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1 **Preparation for reuse activity of waste electrical and electronic**
2 **equipment: environmental performance, cost externality and job**
3 **creation**

4
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12 **Abstract**

13 The European Waste Electrical and Electronic Equipment system introduced measures to encourage
14 both the reduction of the amount of electronic waste and its separation to prepare for reuse. The aim
15 of this study is compare the environmental performance, external costs and social aspect of the whole
16 life cycle of new and reconditioned electrical and electronic equipment by adopting Life Cycle
17 Assessment methodology. Five electrical and electronic equipment categories were investigated and
18 the data collection was made on an Italian context. The refurbishing of breakdown electrical and
19 electronic equipment was assessed by considering different sets of faulty components (Scenario A
20 and B) and a total of 25 scenarios were studied. Moreover, both *attributinal* and *consequential* life
21 cycle inventory modelling framework were adopted to represent the investigated scenarios. The
22 outcomes highlighted that the preparation for reuse process leads to obtaining a sustainable
23 electronic device than the new one, depending on which set of components are replaced. Adopting
24 Scenario B with the attributinal model, the environmental damage of reconditioned electrical and
25 electronic equipment decreases compared to the new one. Conversely, the consequential approach
26 determines an environmental credit for all repaired electronic devices except for one category; in
27 particular, Scenario A produced the largest environmental advantage. The analyses of external costs
28 and social aspects confirm that the preparation for reuse activity allows to obtain a more sustainable
29 product than a new one. For these two latter aspects, the results showed a turnaround passing from
30 attributinal model to consequential one. Noting the variability in results adopting both different life
31 cycle inventory modelling framework and set of replaced components, the Life Cycle Assessment
32 practitioner, that conducted the study, should help the decision-makers to determine which scenario
33 is more sustainable accomplishing an adequate choice.

34 **Keywords**

35 Life cycle assessment, WEEE, preparation for reuse, LCI modelling framework

36 **1 Introduction**

37 The growth of industrialization worldwide has resulted in an increase in electrical and electronic
38 goods production in several markets. The acceleration rate of technological development effectively
39 renders certain products obsolete almost as soon as they are purchased (Goodship and Stevels, 2012).
40 These aspects have led to an inevitable increase in electrical and electronic waste, which has become
41 a significant problem, particularly in environmental terms (de Oliveira Neto et al., 2017). Waste
42 Electrical and Electronic Equipment (WEEE) is a complex mixture of materials and components,
43 which because of their hazardous contents can cause major environmental and health problems if
44 they are not properly disposed. Environmentally friendly recycling was extensively promoted by
45 laws and regulations in recent years (Lu et al., 2018). European Directive 2002/96/EC, using the
46 Extended Producer Responsibility (EPR) principle, ensures that producers can fulfil obligations
47 either individually or collectively, and its aim is “as first priority, the prevention of WEEE and, in
48 addition, the reuse, recycling and other forms of recovery of such wastes so as to reduce the disposal
49 of waste” (EU, 2008). In Italy, European Directive 2012/19/EU was implemented by Legislative
50 Decree No. 49/2014 for EEE. This should contribute to the circular economy and enhance resource
51 efficiency (González et al., 2017). The EU Directive stated, “where appropriate, priority should be
52 given to preparing for reuse of WEEE and its components, subassemblies and consumables”. It also
53 introduced a stepwise increase in the collection target, and from 2016, the annual collection target
54 was defined as the ratio between the collected amount and the average weight of Electrical and
55 Electronic Equipment (EEE) (2017/699/EU) put on the market (PoM) in the previous three
56 preceding years, which will rise to 65% in 2019. Collection targets include both household and
57 professional WEEE.

58 Today, there are different definitions of reuse and related concepts in the literature as detailed
59 described by Lu and colleague (Lu et al., 2018). In this study, we referred to EU definition of *reuse*
60 and *preparing for reuse* (EU, 2008), which identified these activities as crucial for WEEE
61 management:

- 62 • ‘reuse’ means any operation by which products or components that are not waste are used
63 again for the same purpose for which they were conceived;

64 • ‘preparation for reuse’ means checking, cleaning or repairing recovery operations, by
65 which products or components of products that have become waste are prepared so that
66 they can be reused without any other pre-processing;

67 Life cycle assessment (LCA) is an environmental management tool for assessing environmental
68 aspects and potential impacts associated with a product, process, or service. LCA follows a cradle-
69 to-grave approach, taking into account the full life cycle of the product: from raw material
70 acquisition to production, use, and end of life. It is regulated by ISO standards 14040 and 14044.

71 Moreover, LCA methodology is a powerful tool for decision-making and for the End of Life option
72 (EoL), allowing for the identification of hotspots associated with a specific waste management
73 policy and the eventual implementation of focused strategies to reduce environmental (Pini et al.,
74 2018). The European Union has in recent years promoted recycling, reuse, and other forms of
75 recovery in order to reduce the quantity of such waste to be disposed (Directive 2002/96/EC). The
76 EU is also taking measures to restrict the use of hazardous substances in this type of equipment
77 (Directive 2002/95/EC). Hence, in this context Europe was very active in carrying out LCA to
78 support electronic waste management (Xue and Xu, 2017). The LCA methodology was thus selected
79 in this study to compare environmental performance, external costs and social issue of the whole
80 life cycle of the reused WEEE with the new WEEE.

81 In this study, the “preparation for reuse” (in the strict term of EU definition) was considered as the
82 activity to recondition the faulty EEE and the resultant good is following called “reused EEE”. With
83 the terms “repair” and “refurbish” we referred to all activities belonging to “preparation for reuse”
84 treatment.

85 The comparison analysis of the life cycle of the reused electronic good and the equivalent new one
86 was conducted through LCA methodology. The preparation for reuse was assessed by taking into
87 account different sets of faulty components. Both attributional and consequential LCI framework
88 modelling were adopted to model LCA of all scenarios. The obtained environmental results vary
89 greatly considering these two different approaches leading to dissimilar results interpretations and
90 therefore difficulty for the decision makers to take the adequate decision. From this perspective, is
91 the LCA practitioner that conducted study that must to help the decision makers come to the
92 appropriate decision.

93 The present study is part of a wider EU research project (WEEEN Models), the main purpose of
94 which is to create a new sustainable model of WEEE management of an Italian context. In particular,
95 the project was kicked-off considering the pilot city of Genoa.

96 The paper is organized as follows: Section 2 contains a literature review; Sections 3, 4 and 5 describe
97 the LCA methodology step by step, from materials and methods to the LCA results; Sections 6
98 reports the discussion of LCA results and provide conclusions along with suggestions for further
99 research.

100 **2 Research background**

101 This section reports relevant contributions that refer to the sustainability assessment of products
102 and processes, with a special focus on WEEE treatment.

103 LCA represents a useful aid for waste management, and over the last decades it was applied in the
104 waste management field (Soltani et al. 2015). Recovering metals from waste incineration (Boesch
105 et al. 2014), organic fibres (Quirós et al. 2014), digestate (Vázquez-Rowe et al. 2015), and ash
106 solidification and recycling (Di Gianfilippo et al. 2015; Margallo et al. 2014) are examples of waste
107 materials and processes to which LCA was applied. Margallo et al. (2015) and Laurent et al. (2014)
108 provide details of several LCA applications to waste treatment. Extensive recent scientific literature
109 focuses on WEEE treatment. However, few LCA studies regarding the reuse/reconditioning of
110 electronic waste were conducted. Recently, Rodriguez-Garcia and Weil (2016) proposed a literature
111 review of environmental analyses conducted using LCA methodology in WEEE management and
112 recycling. They investigated a time horizon from 1999 to 2015. They found that of the 47 LCA
113 studies reviewed only 3 (Devoldere et al. 2009; Biswas & Rosano 2011; Biswas et al. 2013) focused
114 on waste prevention and used new products as benchmarks. Lu et al. (2017) confirmed that only a
115 few LCA manuscripts focus on the reuse activities of WEEE. They selected four LCA works
116 concerning reuse strategy as EoL: Rose (2000), Schischke et al. (2003), Devoldere et al. (2009) and
117 Zink et al. (2014). Xue and Xu (2017) published a review of the application of LCA on electronic
118 waste management, but they only mentioned reuse issues in the chapter dedicated to the
119 geographical distribution of LCA studies, without addressing this new WEEE management
120 approach even within the gaps and challenges section.

121 We identified four other publications that complete the picture of the application of LCA
122 methodology to reuse/preparation of reuse of WEEE. Cheung et al. (2018) assessed the

123 environmental impacts of lifetime extension versus energy efficiency for the product group of video
124 projectors, based on three liquid-crystal display (LCD) projectors. Andrae et al. (2017)
125 conducted a screening LCA study of a virtual reality (VR) headset in order to evaluate its potential
126 environmental impacts under certain conditions, investigating different EoL treatments scenario
127 among which the 5% reuse of entire product. González et al. (2017) analysed the economic and
128 environmental convenience obtain from a reuse strategy versus the recycling treatment of computers
129 in Spain. Lu et al. (2014) investigated the reusability of typical electrical and electronic products
130 and components in China that used the merged Life Cycle Sustainability Assessment (LCSA). Only
131 Cheung et al. (2018) considered the replacement of faulty parts in the reconditioning activities, while
132 the other two studies regarded the reuse process simply as an extension of the appliance lifetime
133 without taking into account the substitution of inoperative components.

134 Most of the above-mentioned studies only involved a single product, for example washing machines
135 (Devoldere et al., 2009), computers (González et al. 2017 and Schischke et al. 2003), televisions
136 (Rose 2000), compressors (Biswas et al., 2013), smartphones (Zink et al., 2014), mobile phones (Lu
137 et al., 2014), video projectors (Cheung et al., 2018), until going to the newer VR headset (Andrae et
138 al., 2017). Biswas and Rosano (2011) and Lu et al. (2017) considered two appliances: the former
139 considered refrigeration and air conditioning compressors and the latter refrigeration and power
140 supply units of desktops.

141 The focus of this study is on all WEEE categories, not only a single appliance. In Italy, WEEE is
142 classified in five WEEE categories (DMn. 185 of the 25th of September, 2007): heaters and
143 refrigerators (R1), large household appliances (R2), TV and monitors (R3), small household
144 appliances (R4) and lighting equipment (R5). Following, WEEE categories will be called also
145 “groups” or “product categories”. Additionally, all operative processes to refurbish electronic waste
146 (section, check, disassembly and replacement, and cleaning) and the life cycle of new components
147 that can replace failed ones were considered.

148 As underlined in the introduction, LCA covers only the environmental dimension of the
149 sustainability concept. To explore the sustainability of products and processes from a holistic
150 perspective, economic and social impacts should also be assessed. In our project, only external costs
151 were considered in the economic impact category. Chhipi-Shrestha et al. (2015) authored an
152 extensive review of social sustainability, which provides a better understanding of the

153 multidimensional nature of the social sustainability pillar. Their taxonomy allocates social
 154 stakeholders into five categories (workers, local community, society, consumers and value chain
 155 actors) that had been formalised earlier by UNEP/SETAC (2009), and six social categories (human
 156 rights, working conditions, health and safety, cultural heritage, governance and socio-economic
 157 repercussions) with their subcategories. Over 100 social indicators are also included in
 158 UNEP/SETAC (2013). In terms of WEEE treatment, to the best of our knowledge only Lu et al.
 159 (2014) addressed the reusability of typical electrical and electronic products and components by
 160 using the merged LCSA. In this study, one type of social impact was considered, namely job
 161 creation.

162 3 Materials and methods

163 The aspects dealt with in this study, the method used to evaluate them and the related sections in
 164 which they are summarized in the following table.

165 **Table 1 Summary of the environmental, social and economic issues tackled**

	Impact category	Evaluation method	Section
Environmental	Carcinogens	IMPACT 2002+	3.2
	Non-carcinogens		
	Respiratory inorganics		
	Ionizing radiation		
	Ozone layer depletion		
	Respiratory organics		
	Aquatic ecotoxicity		
	Terrestrial ecotoxicity		
	Terrestrial acid/nutri		
	Land occupation		
	Aquatic acidification		
	Aquatic eutrophication		
	Global warming		
	Non-renewable energy		
Economic	External cost	EPS 2015	3.3
Social	Job creation	IMPACT 2002+ modified	3.4

166

167 3.1 Life cycle assessment

168 3.1.1 Goal definition

169 In the Italian context, WEEEs are classified into five categories (DM n. 185 of the 25th of September
 170 2007): R1 – heaters and refrigerators; R2 – large household appliances; R3 – TVs and monitors; R4

171 – small household appliances; and R5 – lighting equipment. The aim of this study is to compare the
 172 environmental performance between the whole life cycle of reused WEEE and new WEEE. The
 173 LCA methodology was applied to achieve this (ISO 14040, 2006) (ISO 14044, 2006) and SimaPro
 174 8.5.2 software calculation was used .

175 *3.1.2 System and functional unit*

176 The system study is the whole life cycles of both new EEE and reconditioned EEE obtained by
 177 preparation for reuse waste process, in particular different set of replaced faulty components were
 178 assessed. In agreements with the project partners, the lifetime of the reused products was assumed
 179 in first instance as equal to half that of an equivalent new product (e.g. if the lifetime of new R1 is
 180 equal to 10 years, then the lifetime of the reused R1 is equal to 5 years). Consequently, the functional
 181 unit (FU) chosen for representing the *entire* life cycle of the new EEE is 1 p (i.e. one new electrical
 182 product), whereas for the reused EEE's life cycle is 0.5 p.

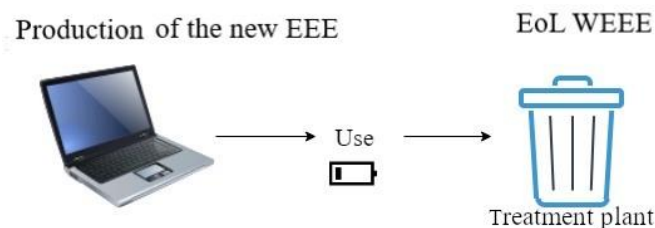
183 Table 2 shows the representative product selected for each WEEE category and the relative weight.

184 **Table 2 Representative product considered for each WEEE category and relative weight**

Representative Product	Weight/FU
Refrigerator (R1)	44 kg
Washing machine (R2)	67,066 kg
LCD (R3)	5,1 kg
Laptop (R4)	3,12 kg
Fluorescent lamp (R5)	0,24 kg

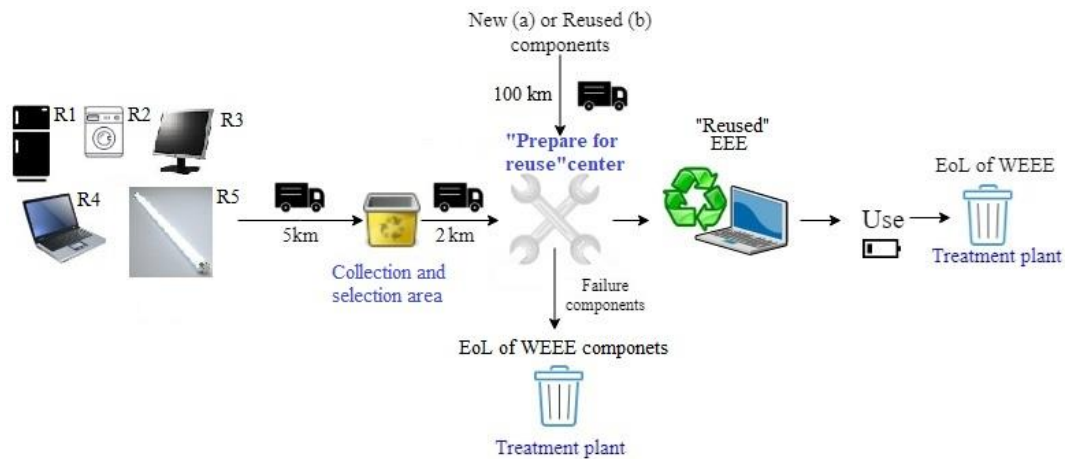
185 *3.1.3 System boundaries*

186 The system boundaries of the life cycle of the new product (Fig. 1) considered the following steps:
 187 *i)* Production; *ii)* Use: consumption in terms of energy, water, etc.; and *iii)* Conventional EoL
 188 treatment (with recycling option). Those of the life cycle of the reused product (Fig. 2) considered:
 189 *i)* Transport to the collection centre of the decommissioned products; *ii)* WEEE selection to define
 190 what can be repaired; *iii)* Repair of reusable products; *iv)* EoL of the replaced components; *v)* Use
 191 of the reconditioned EEE; and *vi)* EoL of reconditioned EEE.



192
 193

Figure 1 System boundaries of the life cycle of the new EEE



194
195
196

Figure 2 System boundaries of the life cycle the reconditioned EEE

197 A representative product was considered for each WEEE group (Table 2), assuming that it generates
198 the same environmental damage as other products belonging to the same category. In the use phase,
199 lower performance of reconditioned EEE was also considered for all appliances except for R5. A
200 higher level of water consumption in the use phase of reconditioned R2 products was also assumed.
201 Different sets of replaced components were evaluated to identify which determined the best solution.
202 The definition of these alternative scenarios was conducted by distributing ad-hoc questionnaires
203 addressed to expert technicians of the preparation for reuse center of the pilot city of the project:

- 204 ✓ Scenario A represents the set of replaced components, which are damaged more frequently
205 first, during the EEE lifetime,
- 206 ✓ Scenario B represents a second group of replaced components, which have broken down
207 more frequently, but in a time order following the previously defined set.

208 For each scenario, two sub-scenarios were evaluated: new (*a*) and reused (*b*) components, which
209 were used to replace those that failed. In the reused components scenario, the faulty parts were
210 replaced with still working parts of WEEE destined for the conventional EoL treatment.

211 The same lifetime assumption took for the entire life cycle of the reconditioned EEEs was made for
212 the reused components as well. The environmental comparison thus involved five scenarios for each
213 WEEE category, namely new EEE, reused EEE Scenario A-*a*, reused EEE Scenario A-*b*, reused
214 EEE Scenario B-*a* and reused EEE Scenario B-*b*. Twenty-five scenarios were assessed per each LCI
215 framework modelling, and more details are given in Chapter 4 “Life Cycle Inventory”.

216 *3.1.4 Data quality*

217 The data for the production of electric products belonging to R3, R4 and R5 categories were acquired
218 from the Ecoinvent database v3.3 (Wernet et al., 2016). Data on the manufacture of electronic goods
219 belonging to R1 and R2 categories are derived from previous LCA studies (Iezzi 2006; Ziosi 2000).
220 The main parts for the replaced components were modelled through Ecoinvent database v3.3
221 processes (Wernet et al., 2016), with only data of those for the compressor (R1) and engine (R2)
222 modules obtained from a previous study (Iezzi, 2006).

223 The primary data include *i*) reconditioning activities of WEEE that after the selection phase must be
224 repaired; *ii*) transport for taking WEEE to the collection area; *iii*) average selection time and total
225 repair time (reconditioning process) for checking, disassembly, replacing and cleaning; and *iv*)
226 information on different replaced components options. This information was all obtained through
227 direct interviews with retailers and technicians.

228 Since, this study started from a national context, the Italian mix electrical energy generated by
229 Ecoinvent database v3.3 (Wernet et al., 2016) was taken into account to model the electricity
230 employed in the study.

231 The background datasets were acquired from Ecoinvent database v3.3, in particular the system
232 model “Allocation at the point of substitution” was used to model the Attributional LCA and
233 “Substitution, consequential, long-“ was applied to the Consequential one.

234 *3.1.5 Attributional and Consequential LCI modelling*

235 The choice concerning the application of Attributional or Consequential LCI modelling framework
236 is a key issue during an LCA study. Although the ISO standards (ISO 14040, 2006) (ISO 14044,
237 2006) and the ILCD manual (JRC-IES, 2010) provide recommendations on how to perform an LCA,
238 there are still differences between the studies due to the different methodological approaches
239 adopted (Thomassen et al., 2008) and, in particular, the LCI modelling framework substantially
240 influences the LCA results (Ekvall et al., 2016). Recently, Ekvall et al. (Ekvall et al., 2016) analyzed
241 the ILCD guidance on the structure of Attributional and Consequential LCI modelling by comparing
242 the different statements in the handbook with each other and with previous research in this area.
243 They concluded that the ILCD handbook is internally inconsistent, particularly when recommending
244 choices between the two LCI models (Pini et al., 2018). Therefore, they indicate that the handbook
245 needs to be revised. In addition, Weidema (Weidema, 2014) pointed to a criticism in the current ISO

246 14044 of which unit processes to include in a product system and how to link these unit process data
247 sets together. He underlined that this causes different interpretations regarding LCI framework
248 modelling (Pini et al., 2018).

249 The distinction between Attributional and Consequential modelling was developed in the process of
250 resolving methodological debates on allocation issues and data selection (Thomassen et al., 2008).

251 *Attributional* modelling identifies the existing impacts generated by a system (Schrijvers et al., 2016)
252 isolated from the rest of the technosphere. This approach quantifies the environmental impacts
253 attributable to the functional unit of a product system on the basis of a mapping of the flows of
254 resources and emissions (input and output) that accompany the product during its life cycle
255 (Hauschild et al., 2017) and (Ekvall et al., 2016). The multifunctionality can be addressed by
256 ‘substitution’, where the functional unit is expanded to include the co-functions (avoided products)
257 of the process/product (Curran, 2018), or by ‘partitioning’, where inputs and outputs are allocated
258 between the system function and the coproducts generated by the system (e.g. mass, energy,
259 economic value allocations etc.). Furthermore, Attributional modelling uses as input data the
260 average data representing the actual physical flows and describing the production system as a
261 whole (Ekvall et al., 2016).

262 *Consequential* modelling describes how environmentally relevant physical flows will change in
263 response to a possible decision and reflects the consequences of a change in production (Weidema,
264 2014). Usually, this approach solves the multifunctionality through ‘substitution’ by identifying the
265 co-products generated by the system and crediting the avoidance of those co-products and their
266 associated impacts that are supposed to be a consequence of the decision taken. Consequential
267 approach uses marginal data to model consequences. Marginal data are only used to model changes
268 large enough to have a direct and large-scale effect on the production capacity of the system (Ekvall
269 et al., 2016). The unavailability of marginal data is a problem when performing Consequential
270 LCA. Further research is needed to identify marginal processes.

271 As the choice of LCI modelling framework is still an open and complex issue to be discussed (Pini
272 et al., 2018), this work adopted both models to assess the environmental burdens associated with the
273 life cycle of reused EEEs.

274 The way in which the LCI modelling frameworks were applied for the ‘preparation for reuse’
275 activity is reported in the paragraph 4.2 (Life Cycle Inventory of reused EEE).

276 3.2 Environmental assessment

277 The Life Cycle Impact Assessment (LCIA) was conducted using the Impact 2002+ method (Jolliet
278 et al., 2003). This method takes into account continental emissions diffusion (Europe) covers more
279 impact categories than other methods and includes more substances. Moreover, it combines
280 midpoint and endpoint approaches. The midpoint indicators link the cause-effects chain of an impact
281 category (Pini et al., 2017). Endpoint indicators are considered to be linked to the cause-effect chain
282 for all categories of impact (e.g., human health impacts in terms of disability adjusted life years
283 (DALY) for carcinogenicity, climate change, ozone depletion, photochemical ozone creation or
284 impacts in terms of changes in biodiversity) (Bare et al., 2000).

285 As impact categories (mid-point) IMPACT 2002+ considers: Carcinogens, Non-carcinogens,
286 Respiratory inorganics, Ionizing radiation, Ozone layer depletion, Respiratory organics, Aquatic
287 ecotoxicity, Terrestrial ecotoxicity, Land occupation, Terrestrial acid/nutri, Aquatic acidification,
288 Aquatic eutrophication, Global warming, Non-renewable energy and Mineral extraction. At the end-
289 point level the impact categories converge into the relative area of protection, therefore the damage
290 categories for this LCIA method are: Human Health, Ecosystem Quality, Climate Change and
291 Resources. Additions and modifications, however, were implemented to provide a more
292 representative index of the system considered as reported in Pini et al. (2014).

293 3.3 Economic assessment

294 The economic issues were evaluated as the *external costs* analysis, derived from the EPS 2015 LCIA
295 method (Steen, 2015). The external cost represents *the monetized costs imposed on society of direct*
296 *and indirect damage caused by pollutants emitted during the manufacture of a product or rendering*
297 *of services, which are not paid by the producers or the consumers nor considered in production or*
298 *consumption decisions* (NRC, 2010). The cost externality is the only economic assessment
299 performed in this study.

300 3.4 Social assessment

301 A new “social” category *Job creation* was added to the LCIA method IMPACT 2002+, to consider
302 the number of new jobs that will be created by the new preparation for reuse activity. Therefore, a
303 new social substance defined as “number of employees” was included in the social category and the
304 characterization factor was set equal to 1 p/p. This allowed for the consideration of benefits

305 generated by the reconditioning activities along with the environmental analysis. The calculation of
 306 the number of the new job positions created is reported in the chapter 5.2.

307 The reconditioned EEES create a new business opportunities allowing job creations throughout the
 308 product lifecycle in terms of, maintenance, repair, upgrade, and reuse (Vasilev, 2015) and not
 309 changing the traditional market demand of new electronic products.

310 **4 Life cycle inventory**

311 4.1 New EEE

312 In assessing the life cycle of the new EEE, the following phases were considered:

313 **Production**

314 The fabrication of new EEE involves the production of main components, auxiliaries, packaging
 315 materials, energy consumption, infrastructure, land use and emissions. For the production of LCDs
 316 (R3), laptops (R4) and fluorescent lamps (R5) the Ecoinvent datasets v3.3 (Wernet et al., 2016) were
 317 used, while as mentioned refrigerator and washing machine manufacture were built ad hoc by
 318 considering previous LCA studies.

319 **Use**

320 The electric energy consumption throughout the lifespan of each group of EEE was calculated.
 321 Additionally, for the R2 category water consumption was considered. Table 3 reports the lifespan
 322 and the use pattern of each electronic product considered in this study.

323 **Table 3 Lifetime and energy consumption per year during the use phase**

Product	Life time	Energy consumption	Data Source
Refrigerator (R1)	10 years	270 kWh/year*	(ENEAA, 2018)
Washing machine (R2)	6 years	196 kWh/year* Water consumption [§] : 165 wash cycle/year * 48 l/wash cycle= 7920 l/year	(Hustvedt et al., 2010); (Szann, 2017)
LCD (R3)	10 years	155 kWh/year	(CNET, 2018)
Laptop (R4)	4 years Average annual day worked by laptop: 240 days/year	Activation mode (office use): Off 16,5 h/day Active 5,5 h/day Stand-by 2 h/day	(Hischier et al., 2007)
Fluorescent lamp (R5)	5 years	29,2 kWh/year	(Hischier et al., 2007)

*Energy class A+; § Wash programme: Cottons 40°C intensive

324 **Final disposal**

325 Conventional EoL treatment of WEEE was evaluated along with the recycling of all valuable
 326 materials (metals, precious metals, plastic, glass, etc.). Open-loop recycling modelling was used,
 327 which means that recovered secondary materials are used for different applications. Thus the
 328 products do not return to the original producer but will be used in other industries (Fleischmann et
 329 al., 1997). Table 4 reports the Ecoinvent datasets v3.3 (Wernet et al., 2016) used to model the EoL
 330 treatment of each WEEE group.

331 **Table 4 Ecoinvent dataset v3.3 used to model EoL treatment**

Product	Dataset
Refrigerator (R1)	<i>Used industrial electronic device {CH} treatment of, manual dismantling</i>
Washing machine (R2)	<i>Used industrial electronic device {CH} treatment of, manual dismantling</i>
LCD (R3)	<i>Used liquid crystal tube display {CH} treatment of, manual dismantling</i>
Laptop (R4)	<i>Used laptop computer {GLO} treatment of</i>
Fluorescent lamp (R5)	<i>Used fluorescent lamp {GLO} treatment of</i>

332

333 4.2 Reused EEE

334 The life cycle of the reused EEE considers the following steps:

335 **Waste collection**

336 In this life cycle step, transport of WEEE from consumer or distributor to the collection centre was
 337 assessed. The average distance between these actors was set equal to 5 km. The transport typology
 338 is represented by 25% small van (Transport, passenger car, EURO 5 {RER}) and 75% lorry
 339 (Transport, freight, lorry 3.5-7.5 metric ton, EURO5 {GLO}). Moreover, the average distance from
 340 the collection/selection area to the preparation for reuse center was taken of 2 km and lorry was
 341 considered as the unique type of road vehicle.

342 **Selection**

343 WEEE selection was assumed to take place in the collection area. This activity concerns 1) the
 344 functionality testing of WEEE and identification of the faulty components that have to be replaced, 2)
 345 the conveyor belt for moving the WEEE during the selection activity and 3) the plant and land
 346 occupation. Table 5 reports the duration of the selection process for each WEEE category.

347 **Table 5 Selection time spent to investigate the functionality of WEEE**

Product	Selection time [hours]
Refrigerator (R1)	0,5042
Washing machine (R2)	0,5042

LCD (R3)	1,0025
Laptop (R4)	2,0025
Fluorescent lamp (R5)	0,101

348

349 **Production**

350 The reused EEE manufacture is simply the by-product of the preparation for reuse activity necessary
351 to get it working. After the reconditioning activity, the electronic waste is referred to as “reused
352 EEE”. Therefore, the multifunctionality of the reconditioning process was solved by using both
353 attributional (“partitioning” approach) and consequential (“system expansion” approach) LCI
354 modelling frameworks. For the former modelling the economic value-based allocation was used to
355 allocate the boundaries between system function and by-product. The economic value associated
356 with the functional unit are all the costs related to the repair activities, namely transport, electric
357 energy, new components, waste disposal (broken components that have to be replaced) and labour
358 costs. The economic value correlated to the by-product is the estimated selling cost of the reused
359 EEE. This information was acquired from interviews with technicians and Table 6 reports the
360 economic value allocation adopted in this work.

361 Attributional LCI modelling with partitioning as basis of allocation returns an environmental
362 damage albeit reduced of the allocation share associated to the generated co-product.

363 **Table 6 Economic value allocation adopted in the Attributional LCI modelling with partitioning**
364 **approach**

Product	Scenario A allocation related to preparation for reuse activity	Scenario A allocation related to reused EEE	Scenario B allocation related to preparation for reuse activity	Scenario B allocation related to reused EEE
R1	33%	67%	26,3%	73,7%
R2	41,6%	58,4%	43,4%	56,6%
R3	40,8%	59,2%	36,4%	63,6%
R4	34,4%	65,6%	34,4%	65,6%
R5	41,4%	58,6%	42,7%	57,3%

365

366 Additionally, the study was modelled adopting Consequential LCI approach in order to solve the
367 multifunctionality identifying the co-products generated by the analyzed system (i.e. reused EEE).
368 There is currently no production chain in Italy and therefore no legitimate market for reconditioned
369 EEEs. In fact, ‘preparation for re-use’ is the activity promoted by European directive 2008/98/EC
370 (Directive that establishes the order of priority of regulations and policy on waste management and
371 prevention) that immediately follows the ‘prevention’ that has the absolute priority. Directive
372 2008/98/EC was adopted by Italy with Legislative Decree n. 205/2010, but this law still has no

373 practical effects due to the lack of implementing decrees. Consequently, it was no possible to assess
 374 any changes in this market demand (no marginal data were available).

375 Therefore, the environmental credit was assessed taking into account only the avoided production
 376 of the new equivalent electronic devices and their relative impacts. No allocation was considered
 377 but a system expansion (avoided products) was applied. In particular, the ‘preparation for reuse’
 378 activity produces the avoided manufacture of new EEE but with a lower energy efficiency as
 379 described below in the “Use” section.

380 The preparation for reuse process consists of 1) the manual disassembly of broken components, 2)
 381 a functionality test for each WEEE component, 3) cleaning with compressed air, 4) transport and
 382 installation of the new components that replace the broken ones, 5) the plant and its land use and 6)
 383 the EoL treatment of broken components.

384 As for the set of replaced components, two different scenarios were considered. Table 7 reports the
 385 sets of replaced components considered in scenarios A and B.

386 **Table 7 Components replaced in the five representative products**

Product	Replaced components	
	Scenario A	Scenario B
Refrigerator (R1)	Compressor Refrigerator liquid gaskets	1 PWB* Resistor Thermostat
Washing machine (R2)	1 PWB* engine belt	1 PWB* Water pump Filter
LCD (R3)	1 Video interface	12 Capacitors
Laptop (R4)	Li-ion battery NiMH battery 4 PWB*	Power pack Hard disk
Fluorescent lamp (R5)	2 Capacitors	2 Resistors

* Printed Wiring Boards

387 The details of the time duration for each reconditioning step are reported in Table 8.

388 **Table 8 Repair time spent for preparing for reuse of WEEE**

Product	Check + Disassembly and Replacement (Scenario a/b)+ Cleaning [hours]
Refrigerator (R1)	0,5 + 1,504/1,5 + 0,25
Washing machine (R2)	0,5 + 1,504/1,5 + 0,25
LCD (R3)	0,5 + 0,503/0,5 + 0,25
Laptop (R4)	1,5 [§] + 0,503/0,75 + 0,033
Fluorescent lamp (R5)	0,0833 + 0,501/0,5 + 0*

[§] This time considers check, formatting and installation of new operating system (e.g. Linux).

* For this product category no clean operation was assumed.

389

390 The durations for check and cleaning of WEEE were assumed the same in both scenarios.

391 **Use**

392 In accordance with the results obtained by data collection in the reuse center located in the pilot city
393 of Genoa, lower performance was taken into account for the use phase of reused EEE by assessing
394 higher energy and water consumption levels. The electric energy consumption increased by 10% for
395 R1 and R3, while in R2 electricity and water consumption increased by 40%. R4 and R5 maintained
396 the same energy performance as the new EEE.

397 **Final disposal**

398 After their regular usage period, the same EoL treatments, i.e. the recovery and recycling of precious
399 materials such as metals, were applied to both new and reused EEE. An equal recycling rate for new
400 EEE and reused EEE were considered.

401 **5 Results**

402 5.1 Life Cycle Assessment

403 To study the variations in environmental performance of the life cycles between new and reused
404 EEE, 25 scenarios were assessed for both attributional and consequential LCI modelling. Different
405 strategic choices were taken in the reconditioning phase in terms of replacement component options
406 (Scenarios A and B), and different natures of the replaced components, i.e., new or reused (Sub-
407 scenario *a* and *b*) were considered. The influence on the environmental results determined by the
408 LCI modelling approaches was investigated.

409 The environmental comparison was made per each EEE category and among the different scenarios,
410 since it is not possible perform the results comparison among the different EEE groups; indeed the
411 analysed electronic devices have different function.

412 The Life Cycle Impact Assessment (LCIA) was conducted using the IMPACT 2002+ modified
413 method. Following are described the main single score environmental results achieved. Single score
414 results were obtained aggregating the four-damage oriented impact categories (human health,
415 ecosystem quality, climate change, and resources) and using a default weighting factor of one (Jolliet
416 et al., 2003). The single score allows to obtain the overall environmental trend of each of the
417 scenarios studied. The detailed mid-point and end-point outcomes were reported in the Supporting
418 Information.

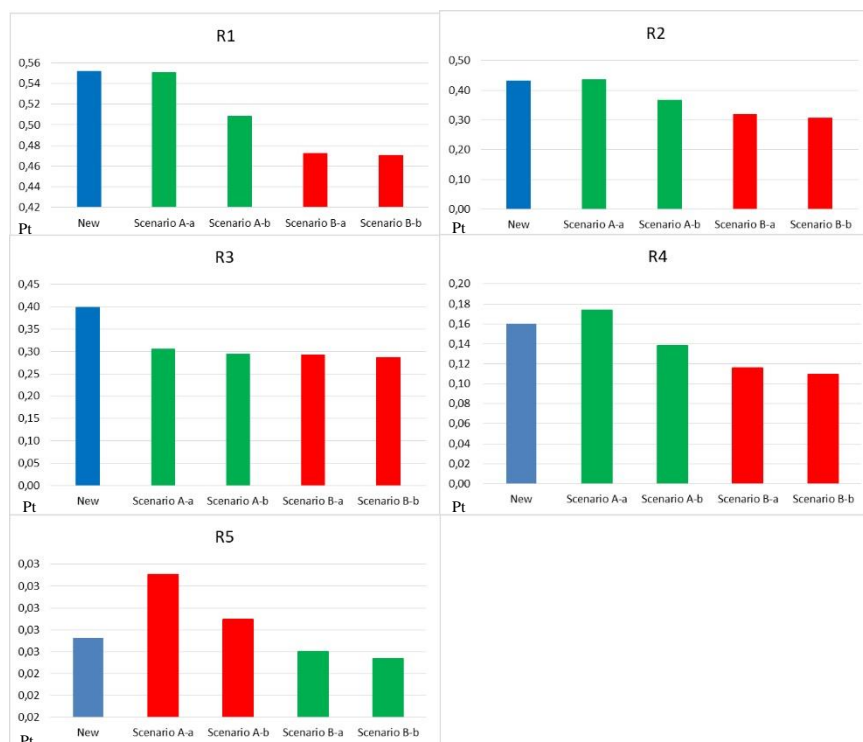
419 5.1.1 Attributional LCI modelling results

420 Figure 3 and Table 9 show the single score environmental outcomes. For all EEE categories,
 421 *Scenario B-b* determined the more “greener” scenario. *Scenario New* produced the worst case for
 422 R1 and R3 groups, whereas *Scenario A-a* becomes it for R2, R4 and R5 categories.

423 **Table 9 Environmental results for each EEE category - Attributional LCI modelling**

Single score	R1	R2	R3	R4	R5
<i>New</i>	0,5521	0,4320	0,3992	0,1601	0,0256
<i>Reused - Scenario A-a</i>	0,5505	0,4352	0,3058	0,1734	0,0285
<i>Reused - Scenario A-b</i>	0,5087	0,3656	0,2934	0,1383	0,0265
<i>Reused - Scenario B-a</i>	0,4725	0,3193	0,2931	0,1158	0,0250
<i>Reused - Scenario B-b</i>	0,4702	0,3063	0,2869	0,1092	0,0247

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427 **Figure 3 Environmental performance of the five EEE categories - Attributional LCI modelling**

428 5.1.2 Consequential LCI modelling results

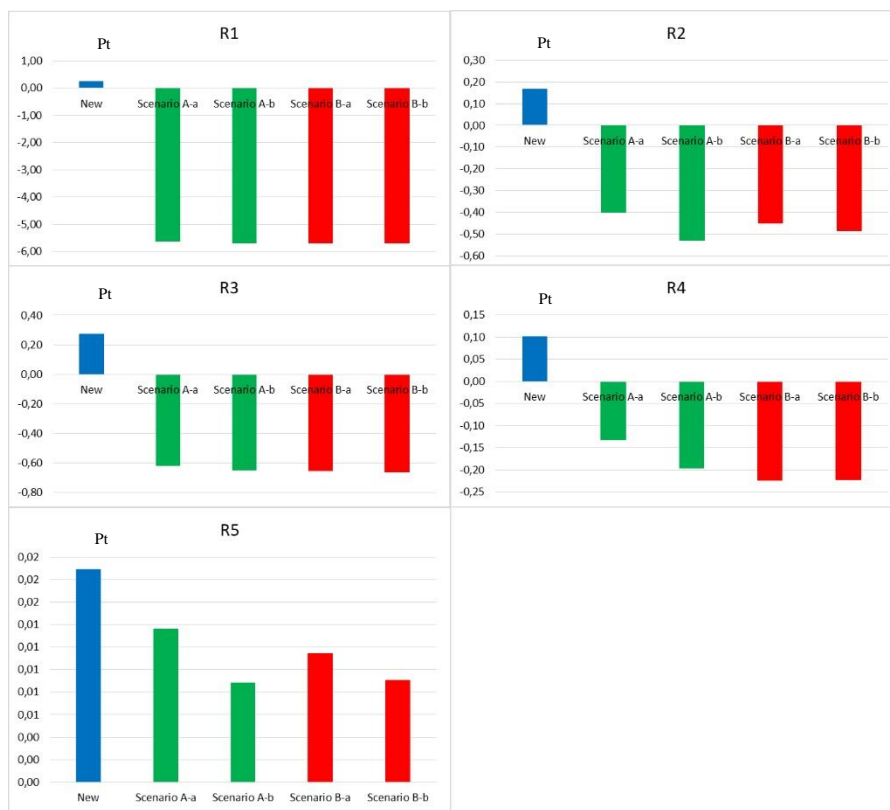
429 As before mentioned the consequential approach typically returns an environmental credit. Figure 4
 430 and Table 10 report the single score environmental outcomes. The environmental results obtained
 431 by this LCI approach vary widely among the different EEE categories. Indeed, *Scenario A-b*
 432 determined the main environmental credit for R1 and R2 thanks to the reduction of damage
 433 associated to the compressor adopting the sub-scenario b (reused components), *Scenario B-b*
 434 produced the more “greener” scenario for R3 and *Scenario B-a* is the most advantageous for R4
 435 mainly thank to the avoided environmental burdens associated to the hard disk materials. Instead,

436 for R5 the environmental performance of all reused scenarios produced a damage (positive values);
 437 this is mainly due to the lower energy performance in the use phase. For this electronic device, the
 438 best case is resulted to be *Scenario A-b*. *Scenario New* produced the worst case for all EEE
 439 categories.

440 **Table 10 Environmental results for each EEE category – Consequential LCI modelling**

Single score	R1	R2	R3	R4	R5
<i>New</i>	0,2364	0,1660	0,2721	0,1013	0,0189
<i>Reused - Scenario A-a</i>	-5,6220	-0,3996	-0,6195	-0,1315	0,0136
<i>Reused - Scenario A-b</i>	-5,6908	-0,5312	-0,6483	-0,1959	0,0088
<i>Reused - Scenario B-a</i>	-5,6860	-0,4496	-0,6521	-0,2231	0,0115
<i>Reused - Scenario B-b</i>	-5,6890	-0,4862	-0,664	-0,2214	0,0091

441



442

443 **Figure 4 Environmental performance of the five EEE categories - Consequential LCI modelling**

444 5.2 External costs

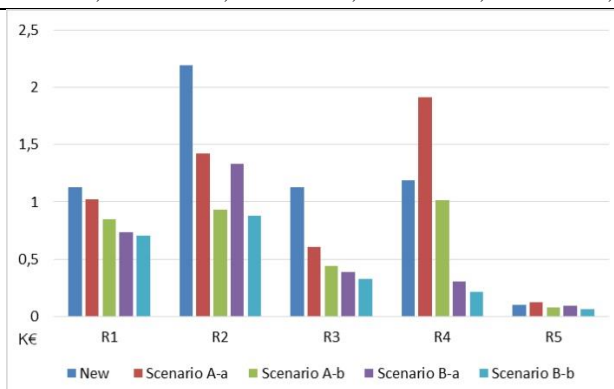
445 5.2.1 Attributional LCI modelling

446 Table 11 and Figure 5 report the external cost for new and reused EEEs. The results highlight that
 447 *New* and *Scenario A-a* determine the mainly contribute in all EEE categories. *Scenario B-b* produces
 448 a lower external cost and therefore the best economic performance.

449 **Table 11 External cost of the life cycles of new and reused EEE per each EEE group - Attributional**
 450 **LCI modelling**

External cost K€	R1	R2	R3	R4	R5
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<i>New</i>	1,129	2,189	1,131	1,192	0,099
<i>Scenario A-a</i>	1,022	1,426	0,606	1,915	0,125
<i>Scenario A-b</i>	0,845	0,929	0,439	1,017	0,082
<i>Scenario B-a</i>	0,732	1,33	0,392	0,303	0,094
<i>Scenario B-b</i>	0,703	0,877	0,328	0,211	0,066



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Figure 5 External cost of the life cycles of new and reused EEE per each EEE group - Attributional LCI modelling

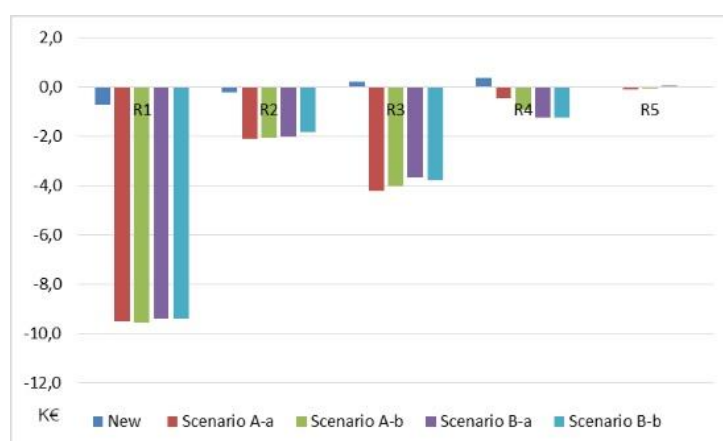
454 5.2.2 Consequential LCI modelling

455 The results (Table 12 and Figure 6) highlight that *Scenario A-b* determined a slight higher credit
456 than other scenarios for R1. *Scenario A-a* produced a higher advantage for R2, R3 and R5 and
457 therefore the best economic performance. *Scenario B-b* instead positively influenced R4 group.

458 **Table 12** External cost of the life cycles of new and reused EEE per each EEE group- Consequential
459 LCI modelling

External cost K€	R1	R2	R3	R4	R5
<i>New</i>	-0,720	-0,226	0,234	0,361	-0,026
<i>Scenario A-a</i>	-9,506	-2,108	-4,213	-0,455	-0,099
<i>Scenario A-b</i>	-9,566	-2,057	-4,034	-0,909	-0,070
<i>Scenario B-a</i>	-9,398	-2,021	-3,689	-1,227	0,001
<i>Scenario B-b</i>	-9,408	-1,820	-3,781	-1,236	-0,019

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Figure 6 External cost of the life cycles of new and reused EEE per each EEE group - Consequential LCI modelling

464 5.3 Social aspects - Job creation

465 The benefit derived from new jobs created by the preparation for reuse activity is carried out for
 466 each EEE category introducing into all different reconditioning processes modelled in Simapro (i.e.
 467 selection, check, disassembly and replacement, and cleaning) the duration (T_i , where i is the specific
 468 reconditioning process) necessary to perform each refurbishment activity. Considering, one work
 469 shift equal to eight hours per worker, it obtained the number of new jobs generated by the
 470 refurbishment activity as following reported:

471
$$\sum_i T_i/8$$

472 The number of new jobs were introduced in the calculation software through a new social substance
 473 defined as “number of employees”, which converges in the “Job creation” social category of the
 474 impact assessment method.

475 The life cycle of new EEEs had no positive contribution, as it does not account for reconditioning
 476 and therefore no job growth was considered.

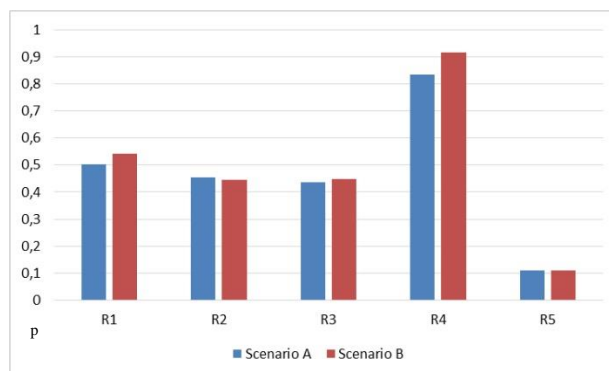
477 5.3.1 Attributional LCI modelling

478 The benefit derived from the *Job creation* category increases in *Scenario B* for the three EEE
 479 categories R1, R3 and R4. *Scenario A* is advantageous only for R2 and R5 (Table 13 and Figure 7).
 480 These results mainly depend on the different duration of the “Disassembly and Replacement”
 481 process and the calculated allocation share.

482 **Table 13 Evaluation of job creation increase adopting the reuse approach for both considered scenarios**
 483 **- Attributional LCI modelling**

Job creation [p*]	R1	R2	R3	R4	R5
<i>Scenario A (a-b)</i>	0,504	0,455	0,436	0,834	0,111
<i>Scenario B (a-b)</i>	0,541	0,444	0,449	0,916	0,109

484 * 1 p corresponds to 1 job create by reuse activities
 485



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Figure 7 Evaluation of job creation for Scenario A and B - Attributional LCI modelling

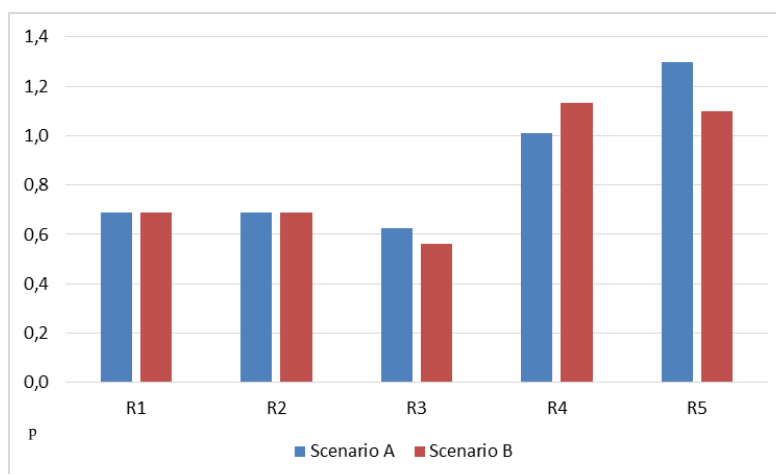
488 5.3.2 Consequential LCI modelling

489 The benefit derived from the *Job creation* category increases in *Scenario A* excepted for R4, mainly
 490 because of the longer replacement activity duration of *Scenario A*, the duration of “Disassembly and
 491 Replacement” process also depends on the weight of replaced components (Table 14 and Figure 8).

492 **Table 14 Evaluation of job creation increase adopting the reuse approach for both considered scenarios**
 493 **- Consequential LCI modelling**

Job creation [p*]	R1	R2	R3	R4	R5
<i>Scenario A (a-b)</i>	0,690	0,690	0,626	1,010	1,296
<i>Scenario B (a-b)</i>	0,689	0,689	0,563	1,134	1,1

494 * 1 p corresponds to 1 job create by reuse activities
 495



496 **Figure 8 Evaluation of job creation for Scenario A and B - Consequential LCI modelling**
 497
 498

499 Table 15 highlights the scenario that main determines the best environmental, social and economic
 500 performance achieve with attributional and consequential LCI modelling framework.

501 **Table 15 Summary table of the best scenarios obtained**

	Environmental	Social issue	External cost
<i>Attributional</i>			
Best case	<i>Scenario B-b</i> (EEE all category)	<i>Scenario A</i> (R2, R5) <i>Scenario B</i> (R1, R3, R4)	<i>Scenario B-b</i> (EEE all category)
<i>Consequential</i>			
Best case	<i>Scenario A-b</i> (R1, R2) <i>Scenario B-a</i> (R4) <i>Scenario B-b</i> (R3)	<i>Scenario A</i> (R1, R2, R3, R5) <i>Scenario B</i> (R4)	<i>Scenario A-a</i> (R2, R3, R5) <i>Scenario A-b</i> (R1) <i>Scenario B-b</i> (R4)

502

503 **6 Discussion**

504 The LCIA results adopting attributional LCI modelling (Tables 1-5, Supporting Information) show
 505 that taking the *New* scenario as the baseline, the obtained outcomes indicate that all scenarios exhibit
 506 better environmental performance than the baseline. The only exception is in *Scenario A-a* (new

507 replacement components) and for the R2, R4 and R5 groups, where the environmental damage is
508 higher than the baseline scenario. In these groups and in this scenario, therefore, there is no
509 environmental convenience in repairing an appliance and it is preferable to buy a new one. However,
510 simply by substituting the set of new replaced components (*Scenario A-b*) with reused components,
511 the environmental damage is reduced and the environmental performance is in line with all other
512 scenarios, becoming advantageous compared to the baseline. *Scenario B* demonstrates a net
513 environmental reduction with respect to the *New* one. Here, the reduction also increases when reused
514 replaced components are used. Regarding job creation, *Scenario B* is advantageous for three
515 categories out of five (i.e., R1, R3 and R4), while *Scenario A* benefits only the R2 and R5 groups.
516 The external cost assessment illustrates that the economic trend of each group is similar to that
517 related to the environmental assessment. All scenarios determine a better economic performance
518 than the *New* scenario, with the exception of R4 and R5 groups.

519 The analysis of results obtaining by consequential LCI modelling (Tables 6-10, Supporting
520 Information) determined, as for attributional approach, that all scenarios are better than the baseline.
521 Even because the *New* scenario generates for all groups an environmental damage (contrarily the
522 *Reused* scenarios produced an environmental credit), in fact the life cycle of new EEEs does not
523 consider the avoided production of the electronic devices since they are disposed to EoL treatments
524 after their lifetime use. The environmental outcomes do not create a specific best performance
525 scenario this depends on the different avoided environmental burdens associated to the new EEE
526 production (avoided product). In particular, *Scenario A* rewards the large household appliances (R1
527 and R2) whereas *Scenario B* is the best scenario for the smaller device categories such as R3 and
528 R4. In this latter scenario, R5 category does not achieve an environmental credit due to the energy
529 consumption in the use phase that does not balance the benefit generated by the avoided production
530 of the new R5.

531 Compared to the attributional LCI approach, it is possible observe a job creation trend reversal,
532 which determines *Scenario A* advantageous for all categories except for R4 group. The external cost
533 evaluation produced an economic trend different to that related to the environmental assessment.
534 *Scenario A* is advantageous for all groups except for R5. The environmental, job creation and
535 external cost assessments generated moderately different trends. Therefore, a univocal results
536 interpretation is rather difficult to develop.

537 It is worth noting that the choices of the set of components that must be replaced and the LCI
538 modelling framework adopted to conduct the LCA study are crucial issues.

539 Indeed, the attributional LCI modelling conducted to the conclusion that *Scenario A* represents the
540 more frequent setting but not the more sustainable and *Scenario B* represents the set that can actually
541 result in a decrease in environmental damage and external costs and an increase in social benefits.
542 However, according to the direct interviews with retailers and technicians, this latter scenario occurs
543 less frequently than Scenario A.

544 Consequential LCI modelling generated diversified outcomes varying with the EEE category,
545 therefore the best-case scenario that conduct the higher environmental credits is not possible defined.
546 Although, for external costs and job creation *Scenario A* showed to be the set of components having
547 the best performance.

548 This highlights the importance of LCA in decision-making and the influence of the results
549 interpretation given by the LCA practitioner that conducts the LCA study.

550 Therefore, taking into account that the consequential LCI modelling enlarges the boundaries of the
551 study until embracing the consequences that the analysed system might cause on market avoiding
552 the production of that specific resource and consequentially changing the market demand, it is
553 possible conclude this LCI approach is unsuitable for this LCA study. In fact, the final market of
554 reused EEEs is not the same as for new EEEs. Currently, as aforementioned, no legitimate market
555 exists. Therefore, reconditioned EEEs could create a new business opportunity, not changing the
556 traditional market demand of new electronic products. Therefore, we suggest to implement the
557 cause-oriented attributional modelling, firstly because this model allows to obtain a snapshot of the
558 understudied system meeting the requests of who commissioned the study (Pini et al., 2018) and
559 secondly for the lack of marginal data concerning the ‘preparation for reuse’ activity, in the Italian
560 context, necessary to model consequential LCA.

561 In conclusion, the Attributional LCI approach carried out that the preparation for reuse activity could
562 lead to obtaining a greener EEE than the new one, but this depends on the components replaced.
563 Nevertheless, through the LCA study the decision-maker can ensure that adopting the scenario is
564 more sustainable.

565 **7 Conclusions and further research agenda**

566 Electrical and electronic equipment is of increasing importance in our daily work and life. In fact,
567 we are now dependent on appliances such as laptops, tablets, mobile phones, washing machines and
568 televisions. The current short lifetime and the widespread use of these devices lead to an inevitable
569 accumulation of WEEE, which at their EoL must be managed in a responsible and conscious way.
570 The present work provides an environmental comparison, through the LCA methodology, between
571 the reused EEE (WEEE reconditioned after the preparation for reuse treatment) and the new one for
572 the *whole* life cycle. For reused EEE, to investigate how the choice of the set of replaced components
573 affects the LCA results, different scenarios were analysed. This research is the first to consider all
574 WEEE categories (i.e., R1, R2, R3, R4, R5), and not only a singular group or just one of its
575 components (e.g., printed wiring boards, engines, capacitors, projectors, etc.). Few LCA studies
576 have to date investigated reuse. Our work is therefore of value, and we believe that future research
577 should focus attention on the environmental assessment of reuse by expanding the analysis to
578 different WEEE groups. This would allow the environmental convenience of the preparation for
579 reuse and traditional EoL treatments of electronic waste to be compared and assessed for a broader
580 range of devices. Indeed, by prolonging the lifetime horizon of electrical and electronic products it
581 may be possible to avoid the production of new goods and the use of materials that those recuperated
582 through conventional WEEE treatment. Alongside the environmental evaluation, the social benefit
583 derived from job creation, the external cost engendered by preparation of reuse activity were
584 assessed. Therefore, the sustainability assessment was thus greatly enriched. Finally, further
585 research should focus on the integration of a multicriteria decision-making approach (MCDM) to
586 LCA analysis, in order to collect others social sustainability measures which will be carried out
587 through a Fuzzy Promethee model group, able to integrate objective (e.g. environmental) criteria
588 with subjective (e.g. social). Moreover, a sensitivity analysis considering different lifespans of the
589 reused EEE and different energy performance in the use phase is worth to be accomplished.

590
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594

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