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Research Paper

Environmental sustainability assessment processes for flat panel displays dismantling

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ABSTRACT

The growing quantity of flat panel displays (FPDs) on the market, combined with rising raw material demand, makes the sustainable management of resulting waste a hot topic. Despite of research often describes innovations in recycling, it often neglects the pre-treatment step. However, it represents a key aspect for the success of the further recovery of valuable fractions, since it affects the integrity of materials, the possible presence of impurities and hazardous substances, but also the sustainability of the whole recycling chain. In this regard, the present paper assesses the sustainability of two options implemented at real scale: a more traditional crushing (followed by magnetic separation) and an innovative solution which combines manual and robotic dismantling, resulting in the separation of high-quality fractions. The analysis, carried out by a life cycle approach, proves the high potential of the innovation from an environmental point of view with emission savings reaching up to 90% in key categories (e.g. climate change). The benefit, confirmed irrespective of the supplied energy mix and the classification of waste resulting from crushing (hazardous or not hazardous), is further highlighted by the possibility to separate high-value fractions, mainly printed circuit boards of three different qualities, based on their valuable metal content. The results represent an important driver towards the implementation of sustainable choices in the field of FPD recycling.

1. Introduction

1.1. Current situation of flat panel display

The Global E-waste Monitor 2024 reports a record of 62 billion kg of waste from electrical and electronic equipment (WEEE) generated worldwide in 2022, which corresponds to around 7.8 kg per capita per year. Projections indicate that this quantity will reach 82 billion kg by 2030. Only 22.3 % of this e-waste was documented as formally collected and recycled in an environmentally sound manner (Baldé et al., 2024). Screens and monitors account for approximately 10 % of generated WEEE. They consist of a variety of components and materials, including plastic housings, metal frames, cables, backlights, printed circuit boards (PCBs), and liquid crystal glass, many of which are potentially recoverable (Amato et al., 2017; Baldé et al., 2024; Fontana et al., 2021). The composition of this kind of equipment varies depending on the brand and technology generation. In this regard, 87 % of FPDs manufactured until 2013 (many of which are now reaching end-of-life) were liquid crystal displays (LCDs), 72 % of which used mercury-containing cold cathode fluorescent lamps (CCFLs). The remaining 28 % was mercury-free, due to the LED use (Peeters et al., 2013). After the collection, FPDs were pre-treated for the separation of the different fractions to send to recycling or landfilling. The two most common techniques used for display dismantling and pre-treatment are automated shredding processes (followed by magnetic separation) and partial manual disassembly (Elo and Sundin, 2014). The selected pre-treatment is fundamental for the effectiveness of further recycling. Manual dismantling, although requiring additional workers, ensures the highest quality of separated fractions. In contrast, shredding causes material losses and reduces the quantity of materials suitable for recycling. This aspect is mainly due to the presence of hazardous materials, incompatible with recycling (e.g. mercury and flame retardants), and the increase of impurities within the separated materials (Ardente et al., 2014; Borrirukwisitsak et al., 2023; Stubbings et al., 2019). The automation system represents an interesting alternative in the WEEE dismantling field, since it limits human involvement, thereby increasing process repeatability and decreasing occupational risks (Büker et al., 2001; Liu et al., 2019; Lu et al., 2023). The automation can be implemented as: fully

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automated disassembly method, that primarily uses automated equipment and robot operations, with absent or limited human involvement; semi-automated operations, referred to hybrid disassembly, in which hazardous, repetitive, or heavy-duty tasks are handled by automatic devices, monitored by operators; intelligent disassembly, a more advanced disassembly method, in which artificial intelligence allows high-efficiency level and greater accuracy. The third option integrates advanced algorithms and machine learning to analyze and identify specific components and to further define the best disassembly option (Lu et al., 2023). The heterogeneity of input panels, usually not designed for recycling, results in different location of the components, which represents the greatest challenge of automatic methods (Elo and Sundin, 2014; Keal et al., 2025). A successful example of robotics integration in the field of WEEE dismantling is Apple's Daisy system, which is capable of disassembling 15 iPhone models, at a rate of 200 devices per hour (Apple, 2019; Keal et al., 2025; Lu et al., 2023). In the field of FPD dismantling, Hiro Robotics, an Italian start-up, founded in 2018, developed an innovative technology, named TEIA, which consists of a robotic line (available at industrial scale) designed for FPD disassembly (Hiro Robotics, 2018).

1.2. *Dismantling in view of a successful circular economy*

It is evident that the steps of dismantling and pre-treatment represent a key factor for the success of the FPD recycling and they can significantly contribute to improving process sustainability. However, the current literature about display recycling mainly focuses on other aspects, such as the recovery of specific materials, as indium from the indium tin oxide (ITO) film (Amato et al., 2020; Dhiman and Gupta, 2020; Wang et al., 2015), or plastics (Ferella et al., 2016; Peeters et al., 2014), often highlighting the sustainability aspects by standardized method of life cycle assessment (LCA)(Amato et al., 2017, 2016; Labra Cataldo et al., 2025), also comparing recycling with baseline options, such as incineration (Yu et al., 2019). Few papers discuss the pre-treatment of FPDs. In this regard, Borrirukwisitsak et al. (2023) consider the manual dismantling option, taking into account different kinds of WEEE, including TV and monitors in Thai context (Borrirukwisitsak et al., 2023). On the other hand, Dodbiba et al. (2012) compare two different lab scale methods for the obsolete LCDs aimed at further indium and glass recoveries, i.e. electrical disintegration and a conventional grinding, identifying the first option as the most sustainable in the categories of depletion of abiotic resources, global warming, acidification, the photo-oxidant formation, the eutrophication, and the human toxicity (Dodbiba et al., 2012). Overall, dismantling remains a marginal topic in sustainability studies on WEEE recycling. Pre-treatment is often excluded from system boundaries, as if it had no effect on environmental sustainability and resource conservation (Cardamone et al., 2021). However, disassembly and pre-treatment represent key steps for the effective implementation of circular economy principles, as they provide insights into how WEEE management in the EU can be adapted to increase component recovery. These stages directly influence subsequent processes such as remanufacturing, reconditioning, repairing, recycling, repurposing, and reusing, in accordance with the Circular Economy Action Plan (European Commission, 2020; Long et al., 2016). In this regard, Vanegas et al. (2018) highlighted how the chosen disassembly technique influences the economic feasibility of FPD recycling, increasing the viability of a circular economy in industrialized regions without, however, focusing on environmental aspects (Vanegas et al., 2018). To fill the knowledge gap on FPD pre-treatment sustainability, the present study compares two options: TEIA technology by Hiro Robotics versus traditional shredding. Industrial-scale data on raw materials and energy balances enabled more robust and reliable results than typically reported in the literature. The findings not only evaluate process sustainability but also highlight opportunities for designing future FPDs for improved recyclability, aligning with circular economy principles and Extended Producer Responsibility.

Table 1
Mass and energy balances, data supplied by Hiro Robotics to UNIVPM for data collection. (Material losses due to machine operations were considered in the balance).

Input	Output
Hiro Robotics Scenario	
End-of-life FPDs 1,800 tons	Valuable fractions
Electricity 75,000 kWh	Aluminium 63 tons
Consumables:	Plastic (ABS) 348 tons
Chromium-molybdenum steel components for unscrewing cell 0.16 kg	Iron 719 tons Cables 20 tons PMMA 177 tons
Steel K110 tearing blades 0.46 kg	PCBs-high quality 9 tons
	PCBs-medium quality 64 tons
	PCBs-low quality 68 tons
	Waste to dispose
	Municipal waste:
	Over screen 140 tons
	LCD panel 180 tons
	Hazardous waste:
	Condensers 3.4 tons
	CCFL 10 tons
Baseline scenario	
End-of-life FPDs 1,800 tons	Valuable fractions
Electricity 185,400 kWh	Aluminium 63 tons
	Iron 719 tons
	Cables 20 tons
	PCBs-medium quality 105 tons
	Waste to dispose
	Hazardous waste:
	CCFL 10 tons
	Condensers 3.4 tons
	Over screen 140 tons LCD panel 180 tons
	Plastic (ABS) 348 tons PMMA 177 tons

2. Materials and methods

2.1. *Software and methods*

The present study is a comparative LCA aimed at identifying of the most sustainable way for the dismantling of waste FPDs, considering two real-scale options, i.e. the innovative TEIA technology developed by Hiro Robotics vs. a traditional crushing. The functional unit selected for the evaluation is 1,800 tons of end-of-life FPDs, the annual capacity of the standard configuration of TEIA technology. This estimate assumes the possibility to dismantle 60 FPD/h, for two shift works (each one of 7.5 h), per 250 days per year, assuming an average weight of each FPD of 8 kg. Mass and energy balances, detailed in life cycle inventory section, were built in accordance with information supplied by Hiro Robotics and Ardente et al. (2014) and reported in Table 1 to ensure the repeatability of the LCA. The steps included in the LCA were goal and scope definition, life cycle inventory, life cycle impact assessment (LCIA) and data interpretation, following the flowchart in Fig. S1. More in detail, the LCIA included classification and characterization (mandatory), normalization and weighting (recommended), according to the standard methods. The software used for data collection is LCA for Experts (by Sphera) v. 10.9.1.10, combined with My Professional Database v. 2025.1. The production process of indium (considered for the estimation of the potential environmental gain resulting from the process) was taken from Ecoinvent 3, integrated within the software SimaPro 9.0.6.1. The method selected for the analysis is EF 3.1, including all the impact categories, recommended models at midpoint, together with their indicators, units and sources (European Commission, 2022a). The whole study is carried out by a LCA approach conforming to the LCA ISO standards 14,040 and 14044:2006 (UNI EN ISO 14040: 2006. *Environmental management – life cycle assessment – principles and framework.*,

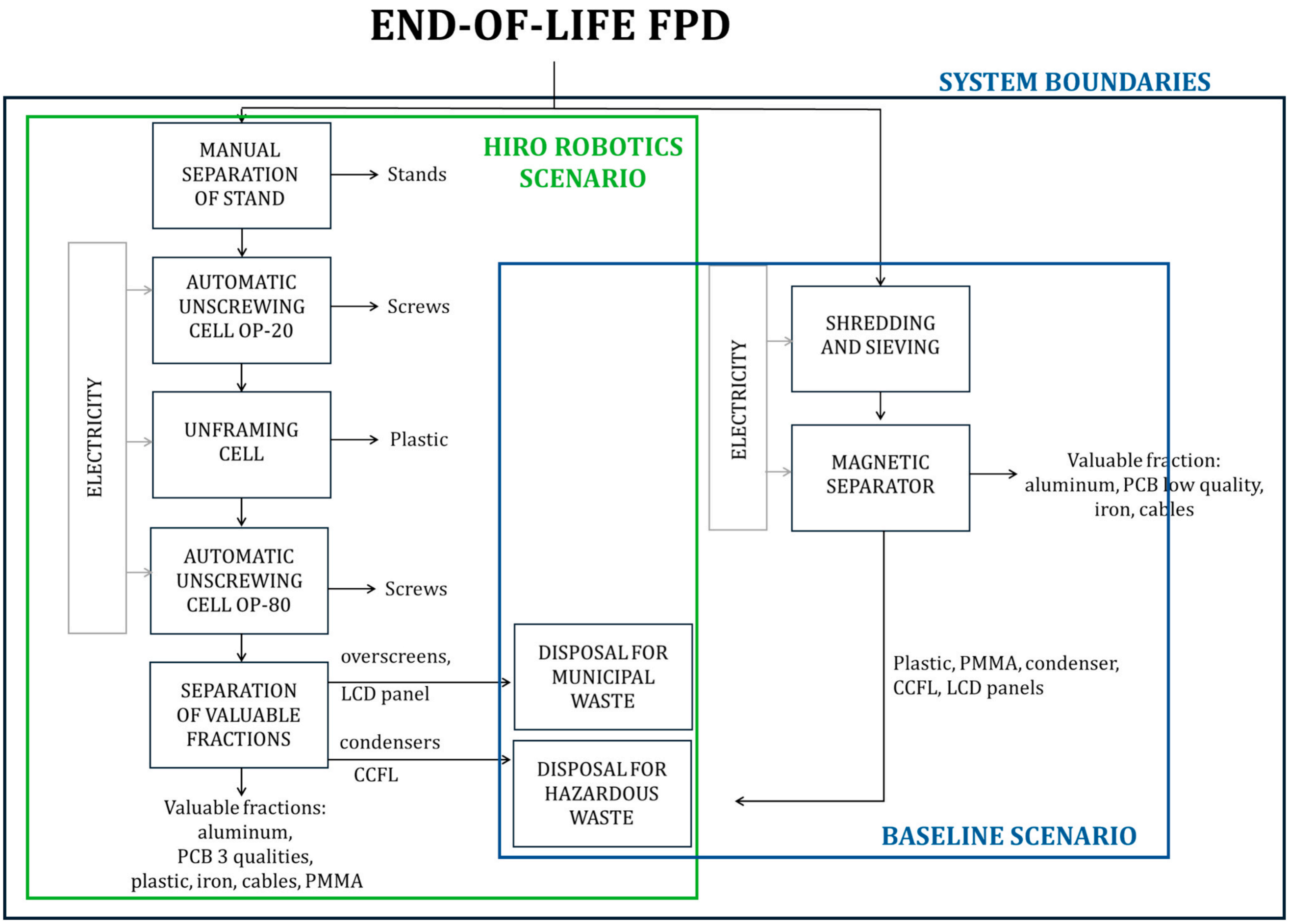

Fig. 1. System boundaries selected for the present analysis.

2006, "UNI EN ISO 14044:2006 Environmental management – Life cycle assessment – Requirements and guidelines," 2006). Table S1 summarizes the impact categories included in the analysis.

2.2. Description of considered scenarios

Fig. 1 represents the system boundaries chosen for the analysis, including two scenarios which started with the supply of end-of-life FPDs. In both cases, valuable fractions were included as output flows and the process residues were sent to the final disposal after the classification as hazardous or not hazardous, based on their properties. The Hiro Robotics scenario allows the production of higher quality fractions, compared to the baseline scenario, due to the combination of manual dismantling and automated steps. The baseline scenario is composed of more traditional mechanical pre-treatments including shredding and sieving and a final magnetic separation. In both cases, electricity is the main input flow.

TEIA technology, considered in the Hiro Robotics scenario, has been designed for the treatment of FPDs (Fig. S2). The plant target is to accelerate the disassembly process through three automated processes, performed with the assistance of industrial robots, alternated with tasks performed by four specialized operators. The cycle time resulting from the combination of robots and operators is 60 FPD/h(based on heterogeneous FPDs of average dimensions adhering to the process specifications).

More in detail, the TEIA unit includes three main elements: 1. automatic unscrewing cell OP-20, a robotic unscrewing station for the disassembly of the rear cover of the waste 2. unframing cell, robotic cell for removal of the front plastic frame, delimited by physical or photoelectric perimeter barriers, with access points for operators when the machinery is stopped, plus a waste discharge conveyor. The unframing machine is fed by an industrial robot 3. automatic unscrewing cell OP-80, a robotic unscrewing station for the disassembly of the internal parts of the waste. Overall, the process follows the steps reported below.

- The operator removes the stand of a FPD and loads it on the input conveyor of the unscrewing cell.
- The FPD enters the unscrewing cell and it is centered by a mechanical device.
- A robot equipped with computer vision systems scans the FPD and removes the screws from the cover. The robot is equipped with an industrial screwdriver, illuminator, and camera.
- The FPD from the unscrewing cell moves to a conveyor belt for the next phase.
- An industrial robot with a specific gripping hand picks up the FPD and loads it onto the unframing machine.
- The unframing machine mechanically forces apart the front frame until it breaks.
- Plastic residues from the frame are removed from the cell by a conveyor belt located beneath the unframing machine.
- The industrial robot picks up the unframed FPD and deposits it onto the discharge conveyor.
- The FPD moves on a transport belt out of the cell and reaches a manual processing station, where an operator removes the no longer integral parts and cabling.
- The operator loads the FPD onto the input conveyor of the next unscrewing cell.

- The FPD enters the unscrewing cell and it is centered using a mechanical device.
- A robot equipped with computer vision systems scans the FPD and removes the screws holding the electronic boards together. The robot is equipped with an industrial screwdriver, illuminator, and camera.
- The FPD exits the unscrewing cell via a free discharge conveyor and reaches an operator pickup point.
- Operators complete the disassembly at their respective stations, which includes sorting the remaining parts and managing the CCFL tubes.

The pre-treatment produces valuable fractions, such as aluminum, PCBs of three different qualities, plastic, iron, cables, PMMA and residue, mainly over screen, CCFL, condenser, the LCD panel.

The baseline scenario, commonly used for the WEEE treatment (categories R3 and R4), includes a primary shredder, with a capacity around 2 tons/h and an installed capacity of 285 kW, plus an additional 40–50 kW for the suction system. A magnetic system allows the separation of a fraction rich in iron and aluminum (Sollau, 2025). This material is sold as a mix of these metals, reducing its value due to aluminum presence. PCBs and cables are manually separated, with material loss around 25 %. During the treatment many valuable components are lost and the resulting PCB flow is comparable to second-quality PCBs. The remaining flow is a waste composed of plastic, PMMA, crushed CCFL, condenser and LCD panel. In this case, the PMMA is considered a waste since shredding makes it not recyclable, contrary to that resulting from TEIA technology. This material is classified as hazardous waste due to the presence of brominated flame retardants, which also makes its incineration difficult (Söderström and Marklund, 2002). Therefore, it is usually sent to landfilling sites for hazardous waste.

2.3. The inventory analysis

Mass and energy balances used for the present analysis (Table 1) were supplied by Hiro Robotics. The company has detailed information about TEIA technology (Hiro Robotics scenario). The design of the baseline scenario reflects that reported in the literature, related to a shredding-based treatment (Ardente et al., 2014).

Some assumptions were included in the analysis.

- An average European grid mix was selected for the electricity production
- As concerns the tearing blades, included among the consumables, stainless steel was considered in place of steel K110, missing in the database. However, this assumption is not considered relevant since the necessary quantity is lower than 0.001 % compared to the treated FPDs, in accordance with the cut-off criteria.
- In Hiro Robotics scenario the non-recyclable fractions were considered plastic, managed on municipal landfilling site (over screens and LCD panel) and as hazardous waste (condensers, and CCFL). CCFL were considered as hazardous waste, properly managed considering the possible Hg content. This assumption guarantees conservative conditions, though CCFL could be enhanced for the recovery of valuable elements (Ippolito et al., 2022; STENA Recycling, 2025). In the baseline case the same fractions with the addition of the shredded PMMA and plastics were managed as hazardous waste, due to the possible presence of bromide compounds. A further sensitivity analysis will assess the possibility of different classification of these residues.
- Transport was excluded from both the scenarios since it is strongly connected to the place where the plant is located.
- Other aspects excluded from the analysis were the infrastructures (not relevant for the defined target) and the human work (usually not quantifiable by an LCA).
- Environmental credits, i.e. the avoided impact for primary production of materials, were associated to the different fractions recovered by the two different processes. It is evident that, for a whole assessment, also the impact of the recycling processes of each fraction should be included in the evaluation. However, this is not the focus of the present report and the credit assumption allowed to estimate the potential value resulting from the different quality materials separated by Hiro technology vs. a most traditional shredding. The credit assumption avoided the allocation procedure, in agreement with that reported in the ISO standards 14044:2006.
- An additional recovery of indium from LCD panels was included among the credits, considering an average indium concentration of 150 ppm (Rocchetti et al., 2015). This practice is not commonly implemented at industrial-scale, but the estimation of the possible environmental gain was considered of interest for the present analysis.
- Material losses of 25 % were considered for baseline scenario (attributed to PCBs, considered as the largest losses), in agreement with Ardente et al. (2014) and Ljungkvist et al. (2016) (Ardente et al., 2014; Ljungkvist et al., 2016)

Table 2
Metal concentrations considered for the estimation of process credits.

	Gold	Silver	Copper
	g/kg		
Low quality	0.07	0.2	100
Medium quality	0.12	0.4	200
High quality	1	4	270

The environmental credit due to the PCB recycling was estimated considering the concentration of gold, silver and copper, excluding other valuable metals (e.g. platinum) to ensure conservative conditions. The recovery of these elements was considered strategic since the current worldwide primary production was estimated around 3.3 ktons of gold (European Commission, 2025a), 25.5 ktons of silver (USGS, 2025)and 22.2 Mtons of copper, (European Commission, 2025b). For these metals it was assumed a 97 % recovery efficiency, in agreement with that reported in the literature (Chancerel et al., 2009; Meskers, C.E.M. Hagelüken et al. (2009); Peeters et al., 2013). The PCBs were classified in three different quality classes (high, medium and low), based on metal content. Table 2 reports the average concentration of gold, silver and copper estimated for the three qualities of PCBs separated by Hiro Robotics technology, starting from scientific literature data (Awasthi and Zeng, 2019; Becci et al., 2024; Kaya, 2019; Meng et al., 2018; Petter et al., 2014). Considering the lowest separation efficiency of baseline scenario, all PCBs were considered as medium quality.

- Plastic considered for environmental credits was assumed to be acrylonitrile butadiene styrene (ABS) (Sin et al., 2025) and it was assumed a recyclability of 75 % (Peeters et al., 2013).
- A complete recyclability of not crushed PMMA from Hiro scenario was assumed, in agreement with efficiency reported in the literature (Kikuchi et al., 2014)
- It was considered recycling yields of 98 % for both aluminum and iron, according to the literature (International Aluminium Institute, 2009; SSAB, 2025).
- A 50 %-efficiency was assumed for the cables, considering their composition variability.

The analysis included a statistical evaluation to assess the effect of variations in the most relevant aspects identified by the LCA (e.g. electricity). The Montecarlo approach, widely used the sustainability analysis, was applied (Amato et al., 2021; Loya-González et al., 2019; Valiante et al., 2019). On the other hand, the quality of data extracted from the databases was estimated by the pedigree matrix, in accordance with the United States Environmental Protection Agency (EPA) guidelines (EPA, 2016).

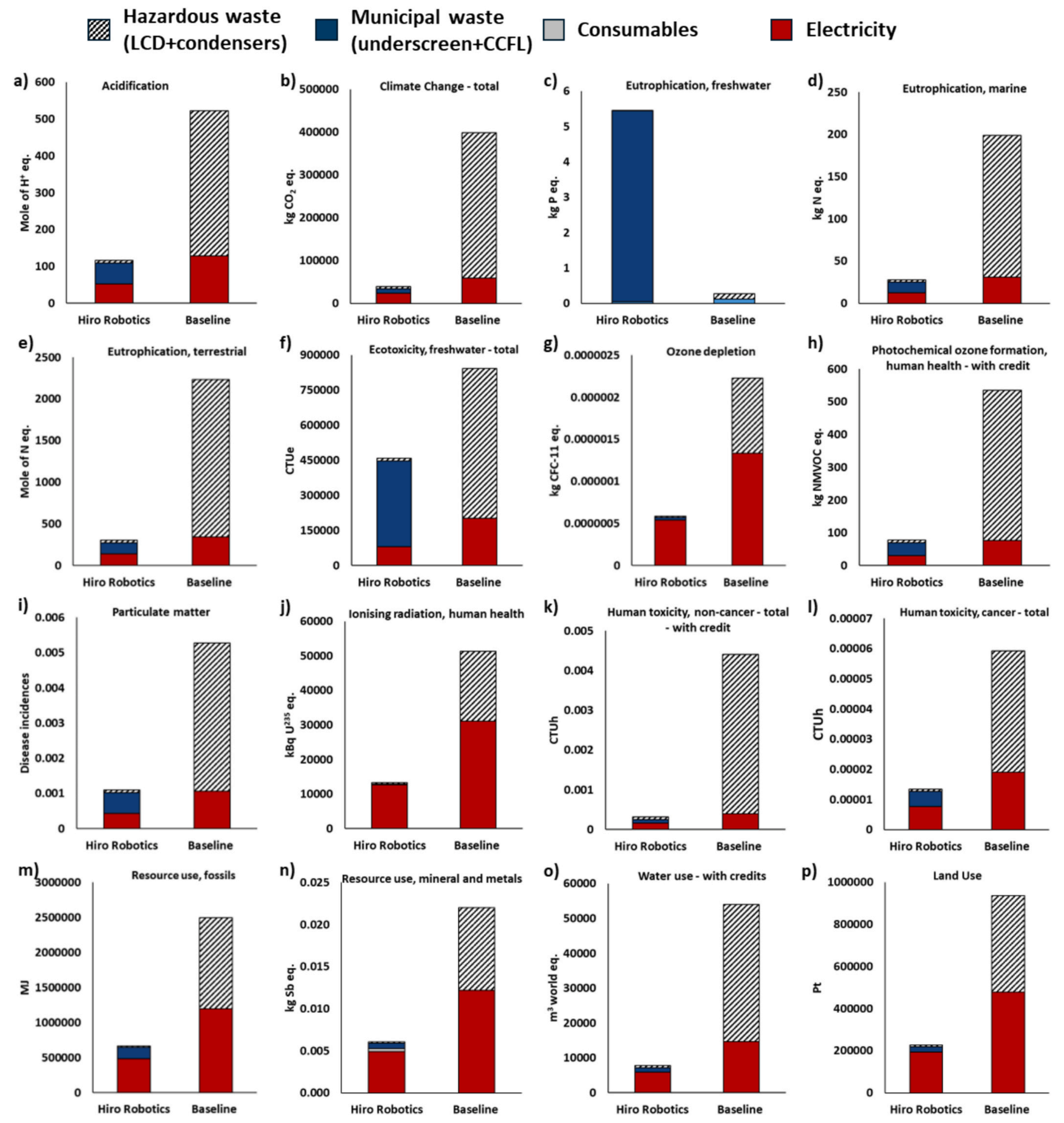

Fig. 2. Results of classification and characterization: comparison between the two considered scenarios. (Functional unit: 1,800 tons of end-of-life FPD).

3. Results and discussion

3.1. Classification and characterization, comparison between the two scenario impacts

The first step of classification and characterization enabled a comparison between the impacts of the two analyzed scenarios, excluding the evaluation of the potential benefits due to the separated fractions. As shown in Fig. 2, the advantage of Hiro Robotics technology is evident across all the categories defined by EF 3.1 method (European Commission, 2022b, 2021), considering the aspects of environmental conservation (Fig. 2ag), human health (Fig. 2hl) and resource depletions (Fig. 2mp. The average benefit resulting from the innovative scenario is around 70 %, with reduction reaching up to 90 % in key categories such as climate change. In this regard, the treatment of 1 kg of waste FPDs results in a climate change burden of 0.03 kg CO_2 eq. when treated using TEIA process, or 0.22 kg CO_2 eq. when treated by traditional crushing. In the Hiro Robotics scenario 99 % of this impact is fossil related, 0.7 % is biogenic and 0.3 % results from land use change (dLuc), mainly due to electricity consumption. In contrast, the baseline scenario's emissions

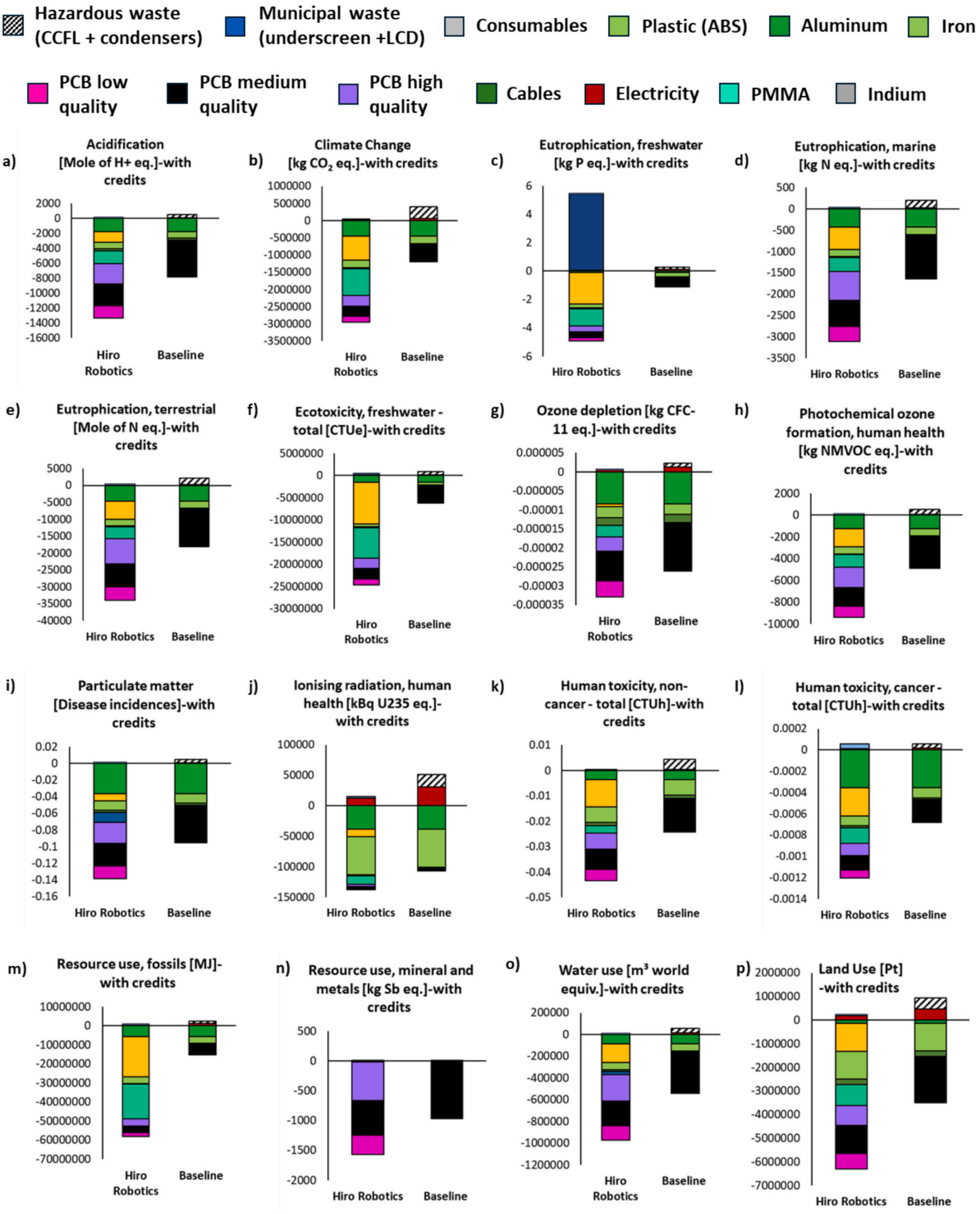

Fig. 3. Results of classification and characterization: comparison between the two considered scenarios, including potential benefit due to the separated fraction enhancements. (Functional unit: 1,800 tons of end-of-life FPD).

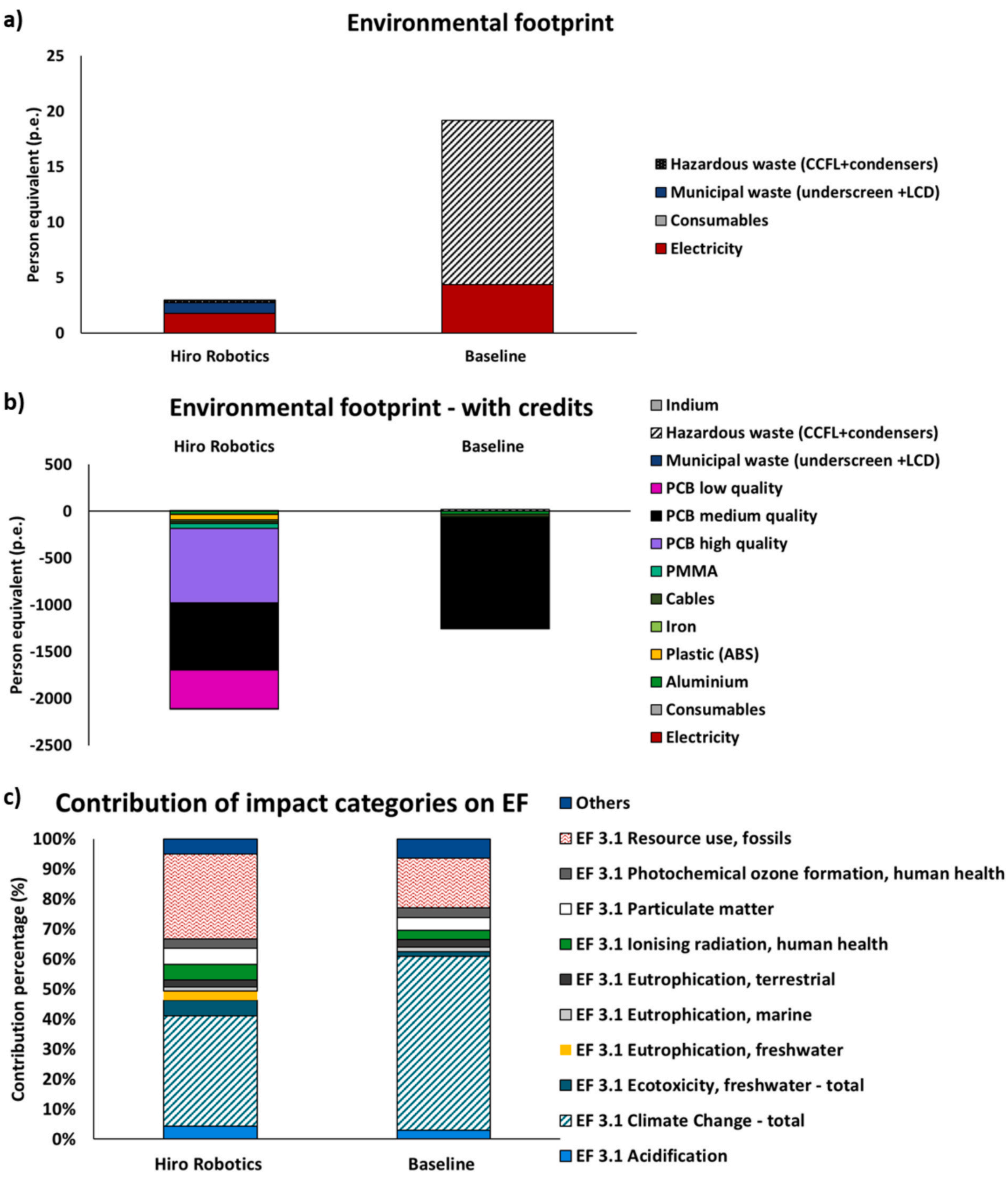

Fig. 4. Results of normalization and weighting, a) comparison between the two considered scenarios, b) including potential benefit due to separated fraction enhancements, c) contribution of impact categories on the whole environmental footprint (Functional unit: 1,800 tons of end-of-life FPD).

are almost completely fossil-based, primarily linked to hazardous waste management.

Eutrophication freshwater is the only exception, mainly due to the landfilling of residual urban waste. However, its overall relevance to the total EF will be assessed in the further normalization and weighting steps. The main issue associated with traditional shredding, affecting the both environmental conservation and the human health, is the generation of the greatest quantity of not-valuable residues, classified as hazardous. On the other hand, the highest electricity demand mainly affects the categories of climate change (Fig. 2a, around 50 % of scenario impact) resource and land uses (Figs. 2m,n,p, more than 65 % of environmental burden) and ionizing radiation (Fig. 2j), where the energy contribution reaches the 83 %, due to the radionuclides, potentially toxic for humans, resulting from both the nuclear energy production, and the mineral oil and gas extraction, used as energy carriers (Frischknecht et al., 2000). In this regard, the average European grid mix used for the analysis includes as the main source nuclear (around 24 %), natural gas (around 20 %) and wind (around 15 %) (Amato et al., 2025).

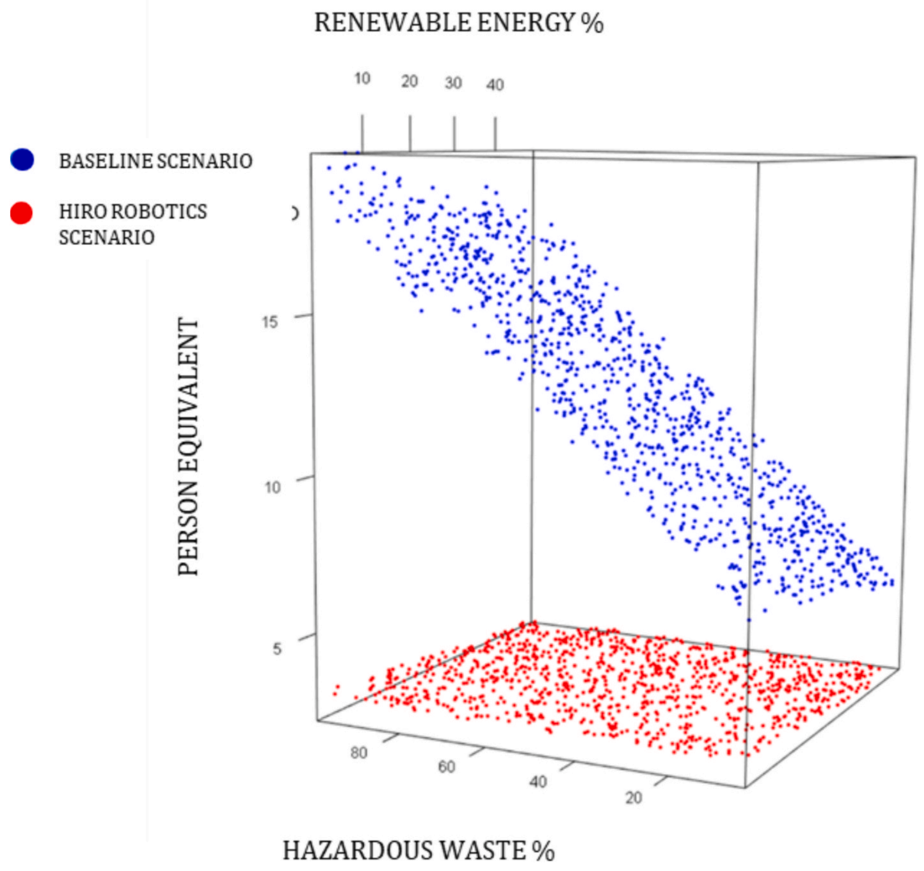

Fig. 5. Results of Monte Carlo analysis (1000 simulation, variables photovoltaic energy supply: 50–100% (in both scenarios), Hazardous waste: 4–100% (only in baseline scenario).

3.2. *Classification and characterization, estimation of the potential benefit resulting from the two scenarios*

The two considered scenarios produce different output flows. In the Hiro Robotics case, the combination of manual and automatic dismantling ensures higher quality of the separated fractions (e.g. three-quality PCBs and PMMA, suitable to be fed to recycling processes), than the baseline option. In this context, the second phase of classification and characterization allowed the definition of the potential benefits resulting from the enhancement of these materials. It is evident that this is only an estimation, since the recycling impact was not included in the analysis. However, this assessment was considered crucial to compare the effectiveness of the two scenarios from an environmental point of view. Fig. 3 reports the results of the estimation, where the negative values represent a benefit (i.e. an avoided impact) for the specific impact categories. Hiro robotics scenario showed the best result in all categories mainly due to PCB separation. As better explained in the assumption section, this environmental credit is estimated on the different content of gold, silver, copper, based on the quality of separated PCBs. This assumption allowed the maintenance of conservative conditions, though the PCBs could contain further valuable materials. The lowest credit estimated for the baseline scenario is justified by a double issue, a lower quality of the resulting PCBs (completely assumed as medium quality) and a material loss around 25 % during the shredding and sieving operations. The potential value of plastics (separated and not shredded in Hiro Robotics scenario) is mainly highlighted in the categories of climate change, eutrophication in different environmental compartments, ecotoxicity (Fig.s 3b-f), human toxicities and fossil resource depletion (Fig. 3k-m). The possible gain due to indium recovery is visible in the categories of ozone depletion and eutrophication freshwater, considering its manufacturing process as by-product of zinc manufacturing. Considering the climate change issue, an environmental credit of −13 kg CO_2 eq/kg of waste FPD was estimated, in line with −20.17 reported in the report of Ljungkvist et al. (2016), relating to semi-automated dismantling. The same report confirms the credit due to baseline shredding operations −6.1 kg CO_2 eq/kg of waste FPD compared to 3.5 estimated in the present paper (Ljungkvist et al., 2016).

3.3. *Normalization and weighting, comparison between the two scenarios*

The final normalization and weighting phases enabled comparison among different impact categories through the application normalization and weighting factors (in accordance with the EF3.1 method), obtaining a comprehensive result, expressed as person equivalent, i.e. the number of average European citizens that generate the same environmental impact per year (Schmidt and Frydendal, 2003). These steps are not mandatory, but they are recommended within the LCA methodology to clarify uncertainties that may arise during classification and characterization.

In this context, Fig. 4a confirms the higher sustainability of the Hiro Robotics scenario compared with the baseline, demonstrating a potential reduction of approximately 85 % in the environmental footprint of FPD dismantling/and pre-treatment. Another noteworthy finding concerns the environmental credits, which highlight the PCBs as the main source of environmental benefit, thanks to the possibility to significantly reduce the burden within the category of resource use, mineral and metals (Fig. 2b). The environmental gain could further increase if additional valuable metals (eg. nickel), present in PCBs, were recovered (Manikkampatti Palanisamy et al., 2022). However, the assumption of considering only gold, silver and copper, with high-recovery efficiency

Table 3
Application of the pedigree matrix.

Process	Reliability	Completeness	Temporal correlation	Geographical correlation	Technological correlation	Average score	Kind of data	Reference
RER: Electricity grid mix	2	2	1	3	3	**2**	Secondary	LCA for expert database
GLO: Copper mix						**1**	Secondary	LCA for expert database
GLO: Gold (primary)	2	2	1	3	3	**2**	Secondary	LCA for expert database
GLO: Silver mix	2	2	1	3	3	**2**	Secondary	LCA for expert database
DE: Steel billet (20MoCr$_4$)	2	2	1	1	1	**1**	Secondary	LCA for expert database
RER: Aluminium ingot mix – production mix	2	2	1	2	2	**2**	Secondary	LCA for expert database
RER: Acrylonitrile butadiene styrene (ABS)	2	2	2	1.7	1.9	**2**	Secondary	LCA for expert database
RER: EAF Steel billet / slab / bloom (average-alloyed)	2	2	1	2	2	**2**	Secondary	LCA for expert database
RER: Cable 5 wire (EN15804 A1-A3)	2	2	1	3	3	**2**	Secondary	LCA for expert database
DE: Polymethyl methacrylate granulate (PMMA)	2	2	1	1	2	**2**	Secondary	LCA for expert database
RER: Plastic waste on landfill	2	2	1	1	2	**2**	Secondary	LCA for expert database
RER: Hazardous waste (statistical average composition) treatment mix (incineration and landfill)	2	2	1	2	2	**2**	Secondary	LCA for expert database
RER: Indium prduction	2	2	2	2	2	2	Secondary	Ecoinvent
Hiro Robotics process	1	1	1	1	1	**1**	Primary	Hiro Robotics
Baseline process	1	1	1	1	1	**1**	Primary	Hiro Robotics

and purities of the recovered elements, allowed the analysis to be conducted under conservative conditions (Baniasadi et al., 2020; Oke and Potgieter, 2024). The literature does not report any significant effect of PCB recovery effectiveness related to board quality since the main difference lies in to the metal contents (Table 2) and the consequent performance of the systems. Nevertheless, assuming a 50 % reduction in the recovery efficiency of both gold and silver (copper was excluded from this assumption, as its complete recovery is well established), the credit of the Hiro Robotics scenario decreases by approximately 40 % but remains higher than the corresponding impact. The normalization and weighting steps allow to further conclude that the negative effect observed on eutrophication freshwater (Fig. 2c) is negligible in the overall assessment, due to the low contribution of this category (Fig. 4c).

3.4. Sensitivity analysis

A sensitivity analysis was performed to assess how the variation of selected parameters could affect the sustainability results. Many factors may influence LCA outcomes, such as input parameters, data, methods and assumptions. In this analysis, two key aspects identified within the LCA framework were examined, electricity supply and waste generation. For the first aspect, the main source of variation considered was the electricity mix, specifically the possible integration of photovoltaic (PV) systems within the recycling facilities in both scenarios. Regarding waste, the analysis considered the classification of residues from the baseline treatment (hazardous vs. non-hazardous), which can vary depending on separation efficiency and the type of display processed. Furthermore, the sensitivity analysis accounted for a ± 10 % to reflect the uncertainty associated with impact variability across different impact categories.

With this aim, a Monte Carlo analysis (implemented in RStudio) was performed to study the effect of parameter variations on the normalized and weighted results, encompassing all the impact categories defined in the EF 3.1 method. A total of 1000 simulations were run to estimate the potential variability of the whole impact of the ideal scenario (corresponding to the inventory in Table 1), varying the parameters in the range reported below.

- The percentage of renewable (photovoltaic) energy supplied to the facility from 0 to 50 %.
- The percentage of hazardous waste generated in the baseline scenario, from 100 to 4 % (condition comparable to that assumed for Hiro Robotics dismantling).

The elaboration reported in Fig. 5 confirms the environmental benefit of the Hiro Robotics technology, irrespective of the selected variables, since the environmental footprint of the baseline scenario (blue dots) remains higher than that of Hiro Robotics scenario (red dots), under all the tested conditions. The analysis showed an environmental footprint of Hiro Robotics scenario ranging between 2.2 and 3.1p.e. and of the baseline scenario between 5.4 and 19.9 p.e.

3.5. Uncertainty analysis

The data uncertainty of the processes included in the LCA was evaluated using pedigree matrix, based on 5 data quality indicators reported in Table S3, in agreement with Weidema and Wesnæs (1996) (Weidema and Wesnæs, 1996). Table 3 summarizes the quality levels and ratings used for the data quality assessment. The first column of the table lists the name of the processes extracted from the database, to ensure the reproducibility of the analysis. The assessment was carried out according to the documentation attached to each process from the database and it proves a low uncertainty of data, with average scores ranging between 1 and 2.

4. Conclusions

Waste pre-treatment represents a critical issue for the recycling chain, since it significantly influences the quality of the recovered fractions. In addition to the technical aspects, the present study demonstrate that the investment in new technologies for dismantling, such as TEIA, can lead to a reduction of environmental burden of up to 90 % in critical categories such as climate change, compared to the more traditional crushing. As confirmed by the statistical analysis, this advantage remains consistent despite variations in some operational parameters (such as the energy source and the characteristics of the generated waste stream). In this regard, the implementation of Hiro Robotics treatment allows an annual saving around 360,000 kg di CO_2-eq., corresponding to a distance traveled of about 1,700,000 km by car (considering an average impact of 0.211 kg CO_2-eq per km for a European passenger vehicle). The benefit further grows when considering the potential recovery of the separated high-quality fractions, enhance downstream recycling processes. In this regard, the analysis estimated an environmental credit of −13 kg CO_2 eq per kg of waste FPD. The main limitation of this study lies in the exclusion of the impacts associated with all recovered fractions; however, this aspect is not considered essential for the present assessment, which aimed to compare the environmental loads of FPD dismantling and pre-treatment operations, an aspect often overlooked in environmental evaluations. The robustness of the results is further reinforced by the use of real-scale data, representative of actual industrial operations. Overall, the study highlights how integrating sustainable dismantling technologies into WEEE recycling chains can effectively combine environmental efficiency with industrial feasibility, paving the way toward more circular and low-impact electronic waste management.

CRediT authorship contribution statement

Alessandro Becci: Writing – review & editing, Software, Investigation, Formal analysis, Conceptualization. **Francesca Beolchini:** Writing – review & editing, Visualization, Validation, Methodology. **Davide Labolani:** Validation, Methodology, Investigation, Data curation. **Alessia Amato:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2025.115284.

Data availability

No data was used for the research described in the article.

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