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DEALING WITH LCA MODELING FOR THE END OF LIFE OF MECHATRONIC PRODUCTS

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Abstract

This paper discusses end-of-life (EoL) modeling issues in Life Cycle Assessment (LCA), through the application to a domestic cooker hood. Two EoL approaches are applied and discussed, namely the avoided burden and the one recommended by the Product Environmental Footprint (PEF) Guide, presently under testing. While no case studies on PEF application have been published yet, to the best of our knowledge, the scientific community is questioning the robustness and relevance of some methodological aspects, especially the EoL formula.

The objective of the work is to provide a case study for supporting the scientific discussion on EoL modeling by: applying the avoided burden approach to the cooker hood EoL; testing the PEF EoL approach on a cooker hood component, the aluminum filter, and compare the results with those obtained from the avoided burden approach; evaluating how both the approaches affect the allocation of burdens/credits associated to recycling. The Global Warming Potential (GWP) and the Abiotic Depletion Potential (ADP) impact categories are investigated.

The study points out that the PEF EoL approach delivers higher environmental impacts than the avoided burden one, due to a reduced contribution from the avoided impacts.

Overall, the application of the PEF EoL approach is more complex, due to the additional and often not available information needed, such as the recycled content of the materials and the disposal treatments that are avoided when recycled materials are used in the product. Also the structure of the LCA datasets may limit the application of the PEF EoL.

Key words: avoided burden, EoL recycling, Life Cycle Assessment, Product Environmental Footprint, recyclability rate

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1. Introduction

The Life Cycle Assessment (LCA) is widely recognized as the best framework for assessing the potential environmental impacts of products, systems and services (EC Communication, 2003). By accounting for inputs (materials, energy) and outputs (emissions, waste) at each step of the product life cycle, it enables options for environmental improvements to be identified. Though the methodology is standardized by the ISO 14040 series (ISO, 2006a, 2006b), subjectivity exists on how to deal with some methodological issues. End-of-Life (EoL) modeling has been discussed for years (Allacker et al., 2014; Ardente and Cellura, 2011; Ekvall, 2000; Frischknecht, 2010; Liu and Muller, 2012), mainly in relation to the topic of multi-functionality in recycling situations. Multi-functionality arises as recycling fulfils the dual functions of waste management and secondary material production (Nakatani, 2014), and thus an allocation has to be performed. There is currently no single, generally accepted approach to modelling EoL, and this is partly justified by the fact that it is

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not merely a scientific issue but a normative one in defining who gets the credits and the burdens of the recycling process. In addition, the reference standard (ISO 14044:2006) only distinguishes between open-loop product systems and closed-loop product systems.

Different approaches have been developed to deal with multi-functionality in recycling, such as the EoL recycling (also known as the avoided burden approach), the recycled content and the 50/50, to mention just a few. Each approach is characterized by different rationales of accounting for burdens and credits associated to the recycling process (Atherton, 2007; Dubreuil et al., 2010; Ekvall and Tillman, 1997; Frischknecht, 2010; Harper et al., 2006; Johnson et al., 2013). Since no agreement exists and ISO standards also leave room for interpretation, stakeholders usually support the use of the EoL approach that better promotes the environmental sustainability of their products on the market.

Modeling the EoL is a challenging aspect in sectors/product groups in which the EoL chain is fragmented and/or not yet fully developed from the technology point of view, like the electric and electronic equipment (EEE). The European Directive 2012/19/EC on Waste Electric and Electronic Equipment (WEEE) (EU Directive, 2012) has set a group of rules and procedures to ensure that each electronic component undergoes the most sustainable EoL treatment, with the general objective to improve the quality of the environment, and at the same time, to protect human health and to use natural resources prudently and rationally. Moreover, this product group is extremely significant from the point of view of the resources as strategic raw materials (significant amounts of base metals and copper, but also small content of precious metals) are used, high rate of EEE are produced and growing of WEEE is expected (Ciocoiu et al., 2013; Cui and Forssberg, 2003).

In fact, resources efficiency has been identified by the "Europe 2020 strategy" as a key element of the progress toward a low carbon economy and sustainable growth (EC Communication, 2010). "Sustainable consumption and production" and "Turning waste into a resource" are two interconnected policies that the "Roadmap to Resources Efficient Europe" (EC Communication, 2011) has identified to transform the economy into a resource-efficient one, which means improved efficiency, commercialization of innovations and better management of resources over their whole life cycle. Several actions are being adopted among which: "*a) the development of a common methodological approach to enable Member States and the private sector to assess, display and benchmark the environmental performance of products, services and companies based on a comprehensive assessment of environmental impacts over the life cycle, b) encouraging a secondary products market as well as the demand for recycled materials through economic incentives and developing of end-of-waste criteria, b) reviewing existing prevention, reuse, recycling, recovery and landfill diversion rate in order to move toward an economy based on reuse and recycling-based, with residual waste close to zero"* (EC Communication, 2011).

In this context, the European Commission has recently proposed a harmonized LCA methodology, the Product Environmental Footprint (PEF) (EC Recommendation, 2013) with the aim to create a single market for green products and to foster both supply of recyclable materials and demand for recycled materials. Moreover the Communication "Towards a circular economy: A zero waste program for Europe" pushes for materials such as metals, plastic, glass to re-enter the economy as secondary raw materials at competitive prices (EC Communication, 2014). In particular, for priority waste streams, such as metals, criteria have already been developed (Council Regulation, 2011).

The PEF Guide introduces an analytical approach to deal with multi-functionality in recycling (Pelletier et al., 2014), and it is currently under tests in several pilots in Europe. Criticisms have been raised, mainly related to the applicability of the approach (Lehmann et al., 2015) and to the fact that it is neither extensively tested nor extensively used, besides not being used in "*real-word decision making in either private or public organizations*" (Finkbeiner 2014).

In the framework of the current initiatives on EEE and PEF, the study here proposed is intended to contribute to the discussion about reliable scenarios for end-of-life of EEE, in particular of a product group presently not covered by the ongoing PEF pilot tests (http://ec.europa.eu/environment/eussd/smgp/pef_pilots.htm. The case study concerns the modeling of the EoL of a household appliance, namely a domestic cooker hood. Household appliances are characterized by considerable energy consumption during the use phase, which usually – in a life cycle perspective - overcomes the environmental impacts of the other phases. However, most of the household appliances, including cooker hoods, are equipped with basic or advanced electronic parts such as electronic boards and, capacitor; moreover, they are characterized by high content of metals (steel, aluminum and copper). Thus, management and optimization of the EoL processes play an important role when dealing with resource efficiency.

More in detail, the aims of the study are: a) to evaluate the EoL of the cooker hood, with the avoided burden approach; b) to test on the aluminum filter component the PEF EoL approach, as the one supported by the EU Commission, and compare the applicability and results to the avoided burden approach, as the one endorsed by the Metal Industry (Atherton, 2007). It is out of the scope of the paper the discussion on end of life treatments for WEEE.

The section "Materials and Methods" introduces i) the studied product, i.e. the cooker hood, ii) the EoL scenario defined for the product, iii) the description of the avoided burden approach application to the cooker hood, iv) the description of the application of avoided burden and PEF EoL approaches to the aluminum filter, which is a product component v) the Life Cycle Inventories (LCIs) arising from the application of the EoL formulas. The environmental impact results are shown in "Result" and, in the last section, main conclusions are discussed in relation to the stated objectives.

2. Material and methods

2.1. Description of the cooker hood and of the EoL scenario

The product under analysis is a domestic cooker hood (Fig. 1) manufactured by an Italian company. The studied model belongs to the T-shape product family and it is installed on the wall. It has both ventilation and filtration functions and can work at four different speed levels with a suction capacity of 660 m^3/h and a 68 dB noise level (at maximum speed). It is equipped with an electric motor (power rate of 250 W), two halogen lamps (20 W each), three aluminum-made filters, dishwasher safe, a filter alarm and a touch screen control panel.

Fig. 1. Cooker hood model

The cooker hood includes different components and materials (Table 1).

Table 1. Cooker hood materials and mass

Materials/components and mass	*(kg)*
Steel	11.9
Copper	0.638
Aluminum	0.546
Plastic	1.428
Glass	0.65
Electric and electronic devices	0.24
Capacitor	0.065

The primary function of the cooker hood is to remove cooking exhaust fumes from the cooking area.

The **functional unit** (FU) is defined as the capacity to draw air from the cooking area with a suction rate of 660m^3/h for one hour per day, to light the cooking area for 2 hours per day (EC Regulation, 2014) and to work for nine years (including all the ordinary and maintenance operations). The considered cooker hood does not include active carbon filtering. The reference flow of this study is one cooker hood working for 9 years.

Though an LCA study has been carried out from cradle to grave (ENEA, 2015), in this paper only the EoL phase is discussed. Thus, the boundary of the system includes the different processes occurring in the EoL stage, namely: collection of the cooker hood at its EoL, sorting (through manual or mechanical disassembly), transport between the different plants, and final treatment. The final treatment may include either secondary material production incineration or landfill.

The impact assessment method is CML 2001 (update Apr. 2013). In this paper those impact categories identified as relevant for resource efficiency (EU Communication, 2011) and the achievement of Kyoto Protocol goals (EU Progress Report, 2003) are analyzed, namely: Abiotic Depletion Potential Elements (ADP Elements), ADP Fossil and Global Warming Potential (GWP). The software Gabi 6 is used for the study.

As far as the EoL scenario is concerned, information currently available is scarce and country-related.

It is widely known that just a share of EEE at EoL is collected to be properly managed as WEEE. In order to raise the collection rate, the directive on WEEE has established that no costs have to be charged to consumers for WEEE management (EU Directive, 2012). The available studies on WEEE report data concerning production rate (UNEP, 2005; Huisman et al., 2007); typical compositions (ETCSCP, 2009); and/or metals/elements included (UNEP, 2013), and highlight the recycling potential. These studies usually concern office equipment, high-tech devices such as mobile phones and domestic appliances different from the cooker hood. Moreover, they do not include information on how the WEEE is effectively managed once collected and transported to the disposal/recycling plants. Therefore, in order to build a reliable EoL scenario, information was needed on a) the available technologies for household appliances dismantling as well as the ones generally adopted at disposal plants, b) the value and amount of scrap flows coming out from dismantling process of household appliances, c) current barriers to more resources efficient management of EEE EoL. To acquire this information the following approach has been adopted:

- visit to disposal plants, collection of technical data (disassembly sequence and time) concerning the actual dismantling process for household appliances and consultation with experienced operators;
- scientific and grey literature survey;
- interviews with experts;
- analysis of technical literature, in particular the Joint Research Center (JRC) report concerning the method for the measurement of recyclability, reusability and recoverability (Ardente et al., 2011).

The cooker hood EoL scenario analyzed consists in the collection and transport to the plant where dismantling is carried out in two stages, i.e. manual and mechanical. It takes into account the value of materials contained in the product and the cost and time for disassembling (Fig. 2).

The manual disassembly enables the following components to be removed: electric motor (including the capacitor), halogen lamps, printed circuited boards (PCBs) and the external cables. The capacitor is classified as hazardous waste. The other parts of the motor are made of valuable materials such as copper, steel and aluminum, which will be processed for recycling. The copper cables are removed manually mainly to increase the recyclability rate of copper. Based on information acquired at the visited disposal plant, halogen lamps can be easily removed, in order to avoid further contamination of the streams of material coming out from the shredder (Buttol et al., 2015). Though in this study the recovery of rare elements from PCBs has not been investigated, and the PCBs have been assumed to be sent to incineration, a scenario of manual dismantling of the PCBs has been assumed. Indeed, in presence of adequate treatment plants, their manual dismantling would allow the recovery of higher amount of precious metals (mainly copper, for low-value PCBs) (Stefãnuţ et al., 2013) if compared with shredding together with other components (Ardente et al., 2012). Overall, the manual disassembly provides metals scrap for recycling and materials for energy recovery.

After the manual disassembly, all the remaining components are mechanically disassembled. The cooker hood is inserted into a shredding machine, which is equipped with separators able to sort ferrous and non-ferrous metals, while the fraction of materials containing plastic, rubber, glass and metals are not further separated.

The energy consumption for the shredding process has been estimated on the basis of data coming from the Ecoinvent 2.2 database. A standard distance of 100 km covered by a diesel truck has been assumed for all transport. For all electricity consumption in this study the EU 27 Electricity Mix 2002 from ELCD was used.

2.2. Recycling process for the involved material supply chains

Based on the described scenario, the materials sent to recycling are steel, aluminum and copper. Both the avoided burden approach and the PEF EoL approach account for burdens and credits of recycling, but with different rationales (see next two paragraphs for details), and require the identification of the following aspects:

- the recycling process, and related efficiency, of each material intended to be recycled;
- the virgin material, whose production will be potentially avoided, for each material addressed to recycling.

The recycling efficiency has been calculated by considering the efficiency of each step along the whole process: collection, sorting, transportation and treatment (here intended as secondary production). No material loss occurs during collection and transport stages, as it has been assumed that all private households, encouraged by the WEEE Directive (EU, 2012), return the cooker hood for proper dismantling. On the contrary, material loss occurs in sorting and treatment and it has been accounted for.

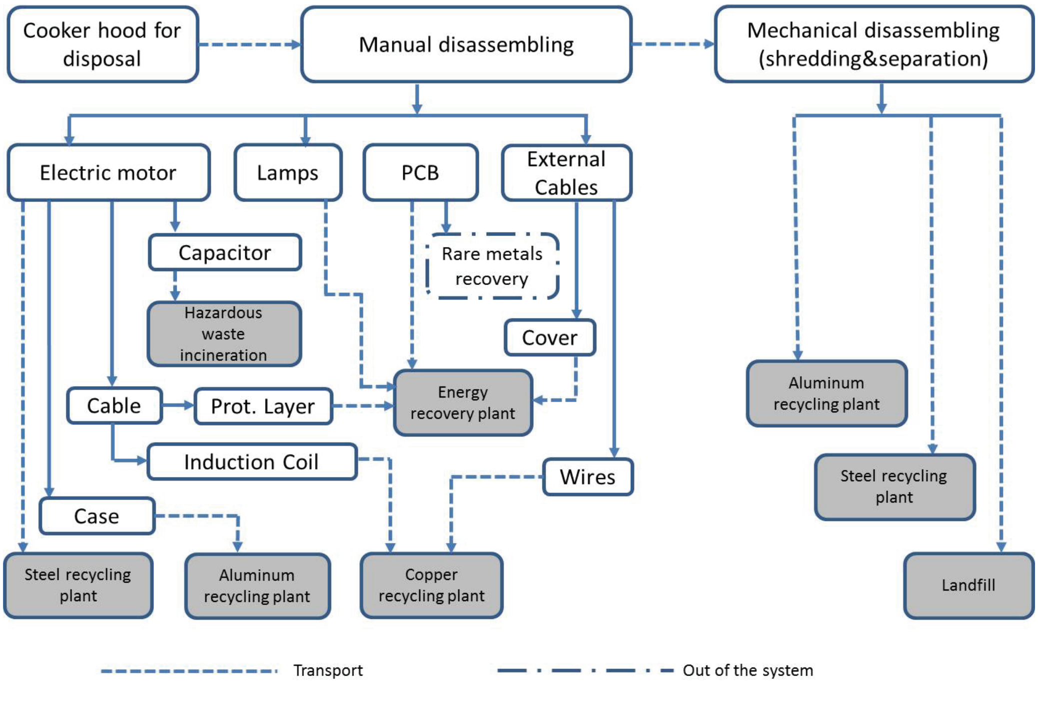


Fig. 2. Cooker hood End-of-life scenario

The sorting efficiency has been identified with the Recyclability rate defined by the JRC-IES methodology (Ardente et al., 2011). This index indicates a potential Recyclability rate of a product on the basis of measurable characteristics and specific assumptions, and considers each component and material used in the product.

The index takes into consideration 1) the disassemblability of the product (*D*) in both manual and mechanical disassembly; 2) the contamination of the material (*C'*) when incompatible materials can be found after disassembly, 3) the degradation of the material (M_D) as a measure of quality loss after use and recycling treatment. The Recyclability rate does not take into account the material lost in the treatment.

The Recyclability of each material (R_m) is considered as a sub-task of the assessment (Eq. 1):

$$R_m = D_m * C'_m * M_{Dm} \tag{1}$$

Table 2 shows values D_m, C'_m, M_{Dm} for both manual and mechanical sorting, taken from Tables 6, 8, 11 and 13 in Ardente at al. (2011).

Data on the efficiency of the treatment come from industrial associations or from Best Available Techniques (BAT) documentation.

The Table 3 shows the recycling process efficiency for steel, aluminum and copper. Details on sorting efficiency (Recyclability rates), treatment efficiency and avoided virgin materials are described here below for steel, aluminum and copper.

2.2.1. Steel

Steel is used for many components of the cooker hood and is managed to be recycled. Recyclability rates have been defined for steel coming out from both manual and mechanical sorting. For manual sorting, we have considered disassembly efficiency equal to 100%, no contamination as well as no material degradation, according to the values and information reported in Ardente et al. (2011). For mechanical sorting, the indexes of disassembling, contamination and degradation consider the losses due to shredding, according to the values reported in Ardente et al. (2011). The Recyclability rates are shown in Table 2.

The efficiency value of the treatment has been estimated on the basis of the Input/Output value reported in the BAT (Remus et al., 2013) for the production of steel from Electric Arc Furnace Route, where we considered that only scraps are processed.

The steel slab from basic oxygen furnace has been identified as the avoided virgin material, and the steel slab from electric arc furnace as secondary steel. The choices of primary and secondary steel production are consistent with the position of the World Steel Association (World Steel Association, 2011). On the basis of the Declaration by the Metals Industry on Recycling Principles (Atherton, 2007), they recognize that a closed-loop (as defined by ISO 14044, part 4.3.4.3.3.) can be applied for steel recycling, thus scrap is considered as an alternative source of equivalent (virgin) ferrous metal.

2.2.2. Aluminum

Aluminum is used for the filter and, in small amount, for the electric motor, namely the aluminum case and the squirrel cage of the electric motor. In the electric motor, only the case can be manually separated and addressed to aluminum recycling plant, while the aluminum of the cage cannot be separated and is sent to the recycling process together with the other steel components. Aluminum that makes up the filter is sorted after shredding to be sent to aluminum recycling plant. Therefore, two Recyclability rates have been defined, for manual and mechanical separation. The same assumptions adopted for steel have been considered. The calculated values are shown in Table 2.

The efficiency value of the treatment comes from data of the European Aluminum Association (2013a) for the production of secondary aluminum ingot.

The avoided virgin material is the aluminum ingot (primary production). This choice is consistent with the position of the European Aluminum Association (2013b) and with the Declaration by the Metals Industry on Recycling Principles too (Atherton, 2007), endorsed by the International Aluminum Institute. According to them aluminum can be recycled to produce wrought or cast aluminum alloys without any downgrading.

2.2.3. Copper

Copper is used for the coil of the electric motor, and for the external cables. All copper is manually separated and sent directly to copper recycling plant. A Recyclability rate equal to 100% has been calculated (Table 2), considering the same assumptions and references specified for steel.

As far as the treatment efficiency and the avoided impacts are concerned, the available inventory dataset on copper wire production is aggregated and already includes burdens and credits associated to treatment (secondary copper production) considering that 95% of copper waste feeds back into production with a recycling rate of 95%. Thus, conservatively, burdens and credits associated to copper wire treatment have not been accounted for in the EoL.

2.3. The application of the avoided impact approach to the EoL of the cooker hood

The avoided burden approach has been used to model the EoL of the whole cooker hood. According to this method the whole burdens and credits associated to recycling (as well as to recovery) are allocated to the studied system and the use of secondary material displaces the use of virgin (primary) materials (ISO 14044).

Table 2. Sorting efficiency for the recyclable materials. The sorting efficiency is identified by the Recyclability rate

MATERIAL	***Recyclability rate ($D * C' * M_D$)***	***Disassembling index - D***	***Contamination index – C'***	***Material degradation index M_D***
Steel - mechanical sorting	47.5%	95%	50%	100%
Steel - manual sorting	100%	100%	100%	100%
Aluminum - mechanical sorting	45%	90%	50%	100%
Aluminum - manual sorting	100%	100%	100%	100%
Copper – manual sorting	100%	100%	100%	100%

Table 3. Recycling efficiency for recyclable materials. The overall recycling efficiency results by the product of the collection, sorting, transport and treatment efficiencies

	Step efficiency				
	Collection	***Sorting (Recyclability rate)***	***Transport***	***Treatment***	***Overall recycling***
Steel	1	1 (manual) 0.475 (mechanical)	1	0.95	0.95 (manual) 0.45 (mechanical)
Aluminum	1	1 (manual) 0.45 (mechanical)	1	0.96	0.96 (manual) 0.432 (mechanical)
Copper	1	1	1	Not available	Not available

This approach focuses on the fate of the product after the use stage and on the consequent material output flows, based on the premise that supply of secondary material is constrained (Johnson et al., 2013).

The application of the approach needs information on:

- recyclability rates and avoided virgin materials on steel, copper and aluminum, described in section 2.2;
- plastic. The plastic of the cooker hood cannot be recycled because of the brominated flame retardants (BFRs) content. Plastic comes partly from manual disassembling (as residual of cables separation for copper recycling, see Fig. 2), and partly from shredding. The plastic rate that is mechanically disassembled cannot be sorted and is sent to landfill. The plastic coming out from manual disassembly, as well as the PCBs and the lamps, is sent to incineration for energy recovery;
- capacitor. Two options were available for the disposal of the capacitor: landfill of hazardous waste and incineration of hazardous waste. Incineration has been assumed as it is more impacting, thus adopting a conservative perspective.
- all materials that cannot be fully separated after shredding are not suitable for recycling because contaminated and are sent to landfill.

The energy consumption due to the shredding and separation processes of the total mass entering in the shredder is included. No environmental impacts occur in the manual disassembly step. In agreement with the Recyclability rates calculated, the mass entering in the treatment plants is 6.34 kg for the steel and 0.295 kg for the aluminum. The whole burdens associated to the treatment of these amounts in the respective plants are accounted for. The treatment delivers 6.02 kg of secondary steel (slab) and 0.285 kg of secondary aluminum (ingot): credits associated to the avoided production of an equal amount of primary steel and aluminum, respectively, are accounted for. The treatment process for aluminum and steel (respectively, secondary aluminum production and secondary steel production) come from the PE database.

The quantity of copper sent to recycling is 0.638 kg.

The cooker hood rate sent to incineration for energy recovery is 0.43 kg, including plastic (cover 0.04 kg, protection layer 0.089 kg, PCBs 0.24) and glass (lamps 0.06 kg). The datasets of life cycle inventory (LCI) for incineration of plastic and glass come from PE/ELCD. The LCIs represent the share of environmental burdens (and credits for energy and metal scrap export, through system expansion) associated to the specific fraction in a European average Waste-to-Energy (WtE) plant treating European average Municipal Solid Waste (MSW). The datasets include the production of 1.09 GJ electricity and 3.2 GJ thermal energy per ton of treated MSW and a European average grid loss of about 7%. The EU 27 District Heating Mix 2002 and EU Electricity Mix 2002 are used for the credit calculation. Credits for the metal recovery are included by considering the standard metal production. Burdens of remelting and re-processing of scraps are considered.

A hazardous solid waste incineration process (HWI) from Ecoinvent 2.2, with a technology representing modern incineration practices in Europe, has been used to model the incineration of capacitor (0.065 kg). The whole burden (100%) is allocated to the waste disposal function of HWI; no credit is included for energy production.

The remaining mixed mass coming from the shredding process is 7.69 kg (steel 5.61 kg, glass 0.59 kg, plastic 1.3 kg, aluminum 0.198 kg) and is sent to landfill. To model the process, the following PE datasets have been used:

- Landfill of ferro metals, for steel and aluminum;

- Landfill of glass/inert waste;
- Landfill of plastic waste.

2.4. Application of the PEF EoL approach to the EoL of the aluminum filter and comparison with the avoided impact approach

The avoided impact approach has been used to modeling the EoL of the whole cooker hood, but for testing and comparison purposes with the PEF EoL approach (EC, 2013), the application to the end-of-life of a component, the aluminum filter, is here presented and discussed. The PEF EoL approach is based on the general idea that both demand and supply are needed to promote material recycling. The recycled material substitutes primary raw material for 50% and other secondary material for the remaining percentage (Ekvall, 2000). According to the PEF EoL approach, 50% of burden and credits associated to recycling (output) are allocated to the system under study. The same percentage is considered for the allocation of burdens and credits due to the use of recycled material in the manufacturing stage (input). Concerning the energy recovery, the whole burdens and credits are included, as in the avoided impact approach. The Eq. (2) represents the PEF EoL formula, as indicated in the Annex V of PEF methodology (EU Recommendation, 2013):

$$\begin{aligned}&\left(1-\frac{R_1}{2}\right)*E_V+\frac{R_1}{2}*E_{recycled}+\frac{R_2}{2}*\left(E_{recycling}-E^*{}_V*\frac{Q_S}{Q_P}\right)+\\&R_a*(E_{ER}-LHV*X_{ER,heat}*E_{SE,heat}-LHV*X_{ER,elec}*E_{SE,elec})+\\&\left(1-\frac{R_2}{2}-R_a\right)*E_D-\frac{R_1}{2}*E^*{}_D\end{aligned}\qquad(2)$$

where,

- R_1, is the “recycled (or re-used) content of material”. It is the proportion of material in the input to the production that has been recycled in a previous system ($0 \leq R_1 \leq 1$).

- R_2 is the “recycling (or reuse) fraction of material”. It is the proportion of the material in the product that will be recycled (or re-used) in a subsequent system. R_2 shall therefore take into account the inefficiencies all over the recycling (or re-use) processes ($0 \leq R_2 \leq 1$). The R_2 index corresponds to the overall recycling efficiency in Table 3.

- R_3 is the proportion of material in the product that is used for energy recovery (e.g. incineration with energy recovery) at EoL ($0 \leq R3 \leq 1$).

- E_V is the specific emissions and resources consumed (per unit of analysis) arising from virgin material (i.e. virgin material acquisition and pre-processing.

- $E_{recycled}$ is the specific emissions and resources consumed (per unit of analysis) arising from the recycling (or re-use) process of the recycled (or re-used) material, including collection, sorting and transport processes.

- $E_{recyclingEoL}$ is the specific emissions and resources consumed (per unit of analysis) arising from the recycling process at the End-of-Life stage, including collection, sorting and transportation processes. In closed loop $E_{recyclingEoL} = E_{recycled}$

- $E^*{}_V$ is the specific emissions and resources consumed (per unit of analysis) arising from virgin material (acquisition and pre-processing) assumed to be substituted by recyclable materials. In closed loop $E^*{}_V = E_V$.

- E_D is the specific emissions and resources consumed (per unit of analysis) arising from disposal of waste material at the EoL of the analyzed product (e.g. landfill, incineration, pyrolysis).

- $E^*{}_D$ specific emissions and resources consumed (per unit of analysis) arising from disposal of waste material (e.g. landfilling, incineration, pyrolysis) at the EoL of the material where the recycled content is taken from. In closed loop $E^*{}_D = E_D$.

- E_{ER}, are specific emissions and resources consumed (per unit of analysis) from the energy recovery process.

- $E_{SE,heat}$ and $E_{SE,elec}$ are specific emissions and resources consumed (per unit of analysis) that would have arisen from the specific substituted energy source, heat and electricity, respectively.

- $X_{ER,heat}$ and $X_{ER,elec}$ are the efficiency of energy recovery process for heat and electricity;

- LHV is the Low Heating Value of the material in the product that is used for energy recovery.

- Q_S/Q_P is the ratio between the quality of secondary material (recycled) and the quality of primary material.

The Recyclability rate and the avoided virgin material defined in section 2.2 for aluminum have been considered. The R_2 index calculated for the filter, which represents the efficiency of the overall recycling process (Table 3), is equal to 0.432 and lower than the Recyclability rate. The R_3 index is zero because no filter fraction is sent to energy recovery. The application of the PEF EoL formula requires also the following information:

- for each material included in the product under study, the percentage of recycled as well as the process for the production of recycled itself (related recycling process);

- for each recycled material used in the product under study, the disposal (e.g. landfilling, incineration) from which material has been diverted.

In this case study, we assumed that the aluminum used in the manufacturing of the product is from primary production ($R_1=0$).

Considering the Recyclability rate, 0.162 kg (45% of the aluminum) are sent to treatment (aluminum recycling plant), while 0.198 kg are sent to landfill. Unlike the avoided impact approach, in the PEF EoL approach, burdens and credits associated to the whole recycling process (from collection to the treatment) are accounted for an $R_2/2$ proportion of filter mass, that means, in our case, a factor equal to 0.216. According to the formula, a landfill process is associated to the remaining mass proportion and the related impacts. Being zero R_1 and R_3, the impacts associated to the filter EoL depends just on the production, recycling (including avoided burden) and disposal. Fig. 3 shows the schema of the PEF EoL and avoided burden approaches application to the aluminum filter, in order to highlight the differences.

The Table 4 summarizes final quantity of aluminum associated to each process occurring within the aluminum filter EoL.

3. Results

3.1. The EoL of the cooker hood, according the avoided burden approach

The environmental impacts associated to the EoL of the cooker hood are here reported for ADP Elements, ADP Fossil and GWP. Figs. 4 - 6 show the total values and process contributions.

The recycling treatment includes the re-processing of steel and aluminum scrap in the recycling plant for the production of secondary materials and the avoided impact includes the avoided primary production of steel and aluminum. The environmental impacts due to landfill of glass and plastic, electricity consumption for shredding and transport are grouped into other contributions.

For all the reported impact categories the most important contributions are from either incineration or treatment. The benefits of material recycling (avoided impact) are evident. The steel avoided production gives the main contribution to ADP fossil and GWP (about 82% of the total avoided impact), while in ADP element the main contribution comes from the aluminum avoided production (about 58%). For both ADP Fossil and GWP the avoided burden is the key factor driving the final results of the EoL. This is due to high energy consumption associated to primary steel and aluminum that will not be produced thanks to the recycling.

Table 5 shows that major contributions to all the impact categories come from the capacitor incineration and the steel treatment. The contribution of landfill is always negligible. The avoided impact of glass and plastic incineration in the ADP elements and fossil is due to energy recovery. Regarding the GWP, the emissions from plastic and glass incineration are higher than those related to the energy recovery, so the results show positive values of the impacts.

3.2. The end of life of the aluminum filter – comparison between the PEF EoL approach and the avoided burden approach

Here below the results are given of the EoL of the aluminum filter in agreement with the two approaches considered. The environmental advantages generated by the EoL and calculated with the PEF EoL approach are lower than those resulting from the avoided impact approach. This applies to all the analyzed impact categories, as shown in Figs. 7 - 9. Differences between the approaches are about 80% and are mainly due to two aspects: i) the amount of material sent to recycling is about five times higher in the avoided burden approach than in the PEF EoL; ii) the environmental impacts due to the production of primary aluminum are much higher if compared to the impacts of the recycling process. Data of literature report that recovering aluminum from scrap to produce secondary aluminum ingot consumes about 6 percent of the energy required to produce primary aluminum (approximately 23.8 kWh/kg of aluminum produced from bauxite ore) (U.S. Department of Energy, 2007).

Table 4. Comparison of mass accounted for in each EoL process of the aluminum filter, according to the avoided burden approach and the PEF EoL approach

	Avoided burden approach (kg)	***PEF EoL approach (kg)***
Aluminum production	0.36	0.36
Shredding	0.36	0.078
Treatment (aluminum secondary production)	0.162	0.035
Avoided impact (aluminum primary production)	0.155	0.033
Landfill	0.198	0.32

Table 5. Detailed analysis on process contributions (burdens) to the environmental impacts of cooker hood EoL. Percentages are calculated on the total positive values of the potential impacts

Contributions	***Environmental burden associated to EoL – ADP Element***	***Environmental burden associated to EoL – ADP Fossil***	***Environmental burden associated to EoL – GWP***
Capacitor incineration	51%	28%	35%
Plastic and glass incineration	-2%	-10%	5%
Steel treatment	32%	43%	37%
Aluminum treatment	12%	3%	2 %
Transport	1%	12%	9%
Electricity	2%	11%	10%
Landfill	2%	3%	2%

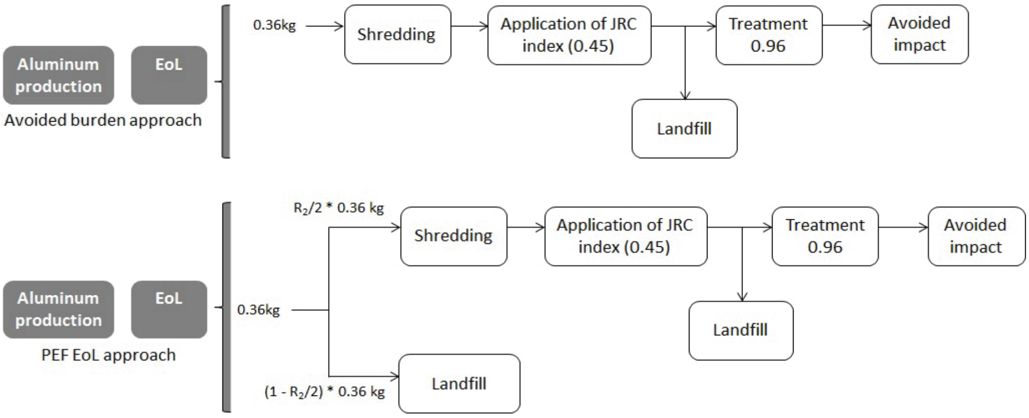
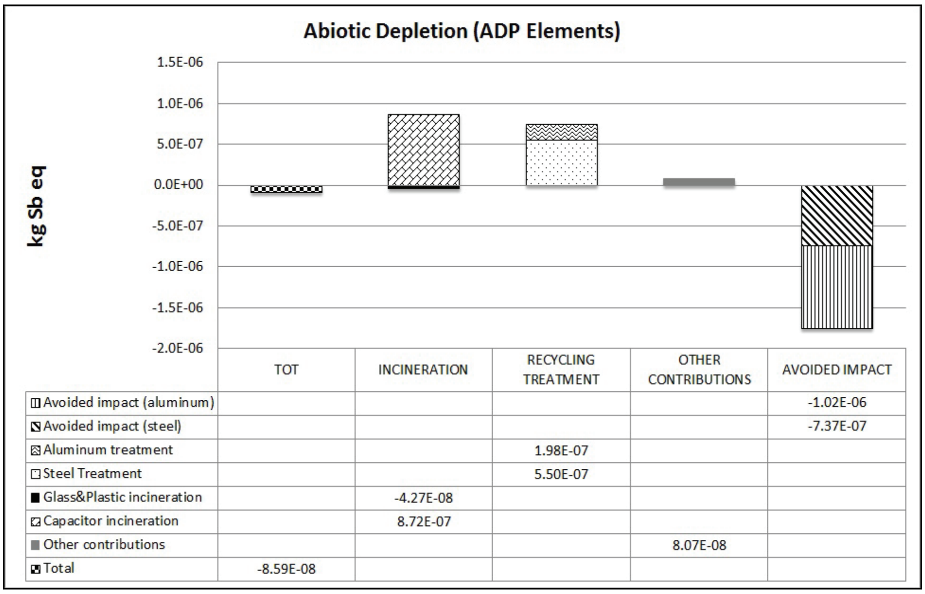
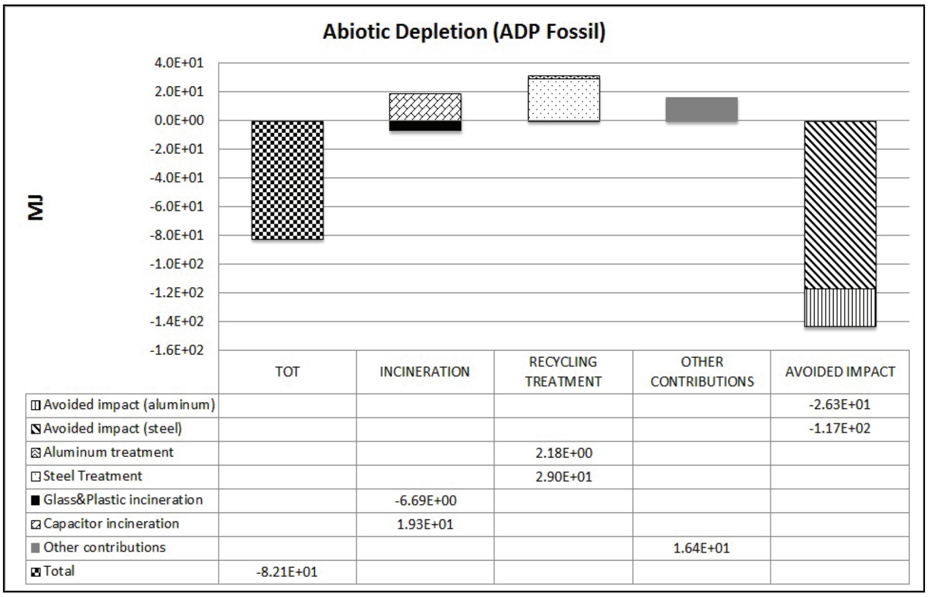


Fig. 3. PEF EoL and avoided burden approaches application to the aluminum filter



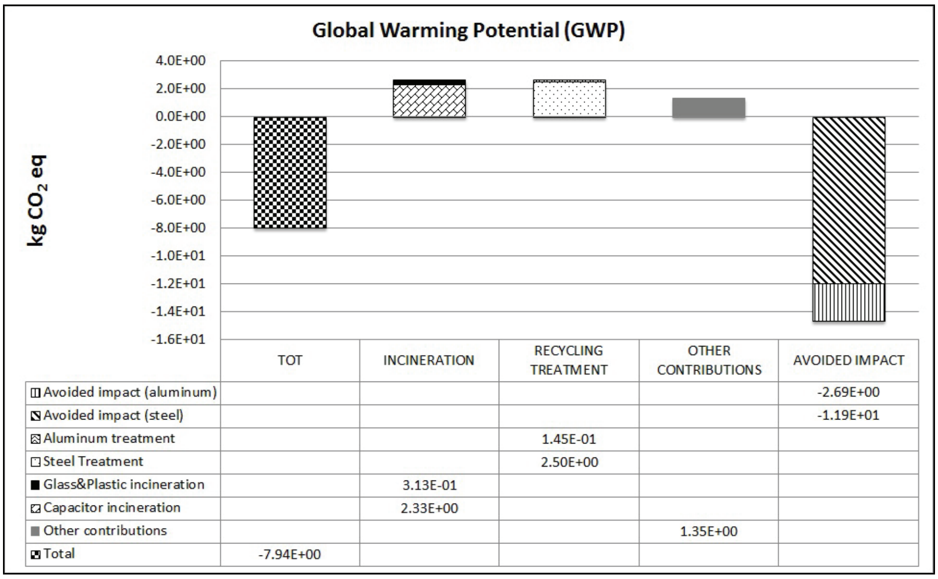
	TOT	INCINERATION	RECYCLING TREATMENT	OTHER CONTRIBUTIONS	AVOIDED IMPACT
▥ Avoided impact (aluminum)					-1.02E-06
▧ Avoided impact (steel)					-7.37E-07
▨ Aluminum treatment			1.98E-07		
□ Steel Treatment			5.50E-07		
■ Glass&Plastic incineration		-4.27E-08			
▨ Capacitor incineration		8.72E-07			
■ Other contributions				8.07E-08	
▦ Total	-8.59E-08				

Fig. 4. Avoided burden approach - Process contributions to the total environmental impacts (burdens and credits) associated to the EoL of the cooker hood – ADP Elements [kg Sb-Equiv.]



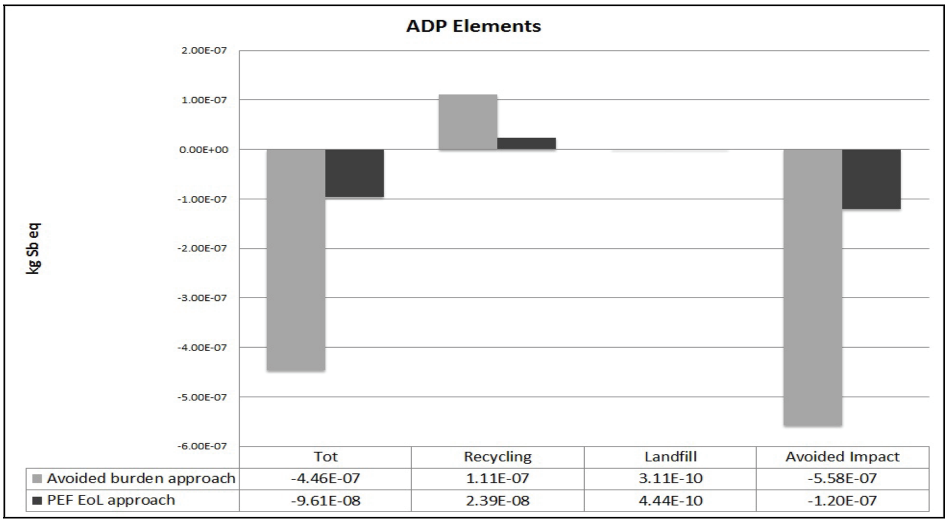
	TOT	INCINERATION	RECYCLING TREATMENT	OTHER CONTRIBUTIONS	AVOIDED IMPACT
▥ Avoided impact (aluminum)					-2.63E+01
▧ Avoided impact (steel)					-1.17E+02
▨ Aluminum treatment			2.18E+00		
□ Steel Treatment			2.90E+01		
■ Glass&Plastic incineration		-6.69E+00			
▨ Capacitor incineration		1.93E+01			
■ Other contributions				1.64E+01	
▦ Total	-8.21E+01				

Fig. 5. Avoided burden approach - Process contributions to the total environmental impacts (burdens and credits) associated to the EoL of the cooker hood – ADP Fossil [MJ]



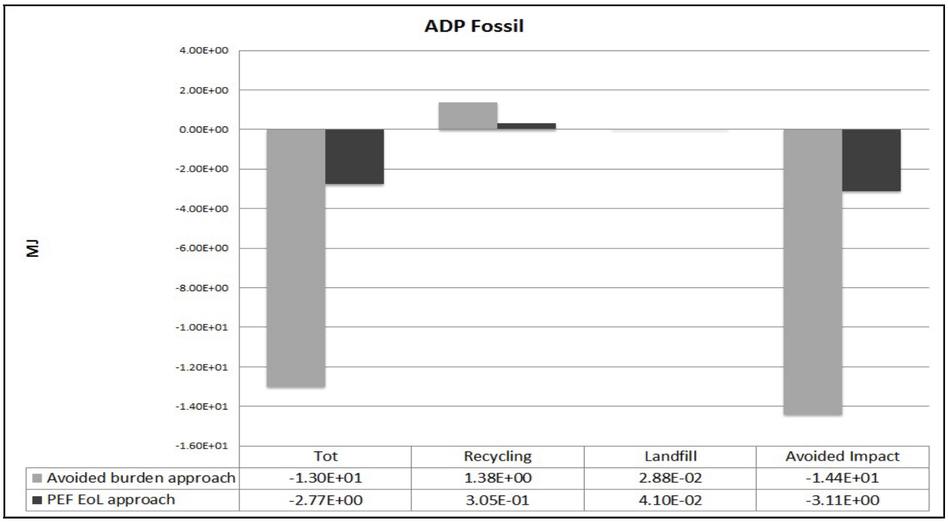
	TOT	INCINERATION	RECYCLING TREATMENT	OTHER CONTRIBUTIONS	AVOIDED IMPACT
▥ Avoided impact (aluminum)					-2.69E+00
▧ Avoided impact (steel)					-1.19E+01
▩ Aluminum treatment			1.45E-01		
□ Steel Treatment			2.50E+00		
■ Glass&Plastic incineration		3.13E-01			
▨ Capacitor incineration		2.33E+00			
■ Other contributions				1.35E+00	
▦ Total	-7.94E+00				

Fig. 6. Avoided burden approach - Process contributions to the total environmental impacts (burdens and credits) associated to the EoL of the cooker hood – GWP [kg CO2-Equiv.]



	Tot	Recycling	Landfill	Avoided Impact
■ Avoided burden approach	-4.46E-07	1.11E-07	3.11E-10	-5.58E-07
■ PEF EoL approach	-9.61E-08	2.39E-08	4.44E-10	-1.20E-07

Fig. 7. Comparison between process contributions to the environmental impact (ADP Elements – kg Sb eq) associated to the EoL of the aluminum used in the filter



	Tot	Recycling	Landfill	Avoided Impact
■ Avoided burden approach	-1.30E+01	1.38E+00	2.88E-02	-1.44E+01
■ PEF EoL approach	-2.77E+00	3.05E-01	4.10E-02	-3.11E+00

Fig. 8. Comparison between process contributions to the environmental impact (ADP Fossil - MJ) associated to the EoL of the aluminum used in the filter

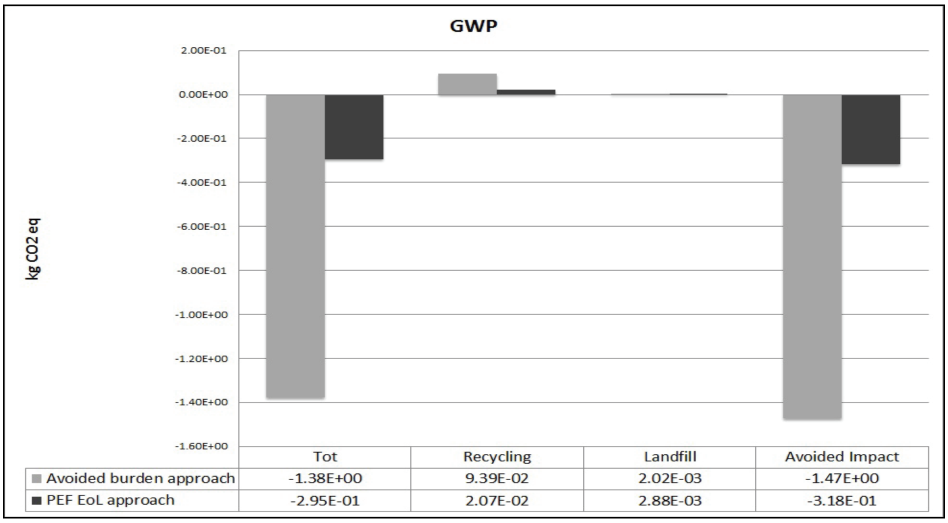


Fig. 9. Comparison between process contributions to the environmental impact (GWP - kg CO_2 eq) associated to the EoL of the aluminum used in the filter

4. Discussion

WEEE contains substantial quantities of valuable materials, in particular base metals such as copper, gold and palladium (Robinson, 2009), which are interesting for recovery purposes. Besides the WEEE Directive (EU Directive, 2012), this is the reason why WEEE collection and recovery have significantly grown in importance all over Europe (Sinha Khetriwal, 2009). Several studies have been conducted assessing environmental loads and advantages of WEEE well established collection and recovery systems at a local scale (Wäger et al., 2011). They highlight that, if the complete recycling chain is considered, the main impacts are associated to the final treatment applied to turn waste into secondary materials (Hischier et al., 2005), and sorting (and dismantling) activities give a small contribution to the total impacts.

Few studies have been conducted on single classes of WEEE, such as household appliances, mainly addressing the economic evaluation of optional recycling processes (Liu et al., 2009) or the environmental impacts all over the life cycle of the products (Bevilacqua et al., 2010).

Instead, critical aspects arise in LCA when modeling the EoL phase, in particular the definition of reference EoL scenario, the EoL treatment of trace elements and the methodological approach to account for burden and credits.

This study aims to add some elements to the discussion of these aspects.

The analysis of the defined scenario of cooker hood EoL shows how the manual disassembly procedure allows higher recyclability rates if compared to mechanical disassembly. However, components design often hampers fast and economic manual separation of materials, thus lowering their recyclability rate. In this scenario the copper is totally recovered for recycling, while the recyclability rates of other valuable materials such as steel and aluminum are strongly reduced by the use of a mechanical disassembly procedure. Nevertheless, the environmental advantages of the recycling are evident in the LCA results for all the three selected impact categories.

A point that should be analyzed more in detail is the potential of recovery and recycling of precious metals, whose primary production significantly affects the impact category ADP (elements). In this study, although PCBs are manually dismantled they have been assumed to be sent to incineration. In fact, as Chancerel et al. (2009) highlight, pre-processing facilities are optimized for recovering mass-relevant materials (steel, copper), while precious and special metals, which are contained at very small concentration in complex components (e.g., PCBs), are often lost.

On one side this calls for the implementation of specialized recovery systems. On the other side, a correct assessment of the potential benefits/disadvantages arising from precious metals recovery requires the definition of detailed technology and management scenarios and the availability of reliable data on resources and energy consumption, waste and emissions related to the recovery processes (Bigum et al., 2012).

As far as the methodological approach to account for burdens and credits is concerned, the application of both the analyzed EoL approaches presents some critical steps, in particular: the identification of the avoided primary material production and the availability of accurate data along the value chain for the calculation of the recyclability rate and R_2 index. Moreover, the application of PEF EoL approach is more complex than the avoided impact one since it requires additional information for the calculation of the other R indexes and the EoL burdens/credits assessment, i.e. the recycled content and the avoided disposal (e.g. landfill, incineration etc.) for the recycled material used in the product. The availability of such information strongly depends on the EoL management operated in each country as well as on the specificity of each material supply chain involved in the product. Further difficulties to model the EoL according to the PEF approach are due to the LCI datasets available. Two critical points can be highlighted: 1) the lack of clear and transparent documentation to understand whether credits and/or burdens for recycling are already accounted for; 2) the availability of aggregated datasets, often not parameterized, which cannot be adjusted according to the needs of the different EoL approaches.

5. Conclusions

A cooker hood EoL scenario has been defined on the basis of a detailed analysis of scientific and grey literature, visit to disposal plants, interviews with experienced operators and scientific experts. The disassembly steps at the dismantling site have been defined on the basis of the materials value and the time and cost needed for components dismantling. Being the recyclability rates "theoretical" and strongly cautious for the studied product, the definition of a realistic EoL scenario, including actual recyclability (and recoverability) rates, and the quantification of its environmental impacts stood out as urgent issues to plan adequate improvement actions for this waste flow and, more in general, for all WEEE. The analysis of the environmental impacts of the EoL scenario has been performed by using the avoided burden and the PEF EoL approaches. The results have highlighted that the application of both of them presents critical steps, discussed in the previous section. Here two aspects concerning the PEF EoL application deserve to be emphasized. Firstly, further guide would be necessary for the calculation and use of R indexes. In fact, if a well-defined and documented EoL scenario is not available, the PEF EoL formula leaves room for interpretation and subjectivity, thus contrasting with the harmonization objectives it aims to. Secondly, since the PEF has the general aim to promote a recycling-based economy, it is urgent to extend the application to other supply chains and to investigate the extent to which it succeeds in achieving this goal.

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