Title
Economic feasibility of recycling rare earth oxides from end-of-life lighting technologies

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Publication Date
2019-11-01

DOI
10.1016/j.resconrec.2019.104432

Peer reviewed

Abstract:

Transition to efficient lighting technologies, such as fluorescent and LED lamps, is an important strategy to mitigate climate change. However, it also increases the demand for critical materials such as rare earth oxides (REOs). While recycling can alleviate the dependence on primary REOs, recycling these materials from lighting technologies is currently economically infeasible, limiting its adoption. As more REOs will become available for recycling, the economy of scale is expected to reduce the cost, therefore improving their circularity. Here we analyze the effects that the scale of recycling operation and REO prices have on the economic feasibility of REO recycling using dynamic material flow analysis and technology learning curve approaches. Our results show that end-of-life REOs from lighting technologies are expected to peak between 2020 and 2027. Increasing recycling plant capacity can reduce cost from about $7,200/t REO phosphors at 100 t/yr capacity to about $2,500/t REO phosphors at 1,500 t/yr capacity. Nevertheless, we found that REO recycling would not be economically feasible under 2018 REO prices, irrespective of scale. For a plant at 800 t/yr capacity, recycling becomes profitable only after a threefold increase from 2018 REO prices. The break-even point can be further reduced at a larger scale. Our results suggest that scaling-up recycling plants in the course of growing volume of end-of-life lighting technologies alone will not automatically increase REO recycling under current market conditions. Significant improvement of REO recycling rate in lighting technologies would therefore require substantially higher REO prices or commensurate policy interventions.

Keywords: Rare earth elements, efficient lighting technologies, dynamic material flow analysis, learning curve approach, recycling, economic feasibility.

1. Introduction

Lighting technologies are undergoing an energy-efficiency transition (De Almeida et al. 2013; UNEP 2017). Transition from incandescent light bulbs to fluorescent lamps (FLs), including compact fluorescent lamps (CFLs) and linear fluorescent lamps (LFLs), started in the 1990s, thanks to their high energy efficiency, long lifetime, affordable prices, and the worldwide phase-out of incandescent light bulbs (Waide 2010; UNEP 2012). Globally, FLs accounted for 60% of newly installed lamps in 2015 (Bardsley et al. 2015). In recent years, as light-emitting diodes (LEDs) have become affordable enough for general lighting, LEDs are expected to replace FLs and become the dominant lighting technology (Penning et al. 2016; Bardsley et al. 2015; Lim et al. 2011). Compared to incandescent light bulbs, FLs usually have higher luminous efficacy of 60 to 95 lm/W, and longer lifetime of 8,000 to 10,000 hours, and LEDs even show better performance compared to FLs, with the luminous efficacy of 90 to 120 lm/W and lifetime over 15,000 hours (Waide 2010; UNEP 2017). Lighting is responsible for about 15% of global electricity consumption (3300 TWh/yr) and 4.6% of greenhouse gas (GHG) emissions (1400 Mt CO_2 eq/yr) (UNEP 2014). According to a recent UNEP report, the transition to more efficient LEDs would lead to an electricity consumption reduction of 800TWh/yr and GHG emission reduction of 390 Mt CO_2 eq/yr by 2030 (UNEP 2017).

Despite the energy and environmental benefits of efficient lighting technologies, they increase the consumption of a variety of metals including aluminum, barium, copper, gallium iron, lead, nickel, zinc, and rare earth elements (REE). FLs contains higher amount of copper, lead, zinc and REEs, while LED contains higher amount of aluminum, barium gallium and silver (Lim et al. 2013). Within these metals, the REEs are considered as critical materials worldwide, and the US Department of Energy ranked several rare earth elements (Yttrium, Europium, Terbium, Neodymium, and Dysprosium) as critical metals, indicating their high importance to clean energy and the high supply risk (Bauer et al. 2011). In the efficient lighting technologies, rare earth oxides (REOs) are used to produce phosphors of FLs and LEDs (Ciacci et al. 2018). The type and amount of REOs required by FLs and LEDs vary among different technologies. FLs use a thin layer of trichromatic phosphors coating inside the glass tube, which converts ultraviolet lights to visible white light (Tan et al. 2015; Wu et al. 2014). For LEDs, a yellow phosphor is often used to convert blue LED light into white light, while other combinations are also in use (Wilburn 2012; Setlur 2009). The use of REOs in phosphors for lighting technologies accounted for 10% of total market demand and 18% economic value in the rare earth market in 2013 (Machacek et al. 2015).

Currently, supply security of rare earth elements (REEs) is uncertain. China dominates global REE mining, processing and refining, raising concerns on potential supply interruptions (Machacek et al. 2015; Wilburn 2012). The global shortage of REE supply and corresponding price hikes during 2009 to 2011, for example, was ignited by the Chinese restriction of REE export quotas (Tan et al. 2015; Massari and

Ruberti 2013; Mancheri 2015). The “balance problem” is another reason causing REE supply tensions; the elementary compositions of REEs found in natural deposits vary significantly, and they usually do not match with the proportion of REEs demanded by the market, causing surpluses of some REEs while shortages of others, which is reflected in the drastic disparity of their prices (Binnemans et al. 2013; Binnemans et al. 2018).

Recycling is considered as a strategy to mitigate the supply risk of critical materials, especially for the countries that depend heavily on imported resources (Binnemans et al. 2013). Recycling REOs from end-of-life (EoL) lighting technologies as a secondary supply requires the characterization of future REOs demand and EoL streams from lighting technologies. In the literature, few studies have traced the stock and flow of REOs from lighting technologies. Machacek et al. (2015) estimated the global demand and potential secondary supply of yttrium, europium and terbium in the lighting sector, focusing on the period from 2015 to 2020. Ciacci et al. (2018) analyzed the europium cycle and the potential for recycling focusing on 28 EU countries. Global scale prospective assessment on the recyclability of REOs from lighting technologies, however, has been lacking in the literature.

Economic feasibility plays a key role in understanding market-based recycling practice (Cucchiella et al. 2016). Industrial REOs recycling from EoL lighting technologies, for example, is scarcely practiced today as REOs recycling can hardly make any profit since the REO price collapse after 2013 (Ciacci et al. 2018); Solvay-Rhodia opened two industrial-scale facilities in France in 2011, which respectively focused on the upstream and downstream processes of REOs recovery from EoL fluorescent light bulbs (Machacek et al. 2015; Solvay 2014), but these two plants had to shut down in 2016 following the demand drop of rare earth in the lighting sector and the global REE price collapse (SudOuest.fr 2016). According to Innocenzi et al. (2016, 2017), recycling REOs from EoL FLs is not economically feasible under the 2016 REO market prices. Amato et al. (2019) also analyzed the profitability of a recycling plant that recovers rare earth elements from EoL fluid catalytic cracking catalysts (FCCC), fluorescent powders and permanent magnets. The result showed that the profitability indexes (defined as the division of net present value over capital investment) of recycling FCCC, fluorescent powder and permanent magnets are 1.26, 0.03 and 1.75, indicating extremely low profitability of the recycling operation of fluorescent powder. These studies, however, focused on the costs of recycling based on the current volume of EoL lighting technologies, which may be reduced in the future given the growing volume of EoL REOs and technology learning.

Our study aims to answer the following questions: First, what are the future trajectories of REO flows from EoL lighting technologies? Second, would the higher volume of REOs from EoL lighting technologies and associated learning enable profitable REOs recycling? If not, what would be the REO price floor needed for profitable recycling of REOs from efficient lighting technologies?

2. Methods and data

In this study, we conducted a dynamic material flow analysis to estimate the global trajectories of REOs demand and EoL flow from efficient lighting technologies (FLs and LEDs) for the time period of 1990 – 2050. Then, based on the volume of REOs EoL flow that are available for recycling, we incorporated the learning curve approach to estimate the possible change of REO recycling cost by considering the effect of economy of scale.

2.1 Dynamic Material flow analysis

Stock and flow model is widely used in the field of industrial ecology to quantify the accumulation, depletion, or flows of materials in a system (Melo 1999; Kleijn et al. 2000; Brunner and Rechberger 2004; D. B. Müller 2006; Hatayama et al. 2010; E. Müller et al. 2014; Heidari et al. 2018). It has been adopted to quantify industrial emission (Van der Voet et al. 2002), nanomaterial release (Song et al. 2017), waste streams (Elshkaki et al. 2005). In this study, we conducted a dynamic material flow analysis which incorporated the stock model to estimate the waste stream generation of REOs from the lighting sector between 1990 and 2050 based on the annual demands and lifetime distributions of different lighting technologies.

The global CFL and LFL demand data were collected from the IEA and US DOE reports (Waide 2010; Bauer et al. 2011), and data were presented in the appendix (Table A1 and A2) . Due to the limited time frames of the original data (CFL is 1990-2030, LFL is 2007 - 2025), projections were made based on the historical growth trends of these two types of lighting technologies to generate a homogeneous time frame from 1990 to 2050. We assumed that the LED technology started to penetrate general lighting market from 2010 by replacing the demand for FLs. CFL was replaced by LED bulbs, and LFL was replaced by linear LED lamps (Linear LED). Three scenarios were set up to represent different LED penetration speeds: low, medium and high. Under the three scenarios, LED started to penetrate general lighting market in 2010 by replacing FLs. The replacement rates increased linearly from 0% at 2010, and reached 100% by 2050, 2040, and 2030 respectively.

The lifetimes of different lighting technologies were collected, and each lighting technology was considered for both residential and non-residential (including outdoor, commercial and industrial) applications due to the different daily operational times in these two sectors. The average operational times for residential and non-residential lighting are about 2.3 and 11.2 hours/day respectively (Mandil 2006; Ashe et al. 2010). For CFLs and LEDs bulbs, we assume 70% of them are used in residential sector, and 30% of them are used in non-residential sector. For LFLs and linear LEDs, 20% of them are used in residential sector, and 80% of them are used in non-residential sector (McKinsey & Company 2012). The lifetimes by year of different lighting technologies within the two application sectors were calculated based on their respective lifetimes by hour and daily operational times (Table 1).

The Weibull distribution has been verified to have better analytical tractability and generate higher goodness-of-fit in estimating a product’s lifetime (Melo 1999; Walk

2009; Wang et al. 2013). Therefore, the two-parameter Weibull distribution was chosen to approximate the lifetime distributions of lighting technologies, and the probability density distribution function is shown as follows:

$$P(l)=\frac{\alpha}{\beta}\times ¿$$

α is the shape parameter, and β is the scale parameter. l is the product's lifetime by year. $P(l)$ quantifies the proportion of inflow that will be disposed at l_{th} year. The shape parameter α of different lighting technologies were collected from literatures, and scale parameter $\beta$of different lighting technologies were calculated based on the lifetime by year $l$using the following formula:

$$\beta=\frac{l}{\exp\left(\Gamma\left(1+\frac{1}{\alpha}\right)\right)}$$

Where Γ is a gamma function:

$$\Gamma(\alpha)=\int_{0}^{\infty} x^{\alpha-1}\times\exp(-x)\,dx$$

The shape and scale parameters of four types of lighting technologies are also presented in Table 1.

Table 1. Lifetime and Weibull distribution parameters for four lighting technologies

	CFL	LFL	LED bulb	Linear LED
Lifetime by hour (hr) [1]	8,000	10,000	15,000	20,000
Lifetime by year residential (yr)	10	12	18	24
Lifetime by year non-residential (yr)	2	3	4	5
Shape parameter (α) [2]	2.1	1.9	2	2
Scale parameter for residential (β)	11.3	13.5	20.3	27.1
Scale parameter for non-residential (β)	2.3	3.4	4.5	5.6

Note:

1. Waide (2010); UNEP (2017)
2. Heidari et al. (2018); Wang et al. (2013)

In the stock model, inflow represents the amount of new lighting technology that is installed for service at a given year. We assumed that the amount of new installed lighting technology each year was equal to the annual demand for that lighting technology. The outflow $O_a(n)$is the total amount of EoL lighting technology *a* that enters waste stream at n_{th} year, which is calculated by:

$$O_a(n)=\sum_{t=1}^{n-1} I_a(t)\times P_a(n-t)\, n>t$$

$I_a(t)$ is the inflow of lighting technology *a* that is installed in the t_{th} year. $P(n-t)$ is the stochastic Weibull distribution which determines the proportion of lighting technology *a* that is installed in the t_{th} year and has the lifetime of *n-t*. The EoL outflow $O_a(n)$ is the sum of the outflows of lighting technology *a* that were installed in previous years and reached the EoL at the n_{th} year.

Table 2. Phosphors and REO content of different efficient light technologies

	Phosphors (g/unit)	Y_2O_3 (g/unit)	Eu_2O_3 (g/unit)	Tb_4O_7 (g/unit)	CeO_2 (g/unit)	La_2O_3 (g/unit)
CFL [1]	1.3	0.61	0.04	0.05	0.19	0.08
LFL (T5) [1, 3]	2.4	0.75	0.05	0.06	0.08	0.25
LFL (T8) [1, 3]	5.8	1.79	0.12	0.13	0.18	0.59
LED bulb [2]	0.0100	0.0049	0.0004	NA	0.0013	NA
Linear LED [2,4]	0.1200	0.0588	0.0048	NA	0.0156	NA

Note:

1. Bauer et al. (2011)
2. Machacek et al. (2015), Lim et al. (2011)
3. The two types of LFL are differentiated based on the diameter: LFL (T5) has 5/8 inch diameter. LFL (T8) has 8/8 (1) inch diameter. The overall LFL is reported in the final result.
4. The average phosphors coating area of a linear LED was assumed to be 12 times of a LED bulb according to Castilloux (2014) therefore the phosphors and REOs contents of linear LED were estimated by multiplying the phosphors and REOs contents of LED bulb by a factor of 12.

The phosphors and REO contents in FLs and LEDs were collected from literatures (Table 2). The annual inflow and outflow of REOs in lighting sector were determined by multiplying the contents of REOs to the amount of lighting technologies:

$$I_{r,a}(n)=C_{r,a}\times I_a(t)$$

$$O_{r,a}(n) = C_{r,a}\times O_a(n)$$

$$I_r(t)=I_{r,a}(t)+I_{r,b}(t)+I_{r,c}(t)+\ldots$$

$$O_r(n) = O_{r,a}(n)+O_{r,b}(n)+O_{r,c}(n)+\ldots$$

$I_{r,a}(t)$ and $O_{r,a}(n)$are the inflow and outflow of REO *r* in lighting technology *a* at the year of *n*; $I_r(t)$ and $O_r(n)$are the inflow and outflow of REO *r* in all lighting technologies (*a, b, c …*) at the year of *n*;$C_{r,a}$ is the content of REO *r* in one unit of lighting technology *a*.

2.2 Learning curve

The unit cost of production has been found to decrease at a rate as the cumulative production increases for a wide range of manufacturing and service sectors, which is referred as the learning curve or “learning by doing” (Argote and Epple 1990)The learning effect can be characterized by a number of mechanisms, such as technology advancement, increased labor productivity, economy of scale and improved material and energy efficiency (Moore 1959; Jaber 2016; Bergesen and Suh 2016). The learning effect was first described by Theodore Wright, who found that the unit labor costs of airplane production declined as a power law function of cumulative production (Wright 1936), and it has also been widely observed in other industries, such as semiconductor (Gruber 1992; Irwin and Klenow 1994; Hatch and Mowery 1998) and energy (Kouvaritakis et al. 2000; McDonald and Schrattenholzer 2001) technologies. As for the electronic waste recycling, Zeng et al., found that technological learning significantly reduced the recycling cost for bulk and precious metals (Cu, Fe, Al, Pb and Au) in waste cathode-ray tube TV due to progressive automation of demanufacturing (Zeng et al. 2018). In this study, the learning curve empirical method was applied to estimate the possible cost reduction of the REO recycling process by considering the recycling scale. The learning curve function is shown as follows:

$$\frac{C_t}{C_1} = \left(\frac{X_t}{X_1}\right)^a$$

$C_t$is the recycling cost at time t; C_1 is the original recycling cost; X_t is the plant capacity at time t; X_1 is the original plant capacity; a is the scale factor.

Industrial scale REO recycling from the lighting sector has been conducted through hydrometallurgical processes including leaching, precipitation, filtration and calcination (Solvay 2014; Machacek et al. 2015; Beolchini et al. 2013). The data of capital and operative costs were collected from literatures for two types of recycling plants: mobile and fixed plant (Table 3). A mobile plant has limited capacity but better mobility, and it is considered a solution for small regions with limited volume of waste stream, while a field plant usually has a higher capacity and is able to manage higher volumes of waste (Cucchiella et al. 2016). The recycling cost is the sum of capital and operative costs. Given the data availability, the boundary of recycling process in this study starts from waste phosphor powders, and the end-product is saleable REOs mixture containing Y_2O_3, Eu_2O_3, Tb_4O_7, CeO_2 and La_2O_3. The cost of purchasing the phosphor powders ($1,000/t) is collected from literature and included in the operative cost calculation in this study (Machacek et al. 2015).

Table 3. Capacity and cost of recycling facilities.

Plant type	Capacity (t/yr) [3]	Capital cost ($/t) [4]	Operative cost ($/t)	Recycling cost ($/t)
Mobile [1]	93	1,972	5,460	7,432
	185	991	4,345	5,336
	277	662	3,971	4,633
	370	496	3,773	4,268
Field [2]	1200	168	2,675	2,842

Note:

1. Innocenzi et al. (2016, 2017). Recycling cost data of mobile plants in these references were collected in 2014 and originally presented as EURO per metric ton (€/t), and we converted

them into USD per metric ton ($/t) by the average 2014 rate of USD:EURO = 0.753:1 (www.macrotrends.net)

2. Strauss et al. (2016)
3. The unit of plant capacity is “metric ton of REO phosphor powders can be treated per year”.
4. Capital cost is reported by amortizing total capital cost over six (mobile plant) and seven (field plant) years.

2.3 Uncertainty analysis

The profit was calculated by subtracting recycling cost from revenue of selling recycled REOs to the market. The 2018 average REO market prices were collected for Y_2O_3, Eu_2O_3, Tb_4O_7, La_2O_3 and CeO_2, and they are $3.0/kg, $56.0/kg, $461.0/kg, $2.1/kg and $2.0/kg respectively (U.S. Geological Survey 2019). The revenue was calculated by multiplying the amount of recycled REOs to their respective market prices. The revenue was subjected to uncertainty caused by the recycling process efficiency rate, REO compositions in the end-product and a discount rate. The recycling process efficiency rate was defined as the ratio of the amount of recycled REOs mixture (end-product leaving the recycling process) to the amount of phosphor powders collected for recycling. The discount rate was defined as the depreciation of the market price of each REO given the end-product being REOs mixture (Innocenzi et al. 2016). Monte Carlo Simulation is a method that can be used to assess model uncertainty (Binder et al. 1993). In this study, 1000 iterations of Monte Carlo Simulation were conducted to estimate the range of revenue, and the 90% quartile range of revenue was reported. The model parameters are assumed to follow the triangular distribution, and their uncertainty ranges were reported in Table 4. A sensitivity analysis was also conducted to analyze the effect of different parameters on the revenue by selling the recycled REO mixture under 2018 market prices.

Table 4. Uncertainty ranges of recycling process efficiency rate, REO composition in the end-product and discount rate.

Recycling process efficiency rate (%) [1, 2]		12.1 – 32.3
REO compositions in the end-product (%) [1]	Y_2O_3	80.0 – 88.0
	Eu_2O_3	4.0 – 5.8
	Tb_4O_7	0.5 – 1.1
	CeO_2	0.4 – 1.3
	La_2O_3	0.01
Discount rate (%) [1, 2]		60 – 70

Note:

1. Innocenzi et al. (2016)
2. Strauss et al. (2016)

3. Results

3.1 Demand for lighting technologies

The result illustrates that demand for FLs experienced a significant increase from 1990 to 2010, but this increasing trend slowed down since 2010 and reached the peak at around 2014 given the LED penetration in the general lighting market (Figure. 1). The LED penetration speed showed significant effect on the demand for FLs. Under the low LED penetration scenario, total demand for FLs remains stable from 2015 to 2025, with a total amount being around 6,500 million units (CFL and LFL account for around 70% and 30% respectively). After 2025, the demand for FLs will rapidly decease. Under medium and high LED penetration, the demand for FLs at peak year of 2014 were about 6,700 and 6,200 million units respectively at the global level (CFL and LFL account for around 70% and 30% respectively). The total demand rapidly declined after the peak year of 2014.

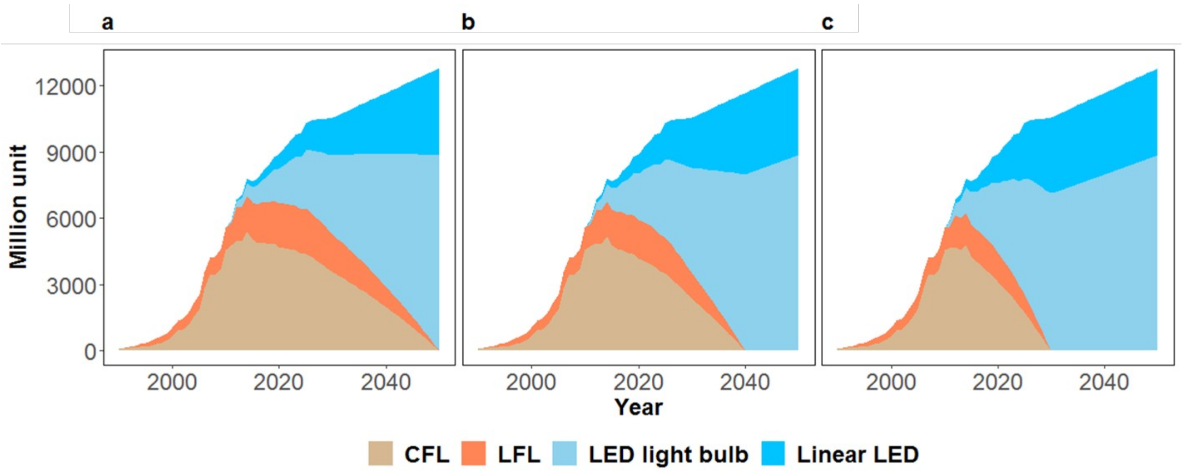

Figure 1. Demand for different lighting technologies under low (a), medium (b) and high (c) LED penetration scenarios

3.2 REO demand and waste stream

The demand for REOs in the lighting sector dramatically increased between 1990 and 2010 following the global adoption of FLs. Under the low LED penetration scenario, the increase in demand for REOs slowed down after 2010 when LEDs started to expand their market shares, and the peak year is at 2019, with the total amount of REOs being around 9,700 t/yr. Under the medium and high LED penetration scenarios, the peak REO demand from lighting technologies is at 2014, with the total amount being around 8,400 to 9,000 t/yr. After 2014, the REO demand rapidly declined under these two scenarios. REO flow from EoL lighting technologies is expected to follow a similar trend but with a few years of delay; the peak year is likely to be around 2020 to 2027 depending on the LED penetration speed, and the total amount of peak REO EoL flow will be around 9,300 t/yr, 8,200 t/yr, and 6,800 t/yr for low, medium, and high LED penetration scenario respectively. After the peak year, the amount of REOs from EoL lighting technologies is expected to exceed the amount of REOs required to meet the demand for lighting technologies. In other words, the annual secondary supply of REOs from lighting sector will be theoretically sufficient to satisfy its demand after the peak year if REOs can be recycled without loss (Figure 2). The estimated demand and waste of REOs from lighting sector between 2010 and 2050 can be found in Table A3.

We also estimated the contribution of different lighting technologies to total REO waste stream (Table A3). The result shows that FLs will be the dominant source of REO secondary supply in the lighting sector until 2030, with more than 95% of share in the waste stream under all the three LED penetration scenarios. After 2030, the contribution to total REO waste stream will vary depending on the LED penetration speed. Under the low LED penetration scenario, the FLs will still account for more than 90% of the REO waste stream until 2050, but under high LED penetration scenario, the LEDs will contribute 85% of the REO waste stream by 2050.

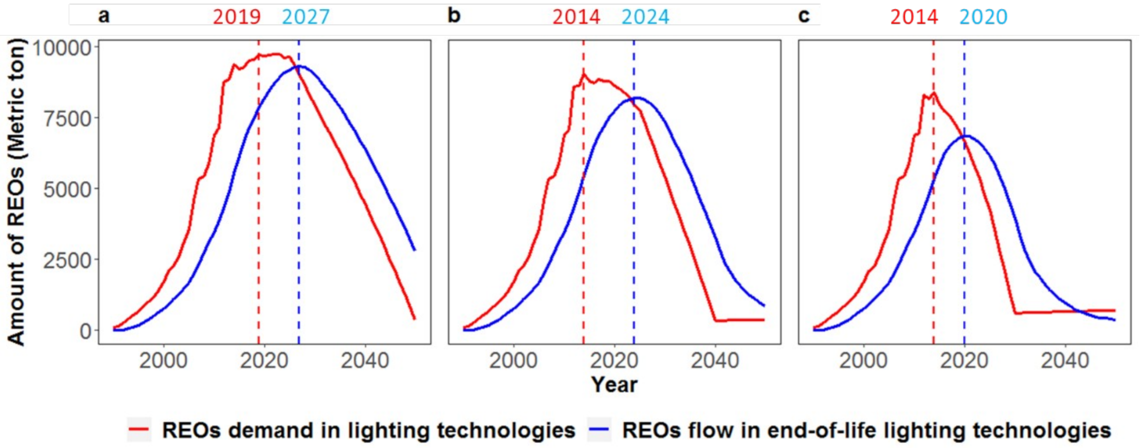

Figure 2. Total REO demand and waste stream in lighting sector under low (a), medium (b) and high (c) LED penetration scenarios (dash lines showing the year when REO demand in lighting technologies equals to REO flow in EoL lighting

technologies)

290

3.3 Recycling cost and profit analysis

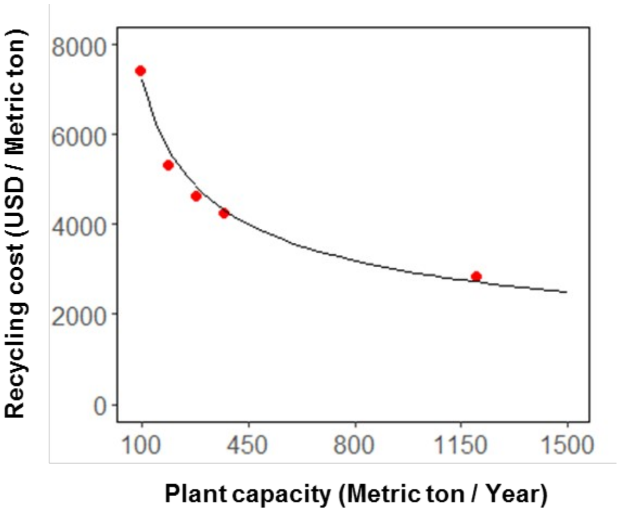

Figure 3. Recycling cost projection under different plant capacities (red dots represent the empirical data collected from literature, black line represents the estimated recycling cost projection).

The projected REO recycling cost from the lighting sector is presented in Figure 3. By inputting the plant capacity data and corresponding recycling cost data into a regression analysis, the scale factor *a* is estimated to be -0.39 for the REO recycling process considered in this study. Model result shows that, to recycle 1 metric ton of phosphor powders from EoL FLs, plant capacity increase can reduce the recycling cost from $7,223/t (plant capacity of 100 t/yr) to $2,496/t (plant capacity of 1,500 t/yr). The profit of REO recycling process was calculated by subtracting the cost from revenue based on the 2018 REO prices and three other break-even price scenarios that allow profitable recycling for three capacity levels (Figure 4). The results show that REO recycling is hardly profitable under the 2018 REO prices regardless of the plant capacity. The break-even REO prices that lead to profitable recycling varies depending on the plant capacity. The break-even REO prices at 100, 800 and 1,500 t/yr of capacities, were 6.3, 2.8 and 2.2 times that of 2018 REO prices, respectively.

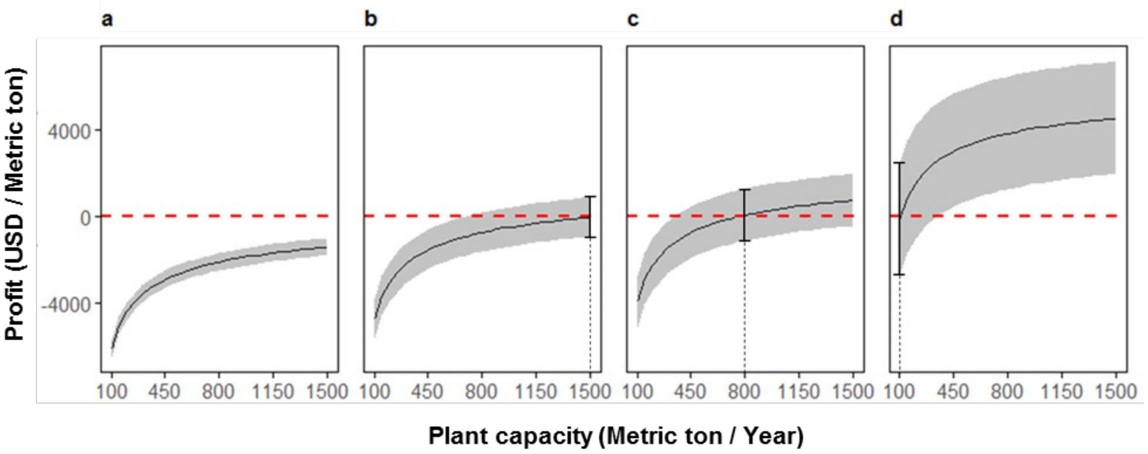

Figure 4. Profitability of REOs recycling process with different plant capacities under 2018 REO prices level (a) and three other break-even prices of plant scale at 1,500 (b), 800 (c) and 100 t/yr (d).

The sensitivity analysis shows that by selling the amount of REO mixture recycled from 1 metric ton of phosphors powder under 2018 REO market prices, the baseline revenue is $1,294. The recycling process efficiency rate has the highest impact on revenue, because it can change the baseline revenue by ±45%. The Tb_4O_7 composition can change the baseline revenue by ±15.4%, which has the most significant impact on the revenue among the five REOs (Figure. 5).

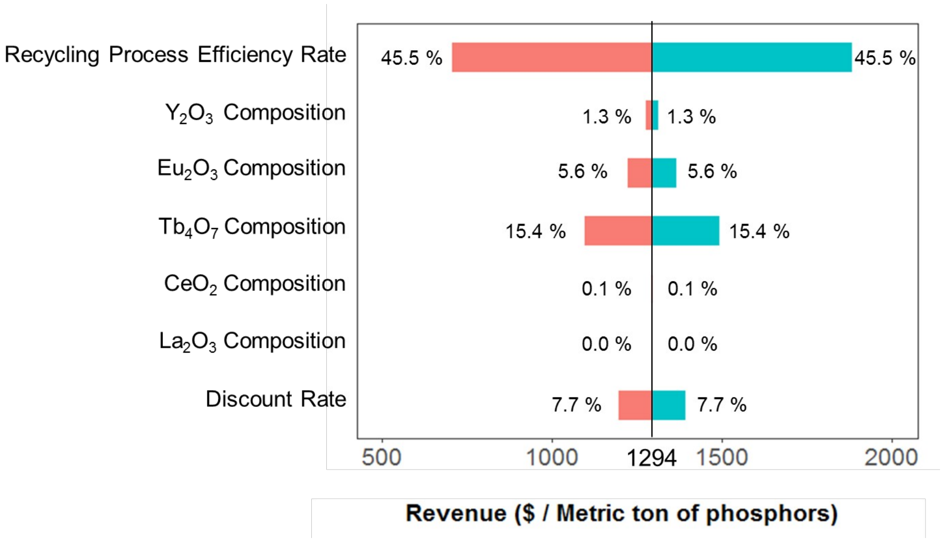

Figure 5. Sensitivity analysis on the effects of different parameters on the revenue of selling the recycled REO mixture under 2018 market prices.

4. Discussion

The result of this study shows that the demand for REOs in the lighting sector has reached the peak at around 2014 to 2019 depending on different LED penetration scenarios. Among the five rare earth elements we analyzed, yttrium, europium and terbium have been considered critical materials by both the US and European Union due to their importance for clean energy and relatively high supply risk (Bauer et al. 2011; EU Commission 2014). As the demand for REOs in the lighting sector will experience decline after the peak year, the criticality of these REOs is likely to decrease in the near future. On the other hand, the amount of REOs from EoL lighting technologies will increase for the next one to eight years, allowing potentially increasing volume of secondary supply of REOs if recycling becomes economically feasible. Exploiting the secondary supply of REOs from EoL lamps through recycling could also counter the supply security concerns over these critical natural resources.

The changes in the market share of lighting technologies and the overall demand for REOs are expected to affect the future supply and demand structure of Y_2O_3, Eu_2O_3, Tb_4O_7, of which 53.7%, 100% and 88.7% have been used for the phosphors manufacturing (Nassar et al. 2015). For instance, Eu_2O_3 is currently used exclusively for phosphors. As FLs are replaced by LEDs in the future, it is expected that the overall demand for Eu_2O_3 will decrease, and so will its criticality and market price. A potential oversupply of europium is also likely to occur as its demand starts to decline after the peak year, therefore recycling will not be a favorable option for Eu_2O_3 (Ciacci et al. 2018; Rollat et al. 2016). However, yttrium and terbium have relatively diverse applications. Currently, 34% of yttrium is used as additives in ceramics and glass, and 11% of terbium is added to the NdFeB magnets as a substitute for dysprosium. As the lighting sector uses less Y_2O_3 and Tb_4O_7, their supply can be possibly absorbed by other applications. For example, terbium is reported to have a better effect in improving the temperature resistance of NdFeB compared to dysprosium, and an increasing amount of this material could be applied in magnets as its future demand in lamp phosphors decreases. Therefore, recycling could become feasible at a meaningful scale for these two types of REOs if demands for other sectors expand (Binnemans et al. 2018).

A lack of economic feasibility, however, still is a major challenge in achieving the circularity of REOs. Although our results indicate that the increase of plant capacity has a potential to reduce cost, recycling of REOs is not profitable given the low REO prices at the moment regardless of the plant capacity. As for a recycling plant at 1,500 t/yr of capacity, the REO prices need to increase by a factor of 2.2 in order to cover the cost of recycling, and for the mobile plant, which usually has smaller capacity, the REO prices need to increase even more to break even. When studying the same REO recycling operation based on mobile plant with the capacity of 184.0 t/yr, Innocenzi et al. (2016) found that the recycling process could be profitable if the final REO mixture could be sold at 15.0 €/kg, which was about 2.8 times of the value of the recycled REO mixture (5.4 €/kg) reported in that study. Using the technology learning curve model, we also estimated that, for a plant with the capacity of 184 t/yr, the break-even REO prices for profitable recycling is 4.0 times that of 2018 REO prices. This value is higher than 2.8, and the reason can be that the REO market prices have been further decreased after 2016, therefore the 2018 REO prices need to increase even more to break even. The sensitivity analysis shows that the recycling process efficiency rate and the Tb_4O_7 composition in the end-product (REO mixture) have the major effects on the revenue. Therefore, technologies that can further increase these two parameters will significantly improve the economic feasibility of the recycling operation.

In the future, it is unclear whether the REO prices would increase sufficiently high enough for the market to recycle REOs on its own, therefore, we suggest that the government can also play a critical role to improve the recycling of REOs from EoL lighting technologies. Currently, the few FLs being recycled have been relying on the extended producer responsibility (EPR) policy, under which government places the responsibility for treatment and disposal of post-consumer products on the manufacturers (Machacek et al. 2015; OECD 2001). Under the EPR, the government either allows manufacturers to charge customers recycling fees at the time of purchase and fund the recycling process (Asari et al. 2008), or levies advanced recycling fees from manufacturers and uses it to subsidize the third-party recycling facility (Fan et al. 2005). However, the current EPR policy aims to manage mercury, not REOs (Peng et al. 2014). Therefore, should REOs recycling be a policy objective, current EPR policy can be expanded to bear the cost of REOs recycling. Besides, Machacek et al (2017) also mentioned that the recyclers usually make the decision on recycling or landfilling the waste lamp phosphors depending on the cost comparison between these management approaches, therefore, increasing the cost or restricting the policy regulation of landfilling the waste lamp phosphors could be another option to improve the REO recycling.

Additionally, our study shows that more than 95% of the potential secondary supply of REOs will be available through EoL FLs before 2030, so we highlight the importance of increasing the collection rate of EoL FLs, which is necessary to enable the economy of scale in REOs recycling. High collection rates of FLs have been observed in only limited countries and regions, such as the EU countries with the average collection rate of FLs being 40%, and Taiwan with a collection rate over 80% (Silveira and Chang 2011), mainly thanks to the mandatory EPR legislation. Other than that, the convenient collection system, developed recycling technology, and other infrastructures that allow adequate rule enforcement, effective information provision, stable financial management are also important factors for the high collection rates in these countries (Richter and Koppejan 2016). However, in other major consumers of the world, such as China, US, Japan and Australia, the EoL FLs collection rates are generally below 15% (Machacek et al. 2015). Therefore, it is necessary to further investigate how to improve the lamp collection rates in these countries.

The comprehensive recycling operation by Solvay-Rhodia started from the dissembling of the waste light bulb, and ended with separated REEs (Solvay 2014). However, due to the data availability, the recycling operation we considered in this research started from collected waste phosphors powder, with the end-product being REO mixture. Therefore, we applied the discount rate to account for the depreciation of the market price of each REO given the end-product being REO mixture. We recommend that future study focus on the economic feasibility analysis of a comprehensive recycling operation for individual REE, for example terbium, which has much higher economic value and can be used in other technologies. This type of research will better inform the recyclers with their decision-making on recycling the REEs.

Although economic feasibility is an important factor in determine the recyclability of REOs, Machacek et al. (2015) also discussed the externalities related to the REO recycling operation (avoided environmental and health impact, creation of jobs opportunities, R&D and innovation, and broader social value), which need to be considered comprehensively when making decision on establishing the recycling facilities. Therefore, future research that studies these externalities will also provide valuable information.

5. Conclusion

In this study, we present a dynamic material flow analysis of REOs in lighting technologies from 1990 to 2050. The result shows, as LEDs penetrate the market, the demand for REOs in the lighting technologies reached the peak at around 2014 to 2019 depending on the LED penetration speed. The amount of REOs available from EoL lamps is expected to increase for the next one to eight years with the peak year at around 2020 to 2027, allowing recycling operations to take advantage of the economy of scale. Increasing recycling plant capacity can reduce cost from about $7,200/t REO phosphors at 100 t/yr capacity to about $2,500/t REO phosphors at 1,500 t/yr capacity, we find that the rate to which the cost of recycling is reduced may not be sufficient to break even under the 2018 REO market prices, irrespective of the scale of recycling operation. Significant improvement of REO recycling rate in lighting technologies would therefore require substantially higher REO prices, policy support, and improvement of recycling technology.

Declarations of interest: none

Acknowledgement

We would like to acknowledge the financial support from the US Environmental Protection Agency via Science to Achieve Results Program Grant No. 83557907. We also acknowledge the UCSB Mellichamp Sustainability Fellowship for the financial aid. We thank Runsheng Song for his help in creating the material flow analysis model in this study.

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Appendix

Table A1. The data of CFL demand from 1990 to 2030

Year	CFL (million unit)	Year	CFL (million unit)	Year	CFL (million unit)
1990	91.8	**2004**	1539.2	**2018**	6035.8
1991	116.4	**2005**	1897.6	**2019**	6263.7
1992	133.8	**2006**	2812.0	**2020**	6275.7
1993	155.2	**2007**	3450.4	**2021**	6443.1
1994	176.5	**2008**	3412.2	**2022**	6583.9
1995	204.3	**2009**	3702.7	**2023**	6750.4
1996	236.0	**2010**	4584.2	**2024**	6726.2
1997	309.7	**2011**	4891.6	**2025**	7007.4
1998	362.7	**2012**	5214.4	**2026**	7101.7
1999	479.1	**2013**	5370.8	**2027**	7122.5
2000	685.3	**2014**	5992.3	**2028**	7126.5
2001	941.3	**2015**	5752.6	**2029**	7127.8
2002	970.9	**2016**	5743.5	**2030**	7131.8
2003	1202.6	**2017**	5934.3		

Data source: Waide (2010)

Table A2. The data of LFL demand from 2007 to 2025

Year	LFL-T5 (million unit)	LFL-T8 (million unit)
2007	129.1	656.7
2008	148.0	694.7
2009	170.8	740.2
2010	189.8	782.0
2011	224.0	820.0
20	235.4	1375.1

12		
2013	254.3	1437.4
2014	280.9	1518.8
2015	292.3	1627.4
2016	326.5	1748.3
2017	345.4	1892.6
2018	360.6	1997.5
2019	383.4	2112.3
2020	406.2	2220.9
2021	425.2	2331.1
2022	440.3	2452.0
2023	455.5	2574.3
2024	470.7	2687.5
2025	493.5	2801.5

Data source: Bauer et al. (2011)

Table A3. REOs demand and waste from lighting sector and the contribution of different lighting technologies to total REOs waste

Year	Y_2O_3 (t/yr)		Eu_2O_3 (t/yr)		Tb_4O_7 (t/yr)		CeO_2 (t/yr)		La_2O_3 (t/yr)		Total REOs (t/yr)		Contribution to total REOs waste stream (%)	
	Demand	Waste	Demand	Waste	Demand	Waste	Demand	Waste	Demand	Waste	Demand	Waste	FLs	LEDs
Low LED penetration														
2010	4,358	2,188	288	145	326	163	1,035	449	862	501	6,869	3,445	100.0%	0.0%
2020	6,148	5,202	408	345	456	388	1,240	1,064	1,419	1,191	9,670	8,188	99.8%	0.2%
2030	5,061	5,743	337	381	369	424	944	1,157	1,180	1,322	7,941	9,028	99.0%	1.0%
2040	2,855	4,071	192	271	199	295	579	844	626	901	4,451	6,382	97.3%	2.7%
2050	276	1,801	23	122	0	120	773	408	0	341	372	2,792	90.4%	9.6%
Medium LED penetration														
2010	4,358	2,188	288	145	326	163	1,035	449	862	501	6,869	3,445	100.0%	0.0%
2020	5,486	4,916	364	326	405	366	1,108	1,012	1,261	1,118	8,624	7,738	99.7%	0.3%
2030	3,453	4,670	231	310	246	342	684	962	786	1,050	5,400	7,334	98.4%	1.6%
2040	256	2,103	21	142	0	144	68	473	0	412	345	3,275	93.0%	7.0%
2050	276	574	23	42	0	26	73	141	0	69	372	852	63.3%	36.7%
High LED penetration														
2010	4,358	2,188	288	145	326	163	1,035	449	862	501	6,869	3,445	100.0%	0.0%
2020	4,296	4,346	277	288	304	323	819	908	946	974	6,641	6,838	99.4%	0.6%

2030	589	2,523	19	169	0	179	1	570	0	504	609	3,946	95.5%	4.5%
2040	637	643	21	46	0	33	1	159	0	85	658	965	71.1%	28.9%
2050	684	279	23	22	0	3	1	71	0	10	708	384	15.5%	84.5%