Modelling the production and recycling of rare earth elements in consequential LCA

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Presentation Outline

- Introduction
- Methods
  - Current methodology
  - Drawbacks current methodology
  - Proposal new method
- Application to Rare Earth Elements
- Conclusion

Introduction

Rare Earth Elements in periodic table

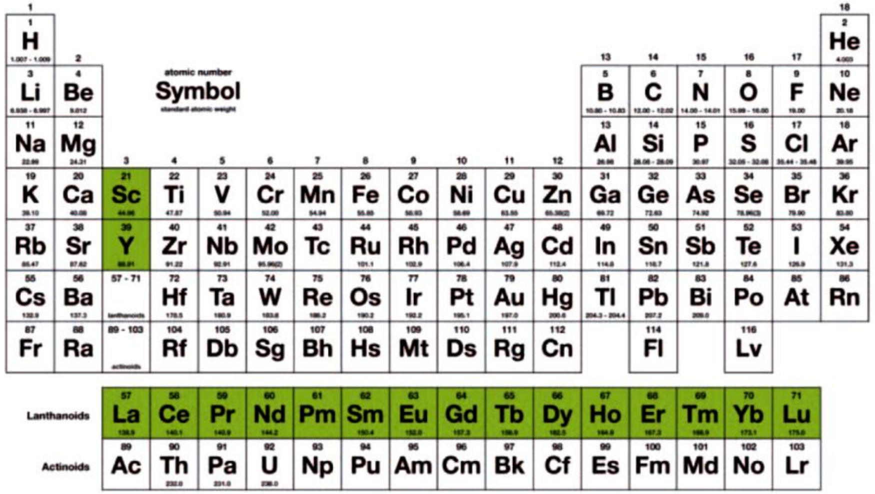
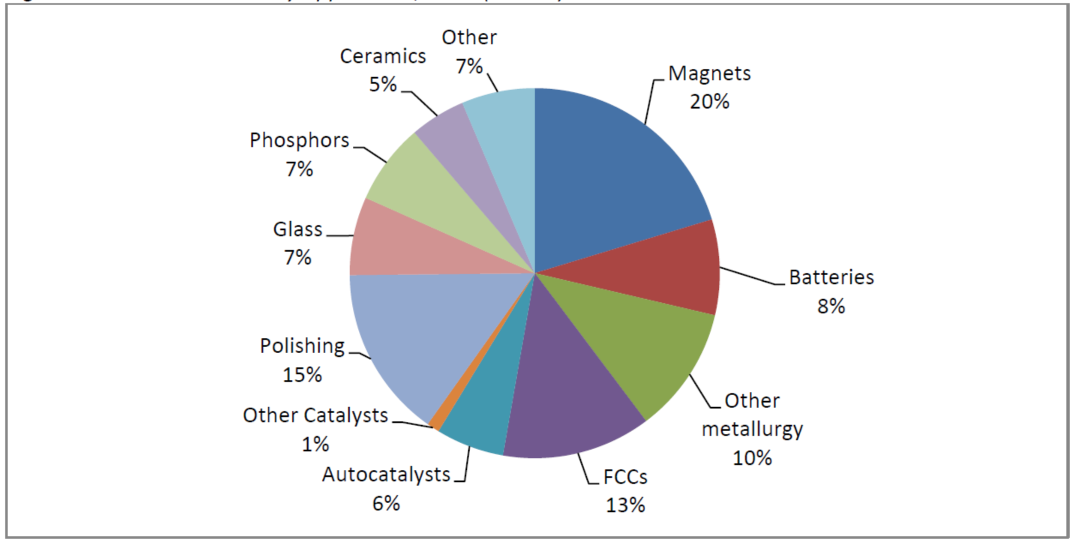


Figure 153: Rare earth use by application, 2012 (tonnes)



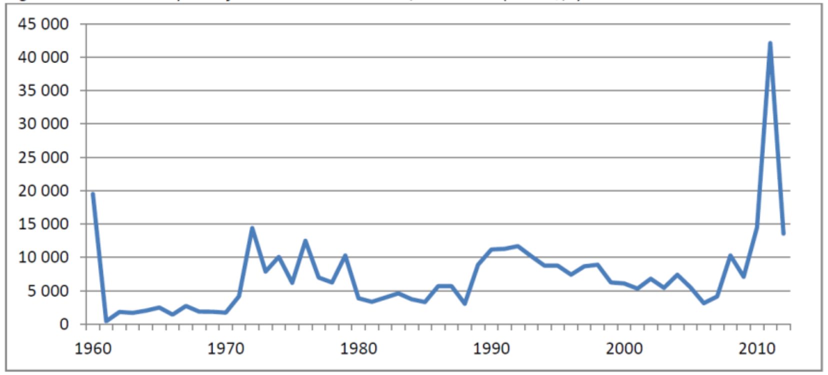
Source: Roskill Information Services / Dudley Kingsnorth, IMCOA (March 2013)

Table 43: World reserves of rare earth elements

Country	Mine production (in tonnes, 2012)		Reserves (in tonnes, 2012)	
China	95,000	86.8%	55,000,000	48.3%
United States	7,000	6.4%	13,000,000	11.4%
Australia	4,000	3.7%	1,600,000	1.4%
India	2,800	2.6%	3,100,000	2.7%
Malaysia	350	0.3%	30,000	0.0%
Brazil	300	0.3%	36,000	0.0%
Other countries	NA	—	41,000,000	36.0%
World total	**110,000**		**110,000,000**	

Source: US Geological Survey (2013), Mineral Commodity Summaries

Figure 152: Historical prices for rare earth elements, unit value (98 US$/t)



Source: USGS (2012), Metal Prices in the United States Through 2010

ERECON. (2014). STRENGTHENING THE EUROPEAN RARE EARTHS SUPPLY-CHAIN Challenges and policy options, 102.

European Commission. (2014b). *Report on Critical Raw Materials for the EU - Critical Raw Materials Profiles*.

Introduction

- Critical materials for low-carbon energy technologies (EC 2014)
  - Needed in supply chain
  - Market and geopolitical parameters
    - Praseodymium
    - Neodymium
    - Europium
    - Terbium
    - Dysprosium
    - Yttrium

European Commission. (2014). *Annexes to the report on Critical Raw Materials for the EU*.

Introduction

- "Options for developing a diversified and sustainable REE supply chain for Europe" (ERECON, 2014):
  - Development of new production routes outside of China
  - Increased resource efficiency
  - Increased recycling
  - Substitution
    - LED → Fluorescent lamps
    - Li-ion batteries → Nickel-metal hydride batteries
    - Solid state drives → Hard disk drive

Consequential LCA

ERECON. (2014). STRENGTHENING THE EUROPEAN RARE EARTHS SUPPLY-CHAIN Challenges and policy options, 102.

Methods – Current methodology

- "Normal" products
  - Primary production:
    - Production by marginal supplier
      - Determining co-product/reference product
    - Substitution for co-products
  - Recycling:
    - Displacement of primary production

Methods – Current methodology

Rare earth	Bastnäsite		Monazite	
	Mountain Pass, CA, United States[3]	Bayan Obo, Nei Mongol, China[4]	Mount Weld, Australia[5]	Nangang, Guangdong, China[6]
Yttrium	0.10	trace	trace	2.40
Lanthanum	33.20	23.00	26.00	23.00
Cerium	49.10	50.00	51.00	42.70
Praseodymium	4.34	6.20	4.00	4.10
Neodymium	12.00	18.50	15.00	17.00
Samarium	0.80	0.80	1.80	3.00
Europium	0.10	0.20	0.40	0.10
Gadolinium	0.20	0.70	1.00	2.00
Terbium	trace	0.10	0.10	0.70
Dysprosium	trace	0.10	0.20	0.80
Holmium	trace	trace	0.10	0.12
Erbium	trace	trace	0.20	0.30
Thulium	trace	trace	trace	trace
Ytterbium	trace	trace	0.10	2.40
Lutetium	trace	trace	trace	0.14
Total	100	100	100	100
	Loparite	Rare earth laterite		Xenotime
	Revda, Murmansk Oblast, Russia[7]	Xunwu, Jiangxi Province, China[8]	Longnan, Jiangxi Province, China[8]	Southeast Guangdong, China[9]
Yttrium	1.30	8.00	65.00	59.30
Lanthanum	25.00	43.40	1.82	1.20
Cerium	50.50	2.40	0.40	3.00
Praseodymium	5.00	9.00	0.70	0.60
Neodymium	15.00	31.70	3.00	3.50
Samarium	0.70	3.90	2.80	2.20
Europium	0.09	0.50	0.10	0.20
Gadolinium	0.60	3.00	6.90	5.00
Terbium	trace	trace	1.30	1.20
Dysprosium	0.60	trace	6.70	9.10
Holmium	0.70	trace	1.60	2.60
Erbium	0.80	trace	4.90	5.60
Thulium	0.10	trace	0.70	1.30
Ytterbium	0.20	0.30	2.50	6.00
Lutetium	0.15	0.10	0.40	1.80
Total	100	100	100	100

(USGS 2015)

- REEs often produced as by-products of other materials
- REEs always produced as co-products of each other
- No alternative primary production route for co-products

- Special modelling (Consequential-LCA 2015, Weidema et al. 2013):
  - Multiple determining co-products
  - Resulting in "economic partitioning" + induced consumption

Consequential-LCA (2015). More than one co-product without alternative production routes. Last updated: 2015-10-29. www.consequential-lca.org

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., … Wernet, G. (2013). *Overview and methodology - Data quality guideline for the ecoinvent database version 3* (Vol. 3). Ecoinvent Report 1 (v3). St. Gallen: The ecoinvent Centre.

USGS. (2015). *2012 Minerals Yearbook rare earths [advance Release].*

Methods – Current methodology

Bayan Obo, Nei Mongol, China	Yield from mining (kg REO/kg ore)	Relative revenue (USGS 2015)
Yttrium	trace	
Lanthanum	0.23	9.70%
Cerium	0.5	21.08%
Praseodymium	0.062	13.07%
Neodymium	0.185	39.68%
Samarium	0.008	0.91%
Europium	0.002	8.95%
Gadolinium	0.007	1.18%
Terbium	0.001	3.58%
Dysprosium	0.001	1.85%
Holmium	trace	
Erbium	trace	
Thulium	trace	
Ytterbium	trace	
Lutetium	trace	

Modelling of REEs (Consequential-LCA 2015, Weidema et al. 2013):

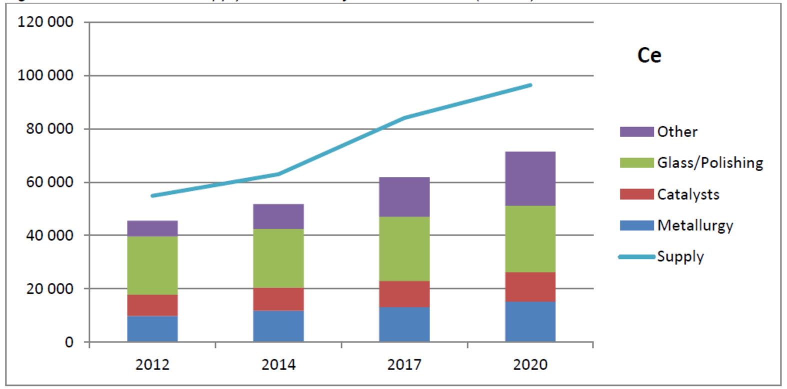
→ Demand for 0.5 kg Cerium leads to mining of 0.21 kg ore
- → Only 0.11 kg Cerium supplied
- → 0.39 kg Cerium made available by reduced consumption of the marginal user (substitution)

→ Co-production of 0.21*0.23 = 0.05 kg Lanthanum
- → Substitution of other material by marginal user (induced consumption)

Consequential-LCA (2015). More than one co-product without alternative production routes. Last updated: 2015-10-29. www.consequential-lca.org
Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., … Wernet, G. (2013). *Overview and methodology - Data quality guideline for the ecoinvent database version 3* (Vol. 3). Ecoinvent Report 1 (v3). St. Gallen: The ecoinvent Centre.
USGS. (2015). *2012 Minerals Yearbook rare earths [advance Release].*

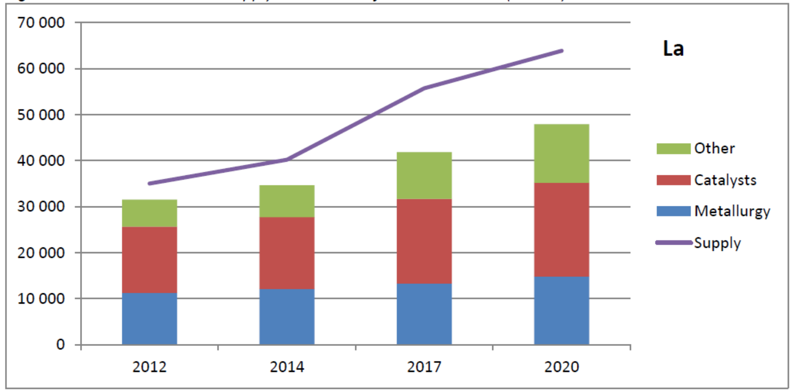
Methods – Drawbacks current methodology

Figure 164: World cerium supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

Figure 161: World lanthanum supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

(European Commission 2014)

- Surplus of Cerium and Lanthanum
  - No induced/reduced consumption
  - Stockpiling
- Bayan Obo mine
  - Largest producer REEs
  - REEs are a by-product of iron mining
    - Iron production is being prioritized (Zhiyi 2012)
    - REE "mining" from tailings

European Commission. (2014). *Report on Critical Raw Materials for the EU - Critical Raw Materials Profiles*.
Zhiyi, L. (2012). Chinese mining dump could hold trillion-dollar rare earth deposit. Retrieved August 26, 2016, from https://www.chinadialogue.net/article/show/single/en/5495-Chinese-mining-dump-could-hold-trillion-dollar-rare-earth-deposit

Methods – Drawbacks current methodology

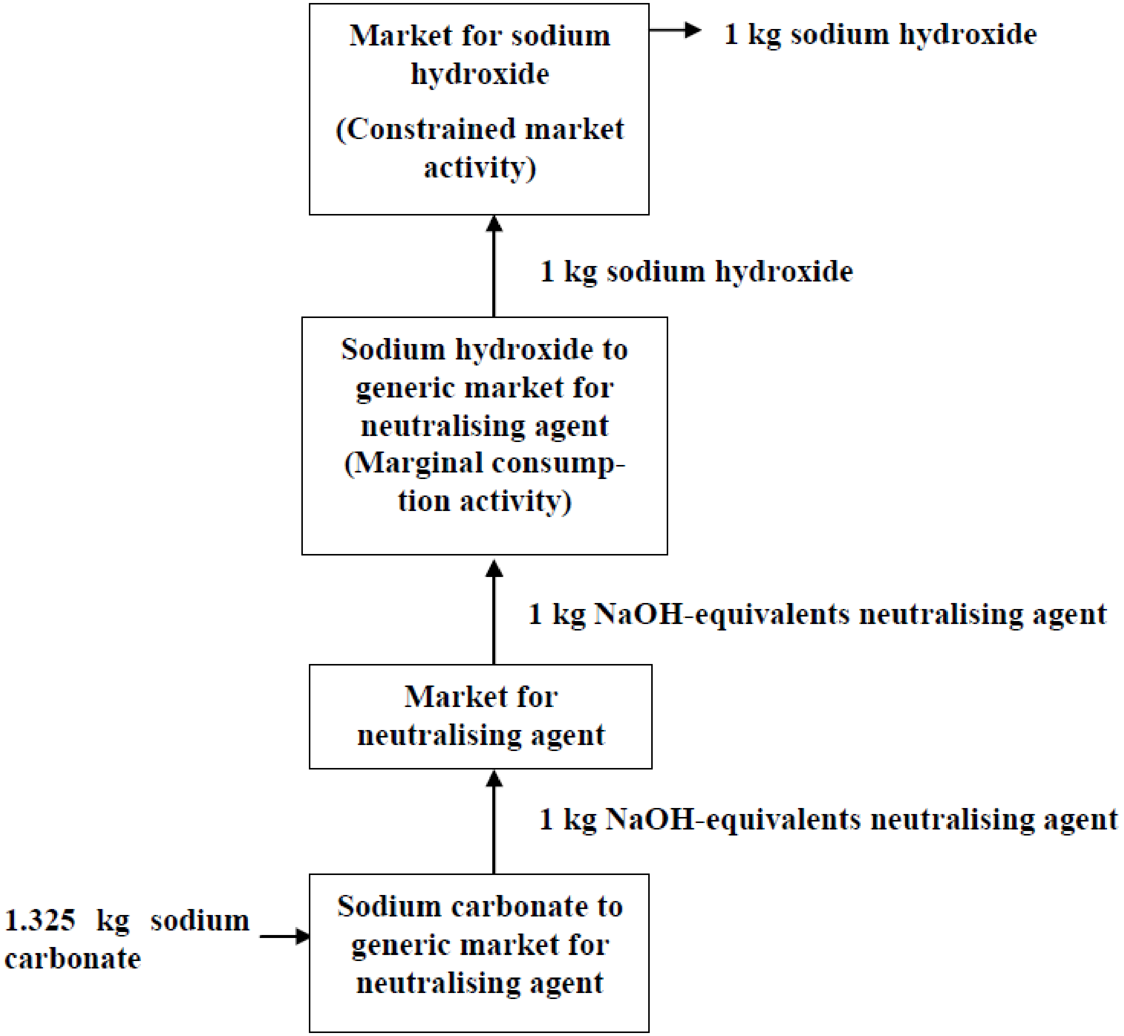
- REEs almost always by-products of other mineral extraction, *except* (Gupta & Krishnamurthy, 2005; Long, Van Gosen, Foley, & Cordier, 2010):
  - Mountain Pass, USA (shut down in 2015)
  - Mt Weld, Yangibana and John Galt in Australia
  - Sichuan, China
  - Ion adsorption mines (Heavy REE), China
- Production could be doubled if REO were not discarded or stockpiled (Gupta & Krishnamurthy, 2005)
- Supply from REE-rich tailings

Gupta, C. K. K., & Krishnamurthy, N. (2005). *Extractive metallurgy of rare earths*. CRC Press, Boca Raton, Florida, United States. doi:10.1179/imr.1992.37.1.197

Long, K. R., Van Gosen, B. S., Foley, N. K., & Cordier, D. (2010). *The Principal Rare Earth Elements Deposits of the United States — A Summary of Domestic Deposits and a Global Perspective*. *US Geological Survey* (Vol. 89). doi:10.1007/978-90-481-8679-2_7

Methods – Drawbacks current methodology

- REEs can displace other materials
  - Elemental level (difficult)
  - Product level
  - Technology level
- Example: sodium hydroxide in ecoinvent 3

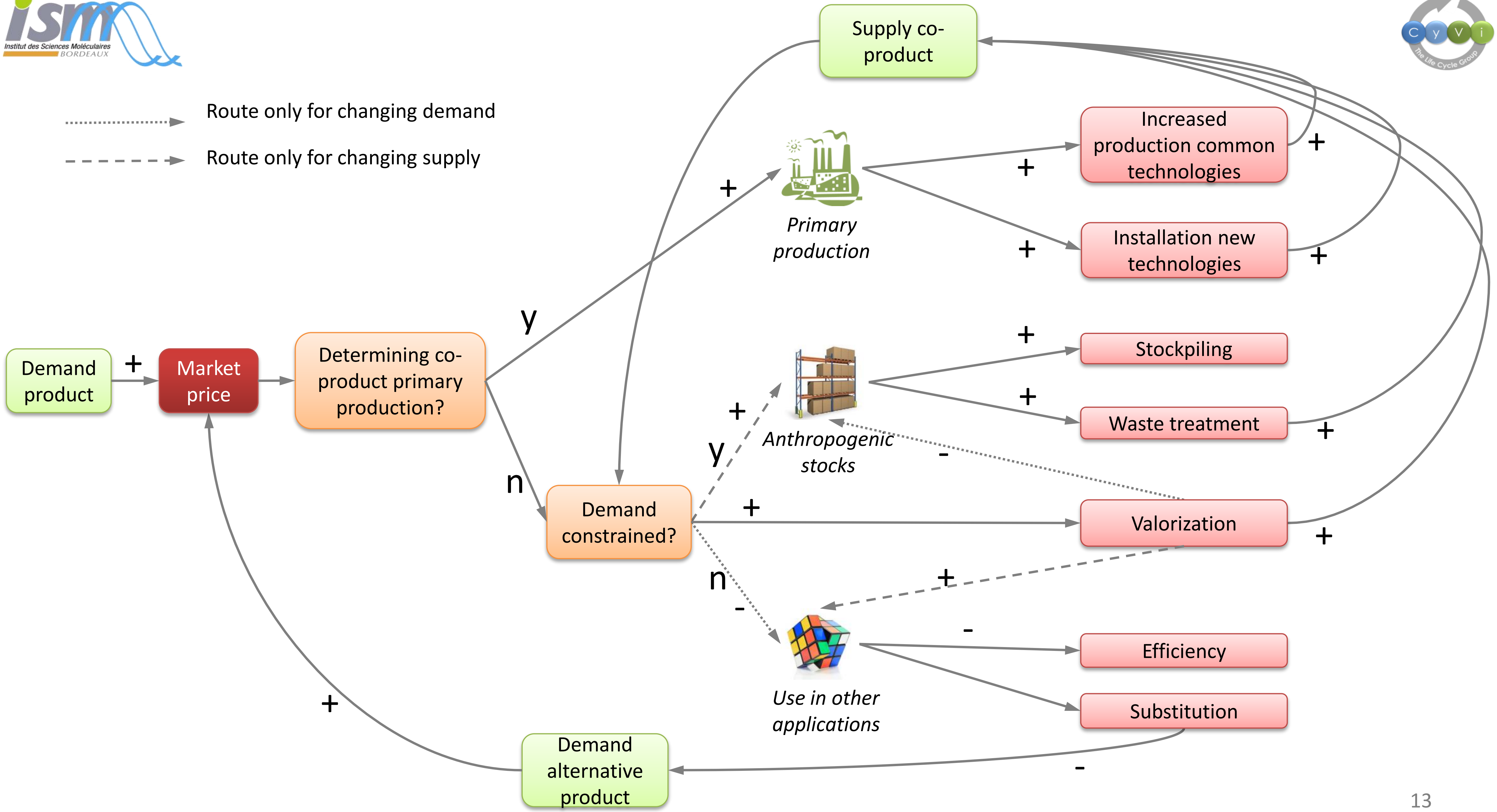


Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., … Wernet, G. (2013). *Overview and methodology - Data quality guideline for the ecoinvent database version 3* (Vol. 3). Ecoinvent Report 1 (v3). St. Gallen: The ecoinvent Centre.

Methods – Proposal new method

- Primary mining only for 1 determining co-product
- Supply from and to anthropogenic stocks
- Substitution of other element/product/technology

- Consistent approach for
  - Primary production
  - Co-products, by-products and recycling



Route only for changing demand
Route only for changing supply
Demand product
+
Market price
Determining co-product primary production?
y
n
Supply co-product
+
Primary production
+
+
Increased production common technologies
+
Installation new technologies
+
Demand constrained?
y
+
Anthropogenic stocks
+
+
Stockpiling
Waste treatment
+
-
+
Valorization
+
n
-
+
Use in other applications
-
Efficiency
Substitution
-
Demand alternative product
+

Application method to REEs – Determining co-product of mining/valorization activity

Mine location	REE as main product?	Determining co-product among the REEs *(first estimate)*
~~Mountain Pass, CA, United States~~	~~Yes~~	~~La~~
Mount Weld, Australia	Yes	Nd
Nangang, Guangdong, China	Yes	Nd
Xunwu, Jiangxi Province, China	Yes	Nd
Longnan, Jiangxi Province, China	Yes	Y
Southeast Guangdong, China	Yes	Dy
Bayan Obo, Nei Mongol, China	No	Nd
Revda, Murmansk Oblast, Russia	No	Nd
Dubbo, Australia	No	Nd
Nolans, Australia	No	Nd
Deep Sand, USA	No	Nd
Steenkampskraal, South Africa	No	Nd
Zandkopsdrift, South Africa	No	Nd
Hoidas Lake, Canada	No	Nd
Thor Lake, Canada	No	Nd
Kvanefjeld, Greenland	No	Nd

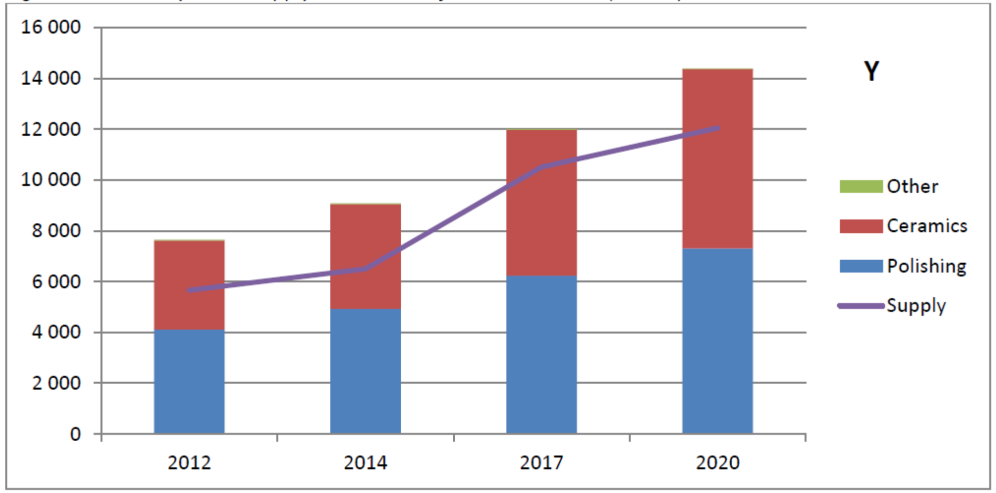
- Method (Consequential-LCA 2015a, 2015b):
  - Calculate total revenue of mine
  - Calculate marginal production costs (80% revenue)
  - Identify which elements are necessary to cover production costs
  - Element with lowest normalized market trend → determining co-product

Consequential-LCA (2015a). Further theory on marginal production costs. Last updated: 2015-10-27. www.consequential-lca.org.

Consequential-LCA (2015b). When all co-products have alternatives. Last updated: 2015-10-27. www.consequential-lca.org.

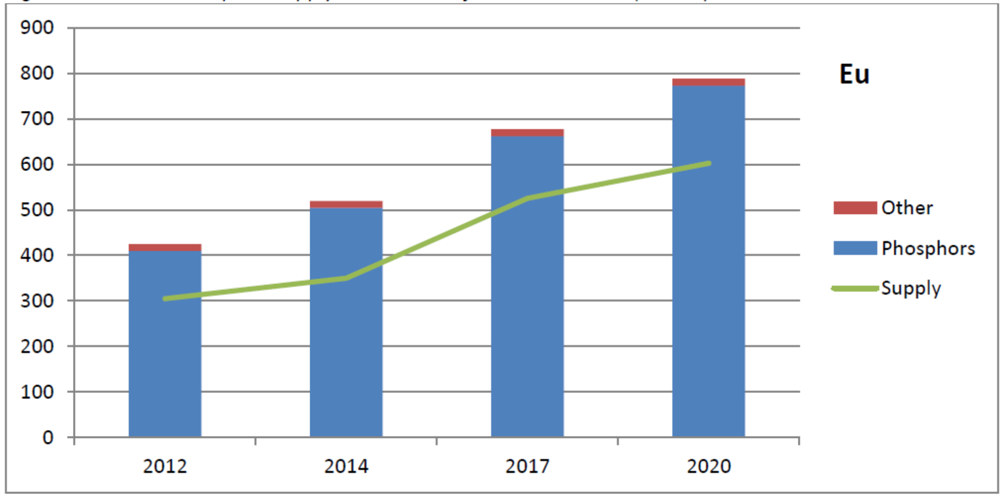
Application method to REEs – Identify demand constraints

Figure 191: World yttrium supply and demand forecasts to 2020 (tonnes)



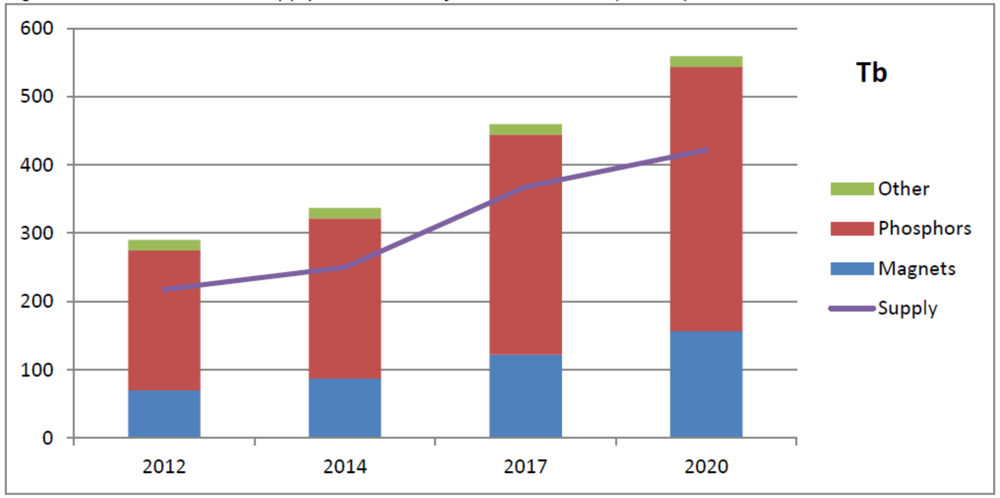
Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

Figure 176: World europium supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

Figure 182: World terbium supply and demand forecasts to 2020 (tonnes)

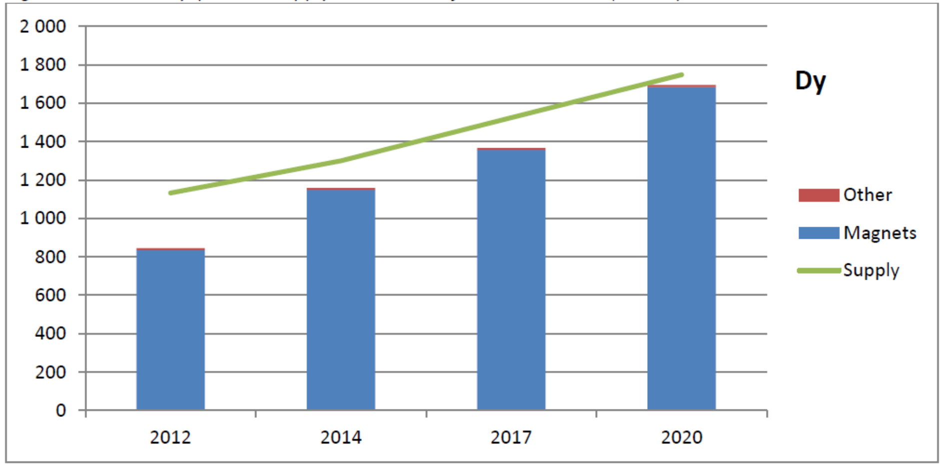


Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

European Commission. (2014). *Report on Critical Raw Materials for the EU - Critical Raw Materials Profiles*.

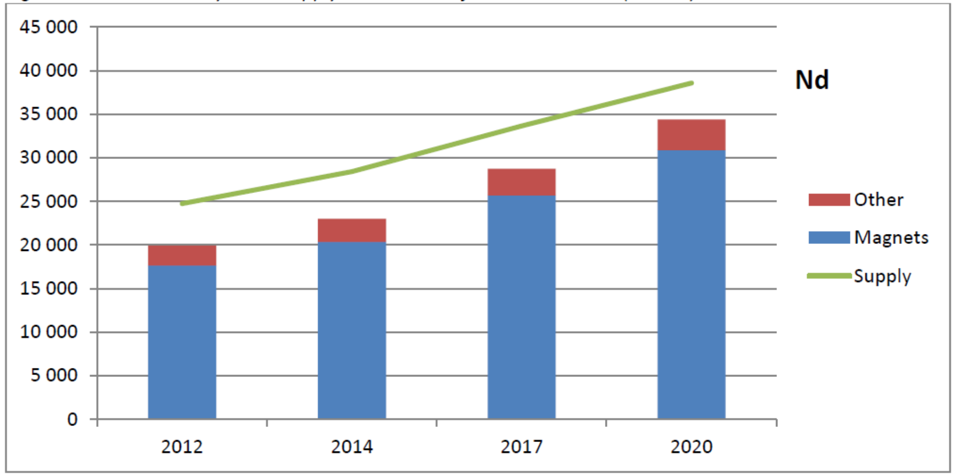
Application method to REEs – Identify demand constraints

Figure 185: World dysprosium supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

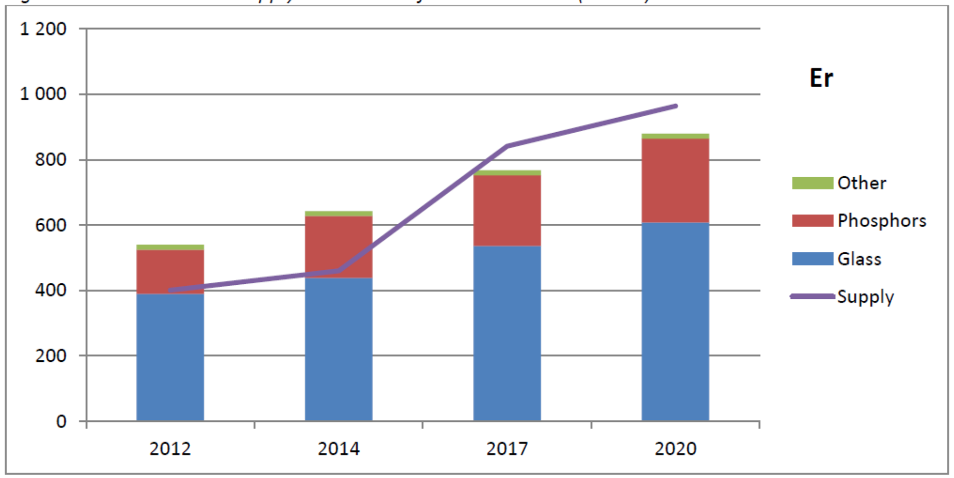
Figure 170: World neodymium supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

European Commission. (2014). *Report on Critical Raw Materials for the EU - Critical Raw Materials Profiles*.

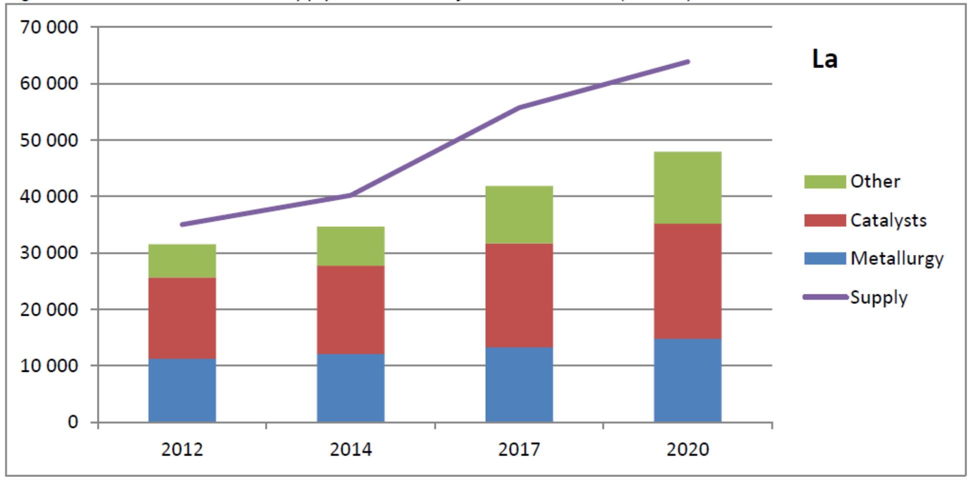
Figure 188: World erbium supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

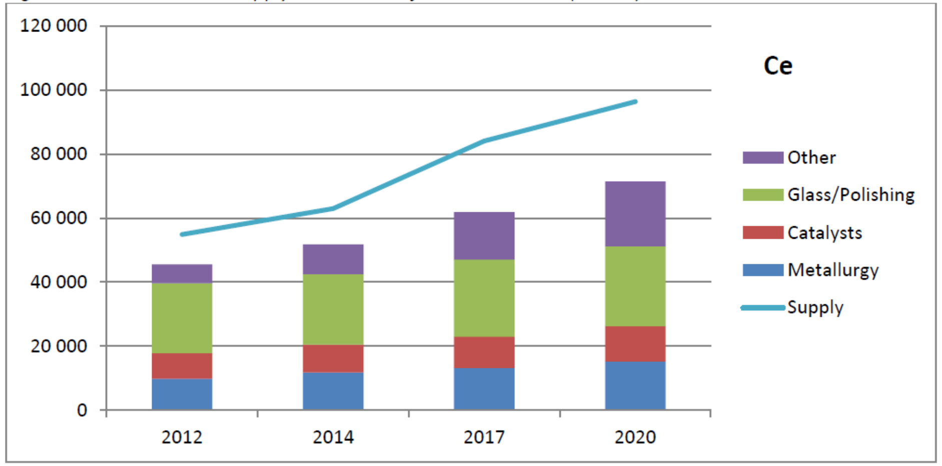
Application method to REEs – Identify demand constraints

Figure 161: World lanthanum supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

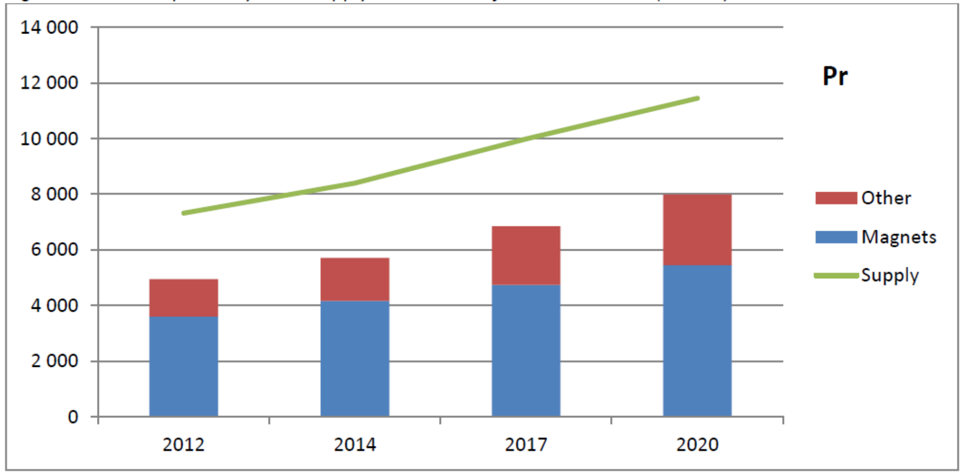
Figure 164: World cerium supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

European Commission. (2014). *Report on Critical Raw Materials for the EU - Critical Raw Materials Profiles*.

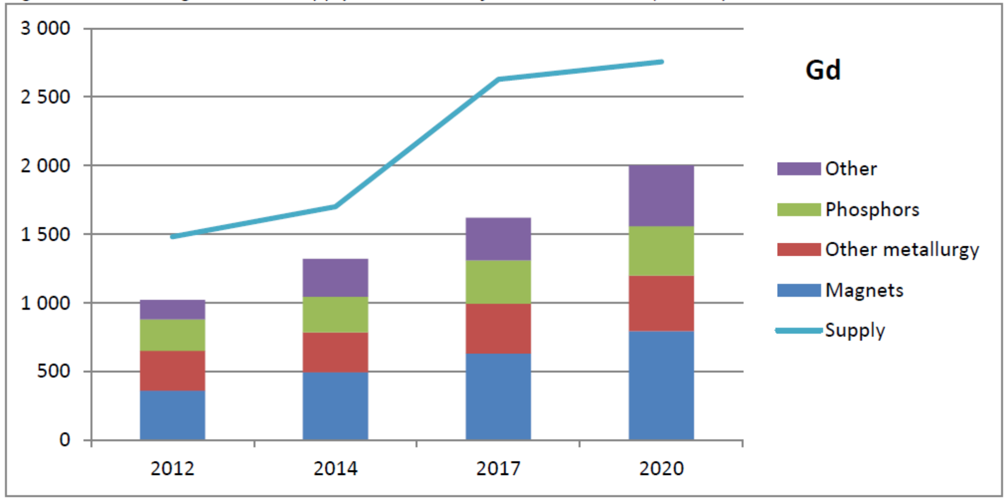
Figure 167: World praseodymium supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

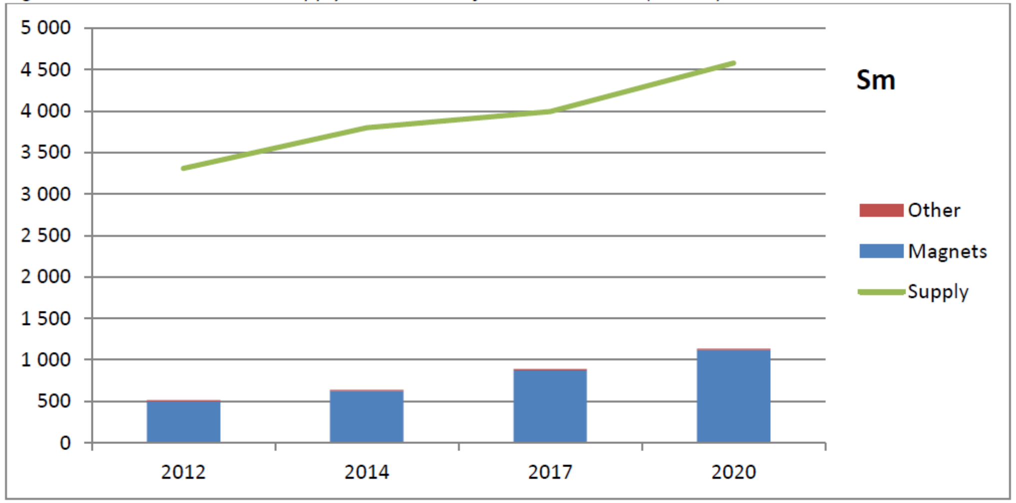
Application method to REEs – Identify demand constraints

Figure 179: World gadolinium supply and demand forecasts to 2020 (tonnes)



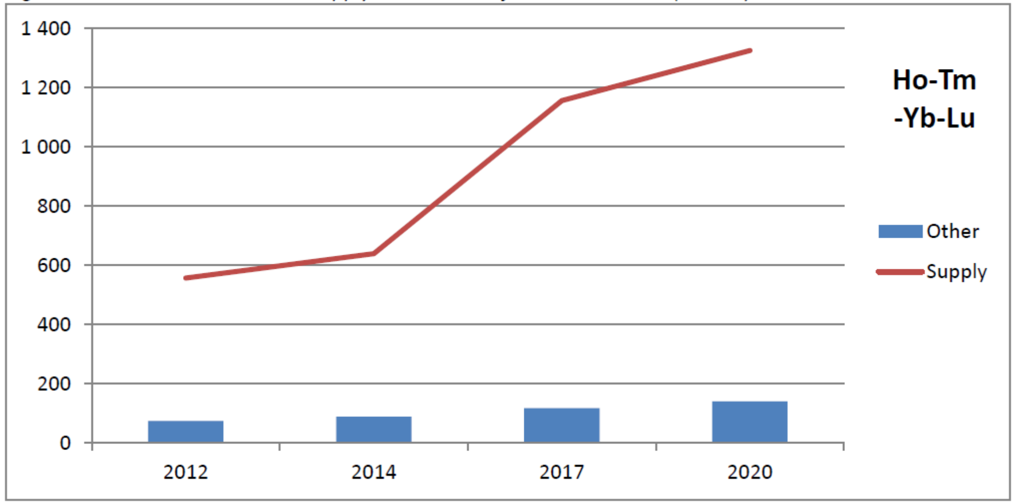
Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

Figure 173: World samarium supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

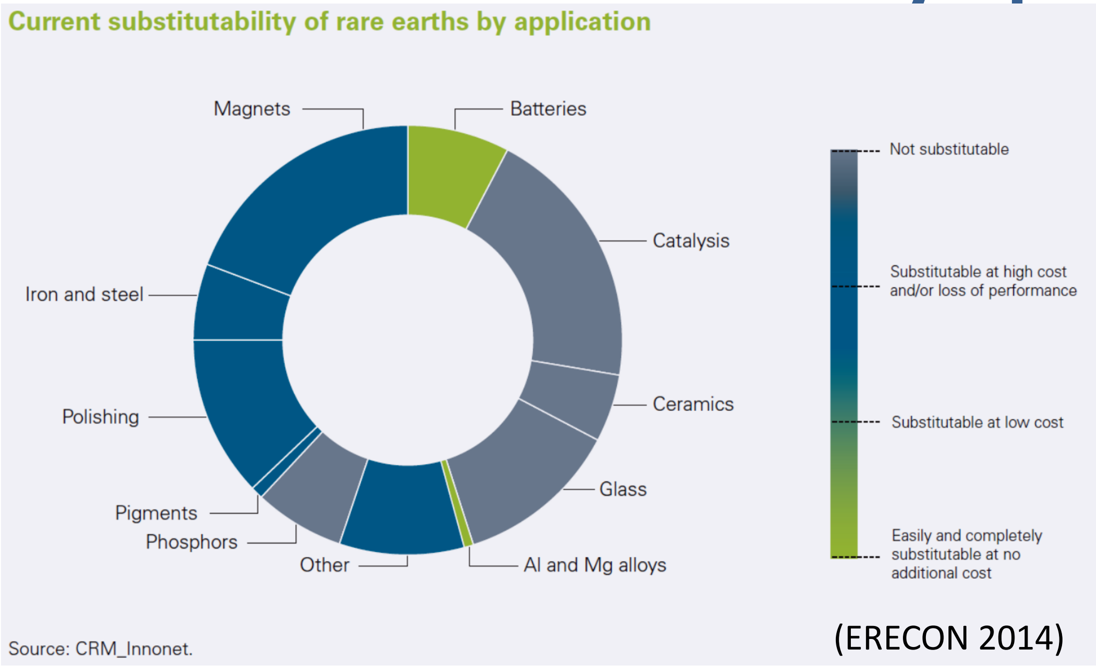
Figure 194: World Ho-Tm-Yb-Lu supply and demand forecasts to 2020 (tonnes)



Sources: Roskill, IMCOA and Technology Metal Research Reports and Presentations (2012-2013)

European Commission. (2014). *Report on Critical Raw Materials for the EU - Critical Raw Materials Profiles*.

Application method to REEs – Identify options for substitution



(ERECON 2014)

Table 1.5 Alternatives to rare earths in applications.

Application	Rare Earth Material	Alternative
Metallurgy		
Nodular iron	Misch metal Misch metal,	Magnesium
Steel	RE silicide	Calcium
Nuclear energy		
Control rod	Europium	Hafnium
Hydrogen storage	Lanthanum nickel alloy	Iron titanium alloy
Glass		
Polishing	Cerium oxide	Plate glass (Pilkington) process
Ceramics		
Glazed ceramic tiles	Cerium	Tin, zirconium
Catalysis	Mixed RE	High octane gasoline

(Gupta & Krishnamurthy 2005)

- Identify applications that are most easily substitutable
- Substitution on technology level, not only elemental level (Habib, 2015)
- Consider side-effects of using a different technology

ERECON. (2014). STRENGTHENING THE EUROPEAN RARE EARTHS SUPPLY-CHAIN Challenges and policy options, 102.

Gupta, C. K. K., & Krishnamurthy, N. (2005). *Extractive metallurgy of rare earths*. CRC Press, Boca Raton, Florida, United States. doi:10.1179/imr.1992.37.1.197

Habib, K. (2015). Critical Resources in Clean Energy Technologies and Waste Flows Critical Resources in Clean Energy Technologies and Waste Flows.

Application method to REEs – Marginal supplier per element

Element	Market outlook	Marginal supplier on the long term (considering current technologies)		
		Primary production	Supply from stockpiles	Decreased use in other applications
Ce	Increasing surplus		✓	
La	Increasing surplus		✓	
Pr	Increasing surplus		✓	
Nd	Tight	✓		
Sm	Large surplus		✓	
Eu	Shortage			✓
Gd	Large surplus		✓	
Tb	Shortage			✓
Dy	Increasing tightness	✓ - Southeast Guangdong, China		
Y	Shortage	✓ - Longnan, Jiangxi Province, China		
Other	Large surplus		✓	

Large influence on the benefits of recycling

Conclusions

- Current modelling of REEs does not represent reality
  - By-product instead of determining co-product
  - Stockpiling is not considered
  - Substitution where it does not take place
  - Inconsistent approach compared to other materials
- Proposal for new approach
  - 1 determining product per production route
  - Supply from stockpiles if surplus exists
  - Consistent for primary materials, co-products, by-products and recycled materials
- Recycling only beneficial for certain elements:
  - Neodymium
  - Europium
  - Terbium
  - Dysprosium
  - Yttrium

Acknowledgements:

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French National Association for Technical Research (CIFRE Convention N° 2013/1146)