Life cycle assessment of a DC-LINK capacitor used for automotive applications
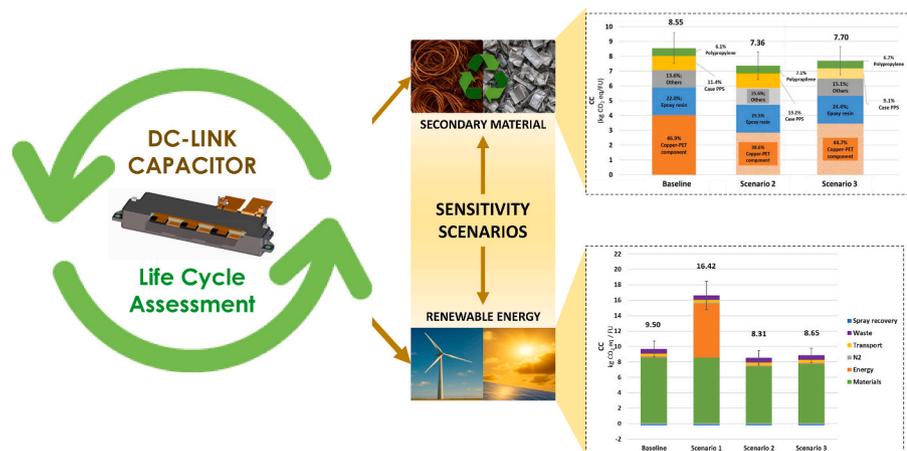
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GRAPHICAL ABSTRACT

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ABSTRACT

In the automotive sector, which is increasingly focused on reducing its environmental impact, limited attention has been given to power systems and components involved in vehicle electrification. This study aims to propose a cradle-to-gate Life Cycle Assessment (LCA) applied to a DC-LINK capacitor (dimensions 130 mm*48 mm*247 mm and expected reference service life - RSL of 8000 h of driving), manufactured by a leading company in the sector. The aim of the research is filling existing gaps concerning the material composition of DC-LINKs and relative environmental impacts. The analysis examines the contributions of the various materials within the product and develops sensitivity scenarios to evaluate the influence of electricity used during manufacturing and the benefits associated with using secondary materials instead of virgin ones. The Climate Change impacts estimated for the Baseline scenario resulted in 9.50 kg CO_2 eq per DC-LINK produced, with material components contributing 88.2 %. The complete hotspot analysis highlighted a general significant influence of the material components, which accounted for at least 57.8 % across all 18 environmental categories examined. The minimal contribution of electricity is justified by the company's decision to use a fully renewable energy mix. The use of

secondary copper and aluminium proved advantageous, as it can reduce the climate change impacts of the finished product by 10–14 % with respect to the Baseline. In conclusion, the findings underscore the importance of considering the entire life cycle when assessing the sustainability of components used in the automotive sector and identifying the best strategies for reducing their impacts.

1. Introduction

Human existence, economic activities, and the industrial development of recent decades have caused widespread environmental concerns worldwide (Madurai Elavarasan et al., 2022; Nathaniel et al., 2021). This development has been driven by various fields, among which some are considered the main contributors to environmental impacts. One of the primary sectors receiving particular attention is the automotive industry, which with around 1 billion cars in use worldwide, bears significant responsibility for producing greenhouse gas (GHG) emissions (Shahzad and Iqbal Cheema, 2024). The automotive industry can be regarded as part of the broader transportation sector, which alone contributes to about 25 % of the total GHG emitted on a global level (P. Zhang et al., 2023). Nevertheless, the automotive sector is considered responsible for the emission of additional pollutants into the environment (e.g., particulate matter and NO_x) (Cunha-Lopes et al., 2023), thereby contributing to a broader range of environmental impacts (F. Liu et al., 2023). For this reason, the market is evolving in search of potential solutions to reduce the environmental impacts associated with vehicle use, primarily addressing direct emissions (Kwilinski et al., 2024; Sharma and Strezov, 2017), and extending to the end-of-life (EoL) of materials used within them (Torta et al., 2024). Concerning the EoL stage, the European Commission proposed on July 13, 2023 a new Regulation, which is currently under review, on EoL vehicles (European Commission, 2023). The final proposal builds on and replaces the two existing: Directive 2000/53/EC, 2021) and Directive 2005/64/CE, 2005. The rules aim to improve the circular design of vehicles to facilitate the removal of materials, parts and components for reuse and recycling; ensure that at least 25 % of plastic used to build a vehicle comes from recycling, recover more raw materials; ensure that producers are financially responsible for EoL vehicles, address the issue of vehicles going "missing," increasing inspections, enhancing interoperability of national vehicle registration systems, and banning on exporting non-roadworthy vehicles.

Awareness of the environmental impact of transportation is steering the market towards electrification (Statista, 2024), not only concerning powertrains, transitioning from fuel-based to electricity-based systems, but also in terms of components (Hall et al., 2010; Thollander et al., 2007). Therefore, although it is now well established that, in vehicles powered by fossil fuels, most emissions occur during the use phase (Bachmann et al., 2015; Shahraeeni et al., 2015; Tong et al., 2015), in a market context shifting towards electrification, the relevance of components and their EoL phase may increase in terms of their contribution to the vehicle's overall environmental impacts (Fonseca et al., 2013). However, this consideration is associated with a lack of information in the literature regarding the wide variety of materials and components involved in automotive manufacture, especially those related to electronic components, challenging the estimation of their environmental impacts (Nordelöf et al., 2019). In particular, our research has highlighted not only a lack of data, both general and site-specific, regarding various materials but also an apparent disregard for addressing this gap. The issue of limited data availability is further complicated by the increasing integration of secondary materials in vehicles (Ortego et al., 2020), which, while beneficial for circularity, represents a good opportunity to deal with the decreasing metal ore quality (Calvo et al., 2016; Watari et al., 2021), makes the search for consistent and site-specific data more complex.

Some electronic components gaining interest are capacitors, devices that store electrical energy by accumulating electric charges on two closely spaced surfaces that are insulated from each other (Sinclair, 2001; Smith et al., 2018). Capacitors are characterised by properties such as: exceptional power density, vast operational temperature range, remarkable reliability, lightweight construction, and high efficiency, making them extensively utilized for energy storage. The two main families of energy storage capacitors are dielectric capacitors and supercapacitors. The first one encompasses film capacitors, ceramic dielectric capacitors, and electrolytic capacitors, whereas supercapacitors are categorized into double-layer capacitors, pseudocapacitors, and hybrid capacitors (W. Liu et al., 2024). These devices are utilized in various applications, with one of the most predominant being in the automotive sector (Moletti et al., 2021). The increasingly dominant role of capacitors in the market (the market size has been estimated at $34.65 billion in 2022, with a growth rate of 5.96 % (Precedence research, 2023), has driven research to investigate their environmental impacts by applying the Life Cycle Assessment (LCA) and complementary methodologies to analyse and compare the different types available and aiming to identify key ecological hotspots.

In this context, LCA plays an important role in assessing the potential impacts of new technologies, thereby helping to guide research and innovation activities to achieve environmentally compatible and sustainable products (Arvidsson et al., 2018). LCA studies focusing on capacitors, and more broadly on electronic devices used in the automotive sector, in considered scarce. In addition, the number of studies found in the literature (Alaviitala and Mattila, 2015; Jiang et al., 2021; Moletti et al., 2021) remains relatively limited and does not fully cover the range of capacitors available, which are made from various materials (e.g., aluminium, aluminium-organic polymer, ceramic, arrays and tantalum), depending on their specific applications or sectors (Smith et al., 2018). This aspect results in an additional complication of the modelling, since the variety of materials and functions that characterize capacitors makes each analysis specific to the unit or type examined, without ensuring that it can be extended to other capacitors of different kinds. This range of variability is also connected to the complex definition of the functional unit, which cannot be confined to a mass-based measure but must also depend on lifetime (reference service life, RSL) and performance. In this perspective, the need to consider operating conditions, degradation parameters, and tolerance to specific conditions further complicates the analysis (H. Liu et al., 2023; Niu et al., 2018). One of the main studies found in the literature was proposed by Nordelöf et al. (2019) who defined a scalable inventory for a power electronic inverter unit intended for controlling electric vehicle propulsion motors. However, this work does not constitute a full LCA; rather, it consists of a data elaboration exercise aimed at investigating the composition of commonly used inverters. De Sio et al. (2025) applied an LCA to a composite prototype battery enclosure for electric vehicles, identifying materials flows and use phase as the main responsible of the impacts observed.

In addition, the advantages or disadvantages associated with the above-mentioned introduction of secondary materials in the final product have rarely been addressed, and, at the time of submission, the only study reporting a comparison between capacitors produced from primary ore and recycled minerals is referred to the Lithium-ion technology (Chigada et al., 2021).

The objective of our research is thus to apply the LCA to quantitatively evaluate the potential environmental impacts associated with a specific product from the family of direct current link (DC-LINK) capacitors. DC-LINKs belongs to a broad and increasingly relevant family of devices widely used in energy conversion systems. Since to our knowledge LCAs on such components are still lacking in the literature,

and this work can be seen as a first step toward a better understanding of their environmental impact. Moreover, the use of primary data strengthens the reliability of our assessment, making the selected DC-LINK a solid case study that can serve as a reference for future investigations in this field. The significance of DC-LINK capacitors in the market is underscored by their estimated market size of USD 1.2 billion in 2024, with projections indicating growth to USD 2.5 billion by 2033, reflecting a compound annual growth rate of 9.5 % from 2026 to 2033 (Verified Market Reports, 2024), which is probably biased by the parallel electrification of the automotive industry (Rísquez Ramos and Ruiz-Gálvez, 2024). These capacitors are developed by KEMET Electronics Italia Srl (specifically by the FILM Division), part of Yageo Corporation, hereafter referred to as KEMET (KEMET ELECTRONICS ITALIA S.R.L, 2024). The results obtained can be used to evaluate and quantify the environmental burdens of the system in terms of different impact categories and to determine the flows and processes that contribute most to the environmental impacts. Moreover, the proposed research will help fill the existing gap concerning the material composition of DC-LINKs, thus enabling the identification of potential hotspots during the manufacturing phase of such devices. In this context, the study provides a hotspot analysis (also called contribution analysis) of a representative DC-LINK product aimed at understanding the relevance of the production stages, with special attention to the contribution of electricity and any secondary materials introduced into system. A peculiarity of our study lies in the opportunity of developing a model largely based on primary data shared by an existing company, so reflecting a real context.

2. Materials and methods

According to the international ISO standards 14040:2006/Amd 1:2020 and 14044:2006/Amd 1:2017+Amd2:2020 (ISO, 2006a; 2006b), LCA is a strategic technique to identify and quantify the potential environmental impacts associated with a product, process or system throughout its life cycle. The common LCA framework (goal and scope definition, life cycle inventory – LCI, life cycle impact assessment – LCIA, and interpretation) applies well-regarded scientific mechanisms and characterization models to relate the LCI results to selected category indicators for a quantitative evaluation of the environmental impacts (LCIA). The interpretation, transversal to the previous three phases, ensures consistency between the aims of the study and its execution of recommendations.

2.1. Case study

KEMET, a subsidiary of Yageo Corporation since 2020, is a leading global supplier of electronic components. Their product portfolio includes Capacitors, Electromagnetic Compatibility (EMC) Solutions, Magnetics, Sensors and Transducers, Electromechanical Devices, Circuit Protection, and Power Solutions. Due to their relevance within the field of interest, the company has been identified as a representative for the provision of primary data related to the production of the DC-LINK under evaluation.

2.2. Goal and scope definition

The proposed LCA study aims to apply LCA to estimate the potential environmental impacts of a representative product of the family of DC-LINK capacitors (Fig. S1 in the electronic supporting material, ESI), to identify key hotspots in the product system and to determine the advantages and disadvantages associated with i) the partial reduction of the fossil-derived electricity in the mix; and ii) the replacement of components of virgin derivation with secondary materials in the final product.

The technology used inside the capacitors (metallised plastic film) is equivalent to that of DC-LINKs. The latter differs from traditional capacitors in their performance requirements (e.g., film thickness or metalization treatment of the film). While traditional capacitors contain only a single film winding (a single film element wound and compacted), the DC-LINK analysed in this study contains multiple windings and resembles a battery module composed of several individual cells. Because of this, the plastic casing is different: it houses multiple windings and is fixed to an external structure using bushings (due to stricter mechanical requirements). Also, for this reason, a busbar is used rather than wires to connect all the elements. Finally, the resin has different properties to effectively encapsulate and protect a component that contains multiple windings. Accordingly, the selected FU is the production of 1 DC-LINK, of dimensions 130 mm*48 mm*247 mm, with an expected RSL of 8000 h of driving, packed and ready to be introduced in the market. The functional unit was defined as one unit of product, since mass- or volume-based units were not considered representative of the operational function of a DC-LINK (Nordelöf et al., 2019). This choice ensures comparability with other DC-LINKs, provided they share the same technical characteristics and service life.

The system boundaries of the present LCA study were established to achieve a cradle-to-gate evaluation and include upstream and core phases. The upstream processes are represented by the supply of raw materials, energy, and the production of semi-finished goods. At the same time, the core phase includes all the operations performed within the company's plants located in Skopje (North Macedonia, MK) and Kjustendil (Bulgaria, BG). The processes involved in the system are identified in (I) Metalization, BG; (II) Winding & Flattering, MK; (III) Masking & Spraying, MK; (IV) Element Treatment, MK; (V) Element Measurement, MK; (VI) Soldering, MK; (VII) Resin Filling, Post & Final Curing, MK; (VIII) Statistical & Quality control, MK; and (IX) End of Line, MK. A block diagram of the production process is shown in Fig. 1. More details about the LCI are reported in section 2.3. The management of waste generated during the core phase is included in the evaluation. Conversely, the downstream phase was excluded from the evaluation due to varying application scenarios and the lack of primary information regarding the use and EoL stages. This exclusion is also supported by C. Zhang et al. (2022), who initially included it in the analysis but subsequently assessed it as negligible across all the impact categories considered. In addition, the expansion of the system boundaries from a cradle-to-gate approach to a cradle-to-grave, would imply the inclusion of the use-phase, which has been recognised as particularly significant in the automotive sector (Gebler et al., 2020; Pero et al., 2018). Accordingly, the expansion of the system boundary would overshadow the production phases, which are currently the key point of the study. For this reason, primary data were prioritised, and the study focused on the available information, which does not include the use phase, since the specific vehicle and its operational context are unknown, nor the EoL management, due to the lack of site- and case-specific data on recycling scenarios, potential recycling performance, alternative waste management options, and the exact locations where the waste will be generated (i.e., where the vehicles integrating the components will be used).

2.3. Life cycle inventory

2.3.1. General assumptions

The data concerning the flows of materials, energy, and auxiliary inputs involved in the company's system (i.e., foreground processes, represented by blue dashed lines in Fig. 1) were entirely provided as primary data. Additionally, the weight of the Chinese-sourced capacitor manufactured in the "capacitor production" process, as well as the energy consumption associated with its production, are also considered primary information. Background processes are drawn from literature and databases. Some general considerations and a detailed description of the inventory are outlined below. The background processes associated with energy, auxiliaries, raw material, and semi-finished product manufacturing and supply were obtained from the ecoinvent 3.9 (Wernet et al., 2016) and Environmental Footprint (European
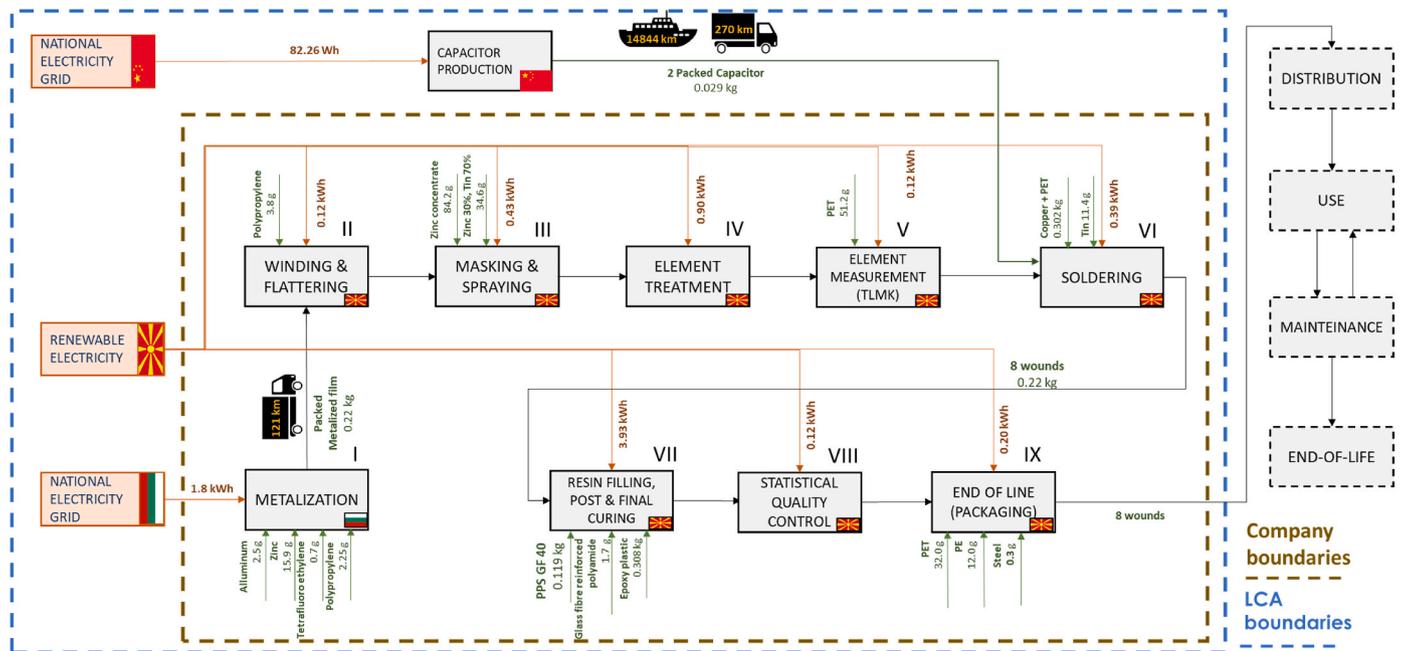
Fig. 1. System diagram including the processes occurring in Bulgaria and North Macedonia. The flags represent the country where the process takes place or where electricity is produced. Distribution, use, maintenance and EoL are excluded from the system boundaries (dashed blocks).

Commission, 2025) databases. The SimaPro software (v.9.6) was selected to read the databases (Goedkoop et al., 2016) and to generate the model. Table 1 reports each material input flow involved in each unit process. Regardless of quantity, no input material or flow has been neglected in this analysis. It is worth noting that, although capacitors may sometimes contain brominated compounds used as flame retardants (Gastol et al., 2016), the ones analysed in this study are free of such substances. This absence avoids the need to focus on the well-known environmental drawbacks associated with these materials, which, if improperly managed at EoL, may leach into the environment and contaminate air, soil, and water. Other relevant substances that could be potentially found in commercial capacitors are PFAS (per- and polyfluoroalkyl substances) (Dias et al., 2024), which are largely employed in the automotive sector for increasing the performance of mechanical systems that are subject to challenging conditions such as mechanical loading, cyclic stresses, and high temperatures, such as vehicle combustion engines, electric motors, batteries and charging systems, power electronics, thermal management systems, and many others (Lin et al., 2009). At the time of the study, the European directive had not yet defined any applicability thresholds for PFAS in this case study, nor specified which products it should apply to. These substances are generally recognised for their environmental persistence. These substances are, however, widely recognised for their environmental persistence, potential for bioaccumulation, and toxicity to both ecosystems and human health (Anik et al., 2025). In contrast to brominated compounds, which are typically associated with environmental impacts primarily when mismanaged at EoL, PFAS may also pose risks during the use phase of products (Sunderland et al., 2019). While such exposure pathways are unlikely in the specific case of capacitors, given the limited likelihood of direct user interaction, this lack of information remains a relevant data gap and is discussed further in the discussion section of the study.

Data related to electricity consumption were also directly provided as primary information. However, it underwent allocations as it was not possible to assign exact quantities to the processes. Specifically, to calculate the electricity involved in the production of the DC-LINK within the MK plant, it was decided to refer to consumption data from April to August 2023 (129,589 kWh), considered representative, in consistency with primary information. After normalisation over the total amount of DC-LINK produced in that period (n° 20861), the amount of electricity consumed to produce one DC-LINK is estimated by the company as 6.21 kWh/pcs. The electricity consumed by each process was then assigned according to the nominal power of the machinery and the times of usage (Fig. S2 and Table S1). It is emphasised that this allocation does not affect the impact values estimated for the system, as it solely serves to facilitate the graphical representations in Fig. 1. The electricity consumed by the MK system to produce 1 DC-LINK capacitor remains 6.21 kWh/FU regardless of the proposed allocation. The ecoinvent proxy representing the BG medium-voltage power generation scenario was modelled according to the last available data from the International Energy Agency (IEA, 2025). The MK electricity mix was modelled according to the same assumptions, but removing the fossil fraction. The removal is due to a deal existing between MK plant and the energy provider, which supplies only green energy. Information related to the waste produced during the manufacturing phase was obtained as primary data. More details are reported in Table S2. The waste generated was assigned to proxy processes drawn from ecoinvent. For materials based on paper, cardboard, polyethene terephthalate (PET), and polypropylene (PP), the model estimated and considered credits associated with waste management (i.e., Waste-to-Energy, WtE). The credit associated with the amounts was calculated by assuming to avoid the production of electricity derived from the MK mix. The electricity mix employed in the models is reported in Table S2 of the ESI. The amount of waste generated by the processes occurring in the BG plant was considered negligible, except for the zinc derived by the metalization phase. Specifically, the whole amount of zinc lost in the spraying step (60 % of the total) is assumed to be recovered. To estimate the credit associated with the recovery, a new process was accordingly modelled on SimaPro, named "*Zinc {GLO}| market for | APOS, U (AP)*".

A nitrogen flow is introduced in the MK Plant and it is used by some of the production processes either for safety reasons, and to improve the capacitor performances. The selected ecoinvent proxy was *Nitrogen, liquid {RER}| market for | APOS, U* and the amount of 0.55 kg/FU was shared by KEMET as primary data. Concerning the transportation phase, each formulation component has been associated with a supplier, one or more means of transportation, and a distance of travel. The distances

Table 1

List containing semifinished-products and materials involved in the system, transportation distances and association with proxy processes drawn from ecoinvent (Wernet et al., 2016) and environmental footprint (EF) databases(European Commission, 2025). The modified processes are accompanied by an asterisk. *ᴾ = packaging material applied for transferring the semi-finished component.

Unit process	Materials	Amount (kg)	Truck Distance (km)	Ship Distance (km)	Proxy	Database
(I)	Aluminium	2.48E-03	2705	/	Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for | APOS, U	ecoinvent
(I)	Zinc	1.59E-02	627	7091	Zinc {GLO}| market for | APOS, U	ecoinvent
(I)	Perfluoroether	6.62E-04	2150	/	Tetrafluoroethylene film, on glass {GLO}| market for | APOS, U	ecoinvent
(I)	Polypropylene	1.10E-01	1722	21262	Polypropylene, granulate {GLO}| market for | APOS, U	ecoinvent
(I)	Polypropylene	1.10E-01	2815	/	Polypropylene, granulate {GLO}| market for | APOS, U	ecoinvent
(I)*ᴾ	Polystyrene	6.69E-03	2815	/	Polystyrene, expandable {GLO}| market for | APOS, U	ecoinvent
(I)*ᴾ	Foam white	3.01E-4	1935	/	Polyethylene, low density, granulate {GLO}| market for | APOS, U	ecoinvent
(I)*ᴾ	Bag	1.95E-3	1200	/	Polyethylene, low density, granulate {GLO}| market for | APOS, U	ecoinvent
(I)*ᴾ	Barrier Bag	2.62E-3	1650	/	Packaging film, low density polyethylene {GLO}| market for | APOS, U	ecoinvent
(I)*ᴾ	Box	1.05E-2	200	/	Corrugated board box {GLO}| market for corrugated board box | APOS, U	ecoinvent
(II)	Polypropylene	1.67E-03	121	/	Polypropylene, granulate {GLO}| market for | APOS, U	ecoinvent
(II)	Polypropylene	2.17E-03	1445	/	Polypropylene, granulate {GLO}| market for | APOS, U	ecoinvent
(III)	Pure Zinc	8.43E-02	1938	/	Zinc concentrate {GLO}| market for | APOS, U	ecoinvent
(III)	Zinc 30 % Tin 70 %	3.46E-02	1938	/	Zinc concentrate {GLO}| market for | APOS, U 30 % and Tin {GLO}| market for | APOS, U 70 %	ecoinvent*
(V)	PET Label	5.12E-2	1252	/	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, U	ecoinvent
(VI)	Oxygen copper, PET	1.96E-01	293	14861	Copper oxide {GLO}| market for | APOS, U	ecoinvent
(VI)	Oxygen-free Copper	1.03E-01	293	14861	Copper concentrate, sulfide ore {GLO}| market for copper concentrate, sulfide ore | APOS, U	ecoinvent
(VI)	Oxygen-free Copper	3.20E-03	293	14861	Copper concentrate, sulfide ore {GLO}| market for copper concentrate, sulfide ore | APOS, U	ecoinvent
(VI)	Pure tin	1.14E-02	2216	17125	Tin {GLO}| market for | APOS, U	ecoinvent
(VI)	Capacitor	2.94E-02	270	14844	Capacitor, electrolyte type, > 2 cm height {GLO}| capacitor production, electrolyte type, > 2 cm height | Cut-off, U	ecoinvent
(VI)	Capacitor, auxiliaries and energy use	2.94E-02	270	14844	Capacitor, auxiliaries and energy use {GLO}| market for | APOS, U	ecoinvent
(VI)	Copper component	2.99E-1	293	14861	Copper oxide {GLO}| market for | APOS, U	ecoinvent
(VI)	Capacitor-components (n°2)	2.94E-2	270	14844	Capacitor, auxilliaries and energy use {GLO}| market for | APOS, U	ecoinvent
(VI)	Concentrate copper compontent	3.20E-3	293	14861	Copper concentrate, sulfide ore {GLO}| market for copper concentrate, sulfide ore | APOS, U	ecoinvent
(VI)	Tin wire	8.43E-2	1938	/	Tin {GLO}| market for | APOS, U	ecoinvent
(VII)	PSS GF 40 %	1.19E-01	244	13381	Polyphenylene sulfide {GLO}| market for | APOS, U 60 % and Glass fibre {GLO}| market for | APOS, U 40 %)	ecoinvent*
(VII)	Glass fibre reinforced plastic	1.65E-03	244	13381	Glass fibre reinforced plastic, polyamide, injection moulded {GLO}| market for | APOS, U	ecoinvent
(VII)	Epoxy resin	3.08E-01	1564	/	Epoxy resin {GLO}| market for epoxy resin | APOS, U	ecoinvent
(IX)	PET label	3.20E-2	1252	/	Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, U	ecoinvent
(IX)	Metal clip	3.20E-4	1327	/	Steel, low-alloyed {GLO}| market for | APOS, U	ecoinvent
(IX)	Bag	1.20E-2	5.2	/	Polyethylene, low density, granulate {GLO}| market for | APOS, U	ecoinvent

travelled between the production site and suppliers were calculated in reference to primary data, by using the EcoTransIT tool (IVE mbH, 2024). Two transportation modes have been identified: ship (sea) and truck (road). The proxy selected to represent the truck refers to a vehicle designed for freight transport with 16–32 tonnes of capacity and a Euro 5 class. The packaging considered in the scope of the study encompasses all raw materials and semi-finished goods entering the production systems. Information regarding the type of packaging (i.e., the material or materials of composition) was provided as primary data or calculated based on primary data. These details were used to assign a proxy database process to the packaging. In the cases in which a proxy was unavailable, a new one was created based on information obtained from the literature. The packaging materials involved in the system are listed in Table S3. No atmospheric emissions occur during the evaluated product systems.

2.3.2. Description of the unit processes

(I) Metalization (BG): The list of raw materials and semi-finished products employed in the metalization step occurring in BG and the respective distances run by trucks and ships and the list of packaging materials are reported in Table 1 and Table S3. The

electricity consumption estimated for this process is 1.80 kWh/FU (Fig. S2, Table S1).

(II) Winding & flattering (MK): The semi-finished material obtained by the metalization of the base polypropylene film is transported from Kjustendil (BG) to Skopje (MK). Then, it is conveyed into the Winding & Flattering process, where 0.12 kWh/FU of electricity is consumed (Table S1). The list of raw materials and semi-finished products employed and the respective distances run by trucks are reported in Table 1.

(III) Masking & spraying (MK): In this process, 0.43 kWh/FU of electricity is consumed (Table S1). The list of raw materials and semi-finished products employed and the respective distances run by trucks are reported in Table 1.

(IV) Element treatment (MK): The comprehensive electricity consumption of the process is 0.91 kWh/FU (Table S1). No additional materials are involved.

(V) Element measurement (MK): This phase is designed to measure electric parameters of the product. It does not imply material consumption, and the electricity consumption of the process is 0.12 kWh/FU (Table S1).

(VI) Soldering (MK): The electricity consumption of the process is 0.39 kWh/FU (Table S1). The list of raw materials and semi-

finished products and the respective distances run by trucks and ships are reported in Table 1. The components of the capacitor R413R333050T0K are produced by external suppliers and are assembled in Anting (CN), with a comprehensive electricity consumption of 41.13 Wh/pcs. The inventory of the R413R333050T0K component was not available at the time of the study, since covered by corporate know-how. For this reason, to avoid a data gap, we merged the ecoinvent processes "Capacitor, electrolyte type, > 2 cm height {GLO}| capacitor production, electrolyte type, > 2 cm height | Cut-off, U″ and "Capacitor, auxiliaries and energy use {GLO}| market for | APOS, U″ as a proxy. The electricity mix associated with the capacitor is constituted by 8 % photovoltaic fraction and 92 % of grid-derived electricity. Accordingly, the electricity consumption reported in the proxy "Capacitor, auxiliaries and energy use {GLO}| market for | APOS, U″, was replaced by the amount communicated as primary data (i.e., 2.80 kWh/kg). No heat flows are involved in the system.

(VII) Resin filling, post & final curing (MK): The electricity consumption of the process is 3.93 kWh/FU (Table S1). The list of raw materials and semi-finished products and the respective distances run by trucks and ships are reported in Table 1.

(VIII) Statistical quality control: The electricity consumption is 0.12 kWh/FU (Table S1). No additional materials are involved in this process.

(IX) End of line: The final product is packed and sent to the market. list of raw materials and semi-finished products and the respective distances run by trucks and ships are reported in Table 1. The electricity consumption of the process is 0.20 kWh/FU (Table S1).

2.3.3. Sensitivity scenarios

The outcomes of the contribution analysis were taken as a reference to elaborate the sensitivity analysis, performed to test the robustness of the model created (Baseline Scenario) and enable identification and quantification of the influence of the main exogenous parameters on the environmental impact of the entire system (Goedkoop et al., 2016). In the case study, according to the Goal and Scope (section 2.2), three objects were identified for the sensitivity investigation: i) the source of the electricity mix consumed by the MK plant (Scenario 1); ii) the renewability grade of the copper and aluminium constituting the main components (Scenario 2); and iii) the mix of the electricity consumed to produce the copper-based components and the plastic case. Within the context of this study, the three sensitivity scenarios presented aim to highlight the contribution of flows that prove to be most relevant for the developed model, as well as to demonstrate the actual influence of aspects that are currently of great interest in the field of industrial process sustainability—namely, the source of energy (Ciacci and Passarini, 2020; Rihner et al., 2025) used and the benefits associated with the use of secondary materials as substitutes for virgin materials (Korkmaz et al., 2024; Schwartz et al., 2024).

2.3.3.1. Scenario 1.

The electricity consumed by the MK plant, in the Baseline Scenario, is entirely produced from renewable sources. Accordingly, to valorise the influence of the choice, it was decided to model a sensitivity scenario assuming the replacement of the renewable electricity flow with that derived from the national MK grid (approximately 70 % of which is fossil-sourced, Table S2).

2.3.3.2. Scenario 2.

The Baseline Scenario conservatively assumes that the whole amount of raw materials and components constituting the DC-LINK are drawn 100 % from virgin resources (no recycled content). However, since the automotive sector is exploring the opportunity of introducing higher amounts of secondary material in the final product, to adhere to circularity principles, a second scenario was modelled in accordance with the company, assuming that 45 % of the copper and 50

% of aluminium derive from secondary sources. This choice allows the determination of the environmental savings when shifting from primary to secondary materials.

However, primary information related to secondary copper and aluminium was not available and, for this reason, it was decided to rely on secondary sources in order to obtain sufficient information to model Scenario 2. In particular, Zhang et al. (2021) provided a detailed inventory related to secondary copper production (Table S4 of the ESI), which has been accordingly modelled on the SimaPro software. No specific data on secondary aluminium production were found in the literature. For this reason, it was considered reasonable to assume that the production process of secondary aluminium is similar to that of primary aluminium. Consequently, the process was modelled by removing the share of primary aluminium input from the ecoinvent proxy "*Aluminium, primary, ingot {IAI Area, EU27 & EFTA}| market for | APOS, U*".

2.3.3.3. Scenario 3.

The electricity consumed by the Anting plant and related Chinese suppliers to produce the copper-based components and the Plastic Case derive from the national grid, and it is produced according to the standard mix Table S2 of the ESI. In this Scenario, the whole amount of electricity consumed for the mentioned purpose is assumed to be entirely produced by a photovoltaic plant located close to the factory.

2.4. Life cycle impact assessment

The LCIA phase consists of a quantitative determination of the potential environmental impacts resulting from the system under scrutiny (ISO, 2006a). To this aim, environmental mechanisms and cause-effect characterization models are applied to relate the LCI results to impact category indicators. The ReCiPe 2016 method (v. 1.08) (Huijbregts et al., 2017) was adopted for the evaluation. The hierarchical perspective was set as the default perspective, with this being the preferred choice in previous LCA applications (Jiang et al., 2021). The LCIA allowed the identification of the main contributing processes to the observed impacts, which were further analysed in sensitivity analysis as following described. ReCiPe 2016 provides a comprehensive estimation of the interactions between the system under scrutiny and the environment for a set of 18 midpoint categories, namely: CC, Climate Change (kg CO_2 eq); OD, Stratospheric ozone depletion (kg CFC11 eq); IR, Ionizing radiation (kBq Co-60 eq); POFh, Ozone formation-human health (kg NO_x eq); PMF, Fine particulate matter formation (kg PM 2.5 eq); POFe, Ozone formation Terrestrial ecosystems kg NO_x eq); TA, Terrestrial acidification (kg SO_2 eq); FE, Freshwater eutrophic. (kg P eq); MEP, Marine eutrophic. (kg N eq); TET, Terrestrial ecotoxicity (kg 1, 4-DCB eq); FET, Freshwater ecotoxicity (kg 1,4-DCB eq); MET, Marine ecotoxicity (kg 1,4-DCB eq); HTc, Human carcinogenic toxicity (kg 1, 4-DCB eq); HTnc, Human non-carcinogenic toxicity (kg 1,4-DCB eq); LO, Land occupation (m^2a crop eq); MRD, Mineral resource depletion (kg Cu eq); FD, Fossil depletion (kg oil eq); WD, Water depletion (m^3). ReCiPe 2016 is one of the most widely used methods in LCA, appearing in 418 papers from 2018 to date (Scopus, 2025). It allows the investigation of a wide spectrum of environmental categories and avoids the problem of burden shifting and the greenwashing phenomenon. Although the method allows for the calculation of impact values at both midpoint and endpoint levels, most studies tend to focus on the midpoint perspective. A search on Scopus, for instance, returns approximately 3959 results for the query "ReCiPe 2016 midpoint", compared to 2950 results for "ReCiPe 2016 endpoint". While this is a rough estimate, it nevertheless highlights a tendency to limit assessments to the midpoint level. One of the main reasons justifying the higher employment of this approach includes the leading of higher levels of uncertainty compared to midpoint indicators, due to the inclusion of subjective factors in their estimation (Bare et al., 2000; Schumacher, 2025). In order to validate

the methodological choice, also in line with ISO 14044, which recommends performing sensitivity checks on significant inputs, outputs, and methodological choices (e.g., the selected LCIA method) to assess result uncertainty, we also simulated the calculation using the CML v3.10 method. The results are reported in Table S10 of the ESI, accompanied by a brief discussion. The comparison shows that the CC category is subject to a slight variation in the result (i.e., 3 %), while larger differences are observed for the other categories. Additionally, the choice was influenced by the existence of previous publications that had employed the same method (Alaviitala and Mattila, 2015; Jiang et al., 2021).

2.5. Uncertainty analysis

Uncertainty evaluation and propagation were performed at midpoint level by employing the pedigree data quality matrix (Weidema and Wesnæs, 1996). A Monte Carlo simulation with 10,000 runs was also carried out to determine how the intrinsic variability of the parameters and the quality of the data used in the modelling may affect the outcomes. The scores selected for compiling the pedigree matrix are reported in Table S5 of the ESI. In general, as discussed above, the LCA model for the system under scrutiny was entered with primary data provided by the company owner of the system. As such, data from the Baseline Scenario can be considered very reliable and fulfil the highest scores for data quality criteria commonly applied in LCA, such as, for instance, geographical, temporal, and technological representativeness.

3. Results

3.1. Baseline scenario results

The environmental impacts for the Baseline Scenario (Table S6 and Fig. 2) highlight a clear hotspot in the materials constituting the DC-LINK. Materials contribute from a minimum of 57.8 % (LO) to a maximum of 99.9 % (HTc). Electricity, derived from the BG national mix for the metalization process (I) and from renewable sources in the MK plant, contributes from a minimum of 0.001 % (HTc) to a maximum of 38.6 % (LO). However, LO can be considered an exception since, by excluding this category, electricity never overcomes the contribution of 4 % to the overall impact in all the remaining categories. The LO values are influenced by the biomass cultivation phase (Wernet et al., 2016). Regarding the remaining flows involved in the system, N_2 maximum contribution is observed in the IR category (9.7 %), and waste maximum contribution appears in CC (5.0 %). Transportation always impacts less than 5.3 % of all the examined categories. The outcomes suggest investigating in detail the material composition of the DC-LINK, in order to determine which components are mainly responsible for the impact observed. The CC hotspot analysis related to the components constituting the DC-LINK revealed that the copper-based components introduced in step VIII resulted to be the main contributor to the CC impacts

(46.9 %), but also to OD, IR, POFh, PMF, POFe, TA, FE, ME, TET, FET, MET, HTc, HTnc, LO, MRD and FD. The CC category is also affected by epoxy resin (22.0 %), along with the remaining materials in descending order of influence. A detailed discussion of the contribution of each involved material is reported in section 3.2.2. The tetrafluoroethylene film proved to be a hotspot in the OD category (25.9 %) due to the involvement in its supply chain of the emission of chlorofluorocarbons (i.e., chlorodifluoromethane, dichlorodifluoromethane, dichlorofluoro methane, trichlorofluoro methane and trifluoro methane), specifically in the production of chlorodifluoromethane (Wernet et al., 2016). Additionally, another noteworthy hotspot, but only for the FD category (21.7 %), was polypropylene, due to the rely on fossil resources of its supply chain. Both materials were involved in Phase I of the process (Metalization). In addition, it is emphasised that the marginal contribution of electricity can be due to the absence of the fossil fraction in the considered mix. This aspect will be explored further in the sensitivity analysis.

3.2. Sensitivity analysis

In this section, the sensitivity analysis is applied to determine the influence of the MK renewable mix (Scenario 1), the employment of percentages of secondary materials (Scenario 2), and the role of the electricity mix employed in the copper-based components and in the Plastic Case (Scenario 3) in the estimation of the environmental impacts. Fig. 3 shows the CC comparison between the four scenarios examined. CC was chosen as the reference category because the carbon footprint is a widely recognised and well-understood indicator globally. It is easily applicable for researchers, companies, and authorities to evaluate the
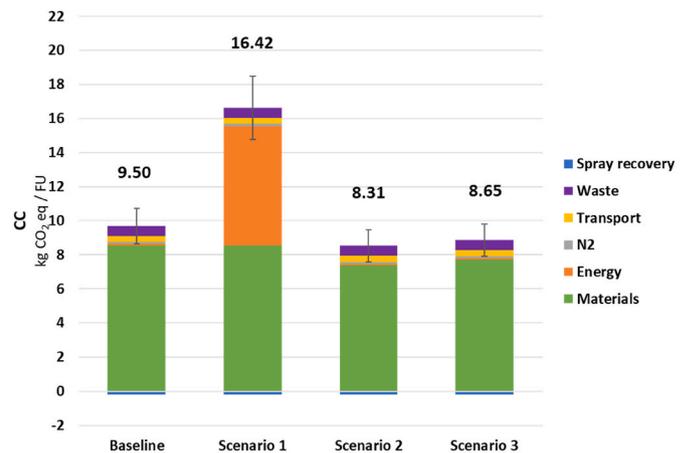
Fig. 3. CC comparison between the three examined scenarios.
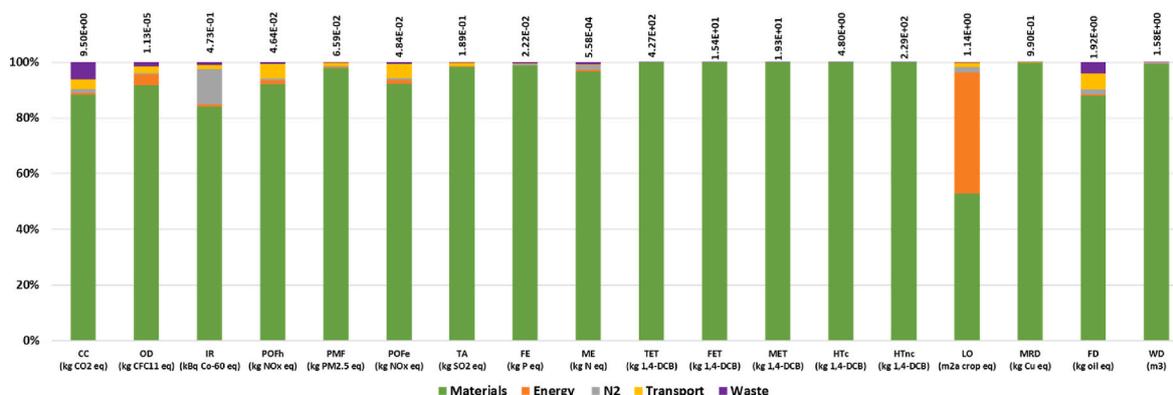
Fig. 2. Life Cycle Impact Assessment of Baseline Scenario according to ReCiPe 2016 methodology.

carbon intensity of products, processes, and activities. Based on the average impact values, Scenario 2 emerges as the preferred option compared to the Baseline, Scenario 3, and particularly Scenario 1. The significant difference between Baseline Scenario and Scenario 1 (+73 % for CC) highlights a significant role of the electricity mix. In the existing context, where electricity already derives from renewable sources, material contribution (green bars) remains the most interesting to be analysed. More details are reported in the following paragraphs. The uncertainty associated with the result reported in Fig. 3 does not allow to predict with certainty which is the best option between Scenario Baseline, Scenario 2 and Scenario 3.

3.2.1. Scenario 1

In Scenario 1 a new impact assessment is provided by assuming that the electricity consumed is generated exclusively from the national mix. Fig. 4 and Table S7 report the estimation in a relative form. The CC overall impact of the system increases by 70 % when the national MK is considered in the model and the electricity contribution shifts from 0.8 % of the Baseline Scenario to 41.2 % of Scenario 1. The contribution of electricity increases for all the examined categories by an average of +20 %, highlighting the effectiveness of the company's choice in using a renewable mix.

3.2.2. Scenario 2

CC category was arbitrarily selected to graphically depict the impacts but it must be precise that each environmental category presents a proper hotspot analysis which is not always consistent with the one observed for CC.

Scenario 2 is developed in accordance with KEMET, assuming to replace the 50 % of the aluminium content in the wire and the 45 % of copper content in the copper-based components. In comparison with the Baseline Scenario, the CC reduction observed for Scenario 2 is 13.8 %, highlighting the potential role of secondary material employment in the reduction of the environmental impacts (Fig. 5 and Table S8).

3.2.3. Scenario 3

In Scenario 3 the electricity consumed by the Anting plant and the Chinese external suppliers to produce the copper-based components and the Plastic Case is assumed to be sourced entirely from a photovoltaic plant. The replacement of the electricity source may improve the CC performances observed for the final product, in particular by reducing the impact of the Plastic Case from 0.97 to 0.70 kg CO_2 eq/FU and of the component constituted by copper and PET from 4.01 to 3.45 kg CO_2 eq/FU. The whole CC impact is decreased by 9.8 % by shifting from Baseline Scenario to Scenario 3. Table S9 summarizes the impacts estimated for this Scenario.

4. Discussion

The LCIA results showed that the system's impacts are highly influenced by the material composition of the DC-LINK and, consequently, by the related production processes and supply chains. The assessment is also affected by the company's decision to partially reduce its reliance on electricity from fossil fuels; a strategy that, at least in the climate change category, highlights the relative contribution of other flows.

The difference in impact between the base scenario and the baseline does not exempt the energy flows from responsibility but rather confirms the relevance of policies promoting the use of renewable electricity. The same, concerning what was observed in the Scenario 3 modelling, by increasing the renewable share of the Anting factory and the Chinese external suppliers who produce the copper-based components, environmental advantages might be achieved.

Focusing on the material components, where intervention may prove more complex due to the wide range of materials and suppliers involved, it was possible to identify a particularly significant contribution from certain substances, such as copper and resin. Although primary data were not available for the simulation run in Scenario 2, the partial substitution of virgin materials with secondary ones, particularly regarding the copper component, proved effective in reducing environmental impacts. This is especially true in the case of secondary materials since the replacement of virgin aluminium and copper with secondary materials appeared to be potentially advantageous, but the uncertainty associated with the results does not allow us to provide a definitive estimation. As an illustrative example, the observed 13.9 % reduction in climate change impacts would correspond to a potential saving of approximately 1.19 kg CO_2 eq per unit. If the total annual production of DC-LINK units by the company is considered, assuming a production volume of 20,000 units (a realistic estimate for the context under analysis), this would translate into an overall reduction of about 23.8 tonnes of CO_2 eq.

The contribution of materials to the overall impact assessment further highlights the importance of using primary data to accurately determine both the specific type and quantity of flows involved, which significantly influence the resulting impact values. In this regard, the availability of information on the presence and concentration of substances potentially harmful to the environment or to human health in products is often linked to the existence of regulations that mandate disclosure or set specific thresholds. In the absence of such regulation, this information is typically unavailable from standard inventory datasets. This is the case in the present study, where the potential presence and concentration of PFAS in capacitors remain unknown. We acknowledge this data gap as a limitation of the study. However, even assuming the presence of these substances in the product, with their consequent emissions and interaction with human beings and the ecosystem, remains difficult to address the impact in LCA, as
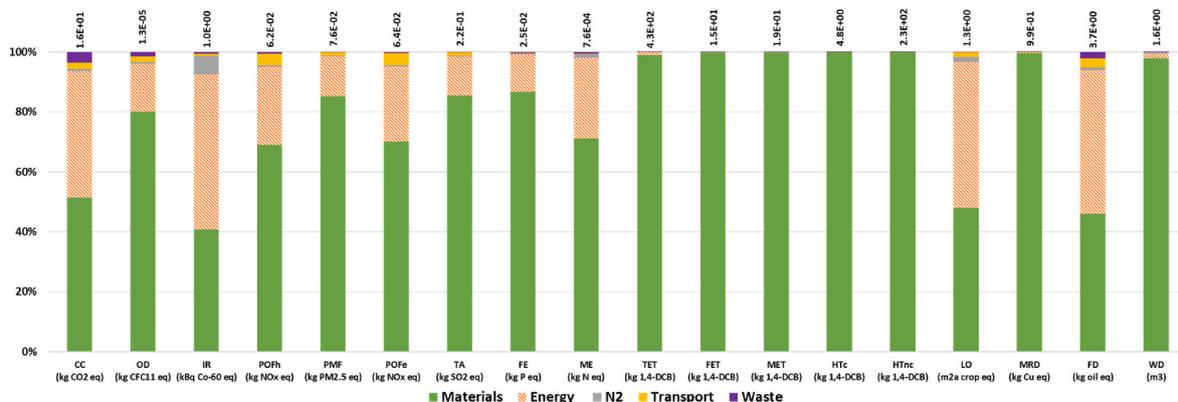

Fig. 4. Environmental Impact Assessment of Scenario 1. Contribution analysis.
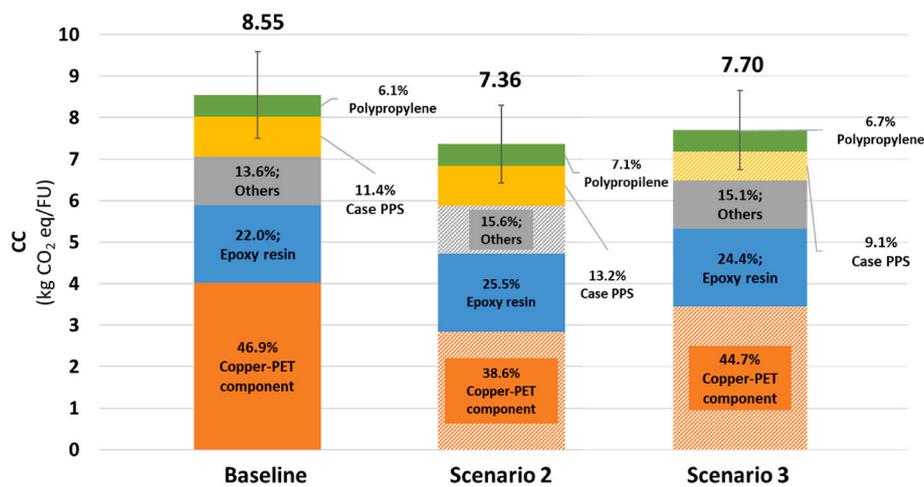
Fig. 5. Impact on CC and contribution analysis of Baseline Scenario, Scenario 2 and Scenario 3.

characterisation factors for human toxicity are not yet available. On the other hand, freshwater ecotoxicity characterisation factors for certain PFAS have recently been published (Aggarwal, 2025), enabling at least partial consideration of these impacts.

Concerning the general composition, in the absence of primary data, it is possible to extract information from patents, as also suggested by Spreafico et al. (2024). However, this option is suggested when the level of detail provided in such documents is sufficiently transparent with regard to the key information needed to build an LCA inventory (i.e., specific material composition of the device, energy consumption of operational phases, environmental emissions, and transport burdens). In this context, the interaction with companies should also be considered an opportunity to share expertise and only as a source of data. The comparability of the obtained results with other studies is difficult to assess due to the variety of applications existing for capacitors. Cossutta et al. (2020) studied the impacts of a rack containing five super-capacitors used to power the car door mirror as part of a photovoltaic-powered assembly. Clearly, the model was elaborated for devices providing functions very different with respect to those dis-cussed in the presented study. However, the hotspot analysis identified a contribution of the energy consumed in the production phase contrib-utes between 20 and 48 % of CC impacts. Even in our case, the energy contribution resulted extremely different between Baseline Scenario and Scenario 1 (from 0.8 % to 42 %), due to the effect of the electricity mix employed. In the optimistic case of the baseline scenario, the contribu-tion is significantly lower than the 20 % observed in the work by Cos-sutta and colleagues. Nevertheless, this reinforces the effectiveness of adopting a mix with a reduced or near-zero fossil content (Arfelli et al., 2023). Moletti et al. (2021) provided an interesting study related to two capacitors employed in the automotive field. In addition, the impact values are reported in the final result only in a relative form, probably due to confidentiality reasons. De Sio et al. (2025, in a recent study, provided an LCA analysis of a prototype battery pack. Excluding the use phase, which has been included in his evaluation, he found out that about 70 % of the CC impacts are due to the raw material employment and the 11 % to energy consumed in the operational phases. Jiang et al. (2021) conducted a detailed hotspot analysis, identifying a marginal contribution of the transport phase for all 18 categories examined, confirming our findings. In fact, the main impacts are associated with material usage and the manufacturing phase. Cossutta et al. (2020) remarked on the potential environmental savings associated with appropriate EoL management of the capacitors. In particular, they estimated a potential impact reduction of the CC impact in the range 8–30 %, according to the type of capacitor. This outcome encourages eco-design practices and also the collection of site-specific information that could enable such an estimation within the context of the proposed

study. Regardless of data availability, which determined the exclusion of use-phase and EoL management in this study, it is well acknowledged that the automotive sector is increasingly aligning with eco-design principles, aiming to enhance the recyclability of EoL vehicle compo-nents (Istriț;eanu et al., 2024; Moita et al., 2024). We intended to pro-vide an overview of the recycling potentials in Europe for the main materials involved in the case study; however, the availability of current state of practices average data, being them from national or continental scale, proved to be very challenging, and in the majority of cases, the available reference resulted in being outdated. In particular, in Europe, about 30 % of EoL copper is currently recycled to date (Circular Econ-omy Network & ENEA, 2024), while globally the total estimated recy-cling rate can be considered higher than 50 % (UNEP, 2011). The percentage seems to be even higher for steel (i.e., 56 %) (EuRICH, 2020). In the automotive sector, >85 % of post-consumer aluminium scrap and essentially all manufacturing aluminium scrap (new scrap) were already considered to be recycled as early as the early 2000s (Tuler and Scott-Taggart, 2001). These estimations are consistent with the report Recycling Rates of Metals – A Status Report, provided by UNEP (2011), which reports global recycling rates >50 %. The same report indicates recycling rates >50 % also for tin and zinc, even if no more reliable data providing average estimations have been found. The recycling potential of plastic material is also scarcely investigated. For propylene, it is estimated that only 1 % of the amount is currently recycled (Alsabri et al., 2022), while no reliable references have been identified for polystyrene. Detailed information could not be found for either glass fibre or epoxy resins; however, both materials are beginning to receive increasing attention (Memon et al., 2022; Y. Zhang et al., 2021). In particular, the latter, being thermosetting, are especially difficult to recycle (S. Zhang et al., 2024).

The results obtained in the proposed study, along with those from a series of other works identified in the literature, encourage the sector to reduce the consumption of fossil-based energy and to prioritise the possibility of introducing secondary materials into the system. This consideration can be extended to the entire automotive sector, high-lighting the importance of transparency in inventories within the in-dustry. Such transparency enables the accurate calculation of environmental impacts and, consequently, guides policies and research towards the use of, for example, secondary materials, in line with Eco-design regulations (European Parliament and The Council of the Euro-pean Union, 2024). This could indirectly stimulate the development of technologies aimed at recovering these materials and encourage com-panies to seek suppliers and stakeholders willing to introduce these materials into the market. Regarding energy, the benefits associated with the use of renewable energy could incentivize companies to reduce the fossil-based fraction of their energy mix.

4.1. Uncertainty analysis

The uncertainty associated with the CC results reported in section 3.3.1.2 does not allow for establishing with certainty which is the best option between Baseline Scenario, Scenario 2 and Scenario 3. The estimated uncertainty depends on the quality of the inventory data and on the LCIA method applied. Regarding the quality of the data used to generate the foreground model, as detailed in section 2.5, it is expected that the only flows worth targeting for a potential reduction in uncertainty are the energy consumed at the MK plant and waste management. In the former case, a direct monitoring of energy consumption should be implemented, as current figures are based on normalised values per unit produced over a period deemed representative. To improve data concerning waste management during production phases, more specific information on the actual treatment of these materials could help reduce uncertainty. However, given the limited contribution of these two flow categories, the resulting reduction in overall uncertainty may not be substantial. With regard to background data, a further improvement in data quality could be anticipated if the representativeness of database datasets is enhanced in the future. Finally, primary data could also be used to model secondary aluminium and copper.

Concerning methodological uncertainty, although the cause-effect mechanisms associated with the various impact categories are generally affected by intrinsic uncertainty, CC is considered one of the most robust and least uncertain categories (European Commission, 2021; Hauschild et al., 2018; Rossi et al., 2024). Therefore, also from this perspective, we anticipate that the overall uncertainty cannot be reduced beyond a certain threshold, and that the inability to establish an absolute preference mainly stems from the closeness of the impact values obtained. However, our first recommendation remains to rely on primary data obtained by suppliers to improve the model and achieve more accurate estimations. This measure should generally improve data quality, reducing the associated uncertainty.

5. Conclusions

The electrification of the automotive sector is driving the continuous development of new electronic products aimed at enhancing vehicle performance and, more broadly, advancing the electronics industry. This transition, driven by the need to reduce the environmental impact of transportation and related sectors, entails the use of raw materials and involves processes whose environmental impact must be carefully assessed. This is essential to accurately determine the actual savings in terms of emissions and pollution.

To bridge the existing gap in the literature regarding this sector, this study applied the LCA methodology to estimate the potential environmental impact associated with a capacitor (namely, DC-LINK), utilizing primary data from a leading company in the field. The results highlighted a significant contribution of raw materials, which, across the 18 impact categories analysed, never accounted for less than 57 % (reaching 88.2 % for climate change). However, the influence of energy consumption was found to be particularly low due to the production site relying exclusively on renewable energy. Consistently, in Scenario 2, assuming the use of a more traditional energy mix (70 % from fossil sources), the contribution of energy consumption increased from an average of 3 % to an average of 18 % (42 % for climate change).

The sensitivity analysis applied to materials showed that introducing a percentage of secondary aluminium and copper into the final product, replacing virgin materials, resulted in an average savings of 40 % (−12 % in climate change impact), emphasising the importance of adopting circular economy principles. The primary data used in the study reinforces the relevance of the results, and the main limitation could be derived from the information which has not been possible to draw from the foreground system (i.e., secondary material manufacturing and supply). Accordingly, future developments of this work should focus on the collection of primary data, also related to these components. This study represents a step forward in understanding the environmental impact and the production systems of materials such as capacitors, whose production and usage are increasing significantly. Consistently, LCA is confirmed to be a versatile and reliable tool for characterising the environmental burdens and benefits associated with an industrial system, supporting strategic planning and policies aimed at achieving sustainable production and consumption patterns.

CRediT authorship contribution statement

Francesco Arfelli: Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniele Cespi:** Writing – original draft, Validation, Project administration, Funding acquisition, Conceptualization. **Fabio Codecà:** Writing – review & editing, Validation, Resources, Data curation, Conceptualization. **Fabrizio Passarini:** Writing – review & editing, Validation, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table of acronyms

BG	Bulgary	LCIA	Life cycle impact assessment
CC	Climate Change	LO	Land Occupation
ESI	Electronic Supporting Material	ME	Marine Eutrophication
EoL	End of life	MET	Marine Ecotoxicity
FD	Fossil Depletion	MRD	Mineral Resources Depletion
FE	Freshwater Eutrophication	MK	North Macedonia
FET	Freshwater Ecotoxicity	OD	Ozone depletion potential
FU	Functional unit	PMF	Particulate Matter Formation
GHG	Greenhouse gasses	POFe	Photochemical Oxidant Formation (human health)
HT	Human Toxicity (carcinogenic)	POFh	Photochemical Oxidant Formation (ecosystem)
HTnc	Human Toxicity (non carcinogenic)	TA	Terrestrial Acidification
IR	Ionizing radiation potential	TET	Terrestrial Ecotoxicity
LCA	Life cycle assessment	USD	United States Dollar
LCI	Life cycle inventory	WD	Water Depletion

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2025.146486.

Data availability

All the data have been reported in the Electronic Suporting Information.

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