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Economic Feasibility of Recycling Rare Earth Oxides from End-of-Life Lighting Technologies

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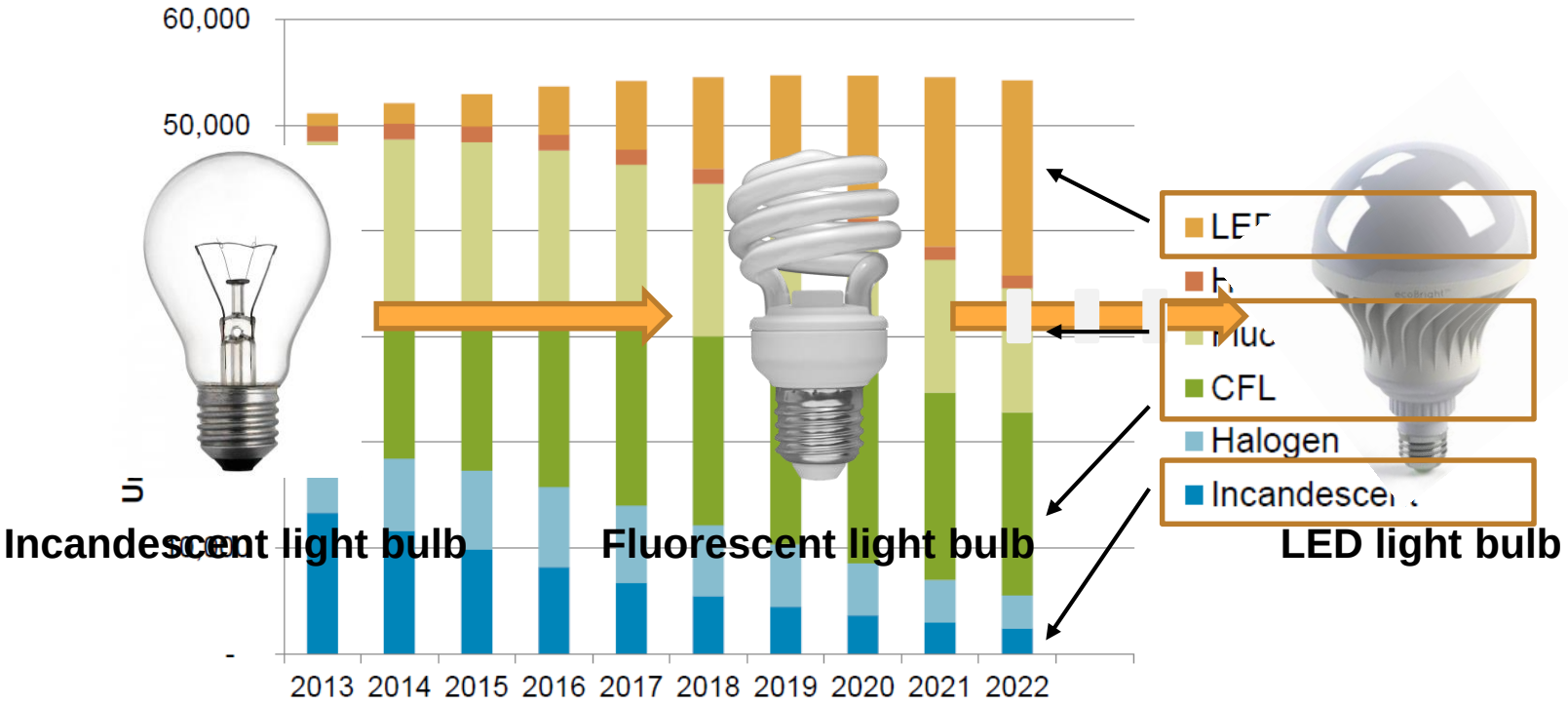
Lighting Technology Transition



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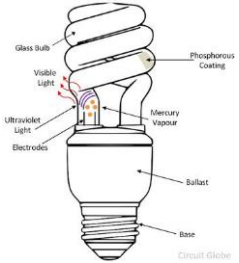
(US DOE 2015)

Rare Earth Phosphors

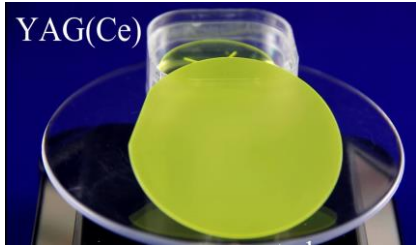


Fluorescent light bulb

Trichromatic Phosphors

39	63	65	58	57
Y	Eu	Tb	Ce	La
88.90584	151.964	158.92535	140.116	138.90547
Yttrium	Europium	Terbium	Cerium	Lanthanum

LED light bulb

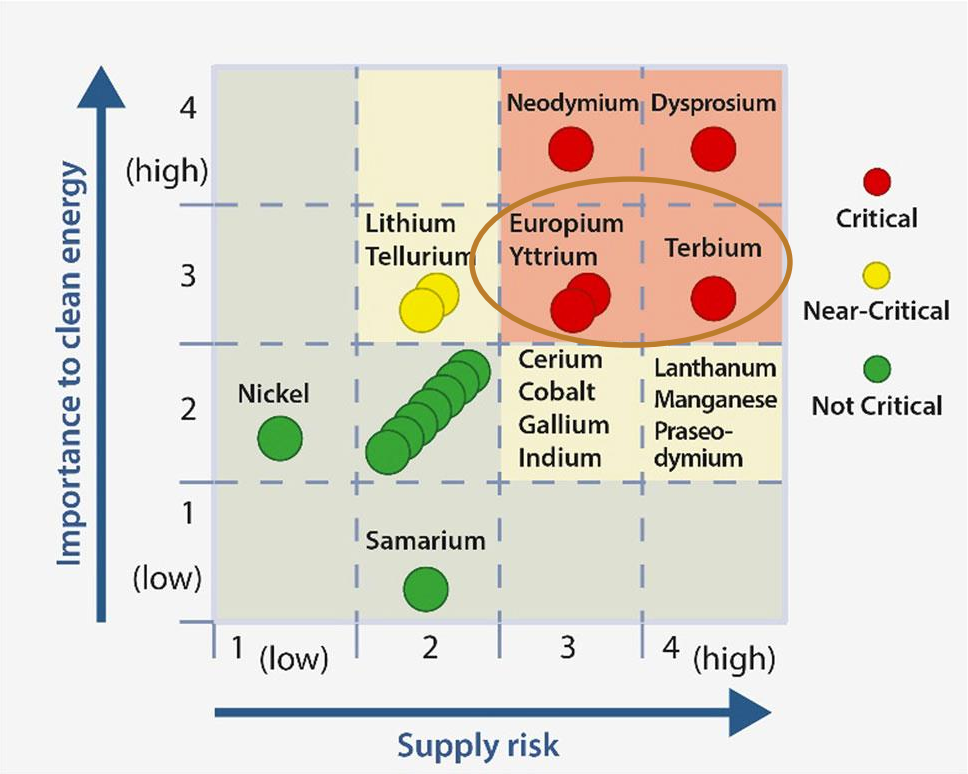


Yellow Phosphor

39	63	58
Y	Eu	Ce
88.90584	151.964	140.116
Yttrium	Europium	Cerium

(Tan et al. 2015, Scholand et al. 2012)

Rare Earth Phosphors



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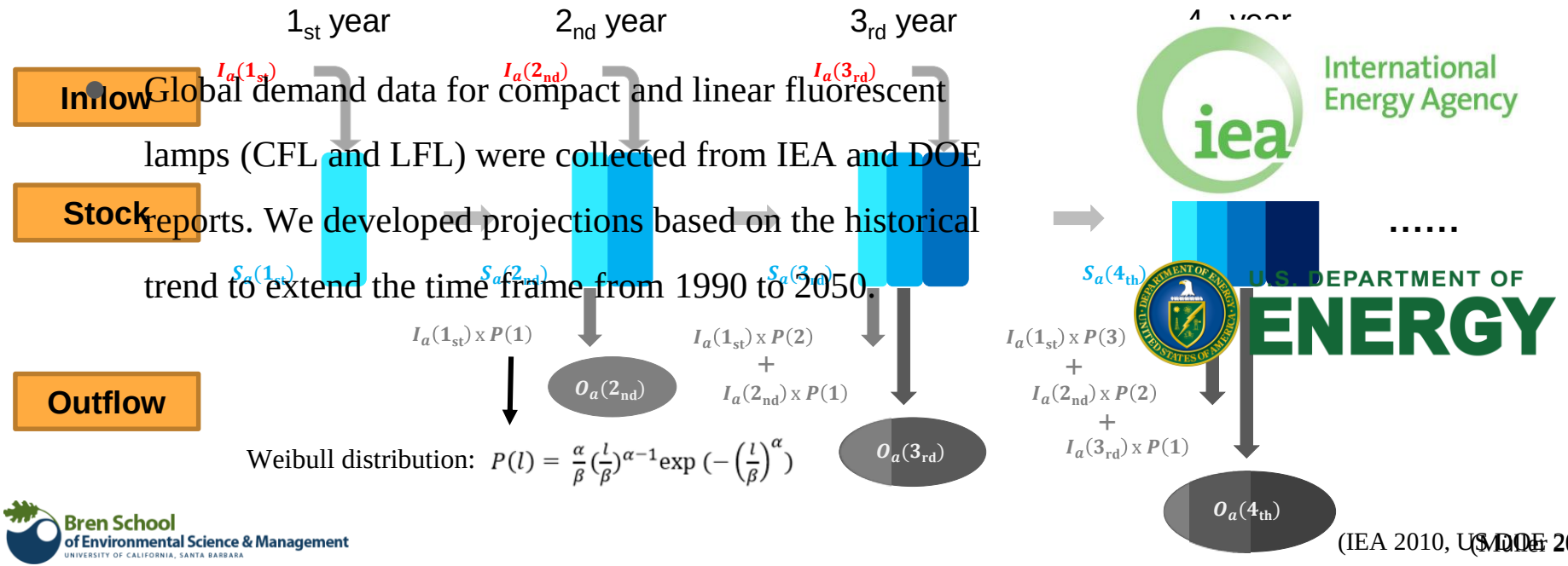
(US DOE 2014)

Can we recycle rare earth elements to alleviate their supply risk?

- How much rare earth oxides will be available for recycling from end-of-life lighting technologies?
- Is the recycling operation economically feasible?

Methods and Data

- **Dynamic material flow analysis** -- estimate the global trajectories of REOs from EoL lighting technologies from 1990 to 2050;



- Global demand data for compact and linear fluorescent lamps (CFL and LFL) were collected from IEA and DOE reports. We developed projections based on the historical trend to extend the time frame from 1990 to 2050.

(IEA 2010, USDOE 2014)

Methods and Data

- **Learning curve approach** -- study the economic feasibility of REOs recycling operation by considering the economy of scale;

Economy of scale

- Recycling cost data at various plant capacities were collected from literatures to calculate the scale factor a;

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

X_1 and X_t are two different plant capacities;

C_{X_1} is the recycling cost of plant with capacity X_1;

C_{X_t} is the recycling cost of plant with capacity X_t;

a is the scale factor.

- Hydro-metallurgic recycling operation was considered in this study, with the end product being rare earth oxides mixture.

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(Argote et al. 1990, Wang et al. 2014)

Result – Global Demand Trajectories of Efficient Lighting Technologies

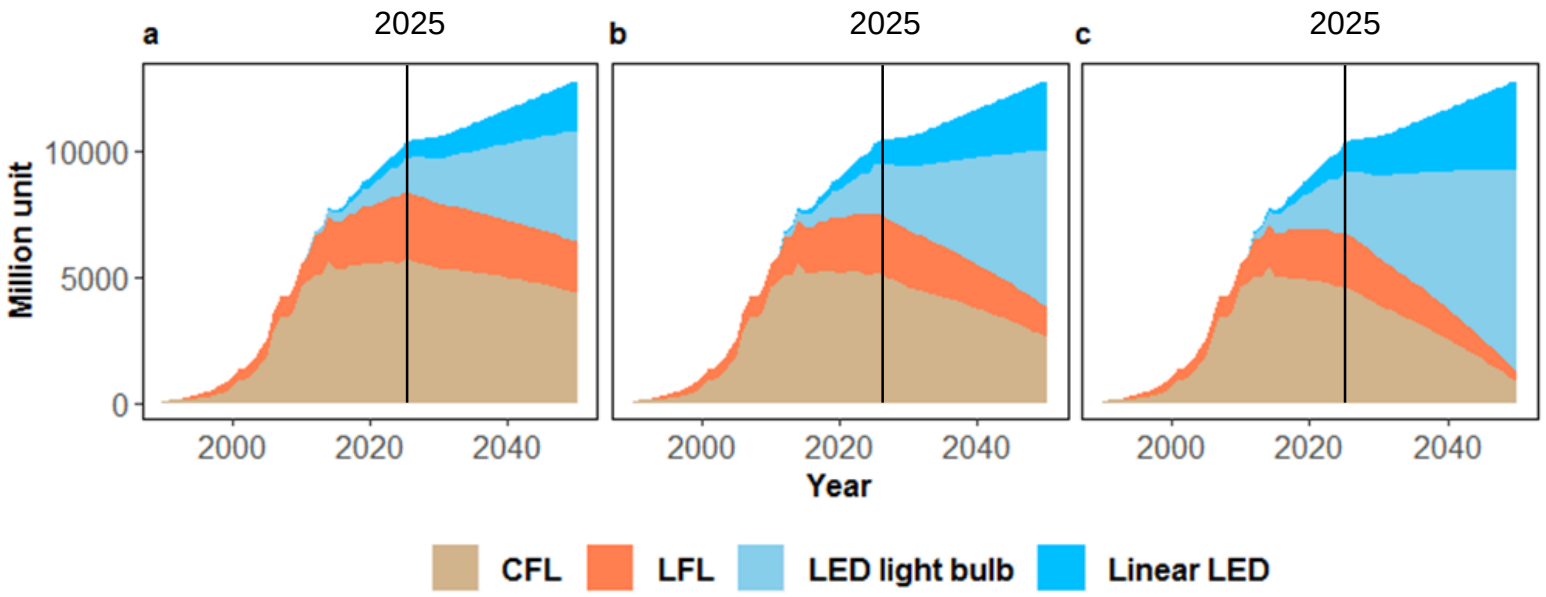

Figure 1. Demand for different lighting technologies under low (a), medium (b) and high (c) LED penetration scenarios

Result – Global Trajectories of Demand and EoL Flow of REOs

- **REOs demand** from the lighting sectors will continue to increase and reach the peak at around 2025;
- **EoL flow of REOs** from lighting technologies will increase and reach the peak at around 2030.

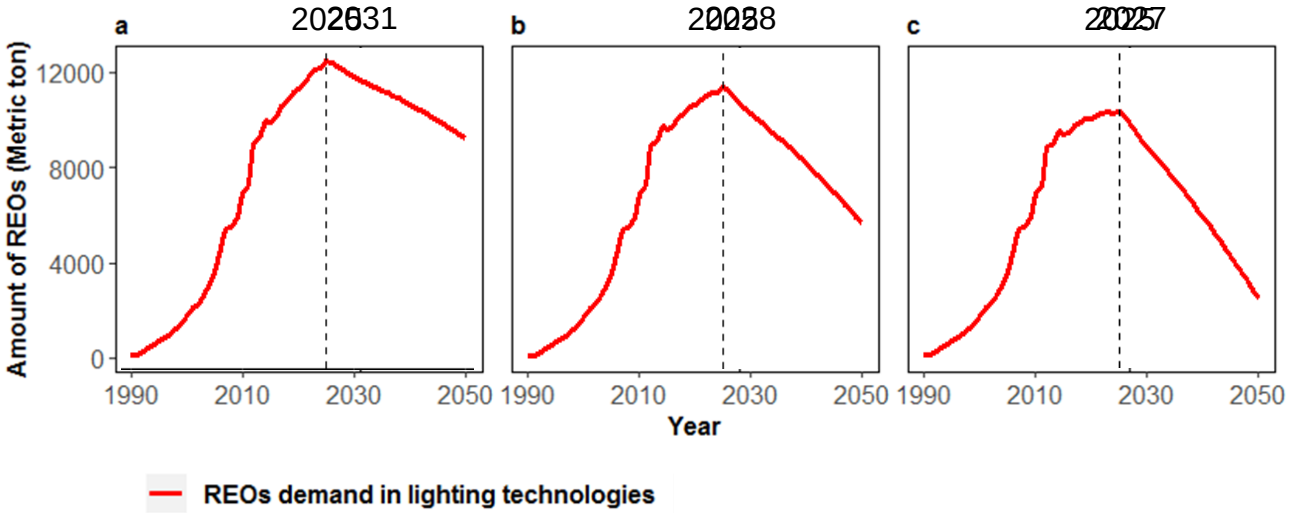

Figure 2. Total REOs demand and waste stream in lighting sector under low (a), medium (b) and high (c) LED penetration scenarios.

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Result – REO Recycling Cost Projection

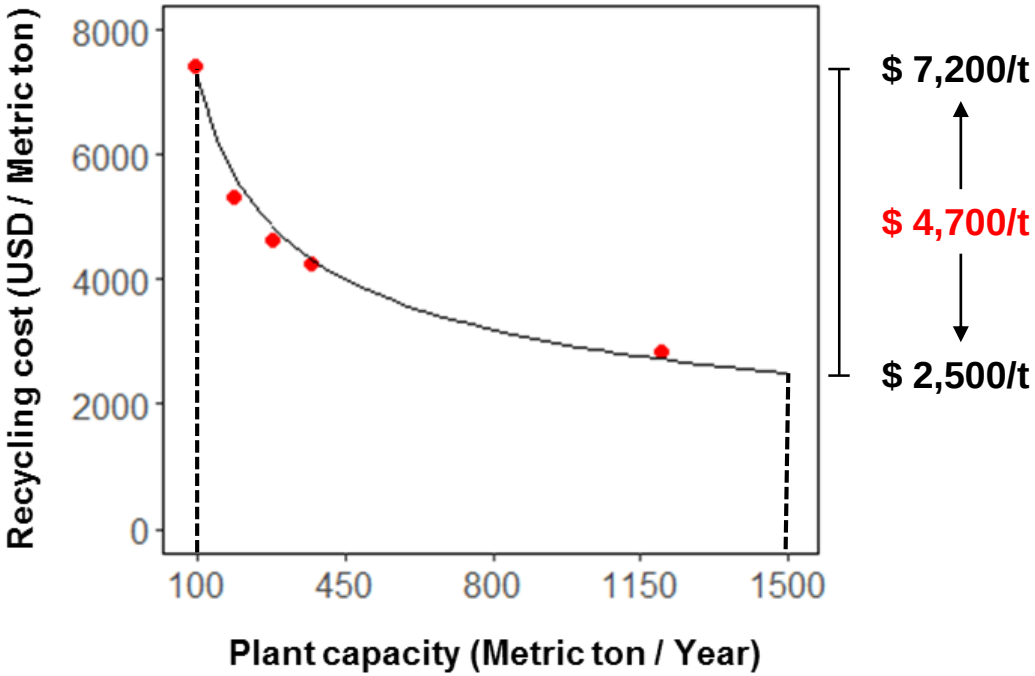

Figure 3. Recycling cost projection under different plant capacities.

Result – Profitability of REO Recycling Operation

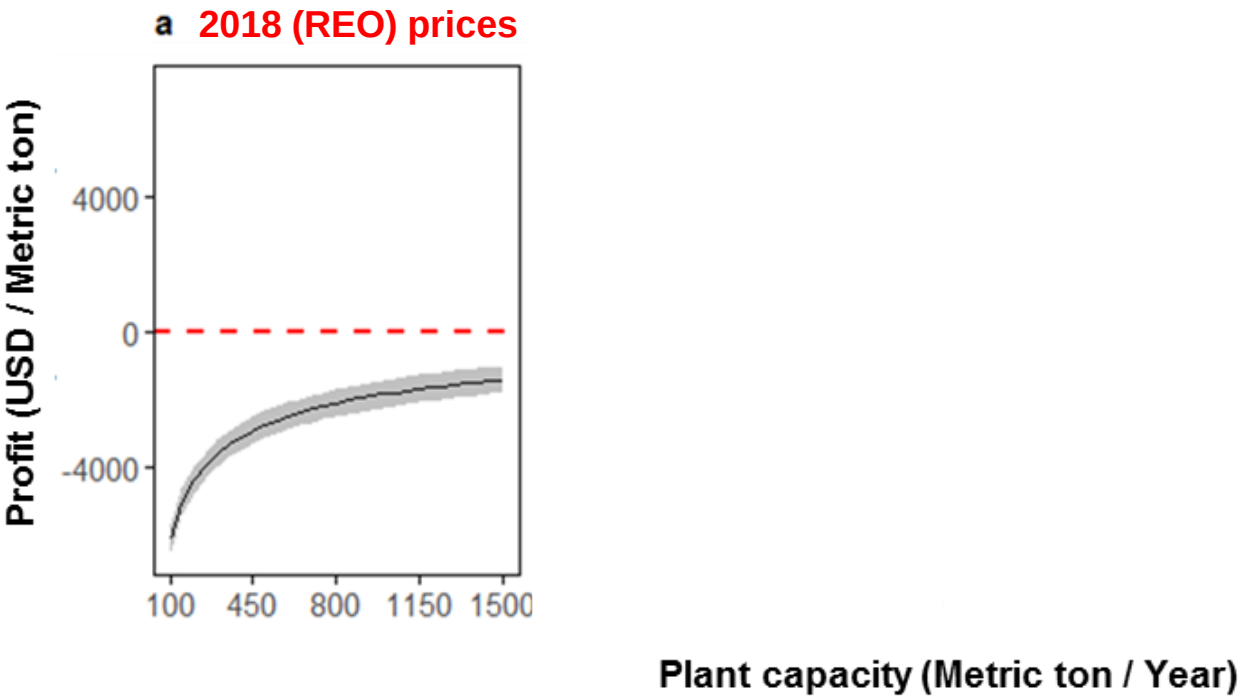

Figure 4. Profitability of REOs recycling process with different plant capacities under 2018 REO prices level (a) and three other break-even prices of plant scale at 1,500 (b), 800 (c) and 100 t/yr (d).

Conclusions

1. There will be a growing volume of REOs from EoL lighting technologies that are available for recycling in the next about ten years.

2. Increasing the plant capacity can significantly reduce the cost of REOs recycling operation, however, under the 2018 REO market prices, the recycling process is not economically feasible, irrespective of plant capacity.

3. Substantially higher REO prices and incentive policy that bears the REO recycling cost would be need to improve the REOs recycling rate.

Acknowledgement

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CHEMICAL LiFE CYCLE COLLABORATIVE

Mellichamp Academic Initiative in Sustainability
Sustainable Materials and Product Design

Supplement Information

Table S26. Estimated 2008 global end-uses of rare earth oxides (as percentage of total for each REO)

End-use	Y_2O_3	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	Other
Catalytic converters		1.0	16.2	1.7	1.0						
Ceramics	32.0	3.1	2.0	4.8	3.5						
Fluid catalytic cracking		46.0	4.7								
Glass additives	2.1	7.5	18.8	1.4	1.5						86.5
Metallurgy, excluding batteries		7.7	14.2	7.2	8.0						
Neodymium magnets				70.3	76.3			68.9	11.3	100.0	
Battery alloys		15.7	9.6	4.6	5.1	72.7					
Phosphors	53.7	2.0	2.3				100	21.3	88.7		
Glass polishing		13.4	25.3	6.6							
Other	12.3	3.7	6.9	3.4	4.7	27.3		9.8			13.5
Total	100	100	100	100	100	100	100	100	100	100	100

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(Nassar et al. 2015)

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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)

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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.

Supplement Information

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.

Supplement Information

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)

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Year	Contribution to total REOs waste stream (%)		Year	Contribution to total REOs waste stream (%)		Year	Contribution to total REOs waste stream (%)	
	FLs	LEDs		FLs	LEDs		FLs	LEDs
	Low LED penetration			Medium LED penetration			High LED penetration	
2010	100.0%	0.0%	2010	100.0%	0.0%	2010	100.0%	0.0%
2020	99.9%	0.1%	2020	99.9%	0.1%	2020	99.9%	0.1%
2030	99.7%	0.3%	2030	99.6%	0.4%	2030	99.4%	0.6%
2040	99.5%	0.5%	2040	99.1%	0.9%	2040	98.6%	1.4%
2050	99.1%	0.9%	2050	98.2%	1.8%	2050	96.2%	3.8%

Low collection rate of fluorescent lamp at global level.

- EU countries (40%), Taiwan (80%)
- China, US, Japan and Australia (< 15%)

(Silveira et al. 2011)

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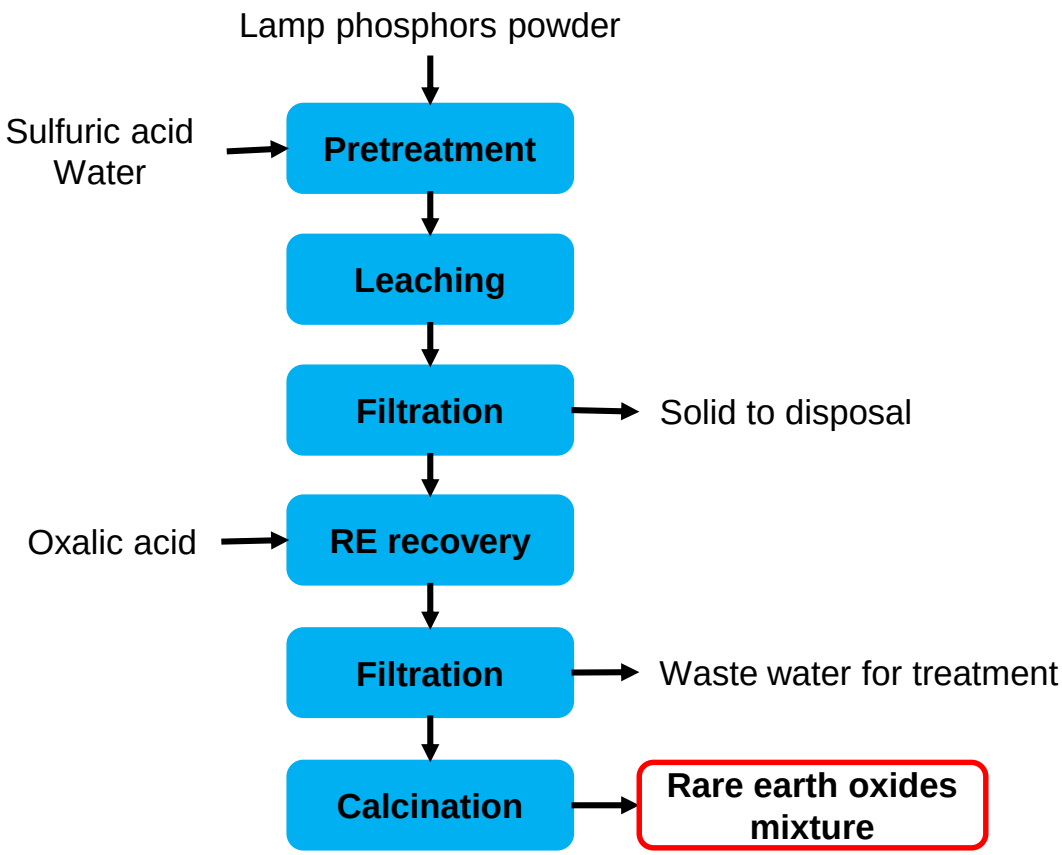

(Innocenzi et al. 2016 & 2017)

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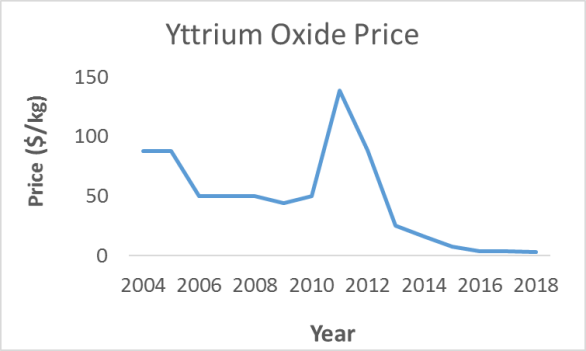

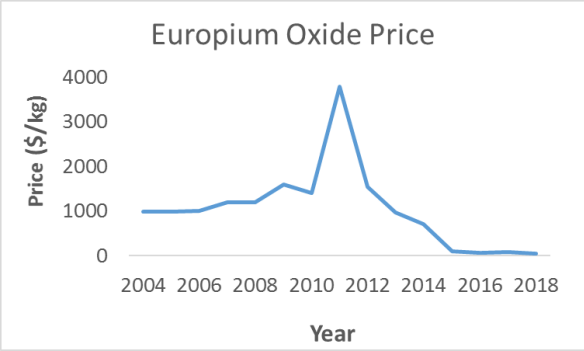

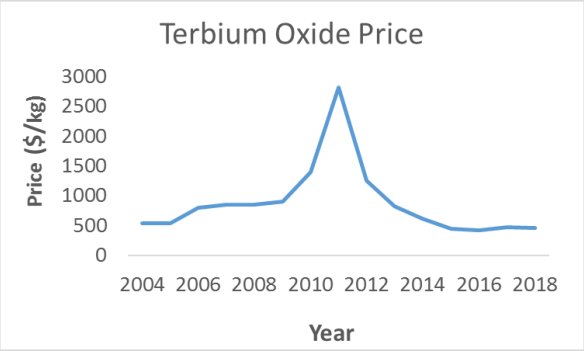

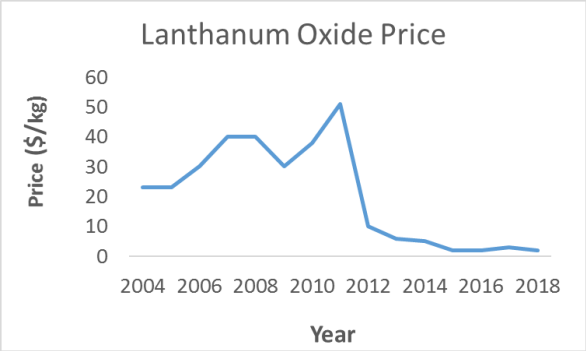

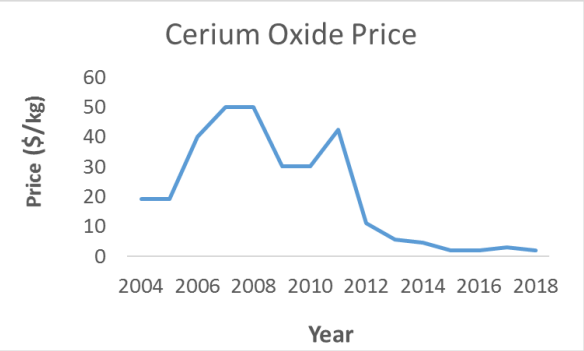

(US Geological Survey)

Supplement Information

Incandescent Lamp

Compact Fluorescent Lamp (CFL)

LED Lamp

Linear Fluorescent Lamp (LFL)

Linear LED Lamp

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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
2012	235.4	1375.1
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)