important to keep efficiency as high as possible, despite the high emissions of materials like SiC, these prove to be widely compensated for by their efficiency improvements. Equally complex is to reduce emissions from the housing. Although it may seem simple to just replace aluminium with another material, aluminium casing does not only bring structural integrity to the converter. It shields it from electromagnetic interference, provides thermal conductivity, is cost-effective and is easily recyclable, an important feature considering that 85% of the average vehicle must be recycled according to EU regulations.

We conclude that results from SCAPE's IIC are promising, as its emissions are lower than those of the commercial inverter in all assessed indicators. However, due to the TRL of the device, accuracy is limited and the hotspots identified are hard to abate and could even be counterproductive to do so in a direct fashion. Thus, we believe that further research should aim to refine the results presented in this report and to consider system eco-design approaches. More specifically we recommend going into greater detail regarding the area of silicon and silicon carbide in manufactured elements, to include the casing, and all the required components integrated in the onboard charger in future studies. Regarding the eco-design, modularity and repairability of electronic converters and the search of synergies – such as sharing housing between engine and converter– between EV components should be investigated.



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8. Annexes

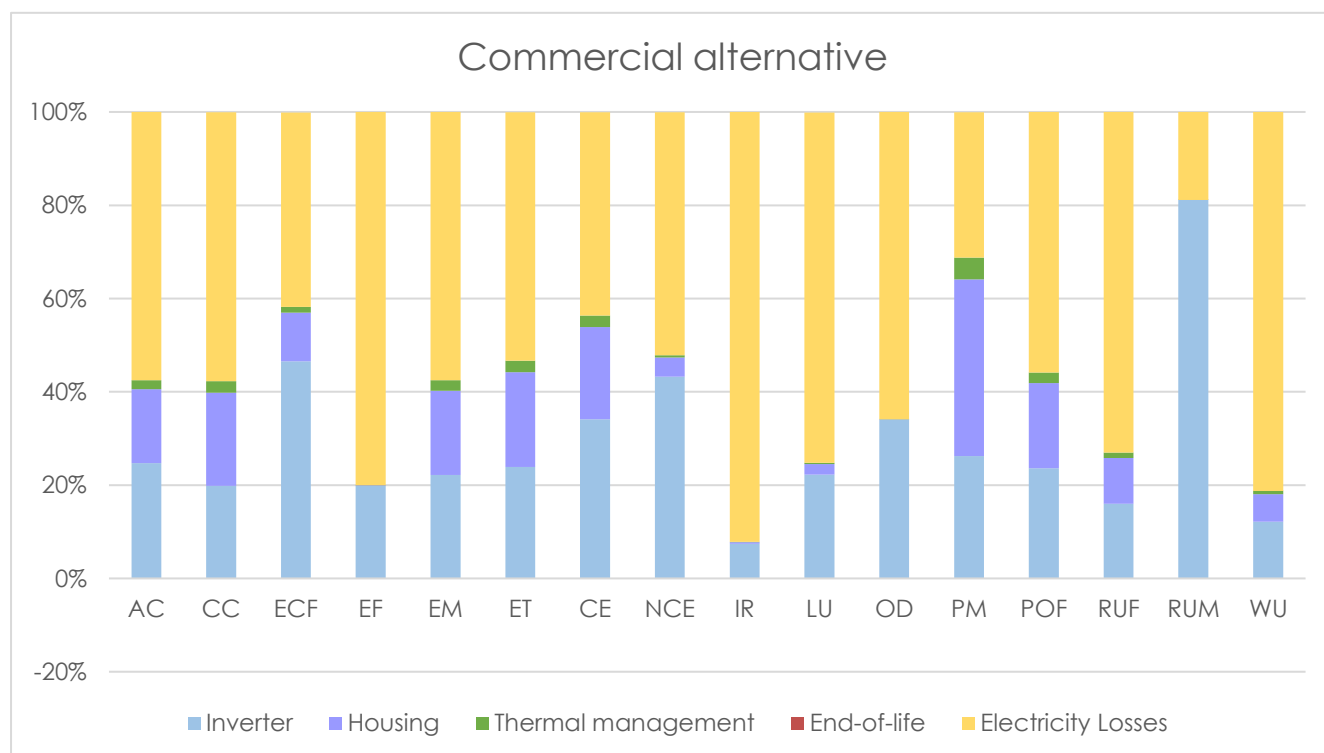


Figure A 1 – Contribution analysis for all impact categories for the commercial inverter.

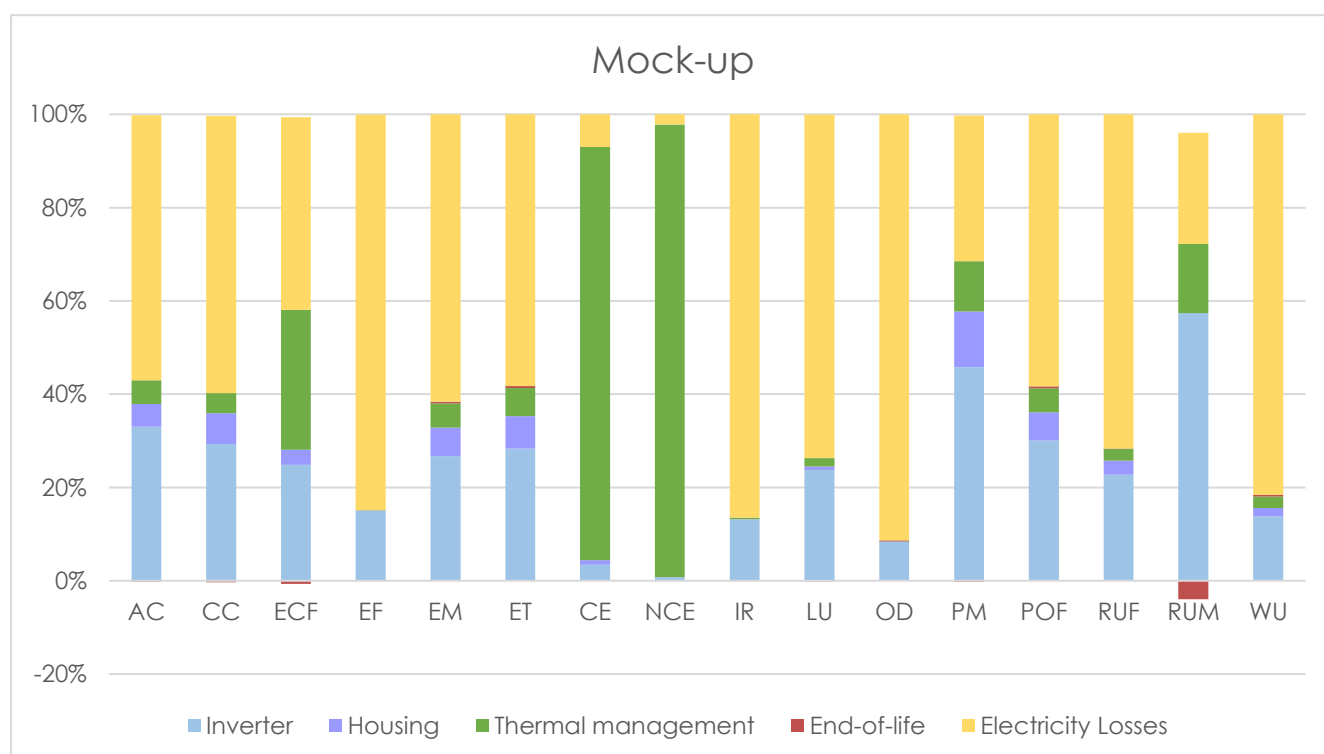


Figure A 2 – Contribution analysis for all impact categories for the mock-up



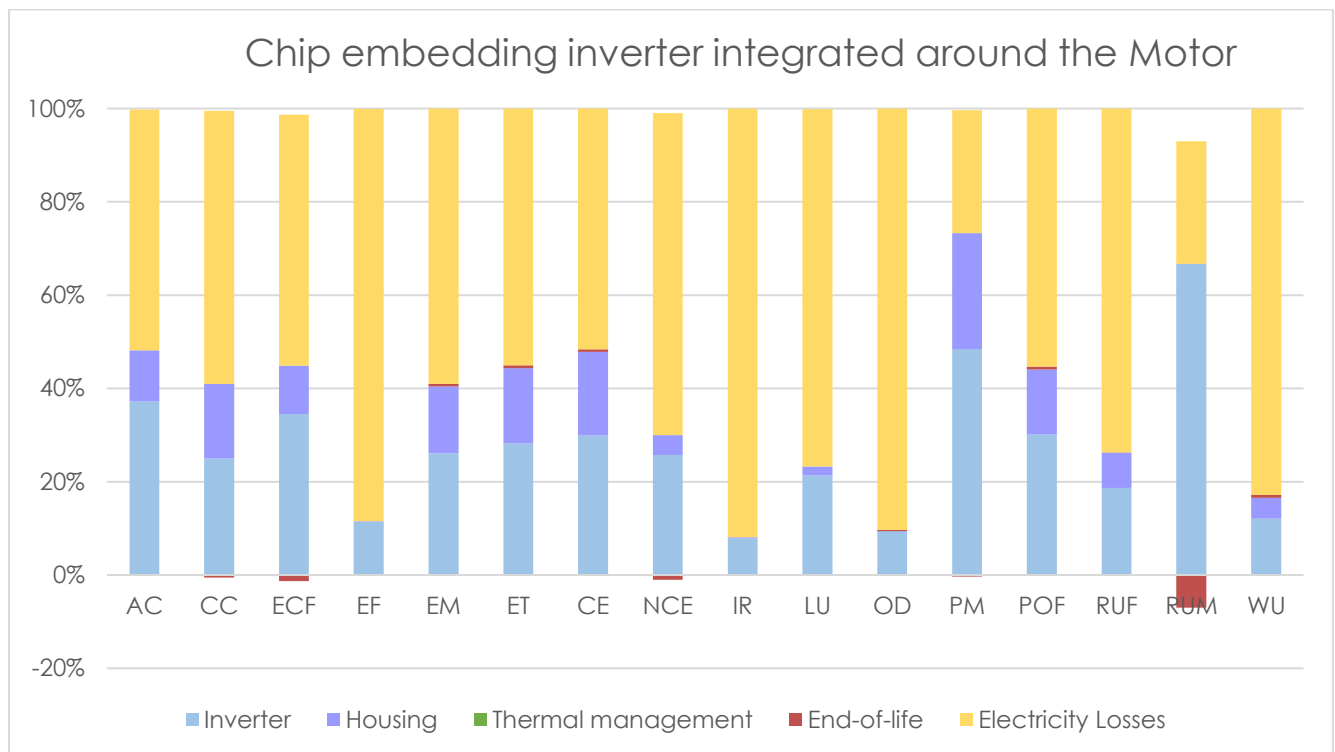


Figure A 3 – Contribution analysis for all impact categories SCAPE's last version of the IIC integrated around the motor, where it uses the motor's Thermal Management but needs casing for each Converter Leg

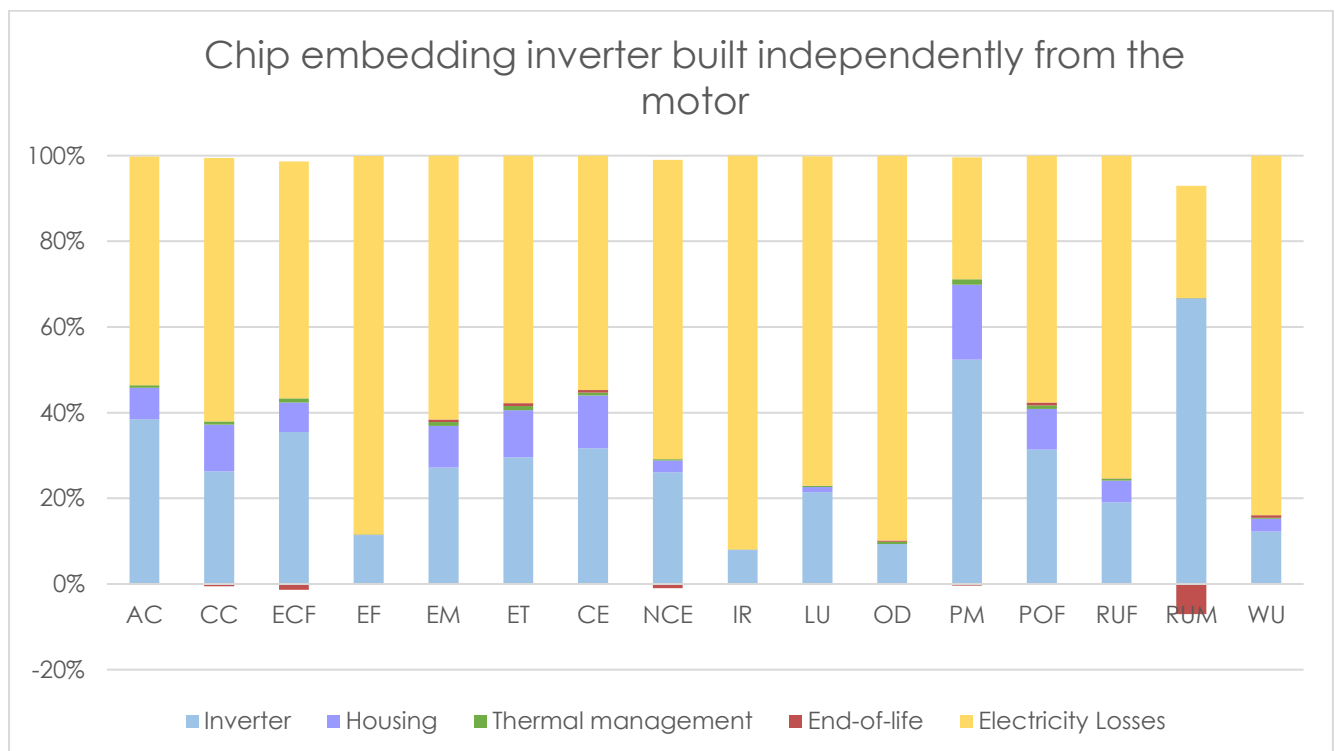


Figure A 4 – Contribution analysis for all impact categories SCAPE's last version of the IIC separated from the motor, where it needs its own Thermal Management but the Converter Legs are in a more compact design, which reduces the casing needs.



Table A1 – List of Critical Raw materials and Strategic Raw Materials [20]

CRMs	Mock-up	Embedded CRMs and SRMs			Unit
		CE- IIC with Motor	CE – IIC Independent	Commercial inverter	
Antimony	5,79E+00	3,28E+00	2,61E-01	2,60E-01	g
Arsenic	4,08E-02	1,54E-02	1,57E-02	1,57E-02	g
Bauxite	3,49E+02	4,53E+02	3,58E+02	3,18E+02	g
Alumina	-	-	-	-	g
Aluminium	4,19E+04	3,11E+04	2,35E+04	1,56E+04	g
Baryte	-	-	-	-	g
Beryllium	-	-	-	-	g
Bismuth	-	-	-	-	g
Boron	2,00E+01	8,92E-01	7,19E-01	7,19E-01	g
Cobalt	2,11E+00	5,27E+00	5,35E+00	5,35E+00	g
Coking coal	-	-	-	-	g
Copper	3,01E+03	7,90E+03	1,63E+03	1,63E+03	g
Feldspar	2,70E-02	7,75E-04	5,41E-04	4,64E-04	g
Fluorspar	7,46E+02	6,63E+02	4,52E+02	3,37E+02	g
Gallium	5,10E-02	6,60E-02	5,49E-02	5,49E-02	g
Germanium	-	-	-	-	g
Hafnium	4,00E-02	3,05E-02	1,64E-02	1,63E-02	g
Helium	6,98E-01	1,61E+01	1,61E+01	1,61E+01	g
Lithium	1,07E-04	1,96E-04	1,75E-04	1,73E-04	g
Magnesium	6,13E+01	2,29E+01	2,65E+01	2,64E+01	g
Manganese	8,22E+02	4,99E+01	3,23E+01	3,09E+01	g
Graphite	8,63E-04	8,09E-02	8,05E-02	8,04E-02	g
Nickel	1,07E+02	3,35E+02	3,17E+02	3,17E+02	g
Niobium	9,01E-02	2,07E-01	7,01E-02	7,01E-02	g
Phosphate rock	-	-	-	-	g
Phosphorus	3,53E+01	5,93E+01	4,86E+01	4,83E+01	g
Silicon	1,03E+02	3,66E+01	3,83E+01	3,83E+01	g
Strontium	1,20E-01	4,84E-02	4,32E-02	4,14E-02	g
Tantalum	2,77E+00	5,50E-01	5,50E-01	5,50E-01	g
Titanium	1,55E+01	1,33E+01	7,01E+00	6,95E+00	g
Tungsten	-	-	-	-	g
Vanadium	1,25E-02	2,49E-01	1,10E-02	9,84E-03	g
Platinum group metals					
ruthenium	1,57E-03	4,66E-02	4,74E-02	4,74E-02	g
rhodium	1,12E-03	2,37E-02	2,41E-02	2,41E-02	g
palladium	8,24E-03	1,40E-01	1,43E-01	1,43E-01	g
osmium	3,23E-04	9,60E-03	9,76E-03	9,76E-03	g
iridium	2,65E-04	7,87E-03	8,00E-03	8,00E-03	g
platinum	1,06E-02	2,37E-01	2,41E-01	2,41E-01	g
Heavy REE					
Europium	7,69E-04	4,38E-04	2,66E-04	2,68E-04	g





Gadolinium	2,63E-03	1,62E-03	9,44E-04	9,47E-04	g
Terbium	2,78E-05	1,78E-05	1,98E-05	1,98E-05	g
Dysprosium	2,63E-03	4,08E-03	2,24E-03	2,02E-03	g
Holmium	-1,52E-05	-9,20E-05	-4,42E-05	-4,11E-05	g
Erbium	-4,20E-04	-6,77E-04	-3,68E-04	-3,31E-04	g
Thulium	-3,74E-08	-3,99E-07	-1,87E-07	-1,75E-07	g
Ytterbium	-1,15E-04	-1,82E-04	-9,92E-05	-8,93E-05	g
Lutetium	-1,14E-07	-8,59E-07	-4,08E-07	-3,81E-07	g
Scandium	3,28E-04	2,22E-04	1,19E-04	1,19E-04	g
Yttrium	1,38E-04	-3,38E-05	5,14E-05	5,67E-05	g

Light REE

Lanthanum	8,96E-02	4,95E-02	3,09E-02	3,12E-02	g
Cerium	1,87E-01	1,06E-01	6,34E-02	6,39E-02	g
Praseodymium	2,32E-02	1,36E-02	7,97E-03	8,01E-03	g
Neodymium	7,47E-02	4,91E-02	2,84E-02	2,81E-02	g
Promethium	-	-	-	-	g
Samarium	2,41E-06	1,69E-03	1,08E-03	1,09E-03	g



D8.9 LCA report on the proposed integrated and scalable power converters

Table A 2 – Sensibility analysis–Emissions for all impact categories considering the electricity from different countries and regions for the present and for 2030. Embedded emissions are considered as those emissions from SCAPE’s converter in its independent version. Embedded emissions include the converter, housing, thermal management and End-of-life.

Sensibility – Electricity from different regions and years														
Impact category	Abr.	Embedded	EU	GLO	ES	ES30	DE	DE30	FR	FR30	IT	IT30	TR	TR30
Acidification [Mole of H ⁺ eq.]	AC	4,219	4,87	14,84	3,99	1,46	3,03	1,85	1,47	0,50	3,90	1,83	10,91	5,42
Climate Change – total [kg CO ₂ eq.]	CC	519,846	855,43	2478,53	669,59	378,12	1056,19	593,44	210,84	130,73	917,78	719,15	1474,63	734,83
Ecotoxicity, freshwater – total [CTUe]	ECF	2474,342	3.262,46	11087,32	2740,21	1430,20	4306,58	2235,32	1767,59	611,35	2662,63	1562,70	4943,50	2281,59
Eutrophication, freshwater [kg P eq.]	EF	0,105	0,80	3,84	0,18	0,07	1,51	0,69	0,09	0,03	0,20	0,08	1,70	0,97
Eutrophication, marine [kg N eq.]	EM	0,494	0,79	2,24	0,69	0,31	0,79	0,50	0,29	0,18	0,61	0,43	1,76	0,72
Eutrophication, terrestrial [Mole of N eq.]	ET	5,209	7,13	16,16	7,13	3,30	6,03	4,41	2,33	1,14	6,84	4,77	15,99	5,67
Human toxicity, cancer – total [CTUh]	CE	3,95E-07	4,77E-07	1,27E-06	4,48E-07	2,72E-07	4,66E-07	3,19E-07	3,10E-07	1,45E-07	4,41E-07	2,99E-07	5,30E-07	2,65E-07
Human toxicity, non-cancer – total [CTUh]	NCE	6,85E-06	1,70E-05	4,59E-05	1,39E-05	6,13E-06	1,76E-05	9,37E-06	1,11E-05	2,90E-06	1,37E-05	6,72E-06	2,22E-05	8,31E-06
Ionising radiation, human health [kBq U235 eq.]	IR	47,881	544,80	599,28	567,84	117,55	242,66	20,93	1291,80	1158,34	116,16	30,65	13,50	75,24
Land Use [Pt]	LU	1149,703	3.879,36	5168,58	2890,75	11216,26	3897,26	15776,54	1463,79	5525,38	4546,41	11682,94	1794,47	8296,73
Ozone depletion [kg CFC-II eq.]	OD	1,83E-06	1,62E-05	5,25E-05	1,55E-05	1,32E-05	1,21E-05	1,04E-05	8,70E-06	6,85E-06	2,16E-05	2,09E-05	1,05E-05	1,16E-05
Particulate matter [Disease incidences]	PM	4,09E-05	1,65E-05	5,32E-05	1,59E-05	1,02E-05	1,38E-05	1,21E-05	1,23E-05	8,07E-06	1,82E-05	1,20E-05	4,84E-05	3,22E-05
Photochemical ozone formation, human health [kg NMVOC eq.]	POF	1,683	2,29	5,94	2,48	1,28	1,72	1,26	0,79	0,43	2,86	2,17	4,68	2,05
Resource use, fossils [MJ]	RUF	6983,538	21.357,54	48091,79	18851,03	7135,37	18624,11	8477,08	28835,17	25192,26	15262,23	11193,94	19608,65	10858,29
Resource use, mineral and metals [kg Sb eq.]	RUM	2,34E-02	1,03E-02	2,15E-02	1,01E-02	5,21E-03	1,16E-02	5,60E-03	9,90E-03	2,44E-03	1,05E-02	4,13E-03	1,01E-02	3,50E-03
Water use [m ³ world equiv.]	WU	128,628	671,62	1134,67	292,65	159,01	332,07	163,93	352,45	286,67	678,95	253,86	685,23	734,89



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