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Rare-earth elements in the circular economy: The case of yttrium

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# 1 RECYCLING YTTRIUM FROM SPENT LAMPS: HOW ECONOMICALLY 2 VIABLE IS IT WITHIN THE CIRCULAR ECONOMY PARADIGM?

3  
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## 9 **Abstract**

10 This paper discusses the economic rationale of recycling in the case of exhaustible raw materials  
11 and assesses how a circular economy perspective can improve sustainable use of critical ones.  
12 We use the case study of yttrium, a Rare Earth Element (REE) belonging to the EU list of critical  
13 raw materials, given its widespread use in the electronics industry and the geopolitical  
14 concentration of its supply. Even if recycling REEs from waste electric and electronic equipment  
15 is a valid alternative to extraction from mines, as proposed by the Circular Economy paradigm,  
16 less than 1% of REEs used today are recycled. Additionally, studies on economic benefits of  
17 recovery REEs are very limited. In this paper, we present the business case of an Italian  
18 recycling company “Relight Ltd” and its project “HydroWEEE” to recover REEs such as  
19 yttrium, from spent lamps. We computed that it is economically profitable to recycle yttrium if  
20 its market price is above €14/kg. Therefore, in 2012 and 2013 recycling was profitable thanks to  
21 the high price of yttrium while during 2014-2016 recycling was not convenient. In these cases,  
22 policymakers are responsible to incentivize recovery and recycling solutions with appropriated  
23 policies.

24  
25 **Keywords:** Rare Earth Element, Circular Economy, Critical Raw Material, Yttrium, recycling,  
26 Waste Electrical and Electronic Equipment

## 28 **1. Introduction**

29  
30 Rare earth elements (REEs) in the last decade turned from a modest group of raw materials to  
31 critical commodities due to their growing demand and to their small and opaque market (Bakaros  
32 et al., 2016).

33 Their exploitation and the investment in rare earth industry have increased with the world  
34 economy recovering from Financial Crisis and the boom of rare earth market (Chen, 2011).

36 When we address resource exploitation, it is essential to recall the best-known model on natural  
37 resource exploitation of the neo-classic school developed by Hotelling in 1931. Hotelling's rule  
38 postulates that for every exhaustible resource it is possible to identify an "optimal path of  
39 exhaustion". From the 1970s academic economists started tackling the Hotelling analytical  
40 framework and Natural Resource economics began to gain importance as a research field with  
41 Hotelling's rule at the heart of it (Gaudet G., 2007). In a more sophisticated version of  
42 Hotelling's rule, in 1998 Hartwick and Olewiler predicted a new rule which foresees a price  
43 dynamic that has four distinct phases.

44 One crucial question regarding resource exploitation is whether there is any real evidence that  
45 the world is going towards a possible depletion of raw materials or at least some of them.

46 An unequivocal answer to this question is very difficult to find on the global scale.

47 The question of resource depletion in these terms is misplaced. No metal will ever be exhausted,  
48 for the simple reason that nothing is created in nature and nothing is destroyed. Taking  
49 advantage of the natural availability of minerals means in a certain sense transferring them from  
50 the mines located underground to other mines, including the finished products that use them.

51 According to Bradshaw and Hamacher (2012), there is no geochemical scarcity but scarcity due  
52 to "geopolitical" origins. A similar view is shared by Charalampides and colleagues (2016) who  
53 report that REEs are defined as critical based on 1) their importance to a specific application  
54 such as renewable energy, 2) lack of substitutes, 3) monopoly in their supply.

55 The diffusion of the ideas of the circular economy has greatly insisted on this point, arguing that  
56 in the first decade of the 21st century the prices of raw materials, after a century of stagnation,  
57 had experienced a sharp surge (Webster, 2015).

58 The concept and development model of CE received growing attention over the last decade.

59 There are at least 114 definitions of CE (Kirchherr et al., 2017) but the fundamental idea is to  
60 substitute the dominant economic development model called "take, made and dispose of" with  
61 the adoption of a "closing-the-loop" production pattern (Ghisellini et al., 2016; Geissdoerfer et  
62 al., 2017).

63 According to Binnemans and colleagues (2013), there are three approaches to tackling the REEs  
64 supply challenge: substitute critical raw earths with less critical elements, invest in sustainable  
65 primary mining (seeking for new exploitable rare-earth deposits and reopening old mines) and  
66 invest in urban mining.

67 In fact, the supply risk of REEs has triggered the development of an innovative recycling system  
68 (Binnemans et al., 2015). Nevertheless, so far only less than 1% of REEs used today are recycled  
69 (Jowitt et al., 2018).

70 As suggested by Ghisellini and colleagues (2016) in their interesting and in-depth literature  
71 review on CE, research on CE implementation has so far been mainly rooted in the analysis of  
72 benefits in terms of physical rather monetary flows whereas the benefits from material recycling  
73 could be environmentally or economically too expensive to provide a net benefit.  
74 On one hand, the benefits of recycling metals from secondary resources compared to the  
75 extraction of virgin ores are known: reduced environmental impact and improved energy-  
76 efficiency (Reck and Graedel, 2012). On the other hand, one open question is whether recycling  
77 metals provides benefits in economic terms compared to the extraction of virgin metals.  
78 The discriminating variables become the cost of separation at source plus the recycling cost: if  
79 these costs are lower than the choke price (the lowest price at which the quantity demanded of a  
80 good is equal to zero), the recycling mine can be economically exploited.  
81 In this research, we aim at partially closing the gap in the literature by providing a case study of  
82 CE implementation in economic terms. More precisely, we study the business case of Relight  
83 Ltd and its project “HydroWEEE” to recover yttrium from spent lamps. We build on the work of  
84 Innocenzi et al. (2016a), which refers to the economic aspects of the HydroWEEE plan, with the  
85 aim to evaluate in more general terms which conditions make it economically convenient to  
86 recycle yttrium (instead of disposing it) in a circular economy perspective. In other words, given  
87 the case study conditions defined in the next section, we estimate the *limit* price which makes  
88 profitable the exploitation of the “recycling mine” compared to the exploitation of the virgin raw  
89 material.

90  
91

## 92 **2. Material and Methods**

93

### 94 *3.1 Case study presentation*

95

96 Relight Ltd was established in 1999 from a project on the collection and recycling of  
97 fluorescent lamps in cooperation with Philips. The Italian national law (Decree 185/2007)  
98 defines five groupings of WEEE (waste electric and electronic equipment) depending on their  
99 typology: R1 – fridges, refrigerators, and air conditioners; R2 – “big white” washing machines,  
100 dishwashing machines, ovens etc.; R3 – TV and monitors, R4 small WEEE and R5 - lamps. In  
101 2016, Relight was authorized to manage 40 thousand tons of WEEE (CEN, 2016). R1 group  
102 accounts for 84 tons and it is collected, stored and shipped to other recyclers. R2 and R4 groups  
103 are also partially treated by Relight (R2 account for 139 tons, R4 for 1,869 tons). R3 is selected,  
104 dismantled and the cathodic tube is properly treated by a cooperative (total of 15,739 tons). The

105 core business of Relight is the treatment of WEEE belonging to R3 which makes up for the 80%  
106 of the input waste as well as the treatment of fluorescent lamps (R5) with 4% of the input of  
107 waste (824 tons/year). Relight is involved in several research projects. In this paper, we present  
108 the HydroWEEE project which was financed by the European Seventh Framework Program in  
109 two phases. The extraction of REEs from WEEE mechanical, pyrometallurgical and  
110 hydrometallurgical processes are used to recover metals from WEEE, but they are not yet  
111 effectively targeted for REEs (Marra et al., 2018). In collaboration with recycling companies and  
112 research institutions, Relight has designed a plant to extract rare earth oxide (REOs) from  
113 fluorescent powder in lamps and cathodic tubes through the development of innovative hydro-  
114 metallurgical processes. In the first phase during years 2009-2012, the pilot plant “HydroWEEE”  
115 was performed with an investment of 1,1 million Euros. In the second phase during years 2012-  
116 2016 “HydroWEEE Demo project” was implemented as the up-scaling of the HydroWEEE  
117 technology in an industrial environment including a demonstration plant. The plant can recover  
118 rare earths from different electronic wastes (batteries, LCD screens, and circuit boards) but it is  
119 most suited for the recovery of yttrium and europium, and other rare elements from fluorescent  
120 powders resulting from exhausted lamps and cathode ray tube recovery. The total investment is  
121 worth 3,76 million Euros. The project was extended up to the beginning of 2017.

122

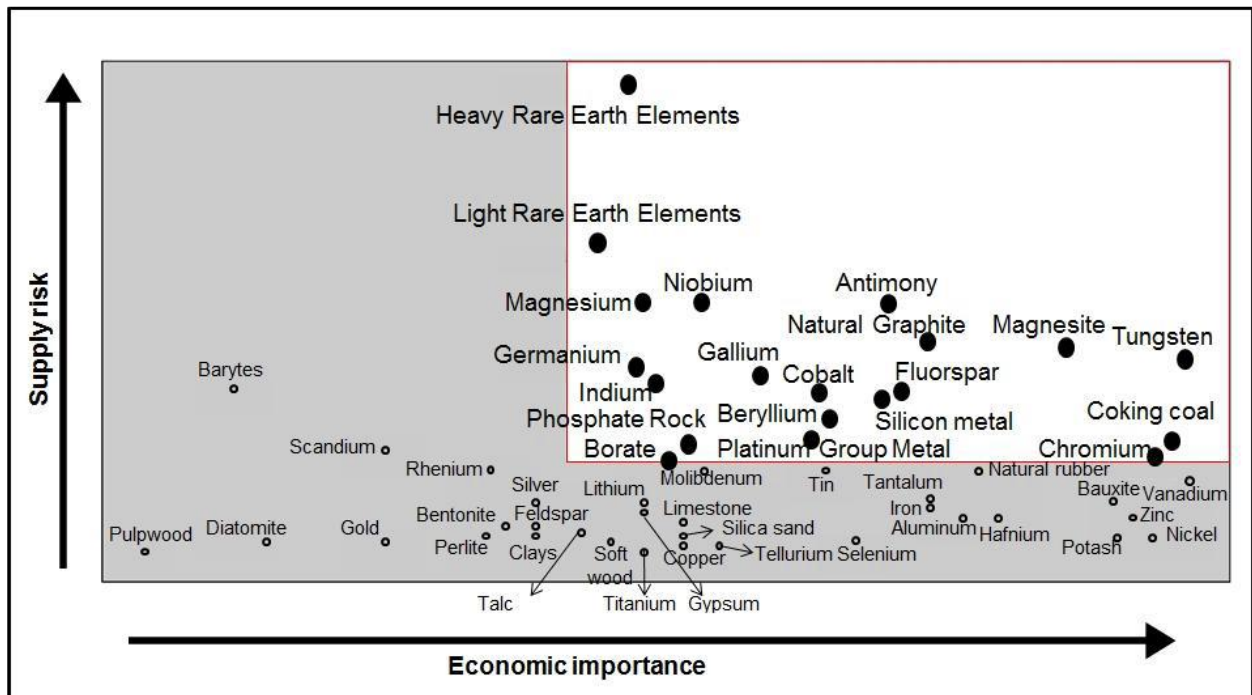
### 123 *3.2 Yttrium: a critical raw material in the international market*

124

125 Yttrium belongs to the rare-earth elements (REEs) more precisely to the heavy rare-earth  
126 element group. REEs are the 15 lanthanide elements plus scandium (Sc) and yttrium (Y) as  
127 defined by the International Union of Applied and Pure Chemistry (IUPAC) (Jowitt et al., 2018).  
128 They play a critical role in many sophisticated technologies in the automotive, renewable and  
129 defence sectors contributing to increasing efficiencies and performance of products. For  
130 example, yttrium is broadly used in fluorescent lamps, CRT television, plasma display panels,  
131 energy efficient lighting (such as LEDs), phosphor powders for low-energy lighting, optical  
132 glasses and batteries, as well as high-tech applications such as laser, superconductors, nuclear  
133 reactors and electronic components for missile defence systems (De Michelis et al., 2011;  
134 Innocenzi et al., 2014; Seo and Morimoto, 2015, Song et al., 2017). Additionally, almost every  
135 vehicle on road contains Y to improve the fuel efficiency of the engine while other important  
136 uses are in microwave communication devise and laser crystals (Hurst, 2010). In 2008 the  
137 European Commission (EC) launched the “Raw Material Initiative” in order to secure a supply  
138 of raw materials critical for their economic importance and supply risk. Among others, rare earth  
139 elements have the highest supply risk and medium economic importance as reported in Figure 1.

140

141 Critical raw materials



142

143

144 Figure 1. Source: EC, 2014

145

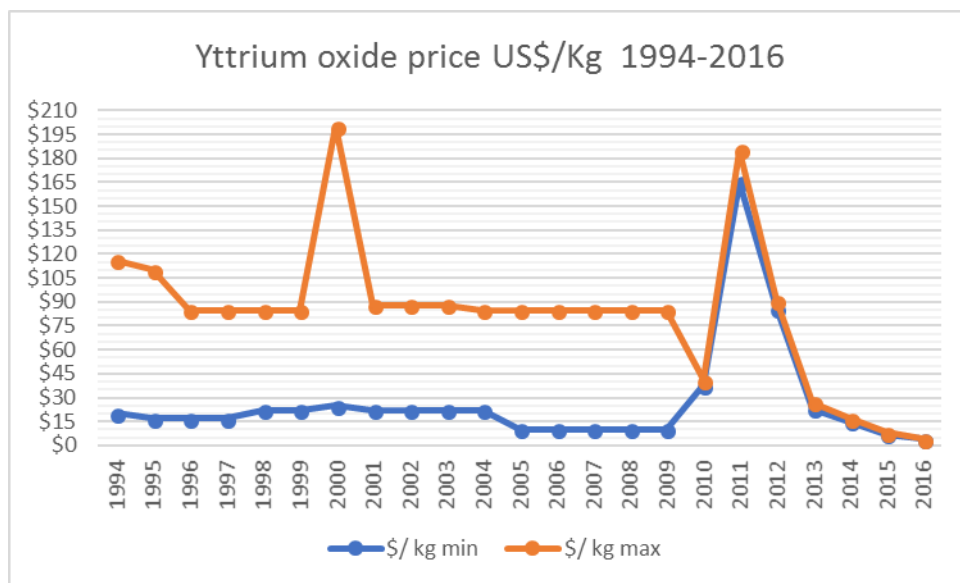
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147 The experts selected 14 critical elements in 2011. Such a list was reviewed in 2014 and in 2017  
148 (EU, 2017) to include 27 critical raw materials (CRMs). Most of them can be found in, and  
149 recovered from WEEE; for example, yttrium can be found in fluorescent lamps. Global reserves  
150 are estimated to be 130 million metric tons on a rare-earth oxide (REO) basis (Van Gosen et al.,  
151 2017). In economic terms, the annual consumption of REOs is limited to around 150,000 tons  
152 and it accounts for \$9 billion, but REOs are critical inputs to other products worth \$7 trillion, in a  
153 global economy worth \$75 trillion (Ganguli and Cook., 2018).

154 Worldwide, China is the main driver in the rare earths market and it became the world's leading  
155 producer and exporter of REEs in 2000 (Marcheri, 2015). The United States was self-sufficient  
156 and the main exporter of REEs prior to about 1990 (when Mountain Pass – California mine was  
157 operating) while they are nearly completely dependent from Chinese REEs imports since 1999-  
158 2000 (Haxel G.B. et al, 2002, Marcheri, 2005). Nowadays China holds a monopoly as more than  
159 90% of mining and refinement is done in that country (Bradshaw and Hamacher, 2012; Seo and  
160 Morimoto, 2015). According to the European Commission (2017), China covered on average  
161 95% of the global production of rare earths in 2010-2014. Specifically, in the case of yttrium,  
162 99% of global production comes from this country (Seo and Morimoto, 2015). Therefore, the

163 prices increased dramatically in 2011 following the decision of China at the end of 2010 to cut  
 164 export quotas by almost 70%. The price of some of the rare metals increased as much as 850%  
 165 (Marcheri, 2015). This triggered international concerns on the supply risks and it led to the  
 166 labelling as “critical” or “strategic” (McLellan, 2014). The World Trade Organisation ruled  
 167 against Chinese export quotas and China removed the quotas in January 2015. In May of the  
 168 same year, China eliminated the export tariffs which were as high as 25% on many of the REEs  
 169 (Marcheri, 2015). This caused another fall in the prices of rare earth metals. As reported in  
 170 Figure 2, the price of yttrium oxide was quite stable from 1994 to 2009 with the exception of the  
 171 year 2000 when the Chinese government took measures to restrict REEs mining and reduce their  
 172 export provoking a decrease in the supply and an increase in their price (Charalampides et al.,  
 173 2015). In 2010 its minimum and maximum value almost coincided while in 2011 it reached the  
 174 peak values (165 and 185 US \$/kg). It then decreased and became more stable from 2016 on  
 175 with a quotation of 4 US \$/kg (U.S. Geological Survey, Mineral Commodity Summaries, annual  
 176 reports 1994-2018). The market price of yttrium (as any other mineral) reflects the extraction  
 177 costs from ores but ultimately the market price is determined by the balance between supply and  
 178 demand (Henckens et al 2016).

179  
180



181  
182

183 Figure 2: Yttrium oxide value in US \$ per kilogram (minimum 99.9% purity)  
 184 Source: U.S. Department of Interior and U.S. Geological Survey, 1994-2018  
 185

186 The 2010-11 international crisis boosted the exploration projects of REE deposits. For  
 187 example, in 2013 a large deposit of deep-sea mud containing rare-elements (including yttrium)

188 was discovered in the western North Pacific Ocean in Japan. As reported in the research  
189 published in “Nature”, such resource has a great potential of exploitation due to its enormous  
190 resource amount and the effectiveness of the mineral processing thereof (Takaya et al., 2018).  
191 Such study estimates the amount of yttrium available in the restricted reach area to account for  
192 62 years of annual global demand and up to 780 years in the entire research area. According to  
193 Bakaros and colleagues (2016), even if more than 400 potential projects were discovered, so far  
194 non-Chinese rare earth producers have managed to enter the market. The exploration boom  
195 disclosed the abundance of REE resources, but the fundamental question is whether they can be  
196 exploited at a reasonable price (McLellan, 2014; Bakaros et al., 2016). One solution to break the  
197 Chinese monopoly is to exploit urban mining and the recycling of WEEE (Binnemans et al.,  
198 2013, ERECON, 2014). From a literature review conducted by Innocenzi (2018b), there are  
199 several researches on spent fluorescent lamps treatment because they contain high concentration  
200 of valuable REEs (such as Y) that makes recycling economically convenient. The most used  
201 processes are pyrometallurgical and hydrometallurgical ones (Innocenzi et al., 2017b).

202 Our research focuses on the case study of the HydroWEEE project assessing the  
203 economic conditions needed to make convenient recycling yttrium from spent lamps.

204

205

206

## 207 **4 Results and discussion**

208

### 209 *4.1 Physical flow: Hydrometallurgical process*

210

211 Relight and its partners developed a process to extract rare earth from fluorescent powders,  
212 lamps and cathodic ray tube screens (CRTs). The process consists of different steps which are  
213 reported in Figure 3. According to the technical study of the process (see De Michelis et al.,  
214 2011; Innocenzi et al., 2013a, 2013b, 2017b), phosphors were leached with sulfuric acid,  
215 followed by the solvent extraction, precipitation and filtration to recover rare earths oxalate  
216 (mainly yttrium oxalate). In the process, the waste solution could be disposed of or reused. Rare  
217 earths oxalates are then calcinated to recover rare earths oxides (REOs).

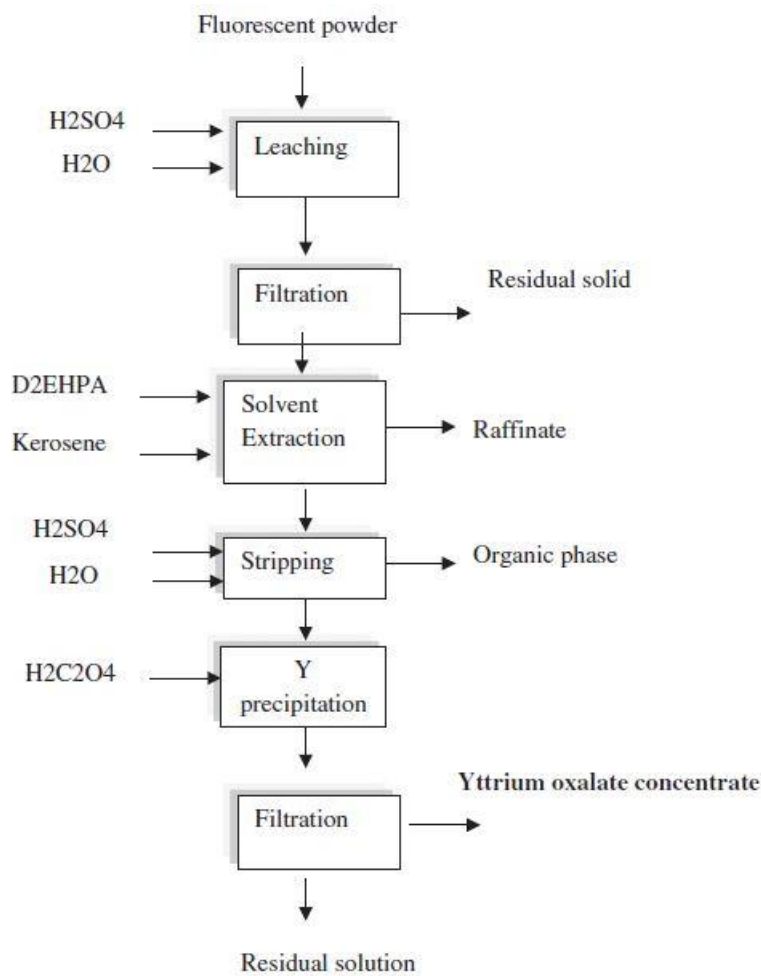
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221





222

223 Figure 3. The process developed in the HydroWEEE project

224

Source: Innocenzi et al., 2017b

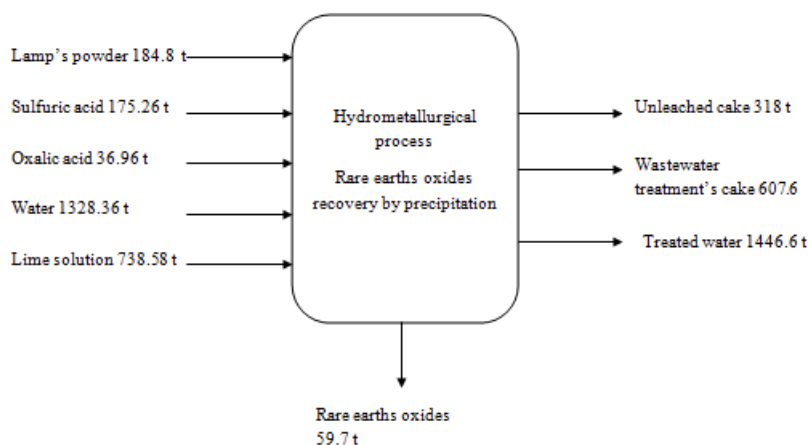
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226 The plant operated on two batches per day with a capacity of 184.8 tons/year of fluorescent  
 227 powders from spent lamps. The annual mass balance of the hydro-metallurgical process  
 228 (precipitation of REEs) is 59.7 tons/year, recovering mainly yttrium oxide (91.3%), Europium  
 229 oxide (4.07%) and Gadolinium oxide (1.08%).

230

The annual mass balance is reported in Figure 4.

231



232

233 Figure 4: Total annual mass balance for the hydrometallurgical process (Innocenzi et al., 2016a)  
234  
235 (... explain the process HERE)  
236

237  
238 The project of recovering valuable metals from spent fluorescent lamps it has been financed by  
239 the European Union with the FP7 Work Program and includes several partners which provided  
240 their specific knowledge. The project has been broadly studied in Innocenzi et al., 2016a, 2016b,  
241 2017a, 2017b, 2018a, 2018b and Ippolito et al., 2017. The relevance of the issue of extraction of  
242 REEs such as yttrium from spent lamps and from cathode-ray tube is proved by the quantity of  
243 researches conducted so far. For example, Hu and colleagues (2017) provide a study on the  
244 available REE recycling methods which are: physicochemical method, acid extraction method,  
245 alkali fusion method, solvent extraction method and hybrid method. According to Wu et al.  
246 (2014), acid leaching and solvent extraction are promising hydrometallurgy processes to extract  
247 rare earth elements. One of the last researches on recovery rare earth from waste fluorescent  
248 lamps, studied the solvent extraction (Pavón et al., 2018). For other studies refer to Hu et al.  
249 (2017), Ippolito et al. (2017), He et al. (2018), Jowitt et al. (2018), Lin et al. (2018).

250

#### 251 4.2 Financial flow

252

253 The main question is: "under which conditions it is economically convenient to recycle  
254 yttrium from WEEE?". In other words, the answer must lie in our investigation of when recovery  
255 of materials from WEEE is convenient in comparison to alternative solutions such as disposal. In  
256 general terms, recovery is economically the best option if the following equation is true:

257

$$258 \quad PR - (SC + TR) > (UC + TD) \quad \text{Equation 1}$$

259

260

261 (Ref: Massarutto, 2009)

262

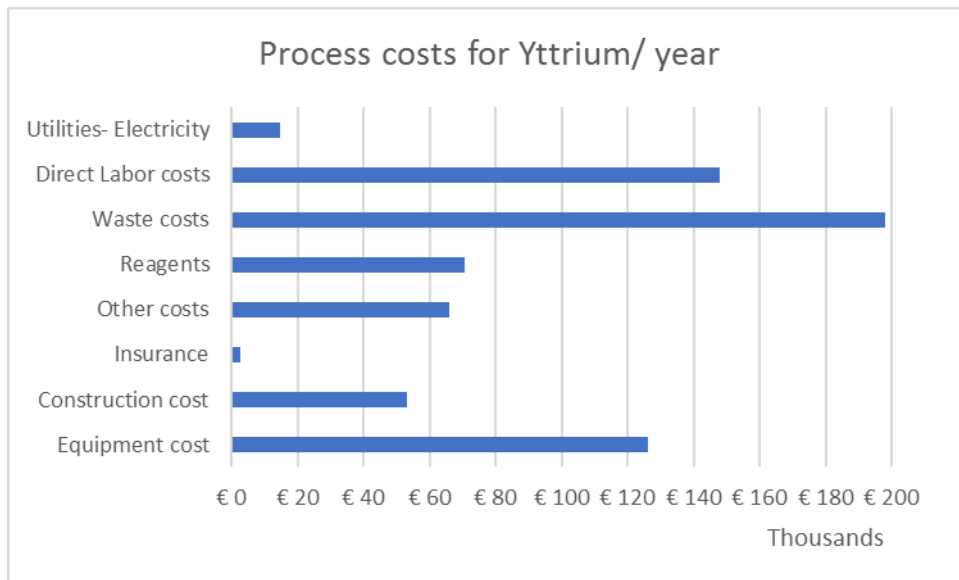
263 In other words, recovery and disposal are equal, in economic terms, when PR is:

264

$$265 \quad PR = (SC + TR) + (UC + TD) \quad \text{Equation 2}$$

266

267 Where PR is the price of the recovered material, SC (separate collection) (is the cost of  
 268 the separated waste collection, TR (treatment and recovery) is the cost of treatment and recovery  
 269 of separate waste, UC (unsorted collection) is the cost of collection and transport of unsorted  
 270 waste, and TD (treatment and disposal) is the cost of treatment and disposal of unsorted waste.  
 271 We refer to the annual report on MSW (Municipal Solid Waste) issued by the National Institute  
 272 for Environment Protection ISPRA (2012-2016) to define the costs of collection and transport of  
 273 unsorted MSW (UC), the cost of treatment and disposal of unsorted waste (TD), and the costs of  
 274 separated waste collection (SC). Note that the SC costs reported by ISPRA, are specific costs for  
 275 fluorescent lamps (classified with EWC code 200121\*, grouping R5 of WEEE). The SC cost  
 276 related to the year 2016 is not available, it being computed as the average costs of the previous  
 277 years. The treatment and recovery (TR) costs of yttrium from spent lamps is computed based on  
 278 Relight's case study and they are reported in Figure 4.  
 279



280  
 281

282 Figure 4: treatment recovery costs of yttrium 2016

283 Source: Our elaboration from Innocenzi et al., 2016a

284

285 The average fixed costs are computed considering that the process produces on average  
 286 54.5 tons of yttrium oxide per year, the HydrowWEEE plant cost 550,000 Euros with a  
 287 depreciation time of 6 years, insurance costs estimated at 2% of equipment costs, other costs  
 288 such benefits (25% of labour costs), and installation costs (5% of equipment costs). Variable  
 289 costs include: re-agents, waste, direct labour and utilities (such as electricity). Full details of  
 290 costs are available in the analysis of Innocenzi and colleagues (2016a). Fixed costs account for  
 291 36.4% while variable costs for 63.6%.

292

293 As reported in equation 2, given the above conditions, the recovery is economical the  
294 best option during 2012-2016 if the price of yttrium oxide is above 14 €/kg as specified in Table  
295 1.

296

297 Table 1: Economic evaluation of recovery Y from fluorescent lamps

year	2012	2013	2014	2015	2016
UC €/kg*	€ 0.0976	€ 0.0993	€ 0.1015	€ 0.1010	€ 0.1050
TD €/kg*	€ 0.1053	€ 0.1107	€ 0.1169	€ 0.1191	€ 0.1244
SC for R5 €/kg*	€ 1.3519	€ 1.3540	€ 1.9870	€ 1.3930	€ 1.5215
TR for Y €/kg**	€ 12.4477	€ 12.4477	€ 12.4477	€ 12.4477	€ 12.4477
PR Y €/kg	€ 14.0025	€ 14.0117	€ 14.6531	€ 14.0608	€ 14.1986

298

299 Source: \* ISPRA annual reports (2012-2016), \*\* Innocenzi et al., 2016a., our  
300 computation

301

302 Moreover, according to this main equation, three hypotheses may occur.

303 Hypothesis 1:  $PR < SC + TR$ , but  $PR > TR - TD$ . Producers are responsible for reaching  
304 collection targets on WEEE such as lamps and flat screen. Once the waste has been collected  
305 (and it is an obligation to collect it), then it is more convenient to recover WEEE rather than  
306 dispose of it. In such a situation, it is enough for the State to oblige producers to collect; then,  
307 once collected, producers (through recyclers) will certainly be able to recover it.

308 Hypothesis 2.  $TR > TD$  Producers are responsible for achieving collection goals on WEEE such  
309 as lamps and flat screen. The recovery costs of WEEE is higher than disposal costs (such as  
310 burning with energy recovery or landfilling) and the price does not cover the recovery costs:  $PR$   
311  $< TR$ . If this were the case, the State should design the EPR (Extended Producer Responsibility)  
312 system by introducing not only collection targets but also specific recovery targets for the  
313 materials. Alternatively, the State could offer a subsidy, e.g. buying the recovered material at a  
314 guaranteed price. However, this is a risky mechanism because if the State pays a higher price  
315 than the market, traders could buy yttrium abroad for a low price and sell it to the State at the  
316 higher guaranteed price.

317 Hypothesis 3.  $PR > SC + TR$ . The market price is so high that recovery is certainly worth it even  
318 without EPR. In this case, the task of the State is to monitor the market and make sure that, after  
319 the yttrium recovery, the rest of the waste is also managed correctly or possibly recovered.

320

321 In Table 2 we test the three hypotheses presented before and the main equation 2 where  
 322 PR is the average value for the quotation of yttrium in Euro/ton, SC+TR are the costs of  
 323 collection and recovery of yttrium from WEEE, and UC+TD are the alternative costs of  
 324 collection and disposal of unsorted MSW.

325 The results are displayed in Table 2. We presume that the cost of treatment and recovery  
 326 (TR) in the “HydroWEEE Demo” is constant during years 2012-2016.

327

328 **Table 2: Hypotheses during years 2012-2016**

year	2012	2013	2014	2015	2016
PR Y €/kg (average value) *	€ 68.9327	€ 18.8300	€ 12.0624	€ 6.7643	€ 3.6156
H1 PR-TR+TD>0	€ 56.5902	€ 6.4930			
H2 PR-TR<0			-€ 0.3853	-€ 5.6835	-€ 8.8321
H3 PR -(SC+TR)>0	€ 55.1330	€ 5.0283			

329

330 Sources: \*U.S. Department of Interior and U.S. Geological Survey; our computation.

331

332 The price of yttrium oxide value published by in the Geological Survey (see Figure 2),  
 333 has been converted into Euro using the Euro reference exchange rate by the European Central  
 334 Bank..

335

336

337 Therefore, recovery is economically the best option in 2012 and 2013 when the price of  
 338 yttrium was on average 68.93 and 18.83 €/Kg. The market price is so high that Hypotheses 1 and  
 339 3 are achieved in these first two years, meaning that recovery is certainly worth it, even if the  
 340 State did not impose expended producer responsibility (EPR) on producers. In the following  
 341 years, the quotation of yttrium is so low that it does not cover the recovery costs. In these cases,  
 342 yttrium is recovered only if it is required by the State which should impose collection as well as  
 343 material recycling goals.

344

345

### 346 3. Conclusions

347

348 Rare-earth elements REEs gained international attention in 2011 when their prices boosted after  
 349 Chinese quota restriction on export. A potential option of extraction of REEs from mines is their  
 350 recovery them from waste. Moreover, “turning waste into a resource is essential to increase  
 351 resource efficiency and closing the loop in a circular economy” (EC, 2015). Nevertheless, not

352 many studies assess the economic conditions which make recovery of raw material convenient.  
353 Relight Ltd is a leading Italian company which recycles WEEE in general and it has developed a  
354 project called HydroWEEE to recover yttrium (one of REEs) from spent lamps. Its HydroWEEE  
355 project annually treats 184.8 tons of fluorescent powders, coming from spent lamps recovering  
356 around 54.5 tons of yttrium oxide. In this case study, we investigated the Relight case of  
357 recycling yttrium from spent lamps, by which it is demonstrated that recycling is a valid option  
358 in economic terms if the market price is above 14 €/kg. Therefore, in 2012 and 2013 it was  
359 convenient to recover yttrium because its price was higher than the costs of separated waste  
360 collection (SC) plus the cost of treatment and recovery (TR). However, during the following  
361 years (2014-2016) the price of yttrium did not cover such costs thus making its treatment and  
362 recovery less convenient than its disposal. Another main question arises: is yttrium really rare?  
363 When China had blocked the export of yttrium, the price was boosted (in the short term). This is  
364 a normal reaction to the inelastic demand arising from the fact that, in the short term, there were  
365 no alternatives. However, this does not predict the price of yttrium in the medium-long term, as it  
366 might be replaced with other metals, or other primary or secondary mines may be exploited, or  
367 other products might substitute those containing yttrium. Therefore, as suggested by other  
368 studies (McLellan et al., 2014; Charalampides et al., 2016) yttrium and REEs are better defined  
369 “critical” or “strategic” in economic terms due to: 1) their fundamental role in some specific  
370 equipment and application, such as renewable energy, medical equipment, defense equipment; 2)  
371 they do not have substitution in the short term; 3) the supply source is at the moment a  
372 monopoly. This economical assessment performed in our case study, even if it is limited to the  
373 specific conditions presented, helps understanding not only the economic rationale behind rare  
374 earth recovery in the case-study analyzed, but it also provides an interesting benchmark to  
375 analyze the commercial potential of similar processes (ERECON, 2014). Besides, policymakers  
376 could incentivize the recovery solutions when market conditions are not convenient with the  
377 following actions: make compulsory the quantity of waste recycled; make compulsory the  
378 quantity of material recovered; incentive the market of second raw materials with fiscal levers or  
379 by imposing a minimum quantity of secondary raw materials incorporated in new products. In  
380 the case of yttrium, European produces are fully dependent on China and the main risk is the  
381 unavailability of materials (Chapman et al., 2013). Therefore, it is crucial to sustain the European  
382 rare-earth recycling industry as well as maintain skills and knowledge along the entire REE  
383 value chain to support the long-term supply security (ECON, 2014, Massarutto, 2014). For  
384 example, the Italian recycling industry builds on a long-lasting tradition and its existence and  
385 vitality are valid deterrents to the powerful Chinese REEs industry. At the European level, the  
386 amendments to the waste framework directive can be an important step towards the reduction of

387 the EU's dependence on the import of raw materials and the facilitating of the transition to more  
388 sustainable material management and a Circular Economy model (EC, 2015).

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