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

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

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Abstract

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

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

1. Introduction

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

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

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

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

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

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

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

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

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

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

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

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

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

2. Material and Methods

3.1 Case study presentation

Relight Ltd was established in 1999 from a project on the collection and recycling of fluorescent lamps in cooperation with Philips. The Italian national law (Decree 185/2007) defines five groupings of WEEE (waste electric and electronic equipment) depending on their typology: R1 – fridges, refrigerators, and air conditioners; R2 – "big white" washing machines, dishwashing machines, ovens etc.; R3 – TV and monitors, R4 small WEEE and R5 - lamps. In 2016, Relight was authorized to manage 40 thousand tons of WEEE (CEN, 2016). R1 group accounts for 84 tons and it is collected, stored and shipped to other recyclers. R2 and R4 groups are also partially treated by Relight (R2 account for 139 tons, R4 for 1,869 tons). R3 is selected, dismantled and the cathodic tube is properly treated by a cooperative (total of 15,739 tons). The core business of Relight is the treatment of WEEE belonging to R3 which makes up for the 80% of the input waste as well as the treatment of fluorescent lamps (R5) with 4% of the input of waste (824 tons/year). Relight is involved in several research projects. In this paper, we present the HydroWEEE project which was financed by the European Seventh Framework Program in two phases. The extraction of REEs from WEEE mechanical, pyrometallurgical and hydrometallurgical processes are used to recover metals from WEEE, but they are not yet effectively targeted for REEs (Marra et al., 2018). In collaboration with recycling companies and research institutions, Relight has designed a plant to extract rare earth oxide (REOs) from fluorescent powder in lamps and cathodic tubes through the development of innovative hydro-metallurgical processes. In the first phase during years 2009-2012, the pilot plant “HydroWEEE” was performed with an investment of 1,1 million Euros. In the second phase during years 2012-2016 “HydroWEEE Demo project” was implemented as the up-scaling of the HydroWEEE technology in an industrial environment including a demonstration plant. The plant can recover rare earths from different electronic wastes (batteries, LCD screens, and circuit boards) but it is most suited for the recovery of yttrium and europium, and other rare elements from fluorescent powders resulting from exhausted lamps and cathode ray tube recovery. The total investment is worth 3,76 million Euros. The project was extended up to the beginning of 2017.

3.2 Yttrium: a critical raw material in the international market

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

Critical raw materials

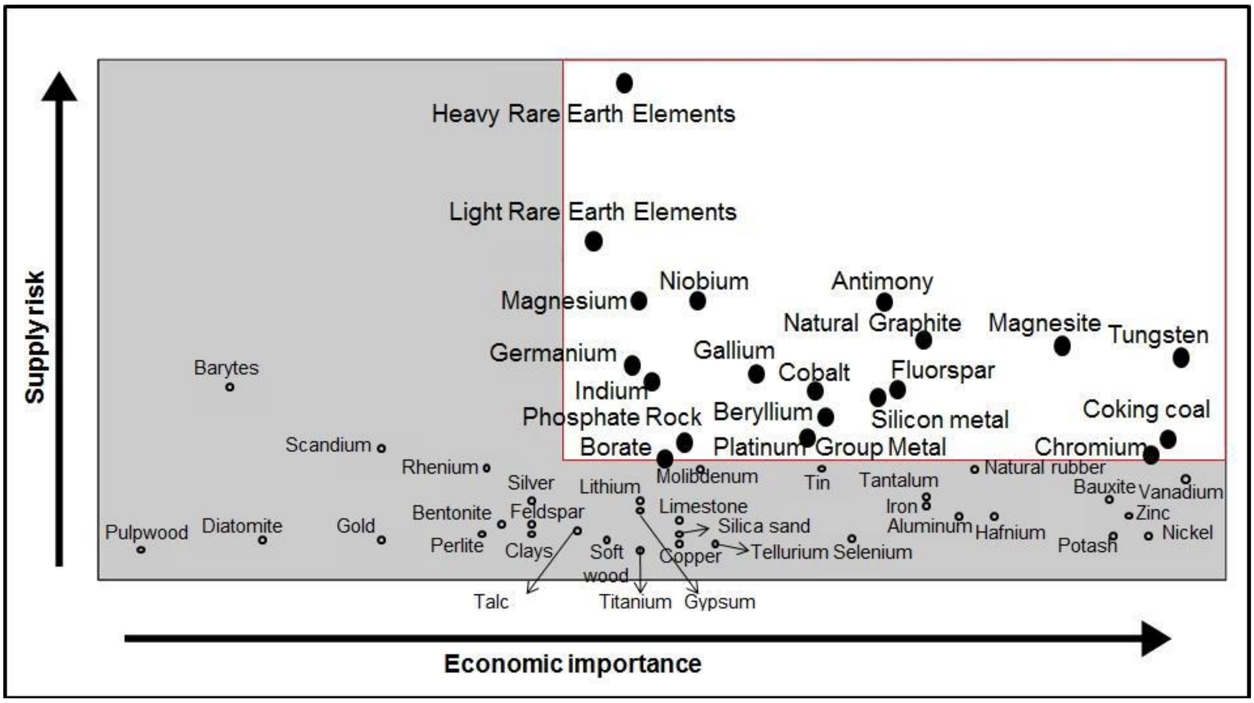

Figure 1. Source: EC, 2014

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

Worldwide, China is the main driver in the rare earths market and it became the world's leading producer and exporter of REEs in 2000 (Marcheri, 2015). The United States was self-sufficient and the main exporter of REEs prior to about 1990 (when Mountain Pass – California mine was operating) while they are nearly completely dependent from Chinese REEs imports since 1999-2000 (Haxel G.B. et al, 2002, Marcheri, 2005). Nowadays China holds a monopoly as more than 90% of mining and refinement is done in that country (Bradshaw and Hamacher, 2012; Seo and Morimoto, 2015). According to the European Commission (2017), China covered on average 95% of the global production of rare earths in 2010-2014. Specifically, in the case of yttrium, 99% of global production comes from this country (Seo and Morimoto, 2015). Therefore, the prices increased dramatically in 2011 following the decision of China at the end of 2010 to cut export quotas by almost 70%. The price of some of the rare metals increased as much as 850% (Marcheri, 2015). This trigged international concerns on the supply risks and it led to the labelling as “critical” or “strategic” (McLellan, 2014). The World Trade Organisation ruled against Chinese export quotas and China removed the quotas in January 2015. In May of the same year, China eliminated the export tariffs which were as high as 25% on many of the REEs (Marcheri, 2015). This caused another fall in the prices of rare earth metals. As reported in Figure 2, the price of yttrium oxide was quite stable from 1994 to 2009 with the exception of the year 2000 when the Chinese government took measures to restrict REEs mining and reduce their export provoking a decrease in the supply and an increase in their price (Charalampides et al., 2015). In 2010 its minimum and maximum value almost coincided while in 2011 it reached the peak values (165 and 185 US $/kg). It then decreased and became more stable from 2016 on with a quotation of 4 US $/kg (U.S. Geological Survey, Mineral Commodity Summaries, annual reports 1994-2018). The market price of yttrium (as any other mineral) reflects the extraction costs from ores but ultimately the market price is determined by the balance between supply and demand (Henckens et al 2016).

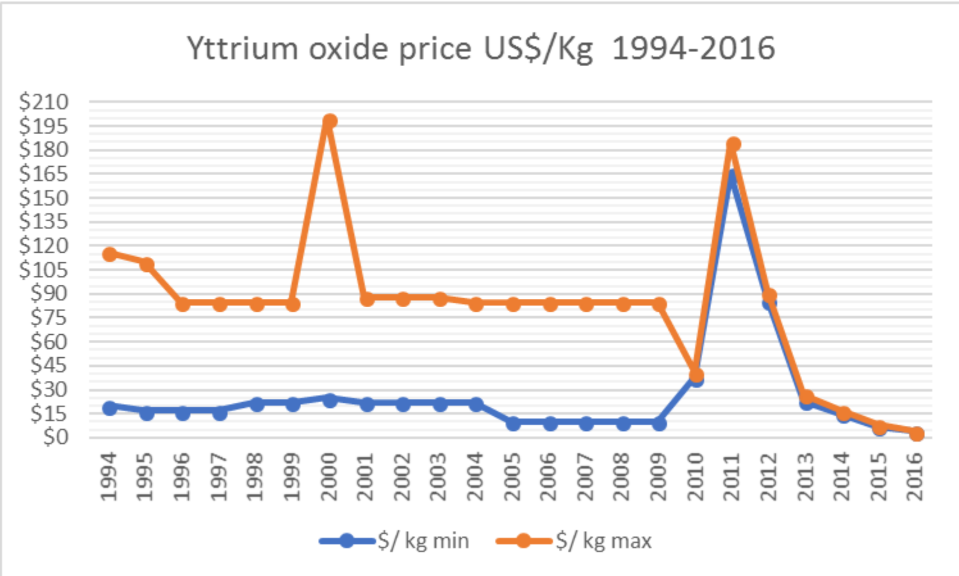

Figure 2: Yttrium oxide value in US $ per kilogram (minimum 99.9% purity)

Source: U.S. Department of Interior and U.S. Geological Survey, 1994-2018

The 2010-11 international crisis boosted the exploration projects of REE deposits. For example, in 2013 a large deposit of deep-sea mud containing rare-elements (including yttrium) was discovered in the western North Pacific Ocean in Japan. As reported in the research published in "Nature", such resource has a great potential of exploitation due to its enormous resource amount and the effectiveness of the mineral processing thereof (Takaya et al., 2018). Such study estimates the amount of yttrium available in the restricted reach area to account for 62 years of annual global demand and up to 780 years in the entire research area. According to Bakaros and colleagues (2016), even if more than 400 potential projects were discovered, so far non-Chinese rare earth producers have managed to enter the market. The exploration boom disclosed the abundance of REE resources, but the fundamental question is whether they can be exploited at a reasonable price (McLellan, 2014; Bakaros et al., 2016). One solution to break the Chinese monopoly is to exploit urban mining and the recycling of WEEE (Binnemans et al., 2013, ERECON, 2014). From a literature review conducted by Innocenzi (2018b), there are several researches on spent fluorescent lamps treatment because they contain high concentration of valuable REEs (such as Y) that makes recycling economically convenient. The most used processes are pyrometallurgical and hydrometallurgical ones (Innocenzi et al., 2017b).

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

4 Results and discussion

4.1 Physical flow: Hydrometallurgical process

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

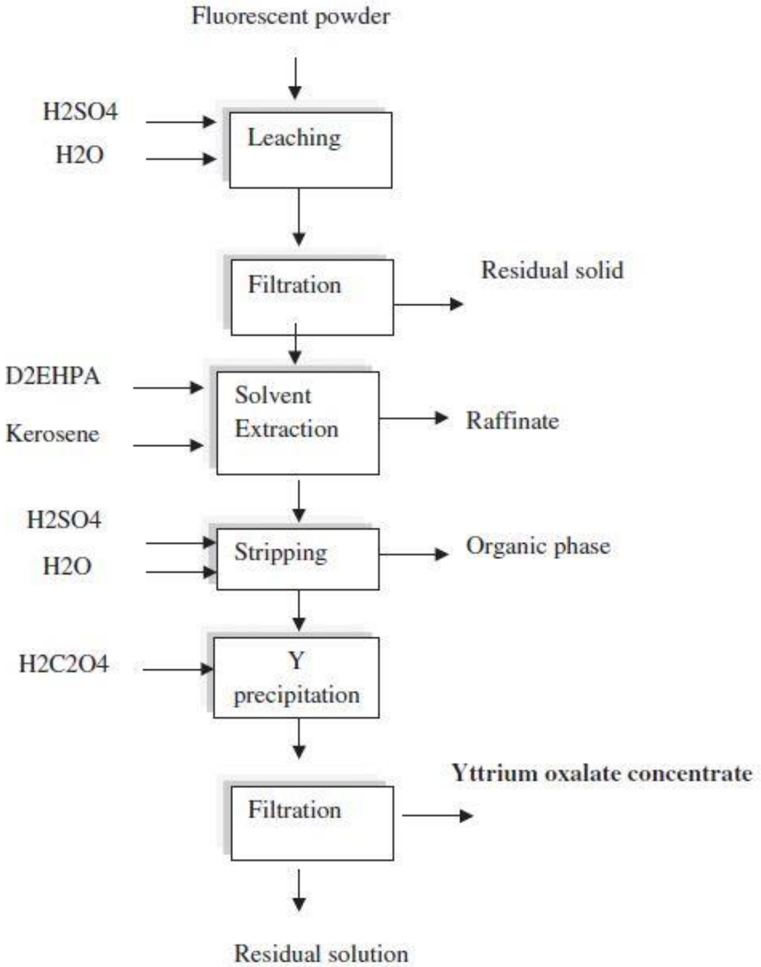

Figure 3. The process developed in the HydroWEEE project

Source: Innocenzi et al., 2017b

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

The annual mass balance is reported in Figure 4.

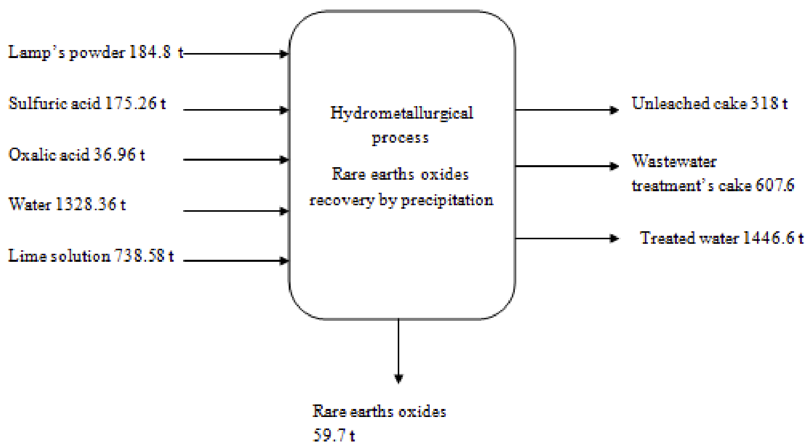

Figure 4: Total annual mass balance for the hydrometallurgical process (Innocenzi et al., 2016a)

(… explain the process HERE)

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

4.2 Financial flow

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

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

(Ref: Massarutto, 2009)

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

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

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

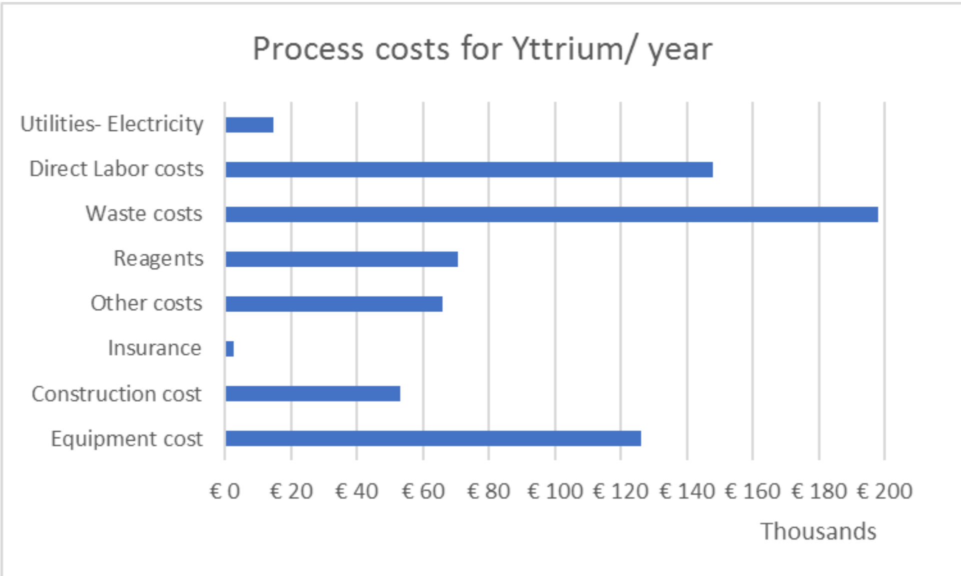

Figure 4: treatment recovery costs of yttrium 2016

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

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

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

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

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

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

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

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

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

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

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

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			

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

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

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

3. Conclusions

Rare-earth elements REEs gained international attention in 2011 when their prices boosted after Chinese quota restriction on export. A potential option of extraction of REEs from mines is their recovery them from waste. Moreover, "turning waste into a resource is essential to increase resource efficiency and closing the loop in a circular economy" (EC, 2015). Nevertheless, not many studies assess the economic conditions which make recovery of raw material convenient. Relight Ltd is a leading Italian company which recycles WEEE in general and it has developed a project called HydroWEEE to recover yttrium (one of REEs) from spent lamps. Its HydroWEEE project annually treats 184.8 tons of fluorescent powders, coming from spent lamps recovering around 54.5 tons of yttrium oxide. In this case study, we investigated the Relight case of recycling yttrium from spent lamps, by which it is demonstrated that recycling is a valid option in economic terms if the market price is above 14 €/kg. Therefore, in 2012 and 2013 it was convenient to recover yttrium because its price was higher than the costs of separated waste collection (SC) plus the cost of treatment and recovery (TR). However, during the following years (2014-2016) the price of yttrium did not cover such costs thus making its treatment and recovery less convenient than its disposal. Another main question arises: is yttrium really rare? When China had blocked the export of yttrium, the price was boosted (in the short term). This is a normal reaction to the inelastic demand arising from the fact that, in the short term, there were no alternatives. However, this does not predict the price of yttrium in the medium-long term, as it might be replaced with other metals, or other primary or secondary mines may be exploited, or other products might substitute those containing yttrium. Therefore, as suggested by other studies (McLellan et al., 2014; Charalampides et al., 2016) yttrium and REEs are better defined "critical" or "strategic" in economic terms due to: 1) their fundamental role in some specific equipment and application, such as renewable energy, medical equipment, defense equipment; 2) they do not have substitution in the short term; 3) the supply source is at the moment a monopoly. This economical assessment performed in our case study, even if it is limited to the specific conditions presented, helps understanding not only the economic rationale behind rare earth recovery in the case-study analyzed, but it also provides an interesting benchmark to analyze the commercial potential of similar processes (ERECON, 2014). Besides, policymakers could incentivize the recovery solutions when market conditions are not convenient with the following actions: make compulsory the quantity of waste recycled; make compulsory the quantity of material recovered; incentive the market of second raw materials with fiscal levers or by imposing a minimum quantity of secondary raw materials incorporated in new products. In the case of yttrium, European produces are fully dependent on China and the main risk is the unavailability of materials (Chapman et al., 2013). Therefore, it is crucial to sustain the European rare-earth recycling industry as well as maintain skills and knowledge along the entire REE value chain to support the long-term supply security (ECON, 2014, Massarutto, 2014). For example, the Italian recycling industry builds on a long-lasting tradition and its existence and vitality are valid deterrents to the powerful Chinese REEs industry. At the European level, the amendments to the waste framework directive can be an important step towards the reduction of the EU’s dependence on the import of raw materials and the facilitating of the transition to more sustainable material management and a Circular Economy model (EC, 2015).

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