# Life cycle assessment of a domestic induction hob: electronic boards

Daniel Elduque [a,1], Carlos Javierre [a], Carmelo Pina [b], Eduardo Martínez [c], Emilio Jiménez [d]

[a] i+ Vehivial, University of Zaragoza, C/ María de Luna,3 - 50018 Zaragoza, Aragón, Spain

[b] BSH Electrodomésticos España, S.A., Avda de la Industria, 49 - 50016 Zaragoza, Aragón, Spain

[c] Department of Mechanical Engineering, University of La Rioja, C/Luis de Ulloa, 20 - 26004 Logroño, La Rioja, Spain.

[d] Department of Electrical Engineering, University of La Rioja, C/Luis de Ulloa, 20 - 26004 Logroño, La Rioja, Spain.

## ABSTRACT

This study analyzes the environmental performance of the electronic boards used in the current generation of induction hob designed and assembled in Spain. A Life Cycle Assessment (LCA) has been performed, defining the functional unit as the electronic boards used in an induction cooktop with 4 hobs and 7.2 kW of nominal power. The electronic boards are two power electronic boards (ELIN PCBAs -Printed Circuit Board Assembly-), and one touch control electronic board (Touch Control PCBA). Each one has been thoroughly analyzed having into account every electronic component. The software used to create the LCA model was SimaPro 7.3.3, using two databases Ecoinvent v2.2 and Chalmers CPM LCA Database.

The most relevant environmental impact in every category is caused by the two ELIN PCBAs. Touch Control PCBA has significant impact in Ozone Layer Depletion, although its value is four times lower than the emissions of one ELIN PCBA. Both ELIN PCBAs show similar environmental impact distribution. Components create between 70 and 85% of the total impact in most categories. Touch Control PCBA has a different environmental impact distribution from both ELIN PCBA.

This analysis of the environmental impact of the ELIN PCBAs and the Touch Control PCBA used in an induction hob has revealed that there are several clear areas for improvement, such as reducing the environmental impact of the components and improving its end-of-life treatment.

[1] * Corresponding author. Tel.: +34 876555211; fax: +34 976761861

E-mail address: delduque@unizar.es

**Keywords:** Electronic boards, induction hob, LCA

# 1 Introduction

During the last decade, the design of electronic products in Europe has been strongly influenced by new legislation. In order to lower environmental impact, the European Union has created several laws devoted to reduce the use of hazardous substances, known as RoHS (2002/95/EC) (European Parliament, 2003); the REACH (Regulation, Evaluation, Authorisation and Restriction of Chemicals) regulation to control chemicals (European Parliament, 2006); the WEEE (Waste Electrical and Electronic Equipment) directive enhances the recycling of electric and electronic equipment (European Parliament, 2012), and also introduced the ecodesign in energy-using products (EuP) (European Parliament, 2005) and energy related products (ErP) (European Parliament, 2009).

Induction hobs are affected by all these laws and are included in preparatory study of Energy-using Products, Lot 23, which focuses on domestic and commercial hobs and grills. That study shows that induction is the most efficient way of cooking commercially available. This product has an important volume in the EU market, a significant environmental impact, and great potential for improvement (BIO Intelligence Service and ERA Technology, 2011). EuP and ErP legislation has mainly focused on energy consumption, which is the main cause of environmental impact in this kind of products, and have introduced limits on standby consumption.

This study analyzes the environmental performance of the electronic boards used in the current generation of induction hob. The Spanish company which designs and assembles this induction hob sells more than half a million induction hobs per year in over 75 countries, and it is leader in Spanish home appliances sector.

A LCA allows us to identify the main types on environmental impact throughout the life cycle and find areas that can be improved in order to reduce the environmental impact. LCA has been applied to a wide range of products and services from mussel cultivation (Lozano et al., 2010) to wind turbines (Martínez et al., 2009; Martínez et al., 2010), including food packages (Fernández et al., 2013), supply chain design (Longo, 2012; Bruzzone et al, 2009) or urban buses (García-Sánchez et al., 2012). Within the existing literature of Life Cycle Assessment studies, there are several based on electronic products, like TV sets (Song et al., 2012) (Hischier & Baudin, 2010) (Aoe, 2007), monitors (Kim et al., 2001), telecommunications exchange (Andrae, et al., 2000), personal computers (Duan et al., 2009) cooker hoods (Bevilacqua et al., 2010). Recently Sikdar performed Life Cycle Assesment studies showing a detailed inventory of the electronic components used in Wifi Access points and Ethernet switches (Sikdar, 2011) (Sikdar, 2013).. Andrae and Andersen (2010) also studied the consistency of LCA of laptops, PC, mobile phones and TV sets.

Other analysis focused on the environmental impact of printed wiring boards (PWB) (Lam et al., 2011) and also the end-of-life of PCB (Wang & Gaustad, 2012; Kasper et al., 2011; Duan et al., 2011) and also the recycling under WEEE legislation (Yamane et al., 2011). Herrmann et al. (2001) compared epoxy (FR4) based PWB against ceramic ones.

Several studies have analyzed the impact of individual components, like RFID antennas (Kantha et al., 2012), integrated circuits (Taiariol et al., 2001; Andrae, et al., 2004; Andrae & Andersen, 2011) and diverse semiconductor devices (Boyd, 2012). Andrae et al. (2005) also analyzed a digital system telephone having into account its individual components.

Recently, a standard to carry out LCA of electronic product was published (ETSI, 2011). focusing on ICT Equipment, Networks and Services. This Technical Specification has been used as a guide.

This paper focuses on the environmental impact of the electronic boards used in induction hobs, a high technology product with hundreds of different electronic components. The electronic boards are two power electronic ELIN(ELectronic INduction) PCBA (Printed Circuit Board Assembly), called ELIN Right PCBA and ELIN Left PCBA (ELINRPCBA and ELINLPCBA) and one Touch Control PCBA (TCPCBA). Each one has been thoroughly analyzed having into account every electronic component.

Induction heating technology is not a recent development, as it is currently used in a wide range of applications, like cooking (Acero et al., 2008), welding (de Santana et al., 2006), sealing (Babini et al., 2003) and melting, hardening or brazing of metals (Fujita & Akagi, 1996; Kristoffersen & Vomacka, 2001; Noda et al., 1997).

The use of induction technology in cooking has been commercially available since the early 1990s. An induction hob uses cutting-edge electronic technology, employing high frequencies to generate an oscillating magnetic field, which heats ferromagnetic vessels through two effects, Foucault currents and magnetic hysteresis. Each burner has a spiral coil, known as inductor, which is operated from 20 kHz to 100 kHz, higher than audible range, and up to 5.5kW (Acero et al., 2008). These currents are supplied by IGBT half-bridge series resonant inverter controlled. The resonant load is composed of the inductor wiring, the vessel, and a resonant capacitor.

The aim of this paper is to quantify the environmental impact of the ELINRPCBA, ELINLPCBA and TCPCBA used in an induction hob which belong to a representative example of an induction hob produced in Europe, by applying the ISO 14040 and 14044 standards of Life Cycle Assessment (ISO, 2006a) (ISO, 2006b).

This paper analyzes a product that is installed in several million homes worldwide, having into account each individual component, allowing us to understand its environmental behavior and how each component affects the overall result.

# 2 Materials and methods

## 2.1 Goal and scope definition

The LCA models of ELINRPCBA, ELINLPCBA and TCPCBA have been developed with the help of producer´s electronic design team. This company has provided samples of the PCBAs and components and has also helped contacting with some of the main product providers.

The main objective of this Life Cycle Assessment is to identify the main environmental impacts of the electronic components in an induction hob. This study has focused on analyzing the electronic components used in the current induction hob generation that is commercialized. This product is completely developed and assembled in Spain. The research and development of this product has been carried out for 30 years, and currently the fifth generation of induction hobs is being sold.

Individual electronic components are produced in a wide range of countries by several suppliers: the ELINPCBAs printed wiring boards are produced in China and assembled in Zaragoza, whereas the TCPCBA is produced in Germany. All these components are finally assembled in the Montaña factory (Zaragoza, Spain) to create the complete induction hob.

## 2.2 Functional unit

The functional unit has been defined as the ELINRPCBA, ELINLPCBA and TCPCBA used in a cooktop with 4 induction hobs. This induction ceramic hob has a width of 60 cm, and 7200 watts of power at a voltage of 220-240 volts and a frequency between 50 and 60 Hertz. This induction hob is currently sold worldwide and the functional unit is used in a wide range of models. The main characteristic of this induction hob is the presence of 4 cooking zones, each one with variable 17-stage power settings. The dimensions, rated power and maximum power of each hob are shown in Table 1.

The main features of the PCBAs are automatic pan recognition, timer with buzzer, heat indicator for each zone, childproof lock, safety time switch off, small cookware detection and anti overflow protection.

## 2.3 System boundaries

As the goal of this paper is to analyze the environmental impact of the PCBAs, within the limits of the LCA model fall the production of the electronic components and PWBs, the transportation to Spain, the assembly, use stage and the end-of-life of the product (see Figure 1). Outside the limits of the system fall the distribution to consumers. Although the aim of this study is to analyze the environmental impact of the PCBAs, following ETSI guidelines, the use phase have been included inside the limits of this study.

## 2.4 Inventory data and cut-off criteria

Each PCBA consists of a PWB and several hundred electronic components. Those components have a wide range of functions: resistors, inductances, capacitors, transistors, microcontrollers... There are two mounting technologies for those components: SMD (Surface-mount device) in which the components are placed onto the PCB´s surface, and Through-hole, when leads are inserted into holes drilled in the PCB.

This study has been performed with internal data from the manufacturer. A detailed list of every electronic component was provided, and each one has been identified and weighed. The weighting process was performed with a 1 milligram precision balance, gathering 10 components each time to increase the precision. Transport processes have been calculated using data provided by the producer and their providers. The cut-off criterion used has been the weight of the different components. Minor differences were found between the weight of the whole PCBA with soldered components and the weight of individual components. Also in bigger components such as inductor ring cores (>100 grams), small weight differences were found caused by manufacturing tolerances. The differences between individual weighting and the global weighting of the PCBAs are less than 1%.

The use of Ecoinvent´s soldering process means that the solder content used in this LCA is actually higher that the content used in the real assembly process, generating a 0.5% increase in total weight, meaning that the environmental impact is slightly overestimated. A sensitivity analysis have been performed by checking the influence of the increased solder content caused by using Ecoinvent soldering process, founding that the differences are not relevant

An induction hob has two different types of ELINPCBA, one with its own power supply, also called ELINLPCBA (ELectronic INduction PCBA), which is placed on the left, and the other one, placed on the right, the ELINRPCBA, which is powered by ELINLPCBA (Figure 2). These are controlled by means of the TCPCBA, which communicates with both ELINPCBA sending power level orders to each burner. Both ELINPCBAs send the state of each hob to the TCPCBA.

The ELINLPCBA is composed of an interference filter, which ensures the system has electromagnetic compatibility, a power supply, a rectifier, a power inverter, a control unit and a cooling element. It powers the fan, the TCPCBA and the ELINRPCBA. The ELINRPCBA is similar to the ELINLPCBA, but it does not have the power supply. Each ELINPCBA has two fusible connections that protect the PWB and its components (Figure 3).

There are two NTC (Negative Temperature Coefficient) thermistors in each ELINPCBA which allow to measure the temperature of the IGBT (Insulated-Gate Bipolar Transistor). If maximum temperature is reached, 135ºC, the electronic cuts-off the power supply

The TCPCBA commands the ELINPCBAs which regulates the power of each induction burner by means of the IGBTs. The ELINPCBAs sends to the TCPCBA information about the presence of the pan and the state of the burner. In case of an error, it is shown in the TCPCBA.

The energy from the AC power is rectified by a full bridge of diodes and filtered to create a direct current bus. After that, a resonant inverter generates a variable frequency current.

Life Cycle Inventory (LCI) has been developed using two databases Ecoinvent v2.2 (Frischknecht et al., 2005) and Chalmers CPM LCA Database (Chalmers University of Technology, 2012). Ecoinvent is a widely-used database available in SimaPro. Chalmers CPM database was developed by the Swedish Life Cycle Center and includes over 700 Life Cycle Inventories datasets. These electronic datasets have been used for components which are not characterized in Ecoinvent v2.2 database: relays and resonators. Fabrication processes of the electronic components are taken from databases, as getting primary data from hundreds of suppliers is not viable.

After classifying and weighting every electronic component, those are linked to the existing components in both Ecoinvent and CPM databases with the help of the producer´s electronic design team. The assignation between inventory data and Ecoinvent database has been done following the guides provided by Hischier et al. (2007)

## 2.5 Assumptions

The software used to create the LCA model was SimaPro 7.3.3, developed by Pré Consultants (Goedkoop et al., 2010a).

The LCA has been calculated with CML LEIDEN 2000 methodology (Goedkoop et al., 2010b), in order to obtain midpoint results avoiding subjectivity (Guinée, 2002). The following midpoint impact categories have been used: Abiotic depletion, Acidification, Eutrophication, Global warming (GWP100), Ozone layer depletion (ODP), Human toxicity, Fresh water aquatic ecotoxicity, Marine aquatic ecotoxicity, Terrestrial ecotoxicity and Photochemical oxidation.

The characterization of each electronic component has mainly been obtained from Ecoinvent database and Chalmers CPM LCA database. This means that components with different weights or structures, but with the same electronic function and classification, are included in the same Ecoinvent dataset correlation.

As this product is mainly sold in Europe, an estimation of its end-of-life (see Table 2) has been done using a WEEE plant for electrical and electronic scrap. The Disassembly/Dismantling/Shredding and Recycling facility allocation was done per mass In this plant the PCBAs are shredded. Through-hole capacitors are manually separated and sent to hazardous waste incineration (Hischier & Baudin, 2010). PWB shredded material is sent to magnetic and eddy current separation, where it is assumed that 70% of PWB´s copper is recovered (Guo et al., 2011). and recycled back in a closed loop system into PWB´s copper as there are not significant property reduction in recycled copper. A 23% copper content was assumed for the PWBs The rest of the material is sent to landfill. Further recycling is not considered as each PCBA has a different component configuration and currently there are not accurate data to properly assess the recycling of each component.
As the standard ISO 14044 requires, allocation has been avoided whenever possible, since the manufacturer has provided information directly related to the product.

## 2.6 Life cycle inventory

. In order to perform this LCA, a significant amount of inventory data has to be processed. For each PCBA the following information is obtained:

- Type and weight of PWB
- Mounting areas for Through-hole and SMD components
- List of components: Type and weight

  Figures 4, 5 and 6 show the inventory structure of each PCBA. Tables 3, 4 and 5 show a summary of the main components of each PCBA. The complete inventory has been used for the LCA but only a simplified one is shown in these tables.

### *2.6.1 Manufacturing processes*

Fabrication process of a PCBA can be divided into three different stages: production of the components, production of the PWB and finally the assembly of PWB and its components.

The mounting of the components by Pb-free solder has been taken into account by measuring the soldering areas of each PCB and using Ecoinvent data for SMD and through-hole mounting.

The production of the components, as there are a wide range of them, has been characterized using Ecoinvent v2.2 and CPM databases. In order to obtain more precise results, each component has been weighed individually.

With the intention of achieving greater precision, the PWB manufacturer, EUROCIR, was contacted. There is a wide range of PWB, which can vary significantly as they can have single, double or multiple layers of copper, made out of FR-2, Fr-3,Fr-4, FR5-FR-6, G-10, CEM-1, CEM-3 (Weil & Levchik, 2004) and also the copper foil thickness can be one ounce per square foot (35 um) or 2 ounces (70 um), depending on the application (Azar & Graebner, 1996). The PWB used for the induction electronic is double layer, FR-4, with 35um of copper foil, which is the same type as the one analyzed by Ecoinvent.

As the PWB has both SMD and through-hole components, it has been considered as a mixture of both technologies as shown in Table 6. These percentages have been obtained with the weight of each type of component in both ELINPCBAs. The PWB is mainly a though-hole PWB but some areas in the lower side are used for SMD mounting.

Eurocir´s factory is placed in China. This means high transport distances, which will affect the environmental impact. Transportation to Spain is carried out by freight-ship and truck to and from harbor (See Table 7).

The TCPCBA allows the operation of the induction hob by means of LEDs, 8 segment displays and capacitive sensors. It is completely made out of SMD components, as shown in Table 5. In this PCBA there are also other non-electronic components like 13 cylinders foams that are used in the capacitor sensor and 8 light channels that are used to show different symbols by means of SMD leds. Several internal control stickers are also taken into account. 8 segment displays have been disassembled in order to weigh the plastic cover, 8 SMD led and its PWB.

### *2.6.2 Use stage*

The use phase is highly dependent on consumer behavior: cooking time, temperature, frequency, choice of cookware, use of lids to cover the food... As this product is mainly sold in Europe, the eco-environmental impact of this phase has also been analyzed using induction hob data from the preparatory study of Energy-using Products, Lot 23: An annual consumption of 190 kWh and a product lifetime of 15 years (BIO Intelligence Service and ERA Technology, 2011). "Electricity, low voltage, production RER, at grid/RER U" has been used to model the electrical consumption.

# 3 Results and discussion

After introducing the whole Life Cycle Inventory in SimaPro, several results can be calculated in order to assess the environmental impact of the functional unit and how it is generated. First of all the global environmental impact is going to be analyzed, obtaining every midpoint category.

After that, a comparison between the three PCBAs is performed. Then a comparison between electronic components, PWB and mounting is carried out so as to determine which the most relevant part is.

Afterwards, a comparison between individual electronic components is done, obtaining the ones which have a higher impact. With those results, several ecodesign measures are proposed to reduce the environmental impact of these PCBAs.

## 3.1 Analysis of the global environmental impact

The results obtained per impact category according to CML methodology are shown in Table 8.

Overall, the use phase creates most of the environmental impact in every category, between 78.8% in Photochemical oxidation and 98,3% in Terrestrial ecotoxicity. (Figure 7). ELIN PWBs, Ring core inductors, Through-hole diodes, film capacitors and through-hole mounting generate a significant part of the environmental impact in almost every environmental category calculated.

Taking into account the use stage, environmental impact of the End-of-life is negligible. Focusing only on the PCBAs, EoL treatments have small positive effects (< 4%) in Acidification, Eutrophication Photochemical oxidation and every ecotoxicity category; on the other hand, they slightly increase (<2%) the environmental impact in ozone layer depletion, abiotic depletion and global warming (See Table 9). These increases are caused by energy consumptions and transportations of the End-of-life treatments.

Another way to analyze the environmental impact of the functional unit is to study where the main impacts are created. For both ELINPCBAs the electricity consumption for raw material extraction and component production causes the principal green house emissions, followed by Polycarbonate, Glass fiber, Silver Tin and Gold Production.

In recent studies, several authors have identified that Acidification and Ozone layer depletion (ODP) categories could be underestimated as CO2 and N2O emission have influence in these categories (Ravnshankara, et al., 2009) (Lane & Lant, 2012) (Andrae, 2012). Including these new characterization indices, significant increases have been found, as Acidification increases from 7.8 Kg to 2767 Kg SO2 eq. and ODP rises from 73 mg to 1005 mg CFC-11 eq.

## 3.2 Comparison between PCBAs

When comparing these three PCBAs, there are significant differences in the environmental impact between ELINRPCBA and ELINLPCBA compared to TCPCBA. The two ELINPCBAs have higher emissions in every category. TCPCBA has significant impact in Ozone Layer Depletion, although its value is four times lower than the emissions of one ELINPCBA.

A comparison between both ELINPCBAs shows more interesting data. Although they have similar appearance, their functions are different, as ELINLPCBA has its own power supply, and its components weight more and it has a bigger total weight, even though it has a smaller PWB.

The environmental impact of the ELINRPCBA is between 0.87% higher in Ozone Layer Depletion and 3.05% lower than the ELINLPCBA in photochemical oxidation, when using CML methodology.

For both ELINPCBAs the main global warming potential is caused by PWB+Mounting, Inductor ring cores, through-hole diodes and film capacitors. ELINLPCBA has a higher presence of electrolytic capacitors whereas integrated circuits have more presence in the ELINRPCBA.

The TCPCBA has a different distribution of the impact. The green house emissions generated by the PWB+mounting have greater importance. This can be caused by three effects. Firstly, its PWB is modeled as a SMD PWB + mounting from Ecoinvent database, as there is not primary data like in Eurocir´s PWB. Secondly, its PWB is for surface mounted devices, a different typology than the one used for the ELINPCBAs, which are mainly for through-hole component. Finally, another factor to understand is that the TCPCBA, not only has to comply with its electronic requirements, but it also has to be easy to use, which means that the distances between the 8-segment displays and the capacitive sensors are also influenced by aesthetical and ergonomical factors.

## 3.3 Comparison between phases: PWB, components and mounting

Next, a comparison between the three production phases (Components, PWB and Mounting) is carried out. (See Tables 10, 11 and 12)

Both ELINPCBAs show similar environmental impact distribution between components, mounting and PWB.

Components create between 70 and 85% of the total impact of ELINPCBAs in most categories. In Photochemical oxidation they add up to 86.6% in ELINRPCBA and 88% in ELINLPCBA, while in the ozone layer depletion they just represent 66.5% in ELINRPCBA and 70% in ELINLPCBA.

Mounting represents between 4.8% in Human toxicity (ELINLPCBA) and up to 11.7% in Acidification (ELINRPCBA). Photochemical oxidation and Abiotic depletion also have relevant percentages in both ELINPCBAs.

The PWBs in the both ELINPCBAs produces between 10 and 20% of the impact in 7 categories. PWBs have high impact in Ozone layer depletion and terrestrial ecotoxicity and low values in Photochemical oxidation.

TCPCBA has a different environmental impact distribution from both ELINPCBAs when analyzing components, mounting and PWBs.

PWB generates the most relevant impact in every category, as it produces between 50.9% and 79.9% of the total impact.

Components produce significant impacts in most environmental aspects, especially in fresh water aquatic ecotoxicity and Marine aquatic ecotoxicity

SMD Mounting produces smaller impacts than the components or the PWB, as it only creates between 0.8% and 5% of the total environmental impact.

## 3.4 Comparison between components

As it has been previously shown, there are three principal components groups in the ELINPCBA Ring core inductors, Through-hole diodes, Film capacitors. Table 13 shows the environmental impact of one L3 ring core inductor, one BRGP Through-hole diode and one CBUS1 film capacitor.

Ring core inductors are heavy components, up to 105 grams per unit. The impacts are mainly created by the production efforts and the use of copper.

Through-hole diodes impact is mainly generated by the productions efforts defined in Ecoinvent dataset.

Film capacitors have also a significant production effort, as they generate most of the impact. The consumption of silver is also relevant in almost every impact category.

The TCPCBA has one component that generates significant impact in every category: IC Logic SMD. These components create important environmental impact because of their raw material composition, which includes the use of gold and also because of their high electricity consumption in its production phase.

After analyzing each midpoint impact category per functional unit (ELINRPCBA, ELINLPCBA and TCPCBA), the main environmental impacts are caused by the following components and processes:

- GWP: ELIN PWBs, Ring core inductors, Through-hole diodes, Film capacitors and Through- hole mounting
- Abiotic Depletion: ELIN PWBs, Ring core inductors, Through-hole diodes, Film capacitors and Through- hole mounting
- Acidification: ELIN PWBs, Ring core inductors, Through-hole diodes, Film capacitors and Through- hole mounting
- Eutrophication: ELIN PWBs, Ring core inductors, Through-hole diodes, Film capacitors, Through- hole mounting, IC logic and Relay
- Ozone layer depletion: ELIN PWBs, Ring core inductors, Through-hole diodes, Film capacitors, Through- hole mounting, PWB Touch and IC logic
- Human toxicity: ELIN PWBs, Ring core inductors, Through-hole diodes, Film capacitors, IC logic and Relay
- Fresh water aquatic ecotoxicity: ELIN PWBs, Ring core inductors, Through-hole diodes, Film capacitors, Through-hole mounting, IC logic and Relay
- Marine aquatic ecotoxicity: ELIN PWBs, Ring core inductors, Through-hole diodes, Film capacitors, Through-hole mounting, IC logic and Relay
- Terrestrial ecotoxicity: ELIN PWBs, Ring core inductors, Through-hole diodes, Film capacitors, Through-hole mounting, IC logic, Relay and PWB Touch
- Photochemical oxidation: Film capacitor and Ring core inductors

## 3.5 Ecodesign improvements

After analyzing the environmental impact of the PCBAs used in an induction hob, there are several clear areas for improvement.

Future ecodesign measures should be focused on the following:

- Substitute electronic components for redesigned ones with lower production efforts. Results have shown that the production phase of components like inductors, capacitors or IC, have significant environmental impact. A reduction in energy consumption in their manufacturing would improve the environmental impact. Also a reduction of raw material consumption, especially of gold, silver and copper would also have important effects.
- To reduce the environmental impact by changing components, equivalent electronic components from different manufacturers should be characterized, in order find the ones with better environmental behavior.
- The environmental impact of the TCPCBA could also be minimized by compacting the capacitive sensors and displays, thus reducing the weight of the PWB.
- Another way of reducing the environmental impact is improving the end-of-life. Higher recovery and recycling rates would reduce the environmental impact. The recycling of precious metals like gold and silver and the reusing of components like ring core inductors.

Just as an example, and on the basis of the discussion in section 3.4 about the components with more impact, it is shown below the effect that could have, two of the improvements suggested, in one of the components of the L3 ring greater impact core inductor.

1. End of live improvement: Instead of sending it to landfill, manual separation andthe recovery of copper and ferrite has been considered for L3 ring core inductor. The reduction of environmental impact in this component can be seen in Table 14. Impact reductions range from 0,60% in the cathegory photochemical oxidation until 29.08% in human toxicity.
2. Redesign of L3 ring core inductor: for this analysis the environmental impact of the component with the production efforts reduced 20% are assessed. The reduction of environmental impact in this component can be seen in Table 15. Impact reductions range from 15,37% in the cathegory Acidification until 19,53% in Photochemical oxidation.

# 4 Conclusions

In this paper, the environmental impact caused by the PCBAs in a cooktop with 4 induction hobs has been analyzed. The most relevant environmental impact in every category is caused by the use stage. Both ELINPCBAs show similar environmental impact distribution between components, mounting and PWB. Components create between 70 and 85% of the total impact of ELINPCBAs in most categories. Mounting represents between 4.8% i and up to 11.7%

The PWBs in the both ELIN produces between 10 and 20% of the impact in 7 categories.

TCPCBA has a different environmental impact distribution from both ELINPCBA when analyzing components, mounting and PWBs. PWB generates the most relevant impact in every category

About individual components, the most relevant environmental impact is caused by Ring core inductors, Through-hole diodes and Film capacitors. Ring core inductors are heavy components, up to 105 grams per unit. The impacts are mainly created by the production efforts and the use of copper.

After analyzing the environmental impact of the PCBAs several improvement areas have been found:

- Substitute electronic components for redesigned ones with lower production efforts.
- To reduce the environmental impact by changing components by others with better environmental behavior.
- To minimize the environmental impact of the TCPCBA by compacting the capacitive sensors and displays, thus reducing the weight of the PWB.
- To improve recovery and recycling rates.

## 5 Acknowledgements

The research in this paper has been partially supported by the Spanish MICINN under Project IPT-2011-1158-920000 and by the Bosch and Siemens Home Appliances Group. The authors would like to thank the help provided by BSH´s electronic design team.

## 6 Figure Captions

Figure 1: System boundaries

Figure 2: Distribution of the PCBAs in the hob

Figure 3: Main components of ELINRPCBA and ELINLPCBA

Figure 4: Inventory structure of ELINRPCBA

Figure 5: Inventory structure of ELINLPCBA

Figure 6: Inventory structure of TCPCBA

Figure 7: Life cycle stages

## 7 References

Acero, J. Burdio, J.M., Barragán, L.A., Navarro, D., Alonso, R., Garcia, J.R., Monterde, F., Hernandez, P., Llorente, S., Garde, I., 2008. The domestic induction heating appliance: an overview of recent research. *Twenty-Third Annual IEEE Applied Power Electronics Conference and Exposition, 2008. APEC 2008.,* pp. 651-657.

Andrae, A., 2012. The effect of revised characterization indices for N2O and CO2 in life cycle assessment of optical fiber networks-the case of ozone depletion and aquatic acidification. *Journal of Green Engineering,* 3(1), pp. 12-32.

Andrae, A., Andersen, O., 2011. Life cycle assessment of integrated circuit packaging technologies. *International Journal of Life Cycle Assessment,* Vol. 16, pp. 258-267.

Andrae, A. S., Andersen, O., 2010. Life cycle assessments of consumer electronics - are they consistent?. *International Journal of Life Cycle Assessment,* Vol. 15, pp. 827-836.

Andrae, A. S., Andersson, D. R., Liu, J., 2005. Significance of intermediate production processes in life cycle assessment of electronic products assessed using a generic compact model. *Journal of Cleaner Production,* Vol. 13, pp. 1269-1279.

Andrae, A., Zou, G. & Liu, J., 2004. LCA of Electronic Products. *The International Journal of Life Cycle Assessment,* 9(1), pp. 45-52.

Andrae, A., Östermark, U. & Liu, J., 2000. Life Cycle Assessment of a Telecommunications exchange. *Journal of Electronics Manufacturing,* 10(3), pp. 147-160.

Aoe, T., 2007. Eco-efficiency and ecodesign in electrical and electronic products. *Journal of Cleaner Production,* Vol. 15, pp. 1406-1414.

Azar, K., Graebner, J. E., 1996. Experimental determination of thermal conductivity of printed wiring boards. *Semi-Therm XII Proceedings. Twelfth Annual IEEE Semiconductor Thermal Measurement and Management Symposium,* pp. 169-182.

Babini, A., Borsari, R., Dughiero, F., Fontanini, A., Forzan, M., 2003. 3D FEM models for numerical simulation of induction sealing of packaging material. *Compel: International journal for computation and mathematics in electrical and electronic engineering,* 22(1), pp. 170-180.

Bevilacqua, M., Caresana, F., Comodi, G., Venella, P., 2010. Life cycle assessment of a domestic cooker hood. *Journal of Cleaner Production,* Vol. 18, pp. 1822-1832.

BIO Intelligence Service and ERA Technology, 2011. *Preparatory Studies for Eco-design Requiremens of EuPs (III) Lot 23 Domestic and commercial hobs and grills, included when incorporated in cookers,* Paris: European Commission (DG ENER).

Boyd, S. B., 2012. *Life-Cycle Assessment of Semiconductors.* New York: Springer Science+Business Media, LLC.

Bruzzone, A.G., Tremori, A., Massei, M., Tarone, F., 2009. Modeling Green Logistics. 3rd Asia International Conference on Modelling and Simulation, pp. 543-548.

Chalmers University of Technology, 2012. *CPM LCA Database.* Available at: http://cpmdatabase.cpm.chalmers.se/ (Accessed 20 March 2012).

de Santana, I. J., Paulo, B., Modenesi, P. J., 2006. High frequency induction welding simulating on ferritic stainless steels. *Journal of Materials Processing Technology,* 179(1-3), pp. 225-230.

Duan, H., Eugster, M., Hischier, R., Streicher-Porte, M., Li, J., 2009. Life cycle assessment study of a Chinese desktop personal computer. *Science of the Total Environment* 407(5), pp. 1755-1764.

ETSI, 2011. *ETSI TS 103 199 V1.1.1: Environmental Engineering (EE); Life Cycle Assessment (LCA) of ICT equipment, networks and services; General methodology and common requirements,* Sophia Antipolis Cedex, France: European Telecommunications Standards Institute.

European Parliament, 2003. *Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous* *substances in electrical and electronic equipment (RoHS)*. Luxembourg. Official Journal of the European Union. EU Publications Office.

European Parliament, 2005. *Directive 2005/32/EC of the European Parliament and of the Council of 6 July 2005 establishing a framework for the setting of ecodesign requirements for energy-using products*. Luxembourg. Official Journal of the European Union. EU Publications Office.

European Parliament, 2006. *Regulation (Ec) No 1907/2006 Of The European Parliament And Of The Council of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency*. Luxembourg. Official Journal of the European Union. EU Publications Office.

European Parliament, 2009. *Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products*.: Luxembourg. Official Journal of the European Union. EU Publications Office.

European Parliament, 2012. *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE)*. Luxembourg. Official Journal of the European Union. EU Publications Office.

Frischknecht, R., Jungbluth, N., Althaus, H.-J., Doka, G., Dones, R., Heck, T., Hellweg, S., Hischier, R., Nemecek, T., Rebitzer, G., Spielmann, M., 2005. The ecoinvent Database: Overview and Methodological Framework. *International Journal of Life Cycle Assessment,* 10(1), pp. 3-9.

Fujita, H., Akagi, H., 1996. Pulse-density-modulated power control of a 4 kW, 450 kHz voltage-source inverter for induction melting applications. *IEEE Transactions on Industry Applications,* 32(2), pp. 279-286.

García-Sánchez, J.A., López-Martínez, J.M., Flores-Holgado, N., Arenas-Ramírez, B., 2012. Life cycle analysis of Euro IV urban buses. *Dyna* 87 (1), pp. 45-57.

Goedkoop, M., de Schryver, A., Oele, M., Durksz, S., de Roest, D., 2010a. *SimaPro 7. introduction into LCA,* Amersfoort, The Netherlands: PRé Consultants.

Goedkoop, M. Oele, M., de Schryver, A., Vieira, M., 2010b. *SimaPro 7 Database Manual. Methods library,* Amersfoort, The Netherlands: PRé Consultants.

Guinée, J., 2002. *Handbook on life cycle assessment: operational guide to the ISO standards.* Leiden: Springer.

Herrmann, c., Gediga, J., Warburg, N., 2001. Eco-comparison between ceramic and epoxy based populated PWBs. *Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment,* pp. 303-308.

Hischier, R., Baudin, I., 2010. LCA study of a plasma television device. *International Journal of Life Cycle Assessment,* Vol. 15, pp. 428-438.

Hischier, R., Classen, M., Lehmann, M., Scharnhorst, W., 2007. *Life Cycle Inventories of Electric and Electronic Equipment: Production, Use and Disposal. ecoinvent report No. 18,* Dübendorf: Empa / Technology & Society Lab, Swiss Centre for Life Cycle Inventories.

ISO, 2006a. *ISO 14040:2006 Environmental management -- Life cycle assessment -- Principles and framework,* Geneva: International Standard Organization.

ISO, 2006b. *ISO 14044:2006 Environmental management -- Life cycle assessment -- Requirements and guidelines,* Geneva: International Standard Organization.

Kantha, R. K., Wan, Q., Kumar, H., Liljeberg, P., Chen, Q., Zheng, L., Tenhunen, H., 2012. Evaluating Sustainability, Environment Assessment and Toxic Emissions in Life Cycle Stages of Printed Antenna. *Procedia Engineering,* Vol. 30, pp. 508-513.

Kasper, A. C., Berselli, G.B.T., Freitas, B.D., Tenório, J.A.S., Bernardes, A.M., Veit, H.M., 2011. Printed wiring boards for mobile phones: Characterization and recycling of copper. *Waste Management,* Vol. 31, pp. 2536-2545.

Kim, S., Hwang, T., Overcash, M., 2001. Life Cycle Assessment Study of Color Computer Monitor. *International Journal of Life Cycle Assessment,* 6(1), pp. 35-43.

Kristoffersen, H., Vomacka, P., 2001. Influence of process parameters for induction hardening on residual stresses. *Materials & Design,* 22(8), pp. 637-644.

Lam, C. W., Lim, S.-R., Schoenung, J. M., 2011. Environmental and risk screening for prioritizing pollution prevention opportunities in the U.S. printed wiring board manufacturing industry. *Journal of Hazardous Materials,* pp. 315-322.

Lane, J. & Lant, P., 2012. Including N2O in ozone depletion models for LCA. *The International Journal of Life Cycle Assessment,* 17(2), pp. 252-257.

Longo, F., 2012. Sustainable supply chain design: an application example in local business retail. *Simulation-Transactions of the Society for Modeling and Simulation International*, 88(12), pp. 1484-1498.

Lozano, S., Iribarren, D., Moreira, M. T. & Feijoo, G., 2010. Environmental impact efficiency in mussel cultivation. *Resources, Conservation and Recycling,* Vol. 54, pp. 1269-1277.

Martínez, E., Sanz, F., Pellegrini, S., Jiménez, E., Blanco, J. 2009. Life cycle assessment of a multi-megawatt wind turbine. *Renewable Energy* 34 (3) , pp. 667-673.

Martínez, E., Jiménez, E., Blanco, J., Sanz, F., 2010. LCA sensitivity analysis of a multi-megawatt wind turbine. *Applied Energy,* 87(7), pp. 2293-2303.

Noda, T., Shimizu, T., Okabe, M., Iikubo, T., 1997. Joining of TiAl and steels by induction brazing. *Materials Science and Engineering: A,* Vol. 239-240, pp. 613-618.

Ravnshankara, A., Daniel, J. S. & Portmann, R. W., 2009. Nitrous Oxide (N2O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century. *Science,* Volumen 326, pp. 123-125.

Sikdar, B., 2013. A study of the environmental impact of wired and wireless local area network access. *IEEE Transactions on Consumer Electronics,* 59(1), pp. 85-92.

Sikdar, B., 2011. Environmental impact of IEEE 802.11 access points: a case study. *ACM SIGMETRICS Performance Evaluation Review,* 38(3), pp. 66-70.

Song, Q., Wang, Z., Li, J., Xianlai, Z., 2012. Life cycle assessment of TV sets in China: A case study of the impacts of CRT monitors. *Waste Management,* Vol. 32, pp. 1926-1936.

Taiariol, F., Fea, P., Papuzza, C., Casalino, R., Galbiati, E., Zappa, S., 2001. Life cycle assessment of an integrated circuit product. *Proceedings of the 2001 IEEE International Symposium on Electronics and the Environment,* pp. 128-133.

Wang, X., Gaustad, G., 2012. Prioritizing material recovery for end-of-life printed circuit boards. *Waste Management,* Vol. 32, pp. 1903-1913.

Weil, E. D., Levchik, S., 2004. A Review of Current Flame Retardant Systems for Epoxy Resins. *Journal of Fire Sciences,* 22(1), pp. 25-40.

Yamane, L., de Moraes, V., Espinosa, D., Tenorio, J., 2011. Recycling of WEEE: Characterization of spent printed circuit boards from mobile phones and computers. *Waste Management,* Vol. 31, pp. 2553-2558.

**Table 1: Dimensions and power characteristics of cooking units in hob**

| Units | Diameter (mm) | Nominal power (kW) | Booster power (kW) |
|---|---|---|---|
| 1 | 150 | 1.4 | 1.8 |
| 2 | 180 | 1.8 | 2.5 |
| 1 | 210 | 2.2 | 3.3 |

**Table 2: Components and end-of-life treatment selected**

| Components | End-of-Life Treatment |
|---|---|
| ELINPCBA and TCPCBA | Shredding, electrical and electronic scrap/GLO |
| Through-hole capacitors | Disposal, capacitors, 0% water, to hazardous waste incineration/CH U |
| PWB copper | 70% Recycling |
| Rests | Disposal, treatment of printed wiring boards/GLO U |

**Table 3: Components of ELINRPCBA**

| Component | Type | Units | Total Weight(g) | Ecoinvent data |
|---|---|---|---|---|
| Electrolyte capacitor | T | 6 | 5.432 | Capacitor, electrolyte type, < 2cm height, at plant/GLO U |
| Film capacitor | T | 26 | 134.397 | Capacitor, film, through-hole mounting, at plant/GLO U |
| 0402 Capacitor | SMD | 48 | 0.0528 | Capacitor, SMD type, surface-mounting, at plant/GLO U |
| Diode | T | 5 | 31.233 | Diode, glass-, through-hole mounting, at plant/GLO U |
| Inductor ring core | T | 3 | 179.318 | Inductor, ring core choke type, at plant/GLO U |
| Relay | T | 2 | 22.839 | Switch, toggle type, at plant/GLO U |
| Transformer | T | 2 | 12.248 | Transformer, low voltage use, at plant/GLO U |
| 0402 Resistor | SMD | 73 | 0.0365 | Resistor, SMD type, surface mounting, at plant/GLO U |

**Table 4: Components of ELINLPCBA**

| Component | Type | Units | Total Weight (g) | Ecoinvent data |
|---|---|---|---|---|
| Electrolyte capacitor | T | 9 | 18.363 | Capacitor, electrolyte type, < 2cm height, at plant/GLO U |
| Film capacitor | T | 28 | 126.365 | Capacitor, film, through-hole mounting, at plant/GLO U |
| 0402 Capacitor | SMD | 50 | 0.055 | Capacitor, SMD type, surface-mounting, at plant/GLO U |
| Diode | T | 8 | 32.364 | Diode, glass-, through-hole mounting, at plant/GLO U |
| Inductor ring core | T | 4 | 188.901 | Inductor, ring core choke type, at plant/GLO U |
| Relay | T | 3 | 34.3535 | Switch, toggle type, at plant/GLO U |
| Transformer | T | 3 | 25.0465 | Transformer, low voltage use, at plant/GLO U |
| 0402 Resistor | SMD | 60 | 0.0293 | Resistor, SMD type, surface mounting, at plant/GLO U |

**Table 5: Components of TCPCBA**

| Component | Units | Total Weight (g) | Ecoinvent data |
|---|---|---|---|
| SMD Resistor 0603 | 79 | 0.1501 | Resistor, SMD type, surface mounting, at plant/GLO U |
| SMD capacitor 0603 | 52 | 0.2756 | Capacitor, SMD type, surface-mounting, at plant/GLO U |
| SMD Transistor | 28 | 0.2413 | Transistor, SMD type, surface mounting, at plant/GLO U |
| 8 segment display | 6 | 4.5 | Polymer housing + SMD PCB + 8 LED |
| IC logic | 5 | 0.510 | Integrated circuit, IC, logic type, at plant/GLO U |
| IC memory | 2 | 0.114 | Integrated circuit, IC, memory type, at plant/GLO U |

**Table 6: SMD and Through-hole distribution in ELINRPCBA and ELINLPCBA**

| ELIN | Through-hole % | Dataset | SMD % | Dataset |
|---|---|---|---|---|
| PWB ELINRPCBA | 98.4% | Printed wiring board, through-hole, lead-free surface, at plant/GLO U | 1.6% | Printed wiring board, surface mount, lead-free surface, at plant/GLO U |
| PWB ELINLPCBA | 98.6% | | 1.4% | |

**Table 7: Dataset selection for transports and SMD and Through-hole mounting**

| Process | Dataset |
|---|---|
| SMD Mounting | Mounting, surface mount technology, Pb-free solder/GLO U |
| Through-hole Mounting | Mounting, through-hole technology, Pb-free solder/GLO U |
| Freight-ship | Transport, transoceanic freight ship/OCE U |
| Truck China | Transport, lorry >32t, EURO3/RER U |
| Truck Spain | Transport, lorry >32t, EURO4/RER U |

**Table 8: Global environmental impact, CML Methodology**

| Impact category | Unit | Total | ELINLPCBA | ELINRPCBA | TCPCBA | USE PHASE |
|---|---|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 9,37E+00 | 2,72E-01 | 2,71E-01 | 3,20E-02 | 8,80E+00 |
| Acidification | kg $SO_2$ eq | 7,76E+00 | 2,10E-01 | 2,07E-01 | 2,86E-02 | 7,31E+00 |
| Eutrophication | kg $PO_4$--- eq | 5,20E+00 | 1,59E-01 | 1,56E-01 | 2,90E-02 | 4,86E+00 |
| Global warming | kg $CO_2$ eq | 1,67E+03 | 3,41E+01 | 3,40E+01 | 4,51E+00 | 1,60E+03 |
| Ozone layer depletion | kg CFC-11 eq | 7,26E-05 | 2,30E-06 | 2,32E-06 | 5,49E-07 | 6,74E-05 |
| Human toxicity | kg 1,4-DB eq | 1,15E+03 | 7,29E+01 | 7,18E+01 | 1,14E+01 | 9,97E+02 |
| Fresh water aquatic ecotoxicity | kg 1,4-DB eq | 8,99E+02 | 3,42E+01 | 3,34E+01 | 6,02E+00 | 8,25E+02 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 1,99E+06 | 8,17E+04 | 7,94E+04 | 1,51E+04 | 1,82E+06 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 2,97E+01 | 2,39E-01 | 2,36E-01 | 4,03E-02 | 2,92E+01 |
| Photochemical oxidation | kg $C_2H_4$ eq | 3,71E-01 | 3,94E-02 | 3,82E-02 | 1,24E-03 | 2,92E-01 |

**Table 9: Effect of end-of-life treatment in environmental impact**

| Impact category | Unit | Impact without End-of-Life | Impact of End-of-life | Reduction |
|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 9,37E+00 | 3,38E-03 | 0,036% |
| Acidification | kg $SO_2$ eq | 7,76E+00 | -4,15E-03 | -0,053% |
| Eutrophication | kg $PO_4$--- eq | 5,21E+00 | -6,23E-03 | -0,120% |
| Global warming | kg $CO_2$ eq | 1,67E+03 | 7,72E-01 | 0,046% |
| Ozone layer depletion | kg CFC-11 eq | 7,25E-05 | 8,42E-08 | 0,116% |
| Human toxicity | kg 1,4-DB eq | 1,16E+03 | -5,75E+00 | -0,499% |
| Fresh water aquatic ecotoxicity | kg 1,4-DB eq | 9,00E+02 | -9,27E-01 | -0,103% |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 2,00E+06 | -4,06E+03 | -0,204% |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 2,97E+01 | -1,44E-02 | -0,048% |
| Photochemical oxidation | kg $C_2H_4$ eq | 3,71E-01 | -1,44E-04 | -0,039% |

**Table 10: ELINRPCBA environmental impact**

| Impact category | Unit | Components | Mounting | PWB |
|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 1,98E-01 | 2,42E-02 | 4,85E-02 |
| Acidification | kg $SO_2$ eq | 1,50E-01 | 2,43E-02 | 3,31E-02 |
| Eutrophication | kg $PO_4$--- eq | 1,21E-01 | 1,19E-02 | 2,28E-02 |
| Global warming | kg $CO_2$ eq | 2,45E+01 | 2,71E+00 | 6,79E+00 |
| Ozone layer depletion | kg CFC-11 eq | 1,54E-06 | 1,35E-07 | 6,43E-07 |
| Human toxicity | kg 1,4-DB eq | 5,55E+01 | 3,70E+00 | 1,26E+01 |
| Fresh water aquatic ecotoxicity | kg 1,4-DB eq | 2,62E+01 | 2,24E+00 | 4,89E+00 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 6,32E+04 | 5,23E+03 | 1,10E+04 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 1,70E-01 | 1,67E-02 | 5,02E-02 |
| Photochemical oxidation | kg $C_2H_4$ eq | 3,31E-02 | 3,63E-03 | 1,50E-03 |

**Table 11: ELINLPCBA environmental impact**

| Impact category | Unit | Components | Mounting | PWB |
|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 2,07E-01 | 2,28E-02 | 4,26E-02 |
| Acidification | kg $SO_2$ eq | 1,58E-01 | 2,29E-02 | 2,90E-02 |
| Eutrophication | kg $PO_4$--- eq | 1,28E-01 | 1,12E-02 | 1,99E-02 |
| Global warming | kg $CO_2$ eq | 2,56E+01 | 2,55E+00 | 5,96E+00 |
| Ozone layer depletion | kg CFC-11 eq | 1,61E-06 | 1,27E-07 | 5,63E-07 |
| Human toxicity | kg 1,4-DB eq | 5,84E+01 | 3,50E+00 | 1,10E+01 |
| Fresh water aquatic ecotoxicity | kg 1,4-DB eq | 2,78E+01 | 2,11E+00 | 4,29E+00 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 6,72E+04 | 4,94E+03 | 9,59E+03 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 1,80E-01 | 1,57E-02 | 4,40E-02 |
| Photochemical oxidation | kg $C_2H_4$ eq | 3,47E-02 | 3,42E-03 | 1,32E-03 |

**Table 12: TCPCBA environmental impact**

| Impact category | Unit | Components | Mounting | PWB |
|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 8,49E-03 | 6,42E-04 | 2,29E-02 |
| Acidification | kg $SO_2$ eq | 1,07E-02 | 7,77E-04 | 1,71E-02 |
| Eutrophication | kg $PO_4$--- eq | 1,20E-02 | 3,64E-04 | 1,67E-02 |
| Global warming | kg $CO_2$ eq | 1,14E+00 | 6,88E-02 | 3,30E+00 |
| Ozone layer depletion | kg CFC-11 eq | 1,12E-07 | 4,22E-09 | 4,33E-07 |
| Human toxicity | kg 1,4-DB eq | 3,99E+00 | 1,91E-01 | 7,17E+00 |
| Fresh water aquatic ecotoxicity | kg 1,4-DB eq | 2,76E+00 | 8,03E-02 | 3,17E+00 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 7,24E+03 | 1,92E+02 | 7,70E+03 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 1,06E-02 | 6,78E-04 | 2,90E-02 |
| Photochemical oxidation | kg $C_2H_4$ eq | 4,60E-04 | 6,25E-05 | 7,17E-04 |

**Table 13: Components environmental impact**

| Impact category | Unit | L3 Ring core inductor | BRGP Through-hole diode | CBUS1 Film capacitor |
|---|---|---|---|---|
| Abiotic depletion | kg Sb eq | 3,12E-02 | 1,19E-02 | 1,17E-02 |
| Acidification | kg $SO_2$ eq | 2,14E-02 | 7,90E-03 | 8,13E-03 |
| Eutrophication | kg $PO_4$--- eq | 1,30E-02 | 5,03E-03 | 6,67E-03 |
| Global warming | kg $CO_2$ eq | 4,38E+00 | 1,60E+00 | 1,15E+00 |
| Ozone layer depletion | kg CFC-11 eq | 2,10E-07 | 9,87E-08 | 8,30E-08 |
| Human toxicity | kg 1,4-DB eq | 4,43E+00 | 1,02E+00 | 4,81E+00 |
| Fresh water aquatic ecotoxicity | kg 1,4-DB eq | 2,54E+00 | 8,18E-01 | 1,59E+00 |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 5,35E+03 | 1,86E+03 | 3,79E+03 |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 2,43E-02 | 6,62E-03 | 1,02E-02 |
| Photochemical oxidation | kg $C_2H_4$ eq | 9,59E-03 | 3,72E-04 | 2,30E-03 |

**Table 14: Impact of the inductor L3 when recycling of copper and ferrite**

| Impact category | Unit | L3 Ring core inductor with recycling | Improvement |
|---|---|---|---|
| Abiotic depletion | kg Sb eq | 3,07E-02 | 1,57% |
| Acidification | kg SO2 eq | 2,01E-02 | 6,13% |
| Eutrophication | kg PO4--- eq | 1,14E-02 | 12,37% |
| Global warming | kg CO2 eq | 4,31E+00 | 1,59% |
| Ozone layer depletion | kg CFC-11 eq | 2,04E-07 | 2,64% |
| Human toxicity | kg 1,4-DB eq | 3,14E+00 | 29,08% |
| Fresh water aquatic ecotoxicity | kg 1,4-DB eq | 2,05E+00 | 19,48% |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 4,19E+03 | 21,72% |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 2,26E-02 | 6,88% |
| Photochemical oxidation | kg C2H4 eq | 9,53E-03 | 0,60% |

**Table 15: Impact of the inductor L3 when applying 20% reduction of the production efforts of the Ecoinvent dataset**

| Impact category | Unit | L3 Ring core inductor with 20% lower production efforts | Improvement |
|---|---|---|---|
| Abiotic depletion | kg Sb eq | 2,57E-02 | 17,67% |
| Acidification | kg SO2 eq | 1,81E-02 | 15,37% |
| Eutrophication | kg PO4--- eq | 1,07E-02 | 17,45% |
| Global warming | kg CO2 eq | 3,68E+00 | 16,03% |
| Ozone layer depletion | kg CFC-11 eq | 1,71E-07 | 18,77% |
| Human toxicity | kg 1,4-DB eq | 3,67E+00 | 17,16% |
| Fresh water aquatic ecotoxicity | kg 1,4-DB eq | 2,09E+00 | 17,67% |
| Marine aquatic ecotoxicity | kg 1,4-DB eq | 4,44E+03 | 17,08% |
| Terrestrial ecotoxicity | kg 1,4-DB eq | 2,02E-02 | 16,95% |
| Photochemical oxidation | kg C2H4 eq | 7,72E-03 | 19,53% |