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1 Selective separation of plastic LED lamp components using electrodynamic
2 fragmentation for material recovery

3

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23

24 **Abstract**

25 The recycling of light-emitting diode (LED) lamps and tubes is becoming increasingly
26 important due to their growing market share as energy-efficient lighting technology. Here
27 we report on the use of high voltage electric-pulse fragmentation to recover elementary
28 components such as LED chips and printed circuit boards (drivers). E27 LED lamps with
29 plastic bulbs, which represent 48% of deposits collected by a French company, are used as a
30 case study. More than 150 lamps were tested on a laboratory reactor for electrodynamic
31 fragmentation. The technological process in which highly energetic electrical pulses were
32 applied to materials immersed in water was studied in order to separate the components of
33 the LED lamps using a minimal specific energy. The estimated energy necessary to achieve
34 total separation assessed at 64%, without grinding pretreatment, was 5.2 ± 0.6 kWh per ton,
35 representing a mass recycling rate of 74%. Based on the disassembled material, the
36 commercial value of the recovered materials was thus estimated. Gold, as the most
37 representative material, was found to represent 0.03% of the mass fraction for 83.6% of the
38 total commercial value. The process disassembling capacity is a key issue to increase the
39 recycling rate of current LED lamps and tubes.

40

41 **Keywords:** Waste LED lighting devices; Material recovery; Selective comminution;
42 Electrodynamic fragmentation;

43

44 **1. Introduction**

45 To reduce energy consumption and increase energy independence ([European Commission,](#)
46 [2009](#)), the technology of light-emitting diodes (LED) has been developed since 2000. By the
47 end of this decade, it is expected that all incandescent and compact fluorescent lamps (CFL)

48 will be replaced by LED lamps, tubes, and panels (ECOSYSTEM, 2019). LED lamps will
49 effectively capture 74% of the market share by 2030, leading to a 46% reduction in energy
50 lighting consumption around the world (Aman et al., 2013; Bruno Gayral, 2017; Natthanon et
51 al., 2018; Doulos et al., 2019). The sharp increase in luminaire efficiency and the gradual
52 reduction in the cost of purchasing LEDs have led to an augmentation in the market share of
53 LED lamps and tubes. Rather by the capacitors and electronic components of the printed
54 circuit boards (PCBs or drivers), the lifespan of LED lamps is around 5-7 years, with an
55 average around 25,000 hours - and up to 50,000 hours - depending on the manufacturers
56 (Narendran et al., 2001; Richter et al., 2019). Nevertheless, LED products are expected to
57 end up in the e-waste stream in massive quantities from 2022 to 2030, which represents a
58 challenge for legislators and recycling companies. There is currently no dedicated industrial-
59 scale technology to treat this e-waste (Mizanur Rahman et al., 2017), and in France, all LEDs
60 are simply stored in the factories such as the ARTEMISE company. ECOSYSTEM, a non-profit
61 ecological organization in France, is in charge of collecting and finding solutions for recycling
62 used LED lamps and tubes. The valuable materials contained in LEDs and their design variety
63 are the main recycling issues (Mizanur Rahman et al., 2019).

64 White LED chips are based on a blue multiple quantum well (MQW) and rare earth yellow
65 phosphors materials (Schubert and Kim, 2005; Dussaigne et al., 2020; Shameem et al., 2020;
66 Isfahani and Faez, 2021). MQW are grown on III-V semiconductor, most commonly with
67 indium, gallium (Pourhossein and Mousavi, 2018), and nitrogen as ternary compounds,
68 leading to the use of InGaN / GaN MQW. It is worth noting that more abundant materials
69 such as zinc oxide-based LED products could be good candidates not only to replace InGaN
70 but also to develop new technologies such as lasing-based white LEDs (Zhang et al., 2013;
71 Nomenyo et al., 2014). However, they are still dealing with stability issues especially in

72 doping that currently prohibit the use of such materials. With the current technology, drivers
73 contain gold, copper, tin, nickel and other precious metals ([Lim et al., 2013](#); [Reuter and Van](#)
74 [Schaik, 2015](#); [Franz and Wenzl, 2017](#); [Pourhossein and Mousavi, 2018](#)), which constitute the
75 highest valuable fraction. Additionally, to reduce fire hazard, brominated flame retardants
76 are used in the plastic matrices ([Lim et al., 2011](#)). The European cyclLED project ([Marwede et](#)
77 [al., 2012](#)) explored the mass flows of selected target materials in LED products. Some
78 elements like gold, silver, palladium, aluminium, copper, tin, and antimony were found in
79 the electronic components. Moreover, other resources are used in a limited number of
80 specific components in the LED chips, such as semiconductors (gallium and indium) or rare
81 earth metals (phosphor) ([Pilotto Cenci et al., 2020](#); [Martins et al., 2020](#)). This study focuses
82 on the recycling of E27 LED light devices to facilitate the recovery of parts or the extracted
83 materials, including precious and strategic metals ([Fouquet and Martel-Jantin, 2014](#)). One of
84 the key issues is determining how to separate the optical systems (bulbs) and bodies without
85 mechanical crushing of components containing metals parts. In this respect, only a recycling
86 process adapted to the specificity of the LED lamps could undertake this separation to
87 recover all the elementary components individually such as LED chips, LED modules and
88 drivers.

89 In the context of the development of new recycling routes for some categories of WEEE,
90 such as solar panels, printed circuit boards or lithium-ion batteries, some researchers have
91 tested the high voltage electric-pulse fragmentation process to increase the recovery rate
92 while reducing production costs compared to mechanical crushing processes.

93 Indeed, it was noted that using high voltage technology allowed for the selective
94 fragmentation of concrete and composite materials ([Van der Wielen et al. 2013](#); [Shi et al.](#)
95 [2014](#); [Touzé et al. 2017](#); [Bru et al. 2018](#)). This technology is based on the rapid return of

96 highly concentrated electrical energy stored in capacitors by creating a fracturing shock
97 wave allowing selective separation (Zhao et al. 2015; Nevala et al. 2019). How about, EDF
98 was tested for the recycling of waste solar photovoltaic panels by considering the energy
99 consumption (Song et al., 2020). It was found that the optimal condition of high voltage
100 fragmentation is 160 kV for 300 pulses with an energy consumption of 53.6 kWh/t, crushing
101 the PV panels into particles of 4.1 mm on average. Printed Circuit Boards waste have also
102 been studied using this technique. It was observed that an increase in the voltage and the
103 pulse number improved the metal recovery rate with a reduction in the size of the crushed
104 products (Zhao et al., 2015). Another study suggests that the metal and nonmetal materials
105 could be dissociated with minimum tensile strength, which makes the circuit boards
106 gradually break into block pieces (Duan et al., 2018). Finally, we can report on the study of
107 lithium-ion batteries (Tokoro et al., 2021) which employed EHF for separating cathode
108 particles and aluminum (Al) foil. One of the main results is that using a voltage of 25 kV,
109 93.9% of the cathode particles are separated from the Al foil, and these particles were easily
110 recovered by appropriate sieving. The parameters studied in these studies were the voltage
111 (20-200 kV), electrode gap (10-40 mm), pulse repetition frequency and number of electrical
112 pulse (1-1000) (Bru et al., 2018).

113 These results suggest that high voltage electric-pulse could offer a new and promising
114 approach to the recycling of specific WEEE waste such LED lamps. So, this study deals with
115 the potential of EDF technology to selectively separate the electronic components of plastic
116 E27 LED lamps without damaging them, which would allow their reuse or further recycling to
117 recover the constituent materials and more specifically precious metals. After reviewing the
118 type of reactor used in this study, we will show how the technique allows for the

119 comprehensive disassembling of the most frequently collected products: i.e. plastic E27 LED
120 lamps.

121

122 **2. Materials and methods**

123 **2.1. Study materials: Plastic E27 LED lamps**

124 To determine the trends and repeatability of the used LED light products collected by the
125 ARTEMISE company, we carried out a monthly sampling campaign starting in September
126 2019 and then continuing on a quarterly basis until June 2020. The results are shown in Fig.
127 1. We characterized six big bags of LED lamps and spotlights with an average weight of 336
128 kg and a total number of 29,600 LED units. As a result of this sampling, E27 LED lamps were
129 found to be the most common type of lamp, accounting for 58-73% of the deposit
130 depending on the sampling period. GU10 LED spotlights were the second most represented
131 type with 16-29% followed by E14 LED lamps accounting only for 3-7%. These three models
132 constitute 88-92% of the total deposit. A similar trend was observed by [Mizanur Rahman et](#)
133 [al. \(2019\)](#) who concluded that E27, E14, and GU10 LED lamps represented 90% of LED
134 products. The mapping of the deposits (Fig. 1-a) reveals that E27 LED lamps with small
135 plastic parts are the predominant model (between 25% and 52% and 38% on average). E27
136 LED with large plastic parts are also frequently represented in the deposit (between 6% and
137 14% and 10% on average). These differ from the small plastic E27 LED lamps by the size of
138 the bulb, which is composed of polycarbonate (PC) ([Cheng. 2002](#); [Martins et al., 2020](#)). This
139 model could not be explored further in this study because of these dimensions. Another
140 model is the GU10 LED spot, which is also common on average it accounts for 22%. Finally,
141 we chose to examine E27 LED lamps with small plastic optical system. The body of these

142 lamps is made of aluminium with a typical thickness of 0.8 mm and covered by a polymeric
143 material with a typical thickness of 0.9 mm (Fig. 1-b).

144 This type of LED lamp represents around 38% of total deposits (Fig. 1-c) and thus constitutes
145 a very representative sampling.

146 **2.2. Laboratory tests**

147 There are two types of high-voltage fragmentation. In the first, known as localised
148 fragmentation, the discharge occurs within the material(s): this is electrodynamic
149 fragmentation (EDF). The second, known as delocalized fragmentation, consists of
150 transmitting a shockwave to the material(s), through a dielectric liquid: this is
151 electrohydraulic fragmentation (EHF) ([Justin Martin, 2013](#)). The voltage rise in the case of
152 EDF is very fast (< 500 ns) with applied values in the order of 90 to 200 kV, whereas the
153 voltage rise in the case of EHF is slower (> 500 ns) with values in the order of a few tens of
154 kilovolts (30-50 kV) ([Pestalozzi et al., 2018](#)). EDF technology was chosen in our study
155 because, as shown above, it has been the most widely used technology in the fragmentation
156 of some WEEE.

157 As shown in the Fig. 2 (a, b), the EDF laboratory-scale tests were carried out using the
158 SELFRAG laboratory-scale device for the batch processing of materials. The system was
159 manufactured by the Swiss company SELFRAG. It is based on a 5.3 L capacity vessel
160 ([SELRAG, 2020](#)) containing 2.78 L of deionized water. The equipment is designed to process
161 products weighing up to approximately 1 kg and measuring between 80 mm (diameter) and
162 40 mm (height).

163 The discharge electrode is immersed in the upper part of the container, while the bottom
164 constitutes the ground electrode (Fig. 2-c). The device produces high voltage electrical
165 discharges between the two electrodes. The operating parameters are the voltage (90-200

166 kV), electrode gap (10-40 mm), pulse repetition frequency (1-5 Hz), and number of electrical
167 pulses (1-1000) (Bru et al., 2018).

168 The unit was used to fragment 164 plastic E27 LED lamps. These lamps represent a total
169 mass of 7.7 kg with an average mass per sample of 47.0 ± 11.6 g. The studied parameters
170 were the voltage and the number of discharges, while the interelectrode distance was kept
171 constant at 40 mm throughout the study. In fact, the dimensions and shape of these E27 LED
172 lamps did not allow us to test a distance of less than 40 mm. The objective of the laboratory
173 scale tests was to study the influence of the generator energy (specific energy in kWh/t for
174 plastic E27 LED lamps) on the fragmentation of samples. As shown in Equation (1), the
175 energy of the generator only depends on the variation of the voltage and the number of
176 pulses applied, and not to the capacitance, which is fixed at 37.5 nF for this laboratory
177 machine. The applied voltage for this study was set between 90 kV and 180 kV.

$$178 \quad E_{gen} = n \times \frac{1}{2} \times C \times U^2$$

179 E_{gen} represents here the generator energy (J), n the number of pulses, C the capacitance (F),
180 and U the pulse voltage (V) (Bru et al., 2018).

181

182 **2.3. Methodology**

183 As will be shown below, it was possible to disassemble the plastic E27 LED lamps into four
184 components: bulb, LED module, driver and body with the Edison screw. Based on this
185 observation, we defined criteria to assess the quality of the disassembled sample. The
186 fragmentation can be considered validated by a recycling company if:

187 The bulb and body are completely separated;

188 The LED module is separated with at least 50% of the LED chips still attached to the
189 aluminium support;

190 The driver is completely separated from the LED module and base;

191 The Edison screw is still attached to the lamp body.

192 For all series, we counted the number of detached bulbs, LED modules, and drivers in order
193 to determine the percentages of selective fragmentation. A total of 164 identical plastic E27
194 LED lamps were individually fragmented. For the most favorable voltage-pulse pairs, eight
195 experiments were carried out to ensure the reproducibility of the validated fragmentations.
196 Reproducibility was assessed by observing and counting the total liberation of the drivers
197 and the LED modules with at least 50% of LED chips still placed on the aluminium modules.

198 Let us now define the condition criteria for the electrical components, namely the LED
199 modules and drivers. Four different conditions were defined for both the module and the
200 driver. For the LED module, the condition: excellent, good, bad, and very bad indicates that
201 75-100%, 50-75%, 25-50%, and 0-25% of the chips are still attached to the aluminium plate
202 respectively. For the drivers, their condition is simply based on a visual analysis with
203 excellent, good, bad, and very bad respectively referring to their unfractured, weakly,
204 significantly, and totally fractured state.

205

206 **3. Characterization of selective fragmentation of plastic E27 LED lamps elements**

207 **3.1. Selective fragmentation**

208 **3.1.1. Results**

209 We tested plastic E27 LED lamps (110 mm height) with a standard diameter optical system
210 (40 mm). They were diagonally positioned in the vessel. Using a logic of experimentation and
211 experimental observations, the voltage range was between 90 kV and 180 kV, with electric

212 discharges ranging from 1 to 30 pulses at a frequency of 5 Hz. The average specific energy
213 was 5.2 ± 0.6 kWh/t. The mapping of the tests shown in Fig. 3-a represents the areas that
214 were tested to determine the area for the dismantling and deconstruction of the plastic E27
215 LED lamps. The aim here was to validate the most suitable parameters for the voltage and
216 number of pulses. Considering the criteria established in the Methodology section above,
217 Fig. 3-b (150 kV; 15 pulses) and 3-c (150 kV; 5 pulses) do not validate the criteria, whereas
218 Fig. 3-d (150 kV; 4 pulses) and 3-e (140 kV; 5 pulses) do.

219 After selecting the most favorable dismantling conditions, we counted seven voltage-pulse
220 pairs for which eight tests were carried out. In this case, 56 plastic E27 LED lamps were
221 investigated, corresponding to a total sample mass of 2.6 kg. Table 1 and Fig. 4 show the
222 selective fragmentation of the plastic E27 LED lamp elements based on visual inspections.
223 Overall, the results of the seven experimental series A to G are very encouraging, resulting
224 on an average overall separation of 64%.

225

226 **3.1.2. Discussion**

227 The B series has an average total fragmentation percentage of 96% with electronic
228 components in very good state and the average specific energy evaluated at 6.2 ± 1.0 kWh/t.
229 The validated tests remain very promising for the design of a future experimental prototype,
230 particularly with a larger vessel more suited to LED devices. This potential solution will also
231 make it possible to increase the distances between the electrodes, which will be better
232 adapted. The idea is to guarantee an efficient electric discharge path in water and
233 consequently develop an electric arc of selective fragmentation that is sufficient for the
234 treatment of all types of LED lamps. This is an essential criterion for recycling companies.

235 Moreover, the notion of reproducibility for the seven series of tests was evaluated. This
236 relates to the total separation of the drivers and the LED modules with at least 50% of the
237 LED chips still found in the aluminium modules as shown in Fig. 4-h. The average
238 reproducibility is estimated to be 78% for LED supports and 64% for PCBs.

239 An estimation of the reproducibility is essential to evaluate whether a series of tests has
240 been validated. In fact, differences were observed for tests conducted with strictly identical
241 operating modes. Significant variations were found in terms of the separation of the
242 constituent elements:

243 LED supports released with all the LED chips attached or detached;

244 LED supports not released with the LED chips detached or sometimes even fractured;

245 Entire separate drivers and in a relatively good state;

246 Drivers not separated and still soldered or nested to the LED modules and bases, and finally,
247 exploded drivers.

248 For this reason, we counted the number of LED chips that remained attached to the LED
249 modules after the selective fragmentation. Overall, 75% of the LED chips were still available
250 after the selective fragmentation. For their optimal recovery in the reuse or recycling
251 scenario, it would be preferable to keep the LED chips on their aluminium supports. This
252 would facilitate the sorting step and thus increase the recovery rate. In addition, keeping the
253 LED chips on their LED modules, as close as possible to their initial forms and states, helps
254 prevent losses of mass and energy ([Reuter and Van Schaik, 2015](#)).

255 The plastic E27 LED lamps with large diameter bulbs could not be fragmented. However, the
256 validated parameters of this study should be applicable to all LED devices composed of
257 plastic bulbs and plastic-coated aluminium bodies such as E27, B22, and E14 LED devices
258 (about 55% of deposits; Fig. 2-c) ([Martins et al., 2020](#)).

259 The reproducibility criteria used for the separation of components ensures their recyclability
260 in an industrial recycling process which, in turn, could be economically viable and profitable.
261 The separation and subsequent recycling processes help make the overall process and sector
262 more environmentally friendly. It is worth mentioning that the eco-design strategies used for
263 LED lamps is also essential in order to efficiently dismantle these new light products
264 ([Dzombak et al., 2017](#); [Pilotto Cenci et al., 2020](#); [Martins et al., 2020](#)).

265

266

267 **3.2. Quality of the bodies and electronic components**

268 **3.2.1. Results**

269 We also considered the state of the aluminium bodies covered with a polymeric coating
270 composed of polybutylene terephthalate (PBT) ([Martins et al., 2020](#)). A visual analysis was
271 performed (Fig. 5) on all the sample bodies. The examination criteria were perforation and
272 deformation due to electrical discharges.

273 In the validated series (voltage and pulses), 97% of the bodies were deformed and 76% were
274 pierced. Therefore, in the case of validated voltage-pulse pairs, the fragmentation energies
275 were optimized. The electric discharges passed through the samples to obtain favorable
276 selective separations for the entire study.

277 The observations were also made with regard to the electronic components, which
278 constitute the added value of such LED devices. For this reason, we analyzed the
279 fragmentation of the LED modules and the drivers (Fig. 6). In the two analyses of the series
280 of validated voltage-pulse pairs, the fragmentation criteria correspond to the states of the
281 electronic components at the end of the tests, which could be excellent, good, bad, or very
282 bad. In the case of the LED modules, the criteria were whether or not the LED chips

283 remained attached to their aluminium support. In the case of drivers, we visually examined
284 the state of the electronic components (coils, capacitors, transformers, etc.).

285 Fig. 6 summarizes the statistical study conducted on the electronic components, namely the
286 LED modules and the drivers. The main idea was to classify the disassembled parts according
287 to their condition.

288

289

290

291 **3.2.2. Discussion**

292 Regarding the LED modules (Fig. 6-a to 6-e), it was found on average 64% were in excellent
293 condition, meaning that 75% to 100% of the LED chips are still positioned on the module.

294 This value can be compared to the average percentage obtained when considering the
295 overall sampling material (i.e., 56%). Furthermore, 15%, 10%, and 10% of the LED modules
296 were respectively in a good (50-75%), bad (25-50%), and very bad condition (0-25%) (vs 13%,
297 10%, and 21% for the overall sampling material). It should therefore be noted that, on
298 average, 79% of the LED modules are in excellent or good condition (vs 69% of the overall
299 sampling material). By contrast, 20% are in a bad or very bad condition (vs 31% for the
300 overall sampling material).

301 Considering these findings, we show that using the same parameters detailed in Table 1,
302 two-thirds of the LED lamps can be treated; in other words, the lamps can be disassembled
303 without deteriorating the LED modules.

304 As shown in Fig. 6-f to 6-j, the same kind of analysis can be applied to the drivers. Our
305 findings show that on average 31% of the drivers were in excellent condition meaning that
306 75% to 100% of the drivers were undamaged, which compares to the 25% for the overall

307 sampling material. Furthermore, 34%, 10%, and 25% of the drivers were respectively in a
308 good, bad, and very bad condition (vs 28%, 17%, and 31% for the overall sampling material).
309 Therefore, it was found on average that 65% of the drivers were in excellent or good
310 condition (vs 53% for the overall sampling material). These results show that EDF was less
311 effective for the drivers than for the LED modules, although the technology is still relevant.

312 To conclude, the comparisons with the overall sampling material shows the effectiveness of
313 the determined parameters (Table 1) for sample fragmentation. Considering these two
314 analyses, we identified the optimal conditions to dismantle the electronic components while
315 preventing their degradation. Additionally, having the components as close as possible to
316 their initial state will help minimize mass and energy losses in the new proposed recycling
317 process ([Reuter and Van Schaik, 2015](#); [Pilotto Cenci et al., 2020](#)). At the end of the tests, we
318 observed that when the LED chips were still positioned on the aluminium support, they were
319 found to be functional. A more systematic study is currently underway to assess the effect of
320 fragmentation treatment. This observation could nevertheless favor the reuse and/or the
321 material recovery (recycling) of the LED chips. Regarding the drivers, based on our
322 observations, recycling seems preferable. In fact, the damage caused by selective EDF
323 deteriorates the electronic components of the drivers in such a way that they cannot be
324 reused as such. To consider a reuse scenario for the drivers or their components, only the
325 manual separation of the LED devices is conceivable at this stage.

326 A final aspect relates to a technical constraint in the treatment of this type of LED product
327 using selective fragmentation. This concerns the inclusion of air in the bulbs, which forms an
328 “air chamber” and prevents the lamp from being correctly positioned in the reactor. A
329 piercing action is thus needed to avoid the floating of the plastic E27 LED devices. If not, this
330 situation would cause a short circuit in which the path of the electrical discharge would only

331 partially impact the bulb, or even not at all. All the electrical energy would then be
332 concentrated on the ground electrode. It is worth noting that in the case of EHF, the final
333 shock wave fragments the samples by generating internal stress such as compressive strain
334 (Vaasjoki and Lindqvist, 2001; Justin Martin, 2013; Touzé et al., 2017; Pestalozzi et al., 2018).

335

336 **3.3. Materials recovery and recycling rate**

337 **3.3.1. Results**

338 Fig. 7-a shows the quantities and percentages of the recovered material for the total study
339 with all different energy levels. The studied sample series is composed of plastic E27 LED
340 lamps, which will represent more than 30% of deposits over the next decade (ECOSYSTEM,
341 2019). In total, 34.2 g of LED chips, 1231.1 g of LED modules, and 923.6 g of drivers (Fig. 7-b)
342 were recovered. Assuming that our samples are comparable to those of Pilotto Cenci et al.
343 (2020), we applied the material coefficients to the recovered electronic components of the
344 plastic E27 LED lamps to estimate the quantities of precious metals. The equation considered
345 for this analysis is below (2).

$$346 \quad \text{Amount of precious metal } j = \sum_{i=1}^{n=3} (\text{Masses of electrical components}_i \times \text{metal rate } ij) \quad \mathbf{(2)}$$

347 The Sankey diagram visualizes these results (Fig. 7-b). The main idea is to integrate the LED
348 lamps into a loop (Baldé et al., 2017) with the aim of reusing and/or recycling them using an
349 efficient and safe process that mitigates environmental impacts and generates economic
350 benefits. Using this integrated closed-loop circuit, waste management will be more
351 straightforward and efficient by minimizing the generation of waste or increasing the
352 economic benefit by considering e-waste as a real source of secondary raw materials (Pilotto
353 Cenci et al., 2020).

354 Regarding plastic E27 LED lamps, their valuable materials include precious metals, some of
355 which are considered critical with a high supply risk (Hennebel et al., 2015; Isildar et al.,
356 2018). Gold, silver, copper, gallium, indium, and rare earth elements can be found in the LED
357 chips, LED modules, and drivers (Reuter and Van Schaik, 2015; Franz and Wenzl, 2017;
358 Pourhossein and Mousavi, 2018). The mass fractions of these materials in plastic E27 LED
359 lamps were estimated to be 0.052%, 0.482%, and 0.381% for gold, silver, and gallium,
360 respectively (Pilotto Cenci et al., 2020). These recoverable materials are mainly found in LED
361 chips. Nevertheless, due to the lack of specific recycling processes for LED lamps (Mizanur
362 Rahman et al., 2017), any new technological process to recover such materials should take
363 economic viability into account. The current study aimed at understanding how the
364 electronic components can be dismantled using EDF tests.

365

366 **3.3.2. Discussion**

367 Based on the results of the fragmentation study and the percentage composition as shown
368 in Fig. 7-a, let us estimate the recoverable fraction of materials in 1,000 kg of plastic E27 LED
369 lamps. The first step of the recycling process is the carcass segregation (optical systems,
370 bodies, and bases), which represent around 720 kg. The second step involves generating a
371 material flow of the LED modules, drivers, and LED chips (around 280 kg). In supplementary
372 data, Fig. S2 summarizes the mass fractions of precious metal ores. More precisely,
373 segregating the carcasses of 1,000 kg of LED lamps results in 160.0 kg of LED modules, 120.0
374 kg of drivers, and 4.4 kg of LED chips. From 284.4 kg of components, only 158.8 kg of
375 precious metals is recoverable, corresponding to 102.4 kg in LED modules, 53.4 kg in drivers,
376 and 3.0 kg in LED chips. Hence, the recycling rates of the components are 64.0% for LED
377 modules, 44.5% for drivers, and 68.4% for LED chips. Other studies have reported a 28%

378 recycling rate for cellphones ([Reuter et al., 2018](#)), 30% for PCBs ([Isildar et al., 2018](#)), and 30%
379 for LCD screens ([Van Schaik and Reuter, 2016](#)). In terms of the economic value, the
380 components and materials with the largest mass fraction may not be the most economically
381 important in terms of recycling ([Pilotto Cenci et al., 2020](#)). It is worth analyzing the main
382 components and materials from an economic perspective.

383 Gold is the most valuable material ([Murakami et al., 2015](#)), while the LED chips are the most
384 valuable components. Despite the low quantity of gold in LED lamps, it remains the most
385 important material from an economic perspective. Indeed, gold is potentially 0.03% (71 g) of
386 the electronic component mass ([ADEME, 2017](#)) but it represents 83.6% ([Magazine
387 RECYCLAGE RECUPERATION, 2020](#)) of the total commercial value, whereas aluminium is
388 33.1% (94.1 kg) of the electronic component mass but it only represents 3.0% of the total
389 commercial value. The small portion of gold in the LED lamps is therefore relevant in terms
390 of the total economic value of the product. These results for the economic strategy of
391 recovering gold from LED lamps were also mentioned in the study of [Kumar et al., 2019](#).

392 In addition, tin and copper have an important distributed mass fraction in the electronic
393 components, and they are interesting materials from an economic perspective. The mass
394 fraction of tin is 8.9% (25.4 kg), representing 9.2% of the total commercial value. As for
395 copper, it is 9.0% (25.6 kg) of the total mass fraction for 3.5% of the total commercial value.

396 Moreover, it is relevant to define the most valuable electronic components according to the
397 normalized economic value per kilogram of LED chips, LED modules, and drivers. Even
398 though the LED chips are the electronic component with the smallest mass fraction, this
399 product is the most valuable component compared to the LED modules (47% of the value of
400 the LED chips) and the drivers (39% of the value of the LED chips). This highlights the
401 importance of using efficient industrial processes to separate the components to ensure and

402 improve the recovery of highly valuable materials and hence maximize the mass fractions of
403 recovered materials.

404 The concentration of materials in e-waste represents a potential of €55 billion with €40
405 billion of metals (Baldé et al., 2017). This requires appropriate industrial processes to recycle
406 the materials (Kumar et al., 2017). Besides the intrinsic value of this secondary source of
407 materials, recycling also reduces the need for primary raw materials (Pilotto Cenci et al.,
408 2020). This kind of analysis allows recycling companies to define their industrial strategy and
409 concentrate on the most profitable secondary raw materials depending on geopolitical
410 factors.

411

412 **3.4. Recommendations to improve the recycling process**

413 The selective fragmentation of plastic LED lamps in this study demonstrated the need to
414 focus on the recovery of electronic components which contain precious metals to increase
415 economic profits. The process will be all the more efficient with eco-designed products
416 whose fragmentation would be facilitated. Thus, the recovery of precious metals would be
417 easier to sort and recycle. The added value of these products is contained in their electronic
418 components and the pulsed powers allow separation of these products while avoiding their
419 physical, and therefore potentially functional, deterioration. These components contain the
420 precious metals which define the economic profitability.

421 The expected increase in the volume of LED lamp waste, as well as their wide variety should
422 lead to adapting the process to operate in industrial conditions of continuous treatment. For
423 example, to achieve a flow rate of up to 10 t/h and to accept up to 7 types of LED lamps (Fig.
424 1-a) in the same stream. This observation is encouraging for an industrial-type device.

425

426 **4. Conclusion**

427 The main objective of this study was to identify the optimal conditions for disassembling,
428 and estimate the recycling potential, of LED-based lighting devices. As a test sample, we
429 chose plastic E27 LED lamps with the goal of reaching a global recycling rate of 80%. The
430 main results obtained in this study are:

431 The efficient separation of the components was achieved without any pretreatment such as
432 grinding;

433 Implementation of a protocol to qualify defragmentation as acceptable or not for recycling
434 companies;

435 The average specific energy to achieve selective and efficient fragmentation was 5.2 ± 0.6
436 kWh/t, with the average overall separation estimated at 64%. These results to be compared
437 with the 152 kWh/t of the shredding process, with a segregation percentage close to zero;

438 Gold represents 0.03% and 83.6% of the mass and commercial value of the recovered
439 electronic components respectively.

440 In order to control the quality of the fragmentation, we could use artificial intelligence,
441 based on image analysis, and recognize the optimal fragmentation of the components to
442 sort and recover the under-products which not be correctly fragmented. They would be
443 retreated by loops in the process. This technology would improve the industrial process.

444 Considering these findings, EDF emerges as a very promising process for LED lamp recycling,
445 since it allows a better valorization of the components through their preliminary
446 disassembly. This research highlights the relevance of recycling this new complex e-waste
447 and the opportunities provided by new technological alternatives.

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455

456 **Conflicts of Interest**

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

459

460 **Supplementary data**

461 Supplementary data associated with this article can be found in the online version

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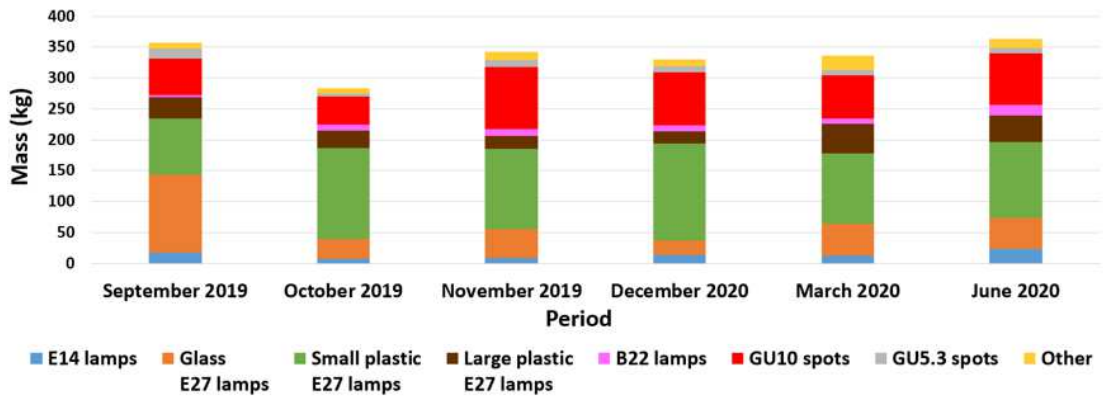
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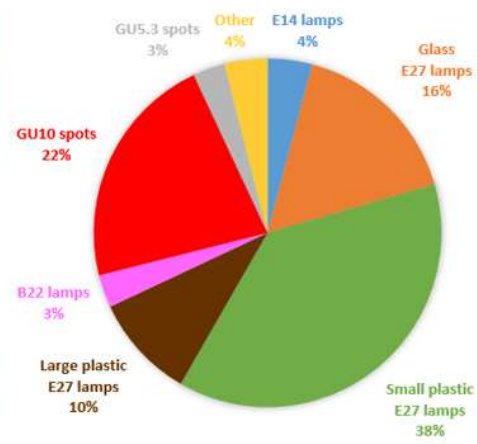
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(a)



(b)



(c)

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664 **Fig. 1.** Deposit study: Typology of the six big bags analyzed between September 2019 and June 2020 (a),
 665 photographs of small plastic E27 LED lamps (b), and average typology of the big bags (c).

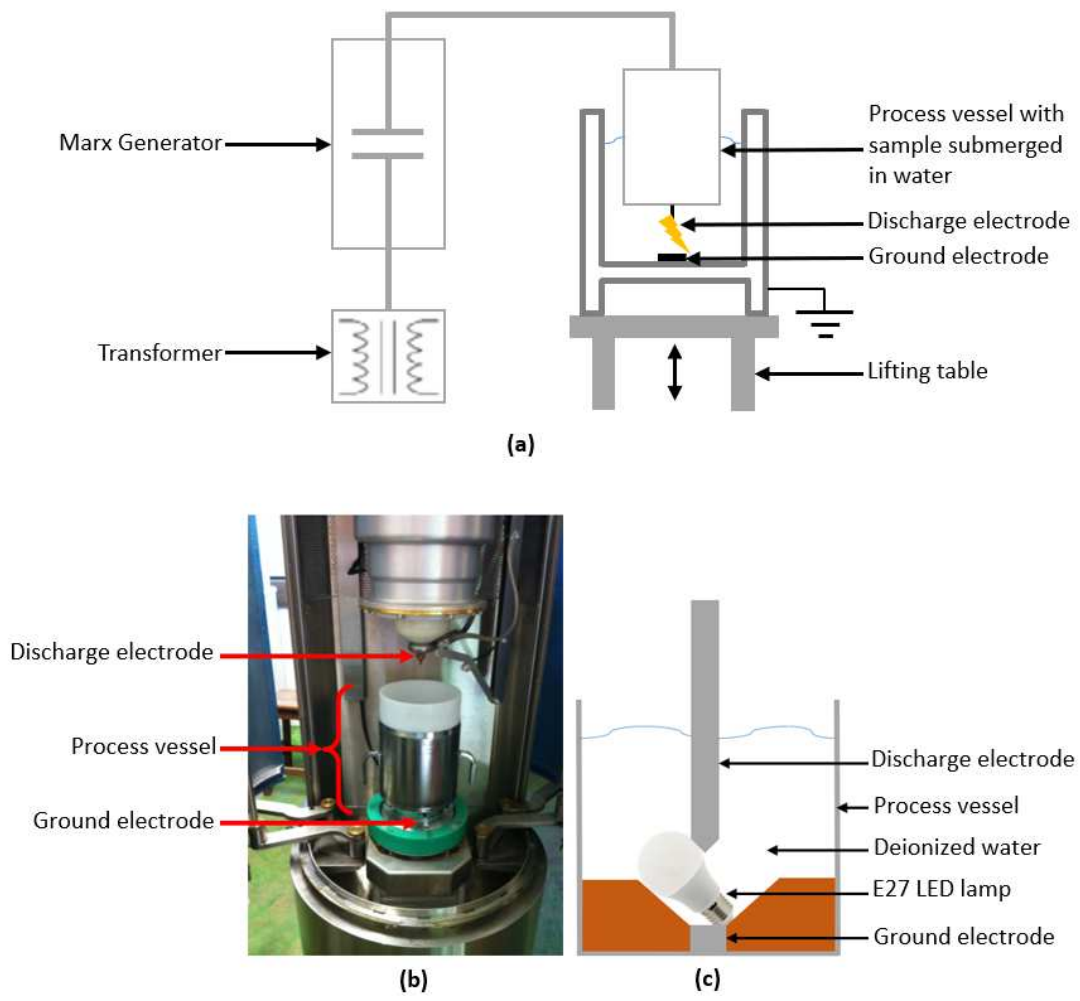
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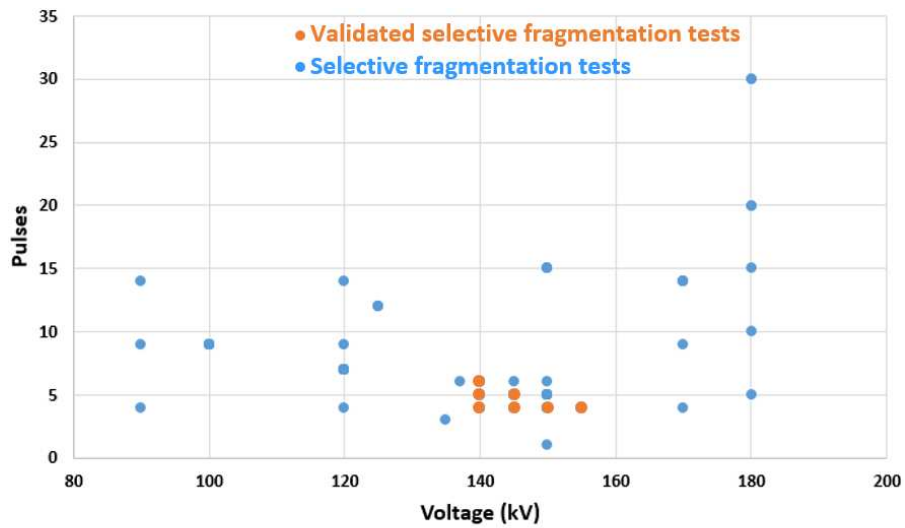
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Fig. 2. Laboratory machine: Schematic representation (a) and photograph (b) of the SELFRAG unit and diagram showing the plastic E27 LED lamp in the vessel (c).



(a)

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(b)

(c)



(d)

(e)

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689 **Fig. 3.** Fragmentation tests: Mapping of the fragmentation tests (a), non-validated fragmentation at 150 kV
 690 with 15 pulses (b) and 150 kV with 5 pulses (c), and validated fragmentation at 150 kV with 4 pulses (d) and 140
 691 kV with 5 pulses (e).

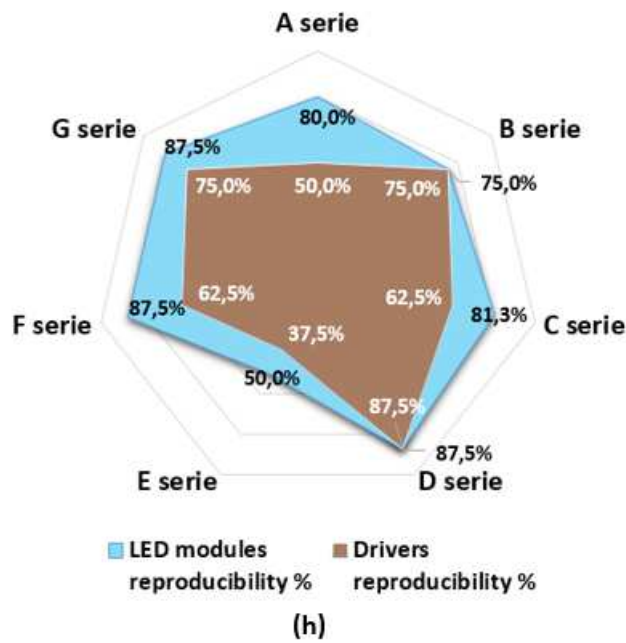
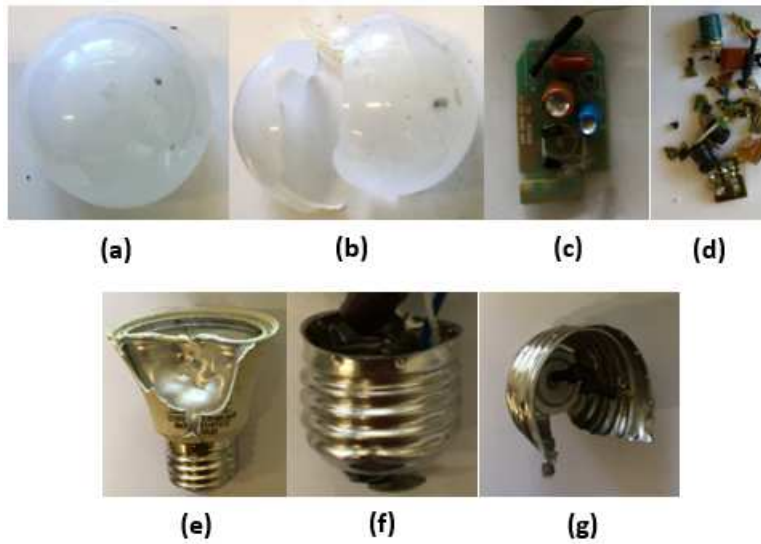
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698 **Fig. 4.** Sample study: Unfractured bulb (a), fractured bulb (b), unfractured driver (c), fractured driver (d),
 699 fractured body (e), unfractured base (f), fractured base (g), and reproducibility of the selective fragmentation
 700 for the seven validated series (h).

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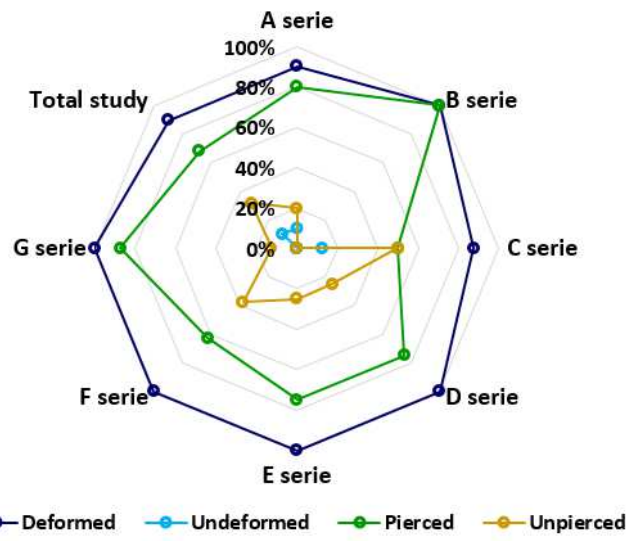
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(a) (b) (c)



(d)

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711 **Fig. 5.** Photographs of the bodies: undamaged body (a), deformed but unpierced body (b), deformed and
 712 pierced body (c), and state of bases for the seven series (d).

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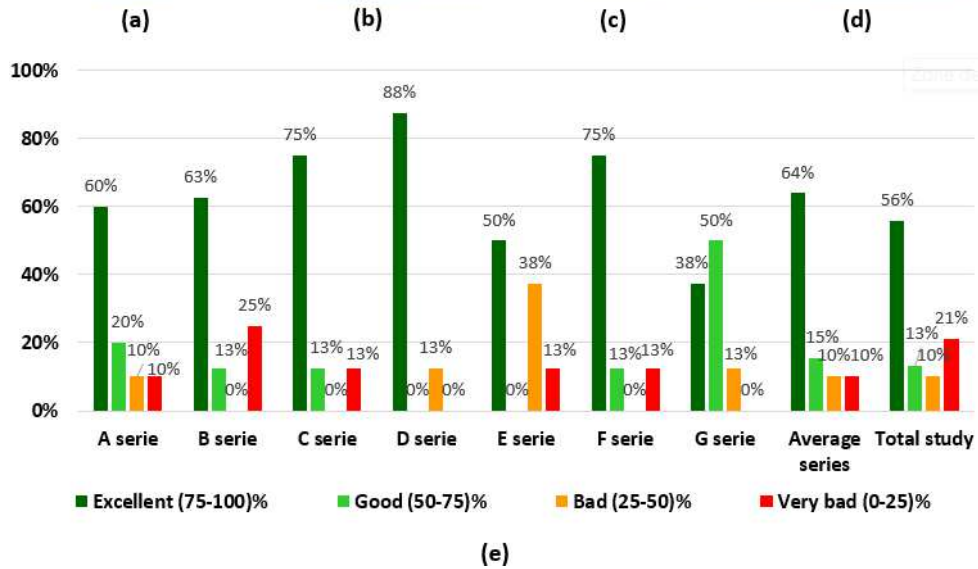
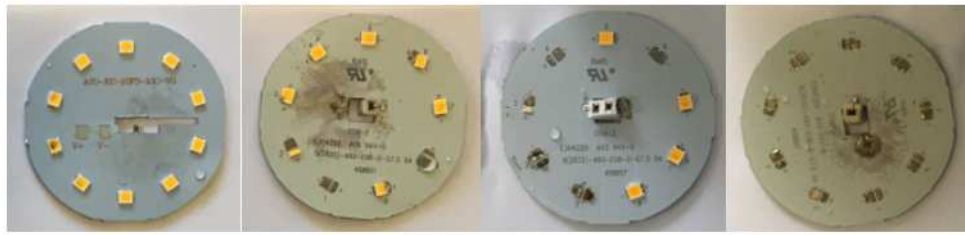
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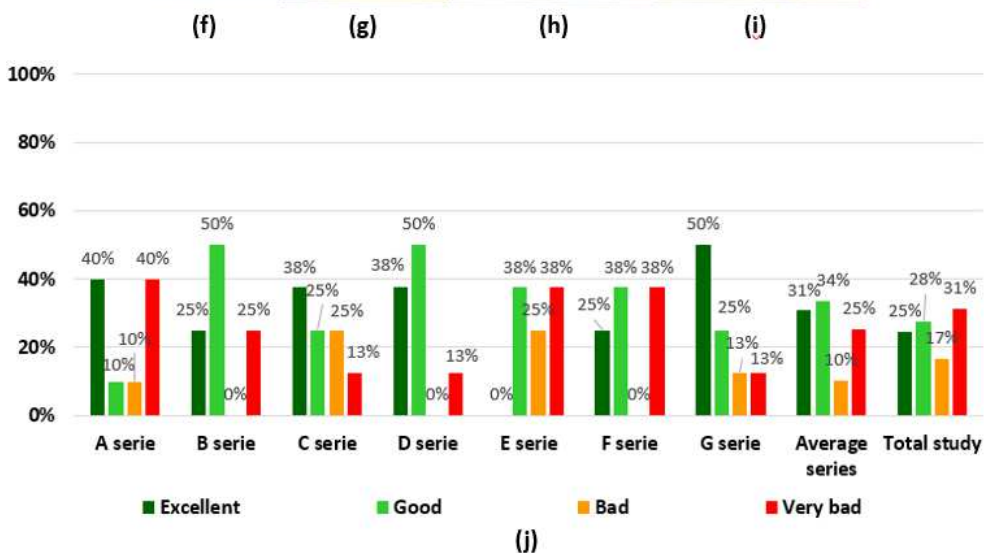
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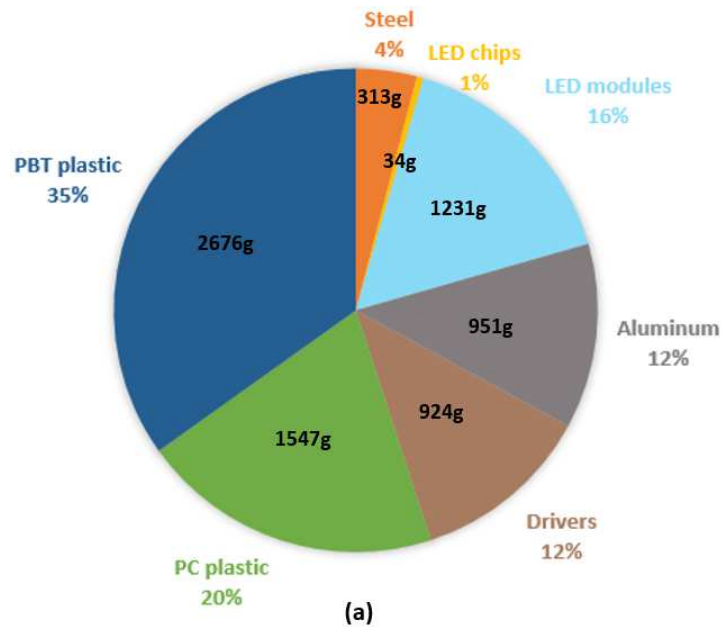


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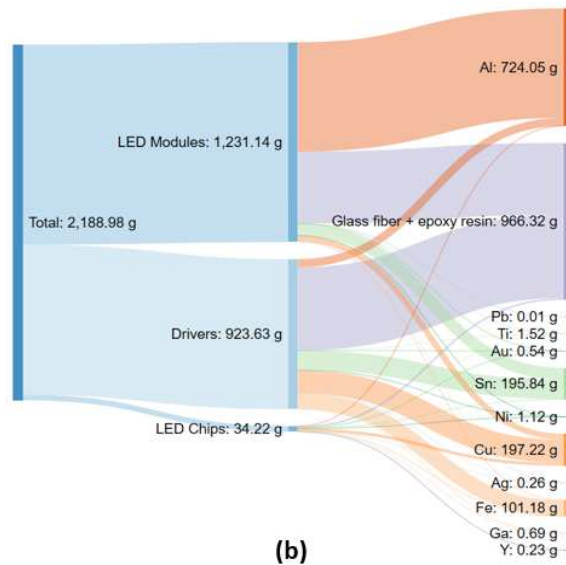


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728 **Fig. 6.** Electronic components in 7.7 kg of LED lamps: Examples of LED modules classified as a function of the
 729 remaining number of LED chips with 100% (a), 67% (b), 44% (c), and 0% (d) of LEDs remaining on the module.
 730 Classification of LED modules condition by 25% steps depending on the number of chips remaining according to
 731 the seven series of EDF treatments (e). Examples of drivers classified as a function of their condition:
 732 unfractured (f), weakly fractured (g), significantly fractured (h), and totally fractured (i). Classification of the
 733 driver conditions according to the seven series of EDF treatments (j).



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736 **Fig. 7.** Quantities investigation of the constituent elements that are potentially recoverable by selective
 737 fragmentation: Percentage graph showing the composition of plastic E27 LED lamps (a). Sankey mass diagram
 738 of precious metals recovered from LED modules, drivers and chips in 7.7 kg of plastic E27 LED lamps (b).
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748 **Table 1**
 749 Summary of the selective fragmentation results for the different constituent elements and the corresponding
 750 parameters (voltage and number of pulses). In supplementary data, Fig. S1 shows the photographs.
 751

Tests series	Voltage (kV)	Pulses	Average specific energy (kWh/t)	Bulbs (%)	LED Modules (%)	Drivers (%)	Total output (%)
A	145	5	5.7	60	70	80	70
B	140	6	6.2	88	100	100	96
C	140	5	5.5	25	50	100	58
D	140	4	4.6	63	38	38	46
E	145	4	5.0	38	50	75	54
F	150	4	4.8	75	50	75	67
G	155	4	4.9	63	63	38	54
Average series A-G	-	-	5.2	59	60	72	64

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