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Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties

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ABSTRACT

Rare earth element (REE) recycling remains low at 1%, despite significant uncertainties related to future supply and demand and EU 2020 energy efficiency objectives. We use a global production network framework of REE flows from mine to REE phosphors in energy-efficient lamps to illustrate the potential of closed-loop recycling for secondary supply under different scenarios of primary supply and forecasted demand for LEDs, CFLs and LFLs. We find that different End-of-Life Recycling Rate scenarios for REE secondary supply range between meeting forecasted REE demand and filling primary supply gaps, and competing with primary supply. Our argument centres on diversifying REE sourcing with recycling and the choice between primary and secondary supply. We stress that secondary REE phosphor supply requires further policy to support lamp collection and a discussion of the value of REE phosphor recycling underlying its economic feasibility.

GRAPHICAL ABSTRACT

KEYWORDS

Rare earth elements, Energy-efficient lamps, Global Production Network, Recycling, Resource Conservation, Circular Economy

1 Introduction

With an increase in energy efficiency of 20% to be achieved by 2020 within the European Union (EU), lighting presents a core area of interest. Replacement of inefficient bulbs by 2020 is expected to enable energy savings to power 11 million households a year. In 2009, regulations pursuant to the EU Eco-design Directive introduced stricter energy efficiency requirements for lighting products, which induced a phase-out of incandescent lamps (EU Commission, 2009, 2014a). By 2016 it is expected that a majority of these lamps will be phased out, with similar legislations implemented in other nations including Australia, BRIC countries, Japan, South Africa, and the United States (UNEP, 2014).

The lifetime of incandescent lamps is about four times shorter and their efficiency significantly less than compact fluorescent lamps (CFLs), with 15 lumens of visible light per watt of electricity consumed (lm/W) versus 63 lm/W (Wilburn, 2012). A linear rather than bulb shape characterizes linear fluorescent lamps (LFLs). Fluorescent lamps emit light when voltage is applied to the mercury gas within the glass body, which produces UV light that is transformed to white light by the phosphor powder coating of the lamp (Lim et al., 2013). Light emitting diodes (LEDs) have a lifetime approximately three to six times that of CFLs (Wilburn, 2012). LEDs emit light when electric current passes through a semiconductor chip and they are distinct to fluorescent lights in that they contain minor proportions of phosphor powder and no mercury.

While the market share of LEDs is projected to accelerate, the transition from fluorescent lights will take time partly due to the upfront costs of LEDs in comparison to CFLs and LFLs. McKinsey & Company (2012) expect CFLs and LFLs to remain with a share in the lighting technology distribution until 2020, yet their significance is anticipated to decrease faster jointly with market demand for REE in fluorescent lamps, as envisioned by Solvay and General Electric and illustrated in Figure 2 (Cohen, 2014). Of central concern to the lighting industry are phosphor powders in these lamps, which contain rare earth elements (REE) used for their luminescent properties and key to producing white light (Binnemans et al., 2013a).

Since the early 1990s, China has gradually emerged as the largest consumer and producer of REE. The country hosts the majority of global mining and processing of these elements and has enacted numerous policies including quotas for mining and export (latter replaced by export licences in January 2015, see Bloomberg News, 2015) and a two-tier pricing system, under which REE cost less in China than in the rest of the world (ROW), introduced by export duties and trading rights, which significantly increases the price of exported REE products (WTO, 2014). Concerns about decreases in REE availability outside China intensified with the price increase of export-destined REE products by up to +600% in 2011 (Massari & Ruberti, 2013). Lawsuits against the REE export policies by China were filed at the WTO (2012) by the EU, Japan and the U.S. and in response to the WTO (2015) Dispute Settlement Body, China removed the application of export duties and export quotas to REEs, and the restriction on trading rights of enterprises exporting REEs. It remains uncertain how subsequent new Chinese industrial policy measures, including new export licences and the ad-valorem tax, will affect the market over the long-term. Strategies to target these concerns address the diversification of REE supply outside China, including re-opening old mines or establishing new mines, and include discussions about whether government intervention would be justified in recognizing the need for integrated value chains (Machacek & Fold, 2014; Tukker, 2014; Zachmann, 2010). Simultaneously, efforts in design to reduce and substitute REE in product components and recycling have surged, aiming to prevent future supply risks.

This study contributes to the discourse on REE recycling with a value analysis of recycled heavy REE europium (Eu), terbium (Tb) and yttrium (Y) from phosphor powders of fluorescent lamps as source of supply at times of EU and U.S. REE criticality classification (EU Commission, 2014b; U.S. DoE, 2011). Today, at most 1% of all REE used in different applications are recycled (Binnemans, 2014; Binnemans & Jones, 2014). The role of REE recycling has been explored and critically reviewed in general (Guyonnet et al., 2015; Moss et al., 2013; Schüler, et al., 2011; U.S. DoE, 2011) and from the viewpoint of specific REE, laboratory experimentation and product groups (Bandara, et al., 2014; Binnemans et al., 2013a; Dupont & Binnemans, 2015; Eduafo, Strauss & Mishra, 2015; Habib et al., 2014; Kim et al., 2015; Rademaker, Kleijn & Yang, 2013; Sprecher, Kleijn & Kramer, 2014; Tunsu et al., 2015). While several studies have concluded that recycling of REEs is worthwhile and requires a broader strategy to enable REE processing capacities, including tracing the REE from mine to end of life (EoL) waste (Rademaker, Kleijn & Yang, 2013; Sprecher, Kleijn & Kramer, 2014), none have provided an in-depth analysis of commercial scale recycling and what is needed to upscale recycling. To this end, this study provides an empirical analysis, using a case study of REE phosphor recycling on a commercial scale and an ex-ante analysis of the market from 2015-2020 to assess and discuss the potential for recycling of REE from energy-efficient lamp phosphors. We discuss what factors, including regulatory instruments and rethinking value propositions, are necessary to realize such potential.

2 Methodology

Our conceptual approach involves a qualitatively informed global production network framework to depict value adding, or processing steps from REE-containing ore to REE content in phosphor powders as used in energy-efficient lamps. This is the framework from which we then research the potential for secondary supply and closing the loop for REE in lamp phosphors through a mixed methods approach involving both a case study and modelling. Our case study provides an ex-post analysis of the experience of commercial REE recycling of REE phosphor containing lamps. This and our forecasts of supply and demand of Y, Eu and Tb then underpin the ex-ante analysis of the potential for development of secondary supply of REE phosphors from 2015-2020.

Global production network of rare earths and phosphors. Five steps, depicted in figure 1, precede the production of REE phosphors. Investor interest in favourable returns on investment finances prospecting and exploration of REE which enables data collection for sequential reporting required for the decision on the granting of an exploitation licence. Mined REE-containing ore is beneficiated by crushing and grinding, mineral separation, adjusted to the REE-mineral type, REE-grade and the mineral assemblage.

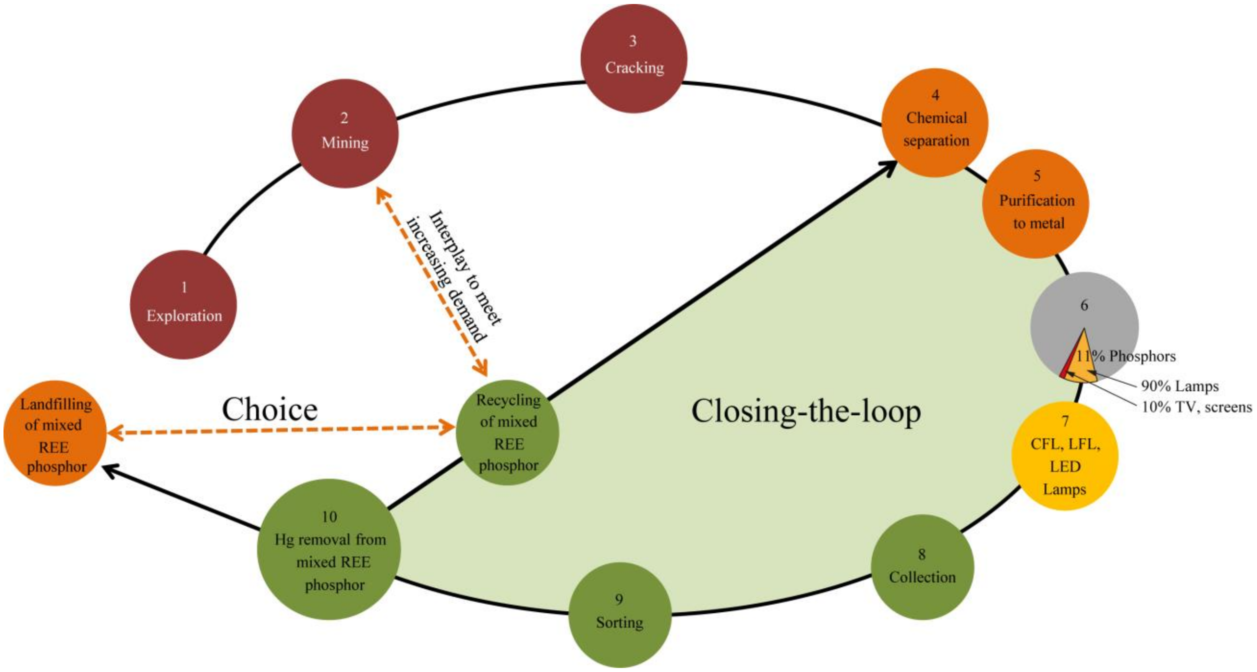


Figure 1. Global production network of REE phosphor-based, energy-efficient lamps. Source: adapted from Erecon (2014) and Simoni (2013) with % indication of REE phosphor

share of total REE market (derived from Castilloux, 2014a) subdivided into estimated 90% of phosphors used in energy-efficient lamps, and 10% for TVs and screens (Balachandran, 2014).

Next a cracking process leaches the REE from the REE-minerals resulting in a concentrate of mixed REE solution. A chemical separation into individual REE follows. Most recent estimates partially produced from primary data suggest that REE use in phosphors accounted for 11% of total REE market demand in 2013 and for 19% of REE market demand value in the same year (derived from Castilloux, 2014a). Usually, phosphor manufacturers buy a concentrated REE product (oxides or compounds, see Lynas Corporation, 2014) for direct use in producing various patented phosphor powder compositions (Wilburn, 2012). The 11% phosphors are then used by various phosphor using applications (Castilloux, 2014a), with an estimated 90% for phosphors in energy-efficient lamps, and 10% for TVs and screens (Balachandran, 2014).

REE-based phosphor powders use varying amounts of REE, resulting in a wide variety of powder compositions (Ronda, Jüstel & Nikol, 1998), but primarily phosphor powders contain some proportion of Y, Eu and Tb to generate red, green and blue phosphors (Balachandran, 2014). Almost all global supply of Eu, about 85% of Tb and close to 77% of Y are used for phosphors (Moss et al., 2013; Tan, Li, & Zeng, 2014). The high purchase cost of phosphors can be attributed to the high (99.999%) purity requirements (Binnemans et al., 2013a) on the REE used and the lower abundance of these heavy REE, relative to lighter REE, in REE-bearing minerals as explained by the Oddo-Harkins rule (Chakhmouradian & Wall, 2012).

The balancing problem (Binnemans et al., 2013b; Falconnet, 1985) adds to this the challenge of selling all REE mined (if stockpiling is disregarded), as demand does not match the natural distributional occurrence of REE. At the time of writing, supply of light REE (e.g. lanthanum and cerium) is not met by equally high demand while some heavier REE (e.g. dysprosium and europium) are in higher demand than supply (Binnemans et al., 2013b). In addition, REE phosphors are both essential and hardly substitutable in the functioning of fluorescent lamps.

In this article we first examine the relationship between global primary supply and secondary supply of lamp phosphor REE through an empirical case, following Guyonnet et al. (2015, pp.1) who emphasize that '*any global (systemic) analysis of mineral raw material supply should consider both types of sources*'. We also model the dynamics in the global production network of REE linked to demand and supply of Y, Eu and Tb for phosphor powders in fluorescent lamps. The assumptions underlying our forecasts are presented below and uncertainties are addressed in the discussion section.

Demand forecast. REE content varies in CFLs, LFLs and LEDs, see Table 1. The data related to the elemental composition of phosphors contained in LFL, CFL and LED has been derived from Castilloux (2014b) for phosphor (g), and Wu, et al. (2014) for REE composition in standard tricolour phosphor. The estimated phosphor composition for all these three lamp types is shown in the following table:

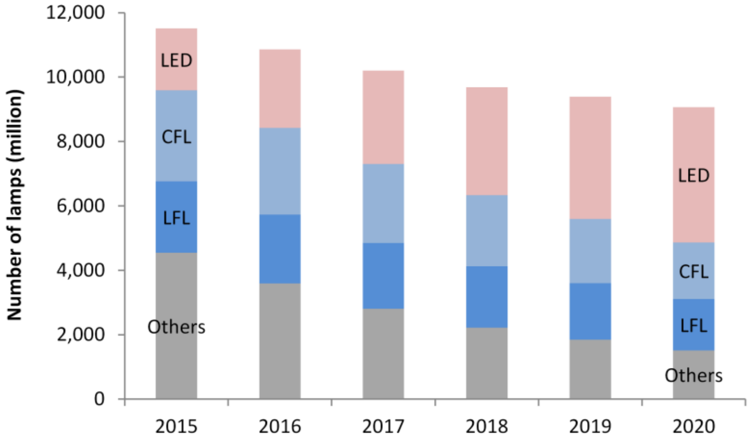
Table 1. Approximate REO content (g/unit) of various energy-efficient light types

	Y_2O_3 (g)	**Eu_2O_3(g)**	**Tb_4O_7 (g)**
Range of content	46.9-51.2%	3.9-4.4%	2.2-2.6%
LFL	1.0975-1.1981	0.0913-0.103	0.0515-0.06084
CFL	0.7035-0.768	0.0585-0.066	0.033-0.039
LED	0.0047-0.0051	0.0004-0.0004	0-0

Sources: Castilloux (2014b); Wu et al. (2014).

In our model we use McKinsey & Company (2012) data on general lighting applications (which encompasses lighting in residential applications and six professional applications, namely office, industrial, shop, hospitality, outdoor and architectural) on the number of lamp types, both new installations and replacements, from 2015 to 2020 for all world regions (Europe, North America, Asia incl. China, Latin America, Middle East & Africa). The number of lamps is multiplied with the averaged total REO (g) as per lamp type in Table 1 to estimate the final demand of Y_2O_3, Eu_2O_3 and Tb_4O_7 for these three energy-efficient lamp types.

Figure 2. Forecasted development of the total global lighting market and lamp type shares



Source: Adapted from McKinsey & Company (2012).

Secondary supply forecast. To enhance our understanding of the future demand of phosphors for lighting purposes and the potential role of secondary supply originating from recycling these waste lighting applications, we model demand for Y, Eu and Tb in energy-efficient lamps from 2015 until 2020. The McKinsey & Company (2012) data estimates a range of lifetimes for the different lamp technologies and we use this combined with U.S. DoE (2012) data to estimate the lifetime of the different lamp technologies in whole years to anticipate availability of lamp waste in the model. We use a lifetime of three years for CFLs and LFLs and of eleven years for LEDs, yet noting that lifetimes are highly sensitive to how the lamps are used (i.e. switch cycles, length of use per day, and other factors). We also conducted a sensitivity analysis for lifetimes as part of the later discussion, provided in Table B.4.

Secondary supply of phosphor from lamps is then estimated with end-of-life recycling rates (EoL-RR), also known as recovery rates (Graedel et al., 2011) which consider a collection rate for lamps as well as an estimate of total recycling of the REE from waste lamps. In the model we use collection rate scenarios of 15-40-70%. The 15% collection rate scenario assumes, in line with status quo and global trends, collection rates in Europe of nearly 40% (Eurostat, 2014) and lower collection rates on the state and sub-state level in the U.S., Canada, and Australia (FluoroCycle, 2014; Silveira & Chang, 2011) as well as more environmentally sound management of waste lamps in developing countries (see e.g. UNEP, 2012). The 15% collection rate also reflects a slow uptake of policies and a lack of collection to date in key regions, for example in China (Tan et al., 2014).

The 40% collection scenario assumes that legislation on extended producer responsibility (EPR) and other supportive legislation will be applied globally in major regions, such as the U.S., China and India. Essentially it reflects the average EoL fluorescent lamp collection rate to-date observed among EU countries, with large disparities between countries but an overall 40% average (Eurostat, 2014). This scenario expects the continuous implementation of legislation related to EoL lamp management on U.S. state and stub-state level (Corvin, 2015; Silveira & Chang, 2011), fruition of plans and pilot projects in India (Pandey, Hooda, & Mishra, 2012), and expansion of China's existing EPR legislation to include lamps (Tan & Li, 2014).

Lastly, the 70% collection rate reflects the EU top-end observed in a few countries (Sweden for example – see Eurostat, 2014 and Table B.5; and Taiwan (Environmental Protection Administration, 2012)) and thus the high end of anticipated global collection. This rate represents a scenario with implemented legislation and well-designed systems in place in major regions around the world.

The efficiency of the recycling process also needs to be considered to estimate secondary supply. Binnemans et al. (2013a) and Tan et al. (2014) assume an overall recycling process efficiency rate of 80%, and we use this assumption with an amendment. We add a key step to the

80% assumption, namely the recycling of REE phosphors from the waste lamp powders between collection and recovery of REE. EoL fluorescent lamps are collected and treated to prevent mercury contamination as there are few other drivers for lamp collection in the first place. For this reason, the EU WEEE Directive explicitly requires removal of mercury for these types of lamps in the recycling process and therefore EU recycling rates for collected lamps are in general over 90% (Eurostat, 2014). While removal of mercury from lamps involves isolation of the phosphor powder layer where the majority of mercury is present, it does not always involve the further recovery of REE from this powder and this fraction is often landfilled as hazardous waste in the EU (Walter, 2011; Interviewee C, 2015). Thus, this step leaves a significant gap in the potential for recycling to achieve higher EoL-RR.

In the low-ambition 15% global lamp collection scenario we assume that overall, only 7% REE phosphors are recovered of the lamps collected and recycled. The medium scenario assumes 40% global lamp collection and a tripling of REE recycling capacity worldwide with an EoL-RR of 19%. In the most ambitious scenario, high collection rates like those seen in Sweden are coupled with the recycling process used in that country in which nearly all waste phosphor powders are sent for further recovery of REE at Solvay for a final EoL-RR of 53% (assumptions for each scenario are summarized in Table 2).

Table 2. Components of End-of-Life-Recycling-Rates under three different scenarios

Scenarios	**Collection rate of lamps**	**REE phosphor recycling rate**	**Recycling process efficiency rate**	**EoL-RR**
Low ambition - top down calculation of EoL-RR of global REE phosphor capacity eqv. to Solvay's capacity (450 t) compared to global total capacity (11,150 t)	15%	55%	80%	**7%**
Medium ambition - top down calculation equivalent to Solvay's capacity (450 t) in Europe, North American and China (1,350 t)	40%	59%	80%	**19%**

compared to global total capacity (11,150 t)				
High ambition - bottom up calculation from best-case Sweden scenario (70% collection as per Sweden and Taiwan; 95% REE phosphor recycling rate in Sweden)	70%	95%	80%	**53%**

Sources: EoL-RR concept as per Graedel et al. (2011) and adapted with REE phosphor recycling rate conceptualized by authors. Overall REE recycling process efficiency rate are adopted from Binnemans et al. (2013a) and Tan et al. (2014). Note: The REE phosphor recycling rate is calculated on the basis of informed estimates of the ‘collection rate of lamps’ and the ‘recycling process efficiency rate’.

Supply forecast. To calculate the volumes of Eu, Tb and Y available to energy-efficient lamps in 2015-2020, we estimate total primary supply volumes. We use current estimates that 100% of Eu, 85% of Tb and 77% of Y are used for phosphors (Moss et al., 2013; Tan et al., 2014) of which 90% would be available to the production of LEDs, CFLS, and LFLs and the remaining 10% for TVs and screens (Balachandran, 2014).

We assume that total primary supply volumes consist of Chinese rare earth oxide (REO) production, current rest of world (ROW) production and forecasted REO production in the ROW. To forecast future ROW production volumes, we consider a set of ROW developed REE projects with publicly available data including planned production volumes, REO distribution, and costs (see Appendix A). Company-reported dates for starting production provided us with a sequence for their potential market entry, which we modelled with three scenarios which considered delays of one, three and five years in the start of production.

We assume that these projects enter the market when REE prices make the anticipated production start economically feasible. To find these prices we used a price model represented by a REE industry cost curve which is based on the indirectly proportional relation of the supply quantities and prices of individual REO (see Appendix A, more details available from Klossek, van den Boogaart, & Hoeck, forthcoming). The price model is built based on REO prices from March 2015 (Metal-Pages) and current supply volumes of individual REO.

Two approaches guided our calculation of current supply volumes of individual REO for the price model (1) based on the total mining quota in China, (2) based on the Chinese export quota and illegal supply. Approach (1) departs from the phase-out of Chinese export quota by May 1st, 2015, and new export licensing. We assume that the total REO mining quota for 2015 in China could be a proxy for the potential maximum supply volume which could come from China. To calculate total REO supply volumes (for each REO individually) we added the expected REO mining quota in 2015 to current ROW supply volumes.

The second approach uses 2015 REO mining quota in China as a proxy for maximum REO production volumes in China in 2015. As the quota for the 1st half of 2015 increased by 11% (Argusmedia, 2015; Shen, 2015) compared to the quota for the 1st half of 2014, we assume that the total quota in 2015 will be 11% higher than the total quota in 2014. For 2015 we assume the same distribution of REO in the mining quota as in 2014 (Chen, 2014). We estimate current ROW production at 14%, assuming China’s share of global production has not changed significantly from the 86% share in 2012 (Tse, 2013 in Wübbeke, 2013). To calculate the volumes of individual oxides we used the same REO distribution as in the total mining quota (as in our view it represents an average distribution in a typical hard rock REE deposit).

In the second approach of Chinese export quota and illegal supply, we acknowledge that Chinese REE export quotas have been phased out and replaced with an export licensing system. We expect that in such a situation a part of the illegal export volumes would be sold via official channels; however the total export volumes (consisting of official and illegal volumes) would not change much. To estimate the export volumes in 2015 (to be a proxy for the supply volumes coming from China at FOB prices[1]) we considered the REE export quota in 2014 as a proxy for the maximum official export volumes. To find total export volumes we added illegal supply volumes to the export quota (assuming a 40% rate of illegal supply in total export volumes as estimated by Argusmedia, 2015).

The results of these two different approaches to calculate current supply volumes differed only slightly. In our view, the Chinese export quota and illegal supply approach is more realistic as it represents maximum REO volumes for export to be sold at FOB prices and considers the domestic REO demand of China, while the first approach assumes that the total REO production of China could be exported which is unrealistic. Our results are therefore showing the second approach, while the first approach is illustrated in Figure A.1. Results of these calculations (tonnes of REO) were converted to tonnes of rare earth metals to be compared to the results of the demand and secondary supply analysis.

Case study. Known as European key player in REE chemical separation, Solvay-Rhodia, hereafter 'Solvay', operates across a bandwidth of industrial sectors including energy, automotive and electronics. It is, jointly with Japanese Shin-Etsu, among the only two outside of China capable of chemically separating REE into both light and heavy individual REE products to purities of acceptance for customers on a commercial scale (Interviewee B, 2013; Shin-Etsu Chemical, 2014). Solvay runs REE chemical separation facilities in China and in La Rochelle, France. It is the first large supplier to the lighting market with a commercialized recycling

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[1] Free On Board (FOB) means that 'the seller fulfils his obligation to deliver when the goods have passed over the ship's rail at the named port of shipment. This means that the buyer has to bear all costs and risks of loss of or damage to the goods from that point. The FOB term requires the seller to clear the goods for export.' (WCS International, 2013)

process of La, Ce, Eu, Tb, and Y (Osram and Philips also ran pilot scale recycling projects) (Binnemans et al., 2013a; Moss et al., 2013; Otto & Wojtalewicz-Kasprzak, 2012).

Our case study relies on both literature review and semi-structured interviews with key actors. To enhance reliability of our empirical data, we interviewed representatives of firms involved at different stages of the recycling network, specifically collectors, recyclers and the REE chemical separator and refiner, Solvay, in line with methods as proposed by Kvale & Brinkmann (2009). Our data collection followed an iterative process. Phases of empirical data collection followed desk research for cross-checking available public data and to triangulate industry data with data from regulatory institutions, including from the European Commission and academic recycling experts. The empirical data served for identifying factors key to recycling REE, such as related to logistics and material components which add to the economic feasibility of REE phosphor recycling. This data also supported our ex-ante modelling.

3 Results

Closing-the-loop with REE phosphor recycling: the case of Solvay. EU funding through LIFE+ of 50% of the project (equivalent to about EUR 1.1 million for 24 months from June 2012) (EU Commission, 2011) supported Solvay to commercially recycle waste lamp phosphors following four years of prior research and development and industrialization (Solvay, 2014). As Figure 3 shows, Solvay receives phosphor powder from recyclers and first removes the mercury, glass and other components to physically liberate the rare earth concentrate, which is then sent to the chemical separation plant. There, the halophosphates are removed and the REE phosphors are cracked resulting in a REE concentrate that can be fed, as in a primary process, into a solvent extraction process for the individual REE chemical separation. High-tech knowledge of technical staff and internally developed, sophisticated software is applied to manage this solvent extraction process (Leveque, 2014). The REEs are then reformulated into new phosphor precursors for new energy-efficient lamps (Solvay, 2014).

Solvay has developed a flow sheet for the recovery of REEs from a mixture of halophosphate and REE phosphors. According to the patent for the process, the final yield of REE is at about 80% (Braconnier, & Rollat, 2010). The objective has been to demonstrate the industrial processing of 3,000 tonnes of lamp waste/year, which corresponds to the forecasted European waste production for 2020 (Golev et al., 2014; Solvay, 2014) and results in 90% waste stream valorisation corresponding to 10-20% of REO (rare earth oxides), glass (by-product) and phosphate (by-product) at Solvay (2014). The REEs lanthanum, cerium, europium and gadolinium, terbium, and yttrium are being recovered (Rollat, 2012). Technical complexities of the recycling process can be better understood in context: Lamp phosphor powder mixtures are the essence of the light characteristics of a fluorescent lamp and different mixtures are used in the powder manufacture (Koninklijke Philips Electronics N.V., 2011) which form the competitive base of lamp manufacturers and they are protected by patents (Li, 2012). Currently Solvay recycles several hundred tonnes of rare earth phosphors each year, primarily from Europe.

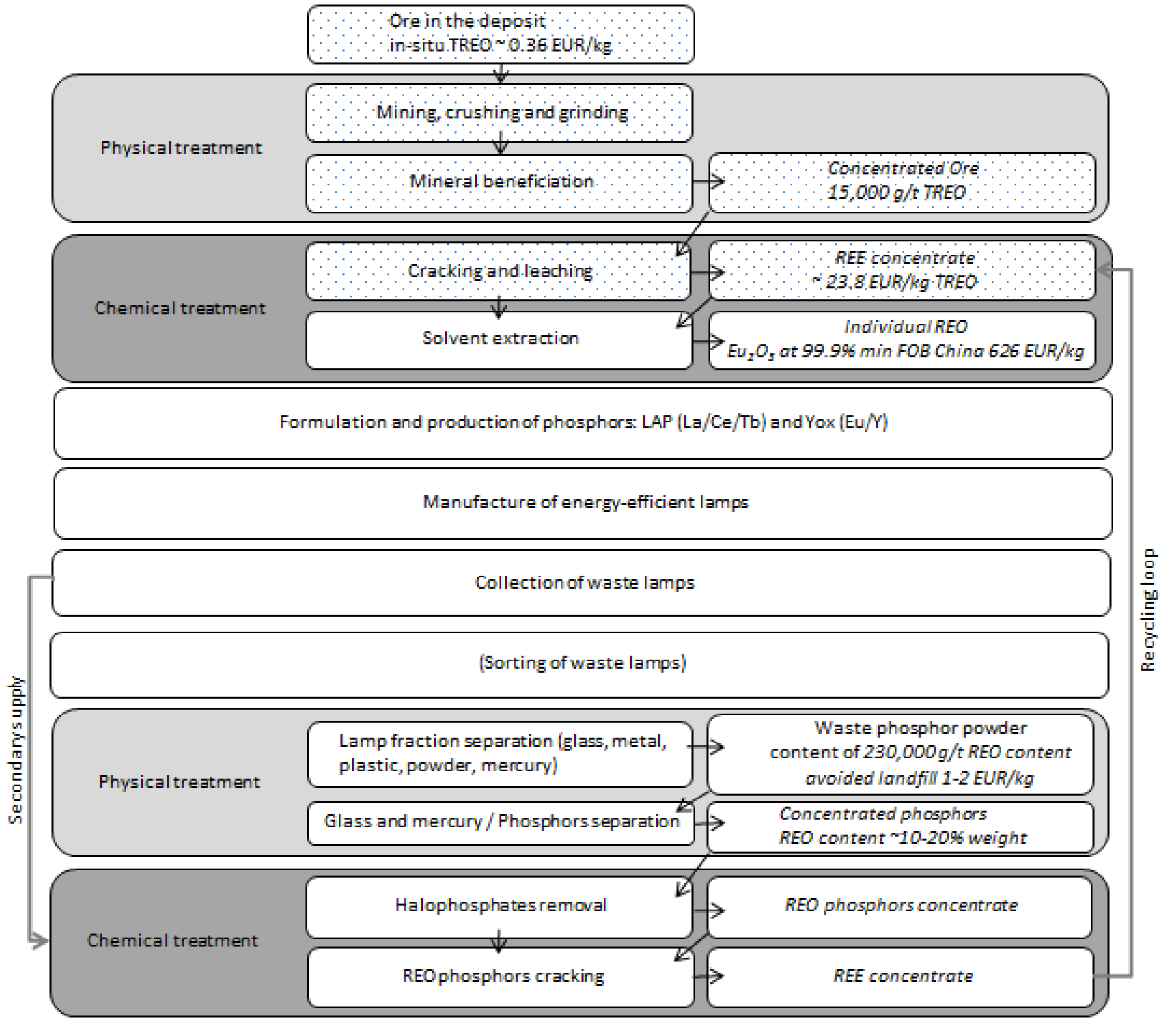

Figure 3. Primary processing steps from mine to the manufacture of energy-efficient phosphor lamps, secondary supply specific recycling processes of phosphor powders and closing-the-loop with a second run through chemical separation (Tan, Li, Zeng, 2014; Metal-pages, 2015; TMR, 2015; Rollat, 2012). Foregone primary REE processing steps are dotted. Note: Possible variations in the ore grade can impact the ore and REE values in further processing steps. This figure exemplifies a classic REE carbonatite which might provide conservative values when compared to not yet-commercially exploited REE-bearing minerals.

While the recycling of phosphor powders is less economical than other internal projects (Walter, 2011), we conclude that it strengthens Solvay's core competence. Depending on global market pricing of REOs, the firm's resources are liberated by sourcing separated REOs externally rather than conducting the chemical separation in-house and thus, the firm's resources are freed-up to pursue high technical sophistication in REE formulation to customer specification. Phosphor recycling reflects an adaptation of Solvay's REE subdivision to overall REE industry dynamics and a diversification strategy in raw material sourcing. Specifically, increasing challenges encountered by Solvay in accessing REE-bearing ore in China (Interviewee A, 2012/13) and general REE price volatility initiates quarterly decision-making on whether to chemically separate REEs internally or to purchase them and solely focus on formulation (Walter, 2011). Golev et al. (2014) stress that the annual objective of 3,000 tonnes of waste lamp waste recycling would secure 'Solvay's need for critical rare earths to manufacture new lamp phosphors (…).' In-house solvent extraction is the precursor to formulation and production of phosphors, constituting a key process to unique compositions of the phosphor powder. Thus, operating the solvent extraction processes might provide avenues to run process test routes and potentially explore new patents.

To understand the drivers for Solvay's commercialization project it is important to put it into context of the overall REE market. As described in the introduction, particularly between 2009 and 2011 concerns about the supply and price of REE arose as a result of numerous issues including Chinese restrictions on REE exports. This was a driver for increased attention in the EU for possible sources of supplies outside of China, as well as, potential secondary supplies. Lamps were a viable source of waste phosphor powder in the EU for a couple of reasons. First, existing legislation (the WEEE Directive) already mandates the collection of this waste stream. Secondly, the recycling process of this waste stream typically involved isolating mercury in the phosphor powder, so this powder was already an available end fraction of the recycling process (Récylum, 2014). Moreover, the costs of collection and recycling in EU countries is borne by the lamp producers and in some cases by municipalities (such as of collection in Denmark). REE chemical separator/refiner Solvay only needed to pay for the fractions from recyclers and the processing from that point onwards. Both researchers and practitioners argue that without legislation, collection and thus recycling of energy-efficient lamps are unlikely to take place (Huisman et al., 2008; Interviewee D, 2014; Richter & Koppejan, 2015). The role of legislation and market drivers for secondary supply are further discussed later, and we contextualize future recycling scenarios within a future market context in our model.

Future potential for closing loops: our model. Our EoL-RR scenarios illustrate how closing--the-loop at different REE phosphor powder recovery ratios can contribute to secondary supply of Y, Eu and Tb for new phosphor production to be used in lamps, TVs or screens. We contextualize these EoL-RR scenarios in a comparison with forecasted demand, as per our modelled scenario that stipulates the uptake of different lighting technologies until 2020, and with primary supply as per our supply forecast model.

Our results demonstrate that a global EoL-RR of 53% as per our best case REE phosphor powder recycling ratio modelled in line with to-date Swedish and Taiwanese lamp collection and REE phosphor recycling efficiency could provide secondary supply of Y, Eu and Tb equivalent to our modelled demand forecast of these three REE for LFLs, and an increasing share of CFL demand for Y, Eu and Tb until 2020.

Our EoL-RR of 19% is based on a tripling of REE phosphor recycling capacity for major markets of China and North America in line with our European Solvay case. Such an EoL-RR rate could contribute with secondary supply of Y, Eu and Tb of close to 50% of demand for these REE to be used in phosphors in CFLs.

The 7% EoL-RR corresponds to the estimated current global secondary supply of Y, Eu and Tb. In this scenario, secondary supply of Y, Eu and Tb contributes less than a third of 2020 demand of Y, Eu and Tb and hardly contributes to the demand by the CFL or LFL.

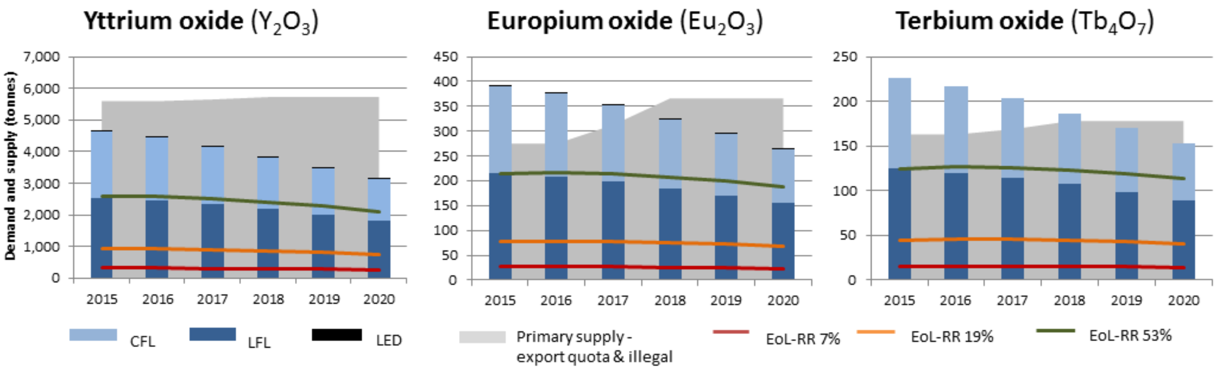

Figure 4. Potential secondary supply distribution for Y, Eu and Tb based on our three EoL-RR as compared to demand per lamp type (bars) and 3 year delay base case primary supply forecast (grey shading, data in Table A.3) from 2015 to 2020. Please note the different y-axis scales. We use REO as unit to enable a comparison of demand, and primary and potential secondary supply estimates, however, the use of REO in lamp phosphors requires their prior purification to metal, as depicted in Figure 1, step 5.

In 2015, the 7% EoL-RR of the three REE phosphors can fill the demand gap with about 7% and can account for up to 9% in 2020. The bandwidth of the 19% EoL-RR to meet demand is at 20% in 2015 and forecasted to more than a quarter of the demand (27%) in 2020. In contrast, and most significant, the 53% EoL-RR enables a secondary supply of the three REE phosphors of more than half of the demand by phosphor-based lamps in 2015 and three quarters of demand by these lamps in 2020 and thus competes directly with primary supply. This 53% EoL-RR illustrates choices about recycling in policy and business decisions which affect future recycling options. It also highlights that these choices require awareness on preferences – whether REE are to be sourced from a host rock or from recycling and why, see Figure 1.

4 Discussion

The case study and our model demonstrate the potential of secondary supply from waste lamp phosphor recycling to meet some of the forecasted demand, but the question remains about what factors impede and promote closed-loop recycling. The Solvay case demonstrated that market mechanisms, as well as, legislative drivers are key to making secondary supply viable.

Accessibility of adequate quantities of REE phosphor waste lamps, marketability of the recycled REE phosphors, as well as ability to derive adequate value (the right price at the right time) for these products have been argued as key bottlenecks to realize closed loop systems (Guide Jr & Van Wassenhove, 2009). In this section we first discuss these bottlenecks in the context of market mechanisms and uncertainties inherent in forecasting the future of the REE market. We discuss the factors that enabled REE phosphor recycling so far and what drivers are necessary for REE phosphor recycling to play a substantial role in meeting future REE phosphor supply.

Uncertainties of demand. REE use in phosphors is dependent on technological and socio-economic developments which impact the market uptake of lighting technologies. The minor REE content in LEDs is noteworthy for demand projections as is the potential redundancy of Tb in a market dominated by LEDs (U.S. Department of Energy, 2011; Wilburn, 2012). While the development of LED technology has progressed faster than anticipated (Danish Energy Agency, Energy Piano & CLASP European Programme, 2015), there are still concerns about the technology being ready to replace all lighting applications (and this was the reason underpinning the recent delay of Stage 6 EcoDesign requirements for lamps in the EU, see Ala-Kurikka, (2015). Also, phosphor powder substitutes might be found which would strongly influence the price customers are willing to pay for products and alternative ROW supplies of REE (Zachmann, 2010). Such a scenario would affect the attractiveness of developing the secondary supply in absence of other drivers.

Recycling can contribute to remedying the balancing problem, described earlier, which affects both primary supply and demand, as argued by other scholars (Binnemans et al., 2013b; Falconnet, 1985). In our supply and demand forecasts we have only considered the phosphors used for lighting and the technological development within this field of application. Yet other applications such as TVs and background lighting screens in tablets, phones and others also currently demand phosphors based on REE (Balachandran, 2014) and there may be growth in this demand by these or future applications (Castilloux, 2014b). Such growth would create new markets for the secondary supply from recycled lamp phosphors. In addition, it is uncertain which technologies will dominate the future lighting market, a factor which will influence the significance of REE lamp phosphor recycling further: For instance, remote phosphor screw-based or tube LED lamps (T8) will demand more REE than regular white LED lamps and LFL tubes (T8) (Castilloux, 2014b).

Uncertainties for recycled REE phosphor demand. Binnemans and Jones (2014) outlined three possible recycling routes: (1) direct re-use of the recycled lamp phosphors, (2) recycling of the various phosphors by physiochemical separation methods, and (3) chemical attack of the phosphors to recover their REE content. Options 1 and 2 are linked to a reuse of the powder by the same manufacturer, while option 3 allows for the use by a different party (Binnemans and Jones, 2014). The first two options would likely require a take-back system by the manufacturer, or the implementation of "closed loop supply chain management" (Guide Jr and Van Wassenhove, 2009). To date, closed loop supply is not unknown, though more typical for industrial goods like machinery, tools, and process catalysts (Graedel et al., 2011). With the first two options, uncertainties as to the quality of the powder would need to be considered. The powder deteriorates over the lifetime of a lamp due to exposure to UV radiation and mercury. In addition, recycling processes will affect the quality of the phosphor powder such as particle size and thus, the recycled phosphor powder will expectedly be inferior to the original product. Our article addresses the third recycling route which reflects the Solvay approach in which the recycled powder is chemically attacked.

Demand for recycled phosphors depends on price, which involves the cost of recycling lamps (which can be relatively high compared to the price of the product) (Philips Lighting, 2012). Key factors include efficient design of the scheme, but also transport distances and end use for the recycled glass, the main fraction by weight of the recycling process (Interviewee D, 2014; WEEE Forum, 2010). Notably, depending on the country, costs for recycling and collection of lamps in Europe can be the responsibility of producers and are not necessarily borne by lamp phosphor recyclers, e.g. Solvay, which only pays the recycler for the separated waste phosphor powder (Interviewee D, 2014). Currently, several externalities are not part of the price of both primary and secondary phosphors. These are discussed later in relation to value.

Uncertainties of primary supply. The primary supply of REE is uncertain with China possibly further consolidating the industry and using integrated production steps subsidized by the two-tier pricing mechanism for import substitution, expected to be upheld under the licensing regime. Further, alternative ROW supply might need to meet growing Chinese REE demand. High-tech skill requirements at each of the processing steps are obstacles for alternative suppliers and add to alternative REE supply risk (Hatch, 2011). Project feasibility, which is evaluated from the reconnaissance exploration to the mine development stage, is tied to several factors as put forward by Klossek & van den Boogaart (forthcoming): land title and location of the deposit; experience of regulatory authorities with the deposit type and commodity; REE grade and REE distribution representing estimated values from geological studies; potential for significant volume production (tonnes); presence of radioactive elements combined with environmental legislation; REE mineralogy; opportunities for project financing; business relationships with separation facilities; availability of expertise, technology, and equipment; strategic alliances and off-take agreements with end-users; cost competitiveness; obtaining mining permits and social licences to mine; as well as estimated values of REE and market conditions.

REE deposits are characterized by the different mineralogy of various REE-containing ores, which may require new, tailor-made processing routes to be developed (Jordens, Cheng & Waters, 2013), as well as additional financial and human resources, and time in testing their feasibility which could result in significant project delays, which is why we model with a one, three and five year delay. Our modelled three year base scenario is shown in Figure 4, produced from data presented in Table A.3. A project start delay by one year modelled on the export quota and illegal supply approach, affects primary supply insofar as that primary supply of Eu first meets and exceeds demand by 20 t in 2019 while in a five year delay Eu demand would first be met and exceeded by 50 t in 2020. The one year delay resembles the results of a three year delay regarding Eu primary supply. In none of the delay scenarios, Tb primary supply meets demand and in all delay scenarios, Y primary supply first meets and exceeds demand in 2020. Regulations regarding radioactivity for certain deposits, limited access to ROW chemical separation know-how and the capital and operational cost requirements to establish a new separation facility, also represent major bottlenecks for alternative value chains of junior REE exploration projects in the ROW (Golev et al., 2014). As some projects could become infeasible, future primary REE supply could be lower or postponed while the commercialization of new physical and chemical separation technologies might increase supply.

Uncertainties of secondary supply. Our model demonstrates the potential of increased REE powder recycling for REE phosphor powder demand of CFLs/LFLs over the time period in which the general lighting market shifts towards LEDs (and beyond). Even in 2020, the CFL/LFL technologies are expected to account for between 26% (McKinsey, 2012) and a third of the lighting market (Hykawy, 2014). Anticipations on the pace of LED uptake differ: For instance, General Electric anticipates that LEDs will reach a 70% market share in 2020 (see Cohen, 2014; Hykawy, 2014), while Wilburn (2012) emphasizes the role of fluorescent lighting for general lighting in the short to medium term. In our model we tried to find a balance, in line with McKinsey which anticipates a LED technology market share of 62% in 2020. While LEDs require significantly less REE and a different individual REE mix, such as reduced or no Tb, this lamp technology continues to require small quantities of Y and Eu. Continued heavy REE demand by phosphors used in general lighting (CFL, LFL, LED) and for background lighting (TVs-plasma, LCD, and X-ray intensifying screens) is anticipated (Balachandran, 2014).

Secondary supply is affected by the availability of waste lamps. We have mentioned the uncertainty about actual lifetimes of energy-efficient lamps because this is a function of actual use. If the lamp lifetimes are longer than our modelled assumptions, our sensitivity analysis showed that this would slightly increase the amount of waste lamps available until 2020 (and most likely beyond).

Promoting secondary supply. As mentioned, our low ambition scenario for recycling is an estimate of the status quo. Achieving higher recycling rates depends on a number of factors, beginning with collection. The case study demonstrated the large role of legislation in making the opportunity for further recovery of REE viable through mandatory collection of lamps (in absence of economic drivers for collection). Our model illustrates that similar timely legislative measures targeting fluorescent lamp collection, could impact end-of-life recycling rates (EoL-RR). The second scenario illustrates a case with more stringent EPR legislation.

The case of Solvay illustrates that such legislation can make REE recycling viable, but it is important to consider the other factors that incentivized Solvay to invest in commercial recycling: First and foremost, the availability of a separation unit at Solvay was a main driver for the decision towards REE recycling. In addition to an available supply of waste lamps, high REE prices and significant supply risk at the time as well as significant EU interest resulted in financial support. The decision to invest was also part of a business strategy that considered the value of the secondary supply differently (this perception of value is discussed in the subsequent section). In absence of price, supply risk, or other value drivers then there may be a need for further legislation to drive not only the collection of waste lamps, but also the further recycling of REE. Such legislation, like a business strategy, can be driven by a different perspective of value and alignment with the goals of a circular economy agenda. Ideally, combining either economic or legislative drivers to promote both collection and recycling of REE would further advance the potential contribution of the secondary supply closer to the case we already observe in Sweden, with a high level of lamp collection coupled with subsequent recycling of REE through Solvay in France.

Timing is significant in the elaboration and implementation of legislative measures that require REE recycling from fluorescent lamp phosphors. At the time of writing, the majority of EoL REE phosphor powder, even from collected EoL CFL/LFL lamps, is still landfilled. While there is evidence of socio-economic value of REE recycling that could already drive recyclers to further process REE, see Balcan (2015) and Ondrey (2014), some recyclers continue to see the small amount of powder as a barrier to act and prefer the small cost of landfilling over a possible change in their operations required to send the powder for further recycling (Interviewee C, 2015). This is problematic and unfortunate from a resource conservation perspective, as the REEs contained in these EoL phosphor powders (Wu et al., 2014) are already enriched, and since they stem from resource-intense concentration processes – physical and chemical beneficiation that involves high energy, water and chemical use – of the mined REE-containing mineral.

Rethinking the value of recycling phosphors. Aside from the challenges in accessibility and marketability of recycled lamp phosphor powders, which can be addressed, the feasibility of recycling is tied to its economics. We have already discussed that the overall cost factors for recycling REE from phosphors entail both costs for collection and the actual recovery. We now look closer at the overall value of a secondary supply of REE phosphors. Consideration of the overall value of recycling would depart from juxtaposing the processes of a secondary supply loop of recycling lamp phosphor powders with those of primary extraction of REE-containing ore. The latter comprises, as depicted in Figure 3, mining, mineral beneficiation, and cracking and leaching. These processes involve significant costs for energy and solvents, and operating expenditures comprising future costs for mine rehabilitation, effluent, radioactive material and waste handling. When compared with recycling, even if it involves a second chemical attack of the phosphor powders, the mining and processing costs up to chemical separation associated with the primary supply will not need to be borne.

Researchers have found higher concentrations of REE in the waste lighting products (i.e. anthropogenic deposits, see Mueller, et al., 2015); some finding more than 15 times higher concentration of Eu, Tb and Y in waste phosphor mixtures as compared to natural concentrations in REE-bearing hard rock minerals (Tan et al., 2014). We would like to stimulate a critical reflection on how it can be possible that recycling of phosphors is not economically feasible despite their high concentration in waste lamps (Langer, 2012; Walter, 2011) and when "only a dozen natural minerals have high enough quantities to be worth the cost of extraction" (Meyer & Bras, 2011). Using a specific process applied to foreign and Canadian EoL phosphor powders with a 98-99% recovery for REE, it has been indicated that REEs could be extracted for as low as USD 6 per kg of mercury phosphor dust (Cardarelli, 2014 in Chemical Engineering, 2014). This cost stands in contrast to the basket value of REE contained, which, averaged on the projects we identified for this study, would amount to about USD 28 per kg (see Table C.1).

With this in mind the focus in assessing the feasibility of phosphor recycling from waste lamps may need to turn to additional, different value dimensions, beyond the conventional exchange value of the phosphor powder (from both the primary and secondary processing routes) to include for instance resilience as a factor in business sustainability. Such value propositions could drive business opportunities for closed-loop recycling.

The Solvay business case of closing-the-loop with REE recycling, illustrated how the core competence of the firm is reiterated in a strategy that addresses two objectives: augmenting resilience against supply criticality and further increasing competitiveness. This case has been enabled by EU legislation that has attached societal value to recycling by means of committing producers to collect and recycle waste products, limiting the landfilling of hazardous waste, and promoting closed loop opportunities. The direct value potential of recycling Eu, Tb and Y used in phosphors of fluorescent lamps is manifested in the addition of a new material stream through phosphor recycling that makes use of existing production capital in a situation of concern and uncertainty over material access and potential scarcity in REE supply. As Guyonnet et al. (2015) argue, complementarity between the primary and secondary sources to meet supply requirements is of particular importance in the case of REE for which requirements are increasing. The firm opens up opportunities for value creation as operating its chemical separation plant might facilitate product and process improvements. Use of secondary supply for phosphors is also attractive for its domestic or regional availability as opposed to a dependence on a few key players, primarily China, and the uncertain development of new REE deposits. Secondary supply can augment certainty about short and medium term supply.

Developing the domestic secondary supply of REE can have wider societal benefits while supporting regional and national goals towards more circular economies. The collection and recycling of lamps has a high societal value in the avoided mercury contamination, which is difficult to quantify in economic terms (though some studies, for example, Hylander & Goodsite (2006) have tried and estimated a cost of USD 2,500 to 1.1 million per kg Hg isolated from the biosphere depending on local factors quantity, nature of pollution, media, geography, technology used etc.) At the same time, collection and recycling of energy-efficient lamps represents a cost in terms of overall material recycling (for example, costs for collection and recycling systems of lamp waste in EU have varied between EUR 0.15 per kg and EUR 2 per kg according to the WEEE Forum (2010)). Reconciling different costs and benefits of avoided pollution by collection and recycling is why legislation is often needed to drive this part of the process (Li et al., 2015).

Recycling of phosphors as indicated above, has societal value in the form of forgone costs of protecting human and environmental health and safety as primary REE processing involves the handling of radioactive elements that have been related to higher health risks, for example to cancer (Lim et al., 2013; Weng, Jowitt, Mudd & Haque, 2013). It should be noted that the exposure to radioactive material is also dependent on the geology of the mined deposit as well as the method of mining utilised (Ali, 2014).

Closing the loop further saves environmental costs associated with the generation and treatment of 63,000 m^3 waste gas, 200 m^3 acidic water and 1.4 tonnes of radioactive waste (all per tonne of REO) (Navarro & Zhao, 2014; Weng et al., 2013). Processes such as in-situ leaching can also result in water contamination and erosion resulting in landslides that potentially endanger lives (Yang et al., 2013) Moreover, the extraction process is very energy intensive, meaning that REE production is associated with higher greenhouse gas emissions than many other mined metals (Weng et al., 2013). Both the health and environmental effects can persist long after mining operations have ceased (Yang et al., 2013). In this light, regulation to limit these negative effects is needed, yet, only reliable checks will ensure regulatory effects, and thus, governance within the country in which REE minerals are mined, is key.

As also put forward by Ali (2014), it is clear that recycling can avoid many of the negative environmental and health externalities described and that these should be considered in valuing the secondary supply. In addition, there are also potential positive externalities in developing a secondary supply of REE. For example, overall it is estimated that various recycling activities yield potential for the creation of 580,000 new jobs and for R&D and innovation, thus contributing to EU 2020 targets and being key to sustaining competitiveness (Meyer & Bras, 2011). Finally, the less tangible value potential from investing in recycling lies in its long-term orientation towards adapting the current economic system. This valuation is built on ideas derived from conceptualizing economics of practice (Bourdieu, 1985) and include broader societal value (Foster, 2006) such as from recycling, reducing and reusing, as part of an economic model constructed on waste prevention – and over the long term, a reduction in resource extraction. Legislative targets will be necessary to drive this transition and to emphasize recycling, as is the case within the EU.

5 Conclusion

We have demonstrated that secondary supply has the potential to contribute to supply of phosphors for lamps (and other products). Secondary supply has considerable advantages over primary supply, of which one of the most notable is that it bypasses the extraction phase and many of the environmental impacts and costs involved in this stage. Secondary supply can constitute a source of supply of REE independent of Chinese quotas or licences and as such contribute to supply security of REE phosphors, at least in the short term. Lastly, establishing secondary supplies for recycling is in line with many policy goals in countries that advance closing material loops of critical materials for a circular economy.

We have also demonstrated that establishing and encouraging secondary supply requires driving factors. We have pointed to the role of legislation in establishing the collection systems for energy-efficient lamps in Europe and enabling commercial recycling. Our model indicates the rationale for such legislative measures in other regions to increase global recycling rates. Also within Europe energy-efficient lamp collection and recovery of REE from lamp phosphor powders can be improved. The latter step is currently not required by legislation. In absence of legislative drivers, we have discussed the need for rethinking the value in recycling phosphors. Lastly, our article demonstrates that time is of the essence for putting drivers in place and the sooner implemented, the greater the potential for REE recovery and closing loops of critical materials for a circular economy.

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APPENDIX A

Input data for primary supply

Table A.1 Input data for the primary supply analysis (1/2)

Company (REE deposit)[1]	*Deposit location*	*Eu_2O_3*, t/yr[2]	*Tb_4O_7*, t/yr[2]	*Y_2O_3*, t/yr[2]	Basket Price, USD/t REO	Planned production start[3]	Life of Mine (LOM)	Planned capacity, TREO tpa	Total CAPEX, USD	CAPEX Annuity USD/t	Annual OPEX, USD/t	Total annual unit costs, USD/t REO
Lynas (Mount Weld CLD)	Australia	117	20	167	26,780	2015	20	20,000[4]	612,991,200	3,791	14,636	18,427
Avalon (Nechalacho, av.[5])	Canada	44	39	780	36,196	2017	20	10,000	1,068,835,426	12,555	22,536	35,090
Tasman (Norra Kärr)	Sweden	19	34	1,842	43,152	2018	20	5,119	378,000,000	8,674	39,690	48,364
Frontier (Zandkopsdrift)	South Africa	118	34	824	28,416	2015	20	20,000	935,057,016	5,492	12,360	17,851
Quest (Strange Lake, av.[6])	Canada	13	60	2,934	38,656	2020	30	10,424	1,631,000,000	16,598	34,248	50,846
RES (Bear Lodge)	U.S.A.	56	11	112	28,641	2017	45	8,500	453,000,000	8,082	16,995	25,077
Matamec (Kipawa)	Canada	14	20	824	39,522	2016	15.2	3,653	360,502,449	17,492	26,057	43,549
Arafura (Nolans)	Australia	77	17	270	28,144	2019	23	20,000	1,084,209,280	6,103	15,670	21,773
Product purity		99.9%	99%	99.999%								

[1] Molycorp is not included in the analysis due to unavailable data on production costs to perform the profitability check.

[2] Calculation of the supply quantities of considered REO, based on the projects' REE production capacities and relative distribution of individual elements in the selected deposits, latter data stems from TMR (2015).

[3] Year when planned capacity is started or expected to be reached.

[4] Lynas is currently producing 3,008 t of REO per year (in 2014) and targeting 11,000 t in 2015.

[5] Averaged Nechalacho Basal and Upper values.

[6] Averaged Strange Lake enriched and Strange Lake Granite values.

Sources: Reports available on the websites of the companies.

Prices (USD/kg)	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	**Eu_2O_3**	Gd_2O_3	**Tb_4O_7**	Dy_2O_3	**Y_2O_3**
Base case (3 yr delay of production start) for **Export quota & illegal**										
2015	9.000	4.200	108.000	63.000	5.000	600.000	49.000	815.000	390.000	12.500
2016	9.000	4.200	108.000	63.000	5.000	600.000	49.000	815.000	390.000	12.500
2017	8.199	3.726	95.937	55.533	4.256	473.153	44.532	756.914	374.416	12.268
2018	7.304	3.225	83.154	47.744	3.533	366.507	39.567	689.296	354.896	11.962
2019	7.304	3.225	83.154	47.744	3.533	366.507	39.567	689.296	354.896	11.962
2020	7.304	3.225	83.154	47.744	3.533	366.507	39.567	689.296	354.896	11.962

Prices (USD/kg)	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	**Eu_2O_3**	Gd_2O_3	**Tb_4O_7**	Dy_2O_3	**Y_2O_3**
Base case (3 yr delay of production start) for **Mining quota**										
2015	9.000	4.200	108.000	63.000	5.000	600.000	49.000	815.000	390.000	12.500
2016	9.000	4.200	108.000	63.000	5.000	600.000	49.000	815.000	390.000	12.500
2017	8.568	3.941	101.415	58.909	4.586	527.030	46.586	783.930	381.793	12.379
2018	7.177	3.210	83.090	47.828	3.510	349.917	37.925	635.969	319.959	10.816
2019	7.177	3.210	83.090	47.828	3.510	349.917	37.925	635.969	319.959	10.816
2020	7.177	3.210	83.090	47.828	3.510	349.917	37.925	635.969	319.959	10.816

Table A.2 Input data for the primary supply analysis (2/2)

Market volumes	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_4O_7	Dy_2O_3	Y_2O_3	Total
% in mining quota 2014	27.9%	42.7%	4.7%	15.4%	1.6%	0.2%	1.2%	0.1%	0.7%	4.6%	
Volumes, t[1]	29,179	44,602	4,899	16,096	1,667	236	1,297	140	717	4,798	**104,545**
Mining quota 2014, t	**104,545**										
Mining quota 2015 (expected[2]), t	**116,550**										
Volumes China 2015 (86%), t[3]	32,530	49,724	5,462	17,944	1,858	**263**	1,446	**156**	799	**5,349**	**116,550**
Volumes ROW (14%), t[3]	5,296	8,095	889	2,921	303	**43**	235	**25**	130	**871**	**18,973**
Total current market volumes 1, t[4]	**37,825**	**57,818**	**6,351**	**20,865**	**2,161**	**306**	**1,681**	**181**	**929**	**6,220**	**135,523**
Approx. volumes export official, t (assumingly 60%)	8,544	13,060	1,434	4,713	488	69	380	41	210	1,405	**30,611**
Smuggling rate (40%), t[5]	5,696	8,706	956	3,142	325	46	253	27	140	937	20,407
Total export volumes (100% equiv. to 86% of world mkt)[6]	14,239	21,766	2,391	7,855	814	115	633	68	350	2,341	51,018
Volumes ROW (14%), t	5,296	8,095	889	2,921	303	43	235	25	130	871	18,973
Total current market volumes 2, t[7]	**19,535**	**29,860**	**3,280**	**10,776**	**1,116**	**158**	**868**	**94**	**480**	**3,212**	**69,992**

[1] Chen (2014)

[2] Assuming an increase of 11% similar to the increase in 1st batch production quota from 2014 to 2015 (Argus Media).

[3] Assuming similar distribution of REO as in the mining quota (see line 3).

[4] To be used in price model (available from Klossek) as current market volumes in the *total Chinese REE mining quota approach*.

[5] 40% of Chinese REEs being sold are illegally sourced (Argusmedia, 2015).

[6] Assumed current market volumes for the price model - assuming that overall exported volumes stay the same (as per TMR estimate), a part of illegal REO will be sold via official channels.

[7] To be used in price model (available from Klossek) as current market volumes in the *export quota and illegal supply approach*.

Table A.3 Base case, Supply - mining quota and export quota & illegal, *3 year delay scenario*

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
ROW current (tonnes) (see Table A.2 – line 7)						
Eu_2O_3	43	43	43	43	43	43
Tb_4O_7	25	25	25	25	25	25
Y_2O_3	871	871	871	871	871	871
China (tonnes) (see Table A.2 – line 6)						
Eu_2O_3	263	263	263	263	263	263
Tb_4O_7	156	156	156	156	156	156
Y_2O_3	5,349	5,349	5,349	5,349	5,349	5,349
(1) Mining quota approach						
Supply volumes (ROW) based on model (tonnes)						
Eu_2O_3			42	219	219	219
Tb_4O_7			7	51	51	51
Y_2O_3			61	968	968	968
Projects on the market			Lynas[1] - 11,000 t	Lynas - 22,000 Frontier	Lynas Frontier Matamec[2]	Lynas Frontier RES[2] Avalon[2]
Total world production (tonnes) (Supply volumes + ROW current + China)						
Eu_2O_3	306	306	348	525	525	525
Tb_4O_7	181	181	188	232	232	232
Y_2O_3	6,220	6,220	6,281	7,188	7,188	7,188
Allocated to LEDs, CFLs and LFLs (90%[3]) (tonnes)						
Eu_2O_3	**275**	**275**	**313**	**472**	**472**	**472**
Tb_4O_7	**163**	**163**	**169**	**209**	**209**	**209**
Y_2O_3	**5,598**	**5,598**	**5,653**	**6,469**	**6,469**	**6,469**
(2) Export quota & illegal supply approach						
Supply volumes (ROW) based on model (tonnes)						
Eu_2O_3			42	101	101	101
Tb_4O_7			7	17	17	17
Y_2O_3			61	144	144	144
Projects on the market			Lynas[1] - 11,000 t	Lynas - 22,000 Frontier[2]	Lynas Matamec[2]	Lynas RES[2] Avalon[2]
Total world production (tonnes)						
Eu_2O_3	306	306	348	407	407	407
Tb_4O_7,	181	181	188	198	198	198
Y_2O_3	6,220	6,220	6,281	6,364	6,364	6,364
Allocated to LEDs, CFLs and LFLs (90%[3]) (tonnes)						
Eu_2O_3	**275**	**275**	**313**	**366**	**366**	**366**
Tb_4O_7	**163**	**163**	**169**	**178**	**178**	**178**
Y_2O_3	**5,598**	**5,598**	**5,653**	**5,728**	**5,728**	**5,728**

[1] This project is not profitable with current production rate but producing (planning production rate increase).

[2] This project does not enter the market (or exit) due to the expected (or actual) economic unfeasibility resulting from the price decrease.

[3] According to Balachandran (2014), 90% of phosphors are used in energy efficient lamps.

The results presented in this table are illustrated in Fig. 4 for approach (2) and in Fig. A.1 for approach (1).

Supportive information: Best case, Supply - mining quota and export quota & illegal, *1 yr delay*

	2015	2016	2017	2018	2019	2020
ROW current (tonnes) (see Table A.2 – line 7)						
Eu_2O_3	43	43	43	43	43	43
Tb_4O_7	25	25	25	25	25	25
Y_2O_3	871	871	871	871	871	871
China (tonnes) (see Table A.2 – line 6)						
Eu_2O_3	263	263	263	263	263	263
Tb_4O_7	156	156	156	156	156	156
Y_2O_3	5,349	5,349	5,349	5,349	5,349	5,349
(1) Mining quota approach						
Supply volumes (ROW) based on model (tonnes)						
Eu_2O_3	42	219	219	219	219	219
Tb_4O_7	7	51	51	51	51	51
Y_2O_3	61	968	968	968	968	968
Projects on the market	Lynas[1] - 11,000 t	Lynas - 22,000 Frontier	Lynas Frontier Matamec[2]	Lynas Frontier RES[2] Avalon[2]	Lynas Frontier Tasman[2]	Lynas Frontier Arafura[2]
Total world production (tonnes) (Supply volumes + ROW current + China)						
Eu_2O_3	348	525	525	525	525	525
Tb_4O_7	188	232	232	232	232	232
Y_2O_3	6,281	7,188	7,188	7,188	7,188	7,188
Allocated to LEDs, CFLs and LFLs (90%[3]) (tonnes)						
Eu_2O_3	**313**	**472**	**472**	**472**	**472**	**472**
Tb_4O_7	**169**	**209**	**209**	**209**	**209**	**209**
Y_2O_3	**5,653**	**6,469**	**6,469**	**6,469**	**6,469**	**6,469**
(2) Export quota & illegal supply approach						
Supply volumes (ROW) based on model (tonnes)						
Eu_2O_3	42	101	101	101	101	101
Tb_4O_7	7	17	17	17	17	17
Y_2O_3	61	144	144	144	144	144
Projects on the market	Lynas[1] - 11,000 t	Lynas - 22,000 Frontier[2]	Lynas Matamec[2]	Lynas RES[2] Avalon[2]	Lynas Tasman[2]	Lynas Arafura[2]
Total world production (tonnes)						
Eu_2O_3	348	407	407	407	407	407
Tb_4O_7,	188	198	198	198	198	198
Y_2O_3	6,281	6,364	6,364	6,364	6,364	6,364
Allocated to LEDs, CFLs and LFLs (90%[3]) (tonnes)						
Eu_2O_3	**313**	**366**	**366**	**366**	**366**	**366**
Tb_4O_7	**169**	**178**	**178**	**178**	**178**	**178**
Y_2O_3	**5,653**	**5,728**	**5,728**	**5,728**	**5,728**	**5,728**

[1] This project is not profitable with current production rate but producing (planning production rate increase).

[2] This project does not enter the market (or exit) due to the expected (or actual) economic unfeasibility resulting from the price decrease.

[3] According to Balachandran (2014), 90% of phosphors are used in energy efficient lamps.

This table is presented for evidence of the 1 year delay scenario for approach (1) and (2).

Support. information: Worst case, Supply - mining quota and export quota & illegal, *5 yr delay*

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
ROW current (tonnes) (see Table A.2 – line 7)						
Eu_2O_3	43	43	43	43	43	43
Tb_4O_7	25	25	25	25	25	25
Y_2O_3	871	871	871	871	871	871
China (tonnes) (see Table A.2 – line 6)						
Eu_2O_3	263	263	263	263	263	263
Tb_4O_7	156	156	156	156	156	156
Y_2O_3	5,349	5,349	5,349	5,349	5,349	5,349
(1) Mining quota approach						
Supply volumes (ROW) based on model (tonnes)						
Eu_2O_3					42	219
Tb_4O_7					7	51
Y_2O_3					61	968
Projects on the market					Lynas[1] - 11,000 t	Lynas - 22,000 t Frontier
Total world production (tonnes) (Supply volumes + ROW current + China)						
Eu_2O_3	306	306	306	306	348	525
Tb_4O_7	181	181	181	181	188	232
Y_2O_3	6,220	6,220	6,220	6,220	6,281	7,188
Allocated to LEDs, CFLs and LFLs (90%[3]) (tonnes)						
Eu_2O_3	**275**	**275**	**275**	**275**	**313**	**472**
Tb_4O_7	**163**	**163**	**163**	**163**	**169**	**209**
Y_2O_3	**5,598**	**5,598**	**5,598**	**5,598**	**5,653**	**6,469**
(2) Export quota & illegal supply approach						
Supply volumes (ROW) based on model (tonnes)						
Eu_2O_3					42	101
Tb_4O_7					7	17
Y_2O_3					61	144
Projects on the market					Lynas[1] - 11,000 t	Lynas - 22,000 Frontier[2]
Total world production (tonnes)						
Eu_2O_3	306	306	306	306	348	407
Tb_4O_7,	181	181	181	181	188	198
Y_2O_3	6,220	6,220	6,220	6,220	6,281	6,364
Allocated to LEDs, CFLs and LFLs (90%[3]) (tonnes)						
Eu_2O_3	**275**	**275**	**275**	**275**	**313**	**366**
Tb_4O_7	**163**	**163**	**163**	**163**	**169**	**178**
Y_2O_3	**5,598**	**5,598**	**5,598**	**5,598**	**5,653**	**5,728**

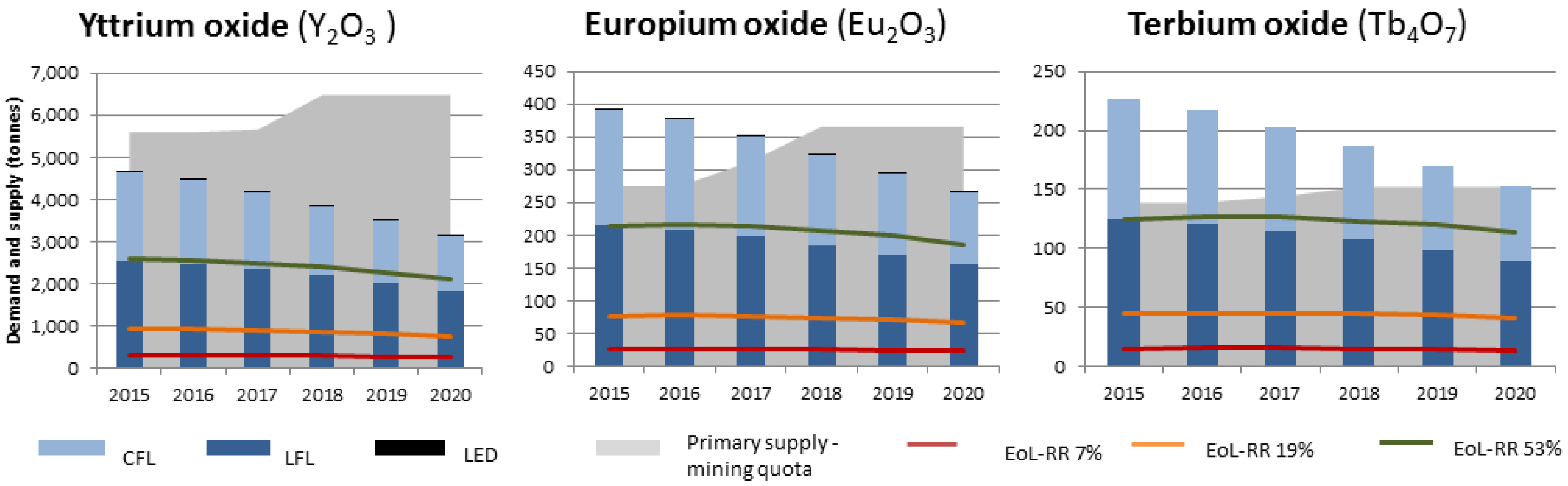
[1] This project is not profitable with current production rate but producing (planning production rate increase).

[2] This project does not enter the market (or exit) due to the expected (or actual) economic unfeasibility resulting from the price decrease.

[3] According to Balachandran (2014), 90% of phosphors are used in energy efficient lamps.

This table is presented for evidence of the 5 year delay scenario.

Figure A.1 Base case, total Chinese REE mining quota approach*, 3 year delay scenario*.



The figure compares secondary supply to demand and primary supply. Potential secondary supply distribution for Y_2O_3, Eu_2O_3 and Tb_4O_7 based on our three EoL-RR as compared to demand (bars) and 3 year delay base case primary supply forecast (grey shading) from 2015 to 2020. This figure is based on approach 1 of the primary supply forecast which uses the total REE mining quota in China. Please note different y-axis scales.

Source: authors.

APPENDIX B

Input data for demand and secondary supply

Table B.1 Demand input data (1/2) – Lamp market and Y_2O_3, Eu_2O_3 and Tb_4O_7 content in lamps

New installations (million)[1]

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
Others	1,073	935	831	749	698	610
LFL	659	630	594	562	521	489
CFL	704	653	616	564	509	436
LED	1,365	1,780	2,163	2,508	2,818	3,125

Lamp replacement (million)

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
Others	3,469	2,654	1,975	1,467	1,150	903
LFL	1,560	1,512	1,447	1,346	1,229	1,106
CFL	2,121	2,039	1,842	1,644	1,491	1,322
LED	560	658	733	848	977	1,078

Total lamps on market (million)

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
Others	4,542	3,589	2,806	2,216	1,848	1,513
LFL	2,219	2,142	2,041	1,908	1,750	1,595
CFL	2,825	2,692	2,458	2,208	2,000	1,758
LED	1,925	2,438	2,896	3,356	3,795	4,203

Rare earth in lamps[2]

	Phosphor (g)	**TREO (g)**
LFL	2.34	1.665
CFL	1.5	1.069
LED	0.01	0.006

Composition as per standard tricolor phosphor (%)[3]

	Y_2O_3 (Range 46.9-51.2)	**Eu_2O_3** (3.9-4.4)	**Tb_4O_7** (2.2-2.6)
LFL	Averaged to 49.05	4.15	2.4
CFL	49.05	4.15	2.4
LED	49.05	4.15	0

REO content (calculated from phosphor(g)*averaged REO content (%) above)

	Y_2O_3 (g)	**Eu_2O_3(g)**	**Tb_4O_7 (g)**	**Total RE (g)**
LFL	1.14777	0.09711	0.05616	1.301
CFL	0.73575	0.06225	0.036	0.834
LED	0.004905	0.000415	0	0.005

[1] McKinsey & Company, 2012. The data summarizes general lighting applications (residential, office, industrial, shop, hospitality, outdoor and architectural, yet excluding automotive and backlighting) for all world regions.

[2] Castilloux, 2014b.

[3] Averaged from Wu et al., 2014, Table 3.

Table B.2 Demand input data (2/2) - Y_2O_3, Eu_2O_3 and Tb_4O_7 demand per LFL, CFL and LED

Y_2O_3 (tonnes)

	2015	2016	2017	2018	2019	2020
LFL	2,546.90	2,458.52	2,342.60	2,189.95	2,008.60	1,830.69
CFL	2,078.49	1,980.64	1,808.47	1,624.54	1,471.50	1,293.45
LED	9.44	11.96	14.20	16.46	18.61	20.62
Total (rounded)	4,635	4,451	4,165	3,831	3,499	3,145

Eu_2O_3 (tonnes)

	2015	2016	2017	2018	2019	2020
LFL	215.49	208.01	198.20	185.29	169.94	154.89
CFL	175.86	167.58	153.01	137.45	124.5	109.44
LED	0.79	1.01	1.20	1.39	1.57	1.74
Total (rounded)	392	377	352	324	296	266

Tb_4O_7 (tonnes)

	2015	2016	2017	2018	2019	2020
LFL	124.62	120.29	114.62	107.15	98.28	89.58
CFL	101.7	96.91	88.49	79.49	72	63.29
LED	0	0	0	0	0	0
Total (rounded)	226	217	203	187	170	153

Total demand (tonnes)

	2015	2016	2017	2018	2019	2020
LFL	2,887.01	2,786.83	2,655.42	2,482.38	2,276.82	2,075.16
CFL	2,356.05	2,245.13	2,049.97	1,841.47	1,668.00	1,466.17
LED	10.24	12.97	15.41	17.85	20.19	22.36
Total (rounded)	5,253	5,045	4,721	4,342	3,965	3,564

Table B.3 Secondary supply – Availability of Y_2O_3, Eu_2O_3 and Tb_4O_7 as per different EoL-RR

Y_2O_3 (tonnes)

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
LFL- EoL	2,688.08	2,667.42	2,616.92	2,546.90	2,458.52	2,342.60
CFL - EoL	2,166.05	2,161.63	2,078.49	1,980.64	1,808.47	1,624.54
LED - EoL						
EoL-RR 7%	320.37	318.72	309.90	298.82	281.62	261.83
EoL-RR 19%	931.99	927.18	901.52	869.29	819.26	761.69
EoL-RR 53%	2,582.39	2,569.06	2,497.96	2,408.65	2,270.04	2,110.52

Eu_2O_3 (tonnes)

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
LFL- EoL	227.43	225.68	221.41	215.49	208.01	198.20
CFL - EoL	176.54	183.26	182.89	175.86	167.58	153.01
LED - EoL						
EoL-RR 7%	26.66	26.99	26.68	25.83	24.79	23.18
EoL-RR 19%	77.56	78.52	77.63	75.14	72.11	67.43
EoL-RR 53%	214.91	217.56	215.09	208.19	199.81	186.84

Tb_4O_7 (tonnes)

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
LFL- EoL	130.80	131.98	131.53	130.52	128.04	124.62
CFL - EoL	102.10	105.98	105.77	101.70	96.91	88.49
LED - EoL						
EoL-RR 7%	15.37	15.71	15.66	15.33	14.85	14.07
EoL-RR 19%	44.72	45.69	45.56	44.59	43.19	40.92
EoL-RR 53%	123.90	126.59	126.24	123.54	119.68	113.37

Table B.4 Sensitivity analysis (SA) for lifetimes of lamps

	Lifetime original (yrs)	SA (yrs)
CFL	3	5
LFL	3	5
LED	11	15

Y_2O_3 (tonnes)

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
LFL-EoL	2,673.16	2,697.26	2,688.08	2,667.42	2,616.92	2,546.90
CFL-EoL	1,815.83	1,953.42	2,086.59	2,166.05	2,161.63	2,078.49
LED-EoL	-	-	-	-	-	-
EoL-RR 7%	296.27	306.94	315.13	319.01	315.38	305.28
EoL-RR 19%	861.89	892.93	916.74	928.03	917.48	888.08
EoL-RR 53%	2,388.14	2,474.16	2,540.12	2,571.40	2,542.19	2,460.71

Eu_2O_3 (tonnes)

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
LFL-EoL	226.17	228.21	227.43	225.68	221.41	215.49
CFL-EoL	153.63	165.27	176.54	183.26	182.89	175.86
LED-EoL	-	-	-	-	-	-
EoL-RR 7%	25.07	25.97	26.66	26.99	26.68	25.83
EoL-RR 19%	72.92	75.55	77.56	78.52	77.63	75.14
EoL-RR 53%	202.05	209.33	214.91	217.56	215.09	208.19

Tb_4O_7 (tonnes)

	2015	**2016**	**2017**	**2018**	**2019**	**2020**
LFL-EoL	130.80	131.98	131.53	130.52	128.04	124.62
CFL-EoL	88.85	95.58	102.10	105.98	105.77	101.7
LED-EoL	-	-	-	-	-	-
EoL-RR 7%	14.50	15.02	15.42	15.61	15.43	14.94
EoL-RR 19%	42.17	43.69	44.86	45.41	44.89	43.45
EoL-RR 53%	116.85	121.06	124.29	125.82	124.39	120.40

Table B.5 Put on market, collection, and recycling of fluorescent lamps in selected EU countries

	Put on Market (tonnes) avg 2007-2009	Waste collected (tonnes) 2010	% of put on market collected 2010	% of put on market recycled 2010
Belgium	3,100	1,247	40.2%	37.5%
Denmark	1,606	694	43.2%	41.1%
France	13,070	3,839	29.4%	27%
Germany	28,204	11,092	39.3%	34.4%
Greece	1,757	124	7.1%	6.6%
Sweden	3,141	1,973	62.8%	62.3%

Source: Eurostat (2014).

EU member states show some of the highest rates in the world along with other countries with compulsory collection legislation like Taiwan, which collects and recycles over 75% of lamps (EPA Taiwan, 2014), however Table B.1 demonstrates further potential for improvement in collection rates. Outside the EU there is less available data, but it is estimated that 95% of fluorescent lamps in Australia are landfilled (FluoroCycle, 2014), while Canada, Japan, Mexico, and South Africa all recycle less than 10% (EU Commission, 2014) The United States has some, mainly state level, laws for management of waste lamps, requiring recycling by business users; however, enforcement is low and the recycling rate in these states is estimated around 23% (Silveira and Chang, 2011).

APPENDIX C

Table C.1 Cost estimates of different REE products for comparison of REE phosphor from primary and secondary (EoL) supply

Input	Ore **~0.42 USD/kg** (In-situ TREO) [1]		REE concentrate **~27.6 USD/kg** (In-situ TREO)[1]	Collected EoL lamps			Phosphor powders	EoL REE phosphor concen-trate	EoL REE phosphor concentrate
Process	Mine & beneficiation	Cracking & leaching (impurity removal)	Chemical separation	Sort-ing	Material from EoL lamps	EoL lamp recycling			
							Remaining glass & mercury / phosphor separation	Halophos-phates removal	REE phosphors cracking
Output	By gravita-tional beneficiation concentrated ore (15,000 g/t REO[6] or 0.2 - 15% grade in deposit[40])	REE concen-trate	Phosphor powders: Y_2O_3 (99.999%) **14USD/kg**[2] Eu_2O_3 (99.9%) **25USD/kg** Tb_2O_3 **620 USD/kg**	sorted EoL lamps	Sorted glass/metal/ plastic	Phosphor powder	Concentrated phosphors (230,000 g/t REO[6] or 10-20 wt% REO[7]) or 15% (CMI, 2014) or 30% tricolour phosphor powder content in recycled phosphor[8]	REE phosphor concen-trate	REE concentrate
Cost of treatment				btw. 0.15 and 2 EUR/kg for collection & recycling (WEEE forum)					
					Glass = net cost* Metals = very small positive return Plastics = small cost for incinerating	Selling the powder to Solvay is slightly less the cost of landfilling with Solvay paying transport costs. [5]	Price reductions for mercury and glass content in phosphor powder. Separating Hg out is very expensive. [5]		REE extraction from mercury phosphor ~ **6 USD/kg**[3]
(Avoided) environ-mental cost	63,000 m^3 waste gas ; 200 m^3 acidic water; 1.4 t of radioactive waste (all per t of REO)[4] Note: 'Impurity removal' refers to the removal of radioactive elements (if present in the REE-bearing mineral host rock).					**~1-2 USD/kg** (or SEK 7-15 /kg) to landfill phosphor powder [5]	**~2,500 – 1.1 million USD/kg Hg** isolated from biosphere[9]		

Notes to Table C.1:

Current hydrometallurgical processes applied recover 15 wt. pct. of rare- earth metals as oxides contained in phosphor dust (CMI Aug 2014 presentation).

* Ad glass: not clean enough for high-end uses - generally NOT used in new lamps.

˜ Ad metals: must be pre-treated and separated by magnets and flotation.

[1] as of TMR database, average of data from TMR for 7 junior REE projects (as per Table A.1., excluding Lynas and China), whereby the listing of two projects by one company has been summed up and averaged.

[2] prices accessible from price charts to non-subscribed users of metal-pages, Oct 2014.

[3] Cardarelli (2014) in Chemical Engineering (2014) who originally states in the context of 98-99% recovery that 'REEs can be extracted for as low as USD 7/kg of mercury phosphor dust', presumably since it is a Canadian based firm, the price is indicated in CAD.

[4] Navarro & Zhao, 2014; Weng et al., 2013

[5] Interviewee D, 2014

[6] MLR, 2002; Noble, 2013 in Tan, Q.; Li, J.; Zeng, X., 2014

[7] Otto, R., Wojtalewicz-Kasprzak, 2012

[8] Khetriwal et al., 2011

[9] Hylander & Goodsite, 2006

The recycling process is cheaper the better and more homogenous the powder quality is. The sorting and collection can influence the efficiency and cost so that enabling a sourcing of the same quality and type of lamp phosphors could make the REE powder recycling process more efficient and cheaper, as pointed to in Binnemans and Jones (2014) with the three recycling routes, yet requires either smaller loops from companies taking back their own product or better separation of lamp types.