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The rare earths revolution:

The dirty secret of green technologies

Energy Economics and Policy

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Spring Semester 2010

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Introduction

Industrialized countries are adopting stricter environmental policies to act against global climate change. These measures require technologies that present increasing energy efficiency or decreasing pollution. Wind turbines, hybrid electrical vehicles and low consumption light bulbs exemplify the trend .They also share the need for rare minerals as an input in their production. Rare earth minerals are a group of elements that have unique properties.

A major concern associated with new green technologies is the geographic and political dependence on the supply of rare earths. In this field, China has become a major player, if not almost the only one, meeting more than 95 % of the global demand during the last 5 years. However, the processing techniques are causing severe environmental damage forcing the Chinese central government to restrict rare-earth production since 2006.

This restriction is increasing a supply shortage which was already worrying Western countries, since they rely more and more on rare earths. In the coming decade, mines in the USA and Australia are expected to reopen and revive the question of its associated policies.

In this paper, we present the rare earth elements and its associated industry. A mine model with a nested constant elasticity of substitution production function is used to model each key region. We then examine different environmental policies that could affect the rare earth market in the coming decade. Our analysis makes clear that the shortage won't be solved with the reopening of the mines. It also highlights how the trade fluxes between continents are modified by export tariffs modification or with China taking a "Green" path.

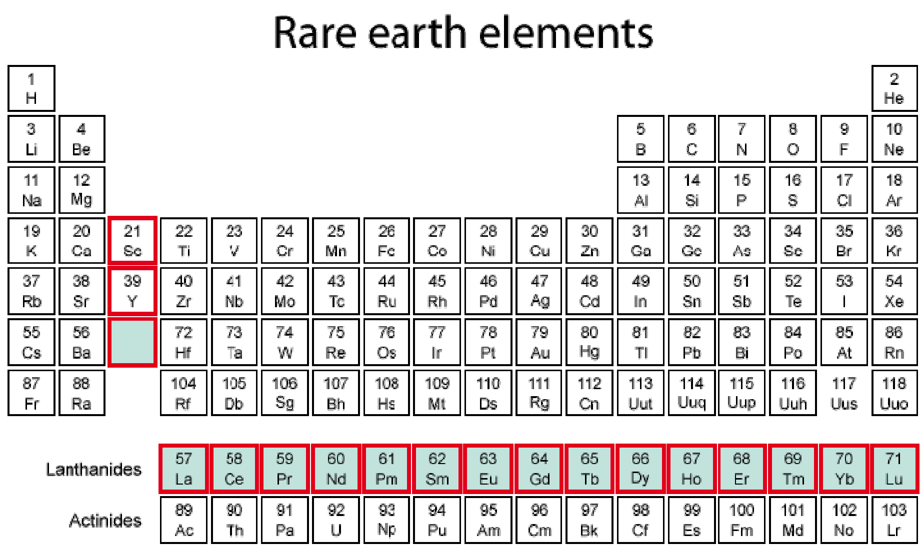
In the following, section 2 and 3 present the rare earth industry and processing techniques. Section 4 explains the model. Section 5 analyses the outcomes of different possible policy scenarios. Section 6 concludes.

What are rare earths

The rare earth elements are 17 chemical elements grouped together because of their simultaneous presence in minerals that lead to their discovery (Figure 1 and Table

1). Promethium's high instability and scandium's limited applications make them irrelevant in our further analysis.

Figure 1: Position of the rare earth oxides in the periodic table (source: Wikipedia)



Contrary to what their name would suggest, rare earth elements exist in moderately abundant quantities: for example, cerium is found in greater concentration in the Earth's crust than copper.

As visible in Table 2, the demand for rare earths is strongly application dependent. Besides, they can only poorly be substituted (U.S. Geological Survey 2010). The most striking example can be taken from permanent magnets. Those are rare earth-based (Neodymium-Iron-Boron, *NbFeB*, and Samarium-Cobalt, *SmCo*), aluminium-based (Aluminium-Nickel-Cobalt, *AlNiCo*) or ceramic-based (Ferrite). The rare earth-based magnets have fluxes at least 3 to 10 times higher than their traditional counterparts. This advantage enables light weight generators, which are a sine qua non condition for hybrid cars and wind turbines.

Table 1: Symbols of rare earth elements (grayed out elements won't be considered further)

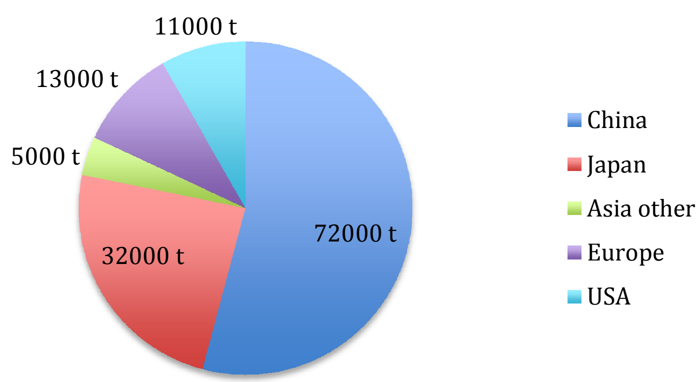
Name	Symbol
Cerium	Ce
Dysprosium	Dy
Erbium	Er
Europium	Eu
Gadolinium	Gd
Holmium	Ho
Lanthanum	La
Lutetium	Lu
Neodymium	Nd
Promethium	Pm
Praseodymium	Pr
Samarium	Sm
Scandium	Sc
Terbium	Tb
Thulium	Tm
Ytterbium	Yb
Yttrium	Y

Table 2: Typical rare earth applications, (Sinton 2006)

Application	Elements used	2005 demand [tons]	Growth drivers
Magnets	Nd, Pr, Dy, Tb, Sm	17'170	• Hybrid vehicle electric motors • Wind power plant generator
NiMH Batteries	La, Ce, Pr, Nd	7'200	• Hybrid vehicle batteries • Rechargeable batteries
Automotive catalysts	Ce, La, Nd	5'830	• Gasoline and hybrids, diesel fuel additive • Global emission standards
Fluid cracking catalysts	La, Ce, Pr, Nd	15'400	• Oil production
Phosphors	Eu, Y, Tb, La, Dy, Ce, Pr, Gd	4'007	• LCD TVs and monitors • Energy efficient compact fluorescent lights
Polishing powders	Ce, La, Pr, mixed	15'150	• LCD TVs and monitors • Silicon wafers and chips
Glass additives	Ce, La, Nd, Er, Gd, Yb	13'590	• Optical glass for digital cameras • Fiber optics
Total		**78'347**	

Magnets and batteries demand show the highest annual growth with 12% and 15%. Both applications are expected to drive the global demand of rare earth elements forecasted around 134'000 tons in 2010 and growing up to 182'000 tons in 2014. Asia, where the majority of manufacturing plants are located, is the largest consumer.

Figure 2: 2010 demand forecast by region (Lynas Corporation 2010)



The rare earth industry

Mines

Ores containing rare earth element are mainly bastnäsite, monazite and ion adsorption clays. Monazite contains thorium, which is slightly radioactive so that stockpiling and transportation costs make it less competitive. Ion adsorption clays contain fewer rare earth oxides than bastnäsite but also need fewer processing steps. One should also keep in mind that mines may have different grading: for the same mined quantity, a higher grading ore produces more concentrate and the environmental impact is smaller.

Table 3Tables 3 and 4 give an overview of the current mining situation.

Table 3: Most important mines and their compositions in percentage of total rare earth oxides (U.S. Geological Survey 2010)

	Mountain Pass, CA, USA, bastnäsite	Bayan Obo, Inner Mongolia, China, bastnäsite	Mount Weld, Australia, monazite	Long Nan, Jiangxi, China, ion-ads. clay	Xunwu, Jiangxi, China, ion-ads. clay
Ce	49.10	50.8	46.74	2.4	2.4
Dy	Trace	0.1	0.12	5.3	Trace
Er	Trace	Trace	Trace	3.6	Trace
Eu	0.1	0.21	0.44	0.03	0.51
Gd	0.2	0.6	0.75	4.4	3.00
Ho	Trace	Trace	Trace	1.4	Trace
La	33.20	26.50	25.50	7.8	43.4
Lu	Trace	Trace	Trace	0.3	0.1
Nd	12.00	15.40	18.50	9.0	31.70
Pr	4.34	3.96	5.32	2.4	9.00
Sm	0.8	1.1	2.27	3.0	3.90
Tb	Trace	0.03	0.05	0.9	Trace
Tm	Trace	Trace	Trace	Trace	Trace
Yb	Trace	Trace	Trace	2.7	0.3
Y	0.10	0.20	0.25	56.2	8.00

Parallel to their production limit, China has imposed an export quota since 2006. The quantities allowed are shrinking from year to year and are currently around 40'000 to 50'000 tons. In the future, it is even expected that some rare earth oxides will not be exported at all. From Figure 2 and Table 4 the global supply shortage then becomes clear.

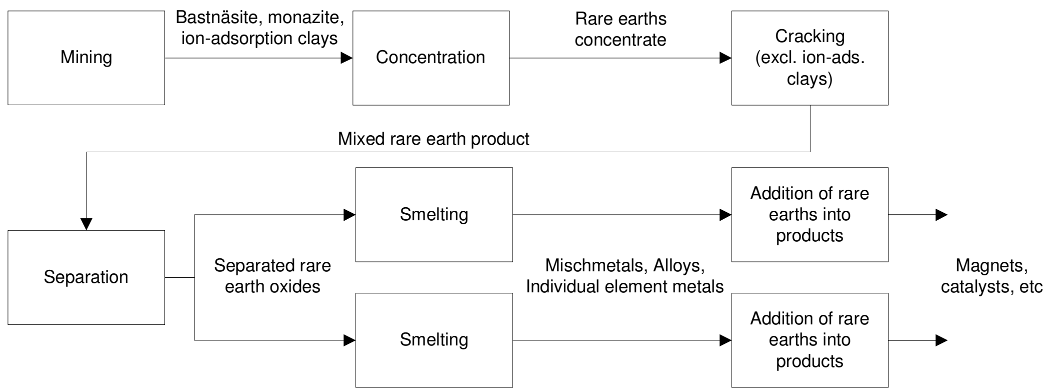
The export quota amplified the existing shortage caused by mines shutdowns in Australia and the USA. Because of environmental concerns and Chinese competition, Molycorp stopped mining in Mountain Pass in 2002. However, thanks to new processing techniques, the mining is expected to restart around late 2011. The Mount Weld mine is also planned to open in 2011. The high grading of this mine (15 %, three times higher than in Bayan Obo) and the forecasted global supply shortage should guarantee its competitiveness.

Illegal mines are common in China, representing up to 50% of the exports (Hurst 2010). The rest of the production is consumed locally in processing plants.

Processing

Figure 3 summarizes the processing steps required to obtain a usable rare earth product.

Figure 3: Processing of rare earth minerals (ion-adsorption clays don't need cracking)



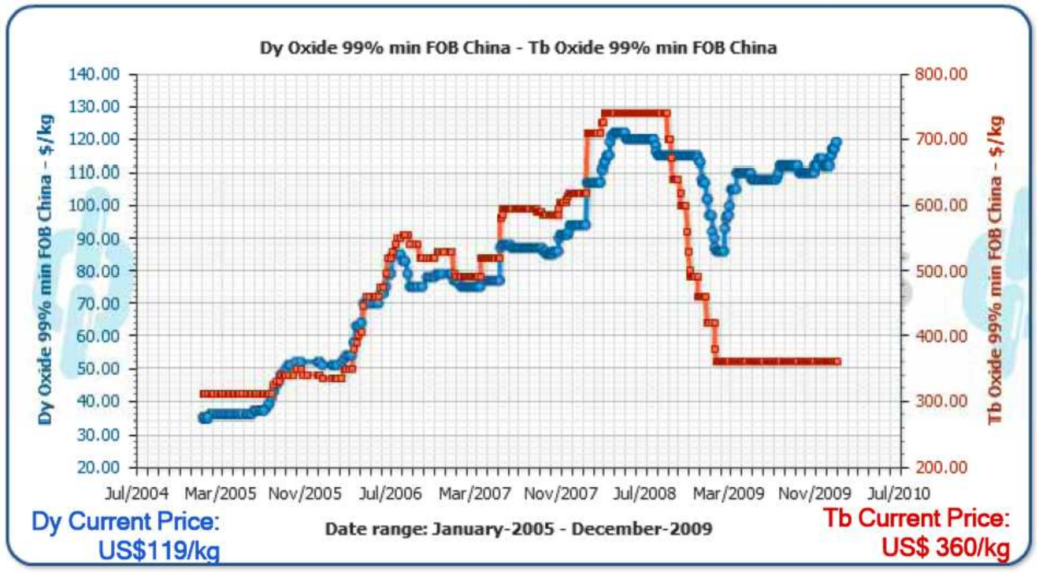
Concentration of bastnäsite and monazite ores is done with gravity separation, magnetic separation and froth flotation. The same step is much easier for ion-adsorption clays with just an aqueous solution. In general, concentration is the step causing the most environmental damages, as reported in Hurst (2010).

> ***Under traditional technology means, refining rare earth elements requires such chemicals as ammonium bicarbonate and oxalic acid. The potential health hazards of ammonium bicarbonate include: Irritation to the respiratory tract if inhaled, irritation to the gastrointestinal tract if ingested, redness and pain if it comes in contact with the eyes, and redness, itching, and pain if it comes in contact with the skin. Oxalic acid is poisonous and potentially fatal if swallowed. It is also corrosive and causes severe irritation and burns to the skin, eyes, and respiratory tract, is harmful if inhaled or absorbed through the skin, and can cause kidney damage. These and other chemicals often find their way into the Yellow River***

Currently, the processing is entirely done in China with high environmental damage. After its reopening, the Mountain Pass mine will run a more efficient and cleaner processing plant than before. Lynas Corp., owner of the Mount Weld mine, also plans to open a processing plant in Malaysia.

From the analysis above, it is clear that each mineral cannot be mined separately. This causes prices of less-used rare earth minerals to drop because of stockpiling (Figure 4).

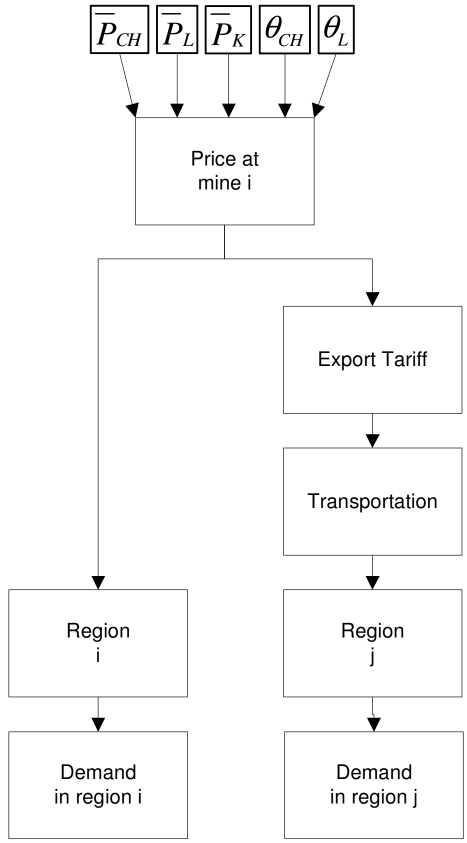
Figure 4: Terbium (red) vs. Dysprosium (blue) prices in December 2009 (www.metal-pages.com)
Prices are Free On Board



The model

Because of the complexity of the market, the model relies on several assumptions. First, the world is divided into 6 zones (China, Japan, other Asian countries, USA, Australia and Europe) plus a dummy zone. The dummy zone ensures that the global demand is equal to supply, making the optimization problem feasible. Second, each region has only one mine. Third, only the short run trade flows are modeled, with the Mountain Pass and Mount Weld mine at full production. Fourth, the mines are homogeneous: grading or compositions are the same. Figure 5 gives the overview of the model.

Figure 5: Overview of the model



The model of each mine is a nested constant elasticity of substitution production function, inspired from the copper model in Lanz, Rutherford and Tilton (2010).

$$P_i = \overline{C}\left[\theta_{CH}\overline{P}_{CH} + (1-\theta_{CH})\left(\theta_L\overline{P}_L^{1-\sigma} + (1-\theta_L)\left(\overline{P}_K\right)^{1-\sigma}\right)^{\frac{1}{1-\sigma}}\right] \tag{1.1}$$

P_i is the price of the rare earth oxide in region *i*; $\overline{C}$ is the average world price of a rare earth ore; $\overline{P}$ are the input prices of chemicals (*CH*), labor (*L*) and capital (*K*) normalized to one; θ is the value share of inputs; σ is the elasticity of substitution between labor and capital.

Table 4: Regional input parameters

	θ_{CH}	θ_L	$\overline{P}_{CH}$	$\overline{P}_L$	$\overline{P}_K$
China	0.6	0.3	1	0.2	0.7
Asia other	0.6	0.3	1	0.3	0.7
USA	0.3	0.6	1	1.1	1.3
Australia	0.3	0.6	1	1	1.3

Because no value share data exist for the market, values in Table 4 are empirical. We assume that chemicals are produced globally. Thus, the price of chemicals is the same everywhere, with a high value share since processing relies a lot on them. The plants being currently built in Australia and the USA are expected to be cleaner. Labor costs and their value share are lower in Asia.

The average world price is also difficult to compute because of different proportions of oxides per ton of ore. Instead, we will take the February, 2010 price from Lynas Corporation (2010). We only consider the short-run and thus the elasticity of substitution is set to 0.

Once the regional prices are known, we add transport costs and export tariffs, both normalized to one. Tariffs are estimated from U.S. Geological Survey (2007): China is currently trying to limit exports by applying a higher tariff. We also believe that the USA and Australia will use export tariffs in order to keep an amount for local consumption. We estimate transportation as a function of distance.

Table 5: Estimated normalized transport costs

FROM/TO	China	Japan	Asia other	Europe	USA	Australia
China	1	1.1	1.2	1.4	1.6	1.6
Japan	1.1	1	1.4	1.4	1.5	1.6
Asia other	1.2	1.4	1	1.3	1.6	1.5
Europe	1.4	1.4	1.3	1	1.3	2
USA	1.6	1.5	1.6	1.3	1	1.6
Australia	1.6	1.6	1.5	2	1.6	1

Forecasted regional demands are taken from the U.S. Geological Survey (2010), with the exception of Australia for which an estimate was made. Capacities are taken from Lynas Corporation (2010), as well as the Chinese quota.

Table 6: Other inputs parameters

	Demand [tons]	Capacity [tons]	Quota [tons]	Tariffs
China	72000	85000	45000	1.2
Japan	32000	0	1.00E+10	1
Asia other	5000	3000	1.00E+10	1
Europe	13000	0	1.00E+10	1
USA	11000	20000	1.00E+10	1.1
Australia	3000	20000	1.00E+10	1.1

Finally, we close the model by minimizing the average price:

$$\min \frac{\sum_{i,j} X_{ij} P_i \cdot t_i \cdot TC_{ij}}{\sum_{i,j} X_{ij}} \tag{1.2}$$

Subject to

$$\sum_j X_{ij} \leq \text{ Capacity } (i \text{ is constant})$$

$$\sum_i X_{ij} \geq \text{ Demand } (j \text{ is constant})$$

$$\sum_j X_{ij} \leq \text{ Quota } (i \neq j, i \text{ is constant})$$

Where X_{ij} is the quantity in tons of oxide transported from region i to j with transport costs TC_{ij}, an export tariff t_i and a free on board price P_i (without tariffs and transportation, i.e. the price at mine *i* in our case).

Policies simulation

Case 1: Initial Case

Table 7 shows the trade fluxes with the assumptions previously made. The average price is 16'264 $/ton.

Table 7: Results with Mountain Pass and Mount Weld at full production [in tons]

FROM/TO	China	Japan	Asia other	Europe	USA	Australia
China	40000	28805	3833	7948	4413	0
Japan	0	0	0	0	0	0
Asia other	3000	0	0	0	0	0
Europe	0	0	0	0	0	0
USA	11277	0	0	3958	4765	0
Australia	11646	3195	1167	0	993	3000

Table 8: Supply shortage per region [in tons]

China	Japan	Asia other	Europe	USA	Australia
6077	0	0	1094	829	0

The supply shortage per region shows an unlikely situation where China would have to import part of the local consumption. The assumptions made and the modeling could be improved.

Case 2: China increases tariffs and closes illegal mines

In this scenario, China would be acting to reduce environmental damages by forcing a local consumption and closing illegal mines. The tariff is set to 1.4 and the capacity is lowered to 65’000 tons.

Table 9: Results with China taking a *Green Way* [in tons]

FROM/TO	China	Japan	Asia other	Europe	USA	Australia
China	20000	17696	3611	11976	9850	1866
Japan	0	0	0	0	0	0
Asia other	1484	0	287	414	410	405
Europe	0	0	0	0	0	0
USA	16041	3273	294	187	187	17
Australia	15924	3336	409	0	91	241

Table 10: Supply shortage per region [in tons]

China	Japan	Asia other	Europe	USA	Australia
18550	7695	399	422	462	471

The trade fluxes are unrealistic for the same reasons as in Case 1. However, the price increases to 19’960 $/ton, which is consistent with the increased supply shortage. In this scenario, Chinese local consumption is divided by 2 and the imports from Australia to China increase by 37%. In this scenario, the price elasticity of supply is 1.035.

Case 3: Protectionism measures in USA and Australia

USA and Australia would set higher export tariffs at 1.4 to force local consumption.

Table 11: Results with USA and Australia being protectionists [in tons]

FROM/TO	China	Japan	Asia other	Europe	USA	Australia
China	40000	32000	5000	8000	0	0
Japan	0	0	0	0	0	0
Asia other	3000	0	0	0	0	0
Europe	0	0	0	0	0	0
USA	4000	0	0	5000	11000	0
Australia	17000	0	0	0	0	3000

Table 12: Supply shortage per region [in tons]

China	Japan	Asia other	Europe	USA	Australia
8000	0	0	0	0	0

Compared to the Case 1, this scenario forces both countries effectively to consume the local production. The price is 16’847 $/ton and there is no significant increase since the global supply and demand remain the same.

Figure 6 and Figure 7 summarize the outcomes of the three scenarios.

Figure 6: Net trade fluxes for each region.
A positive net flux means that the region is importing

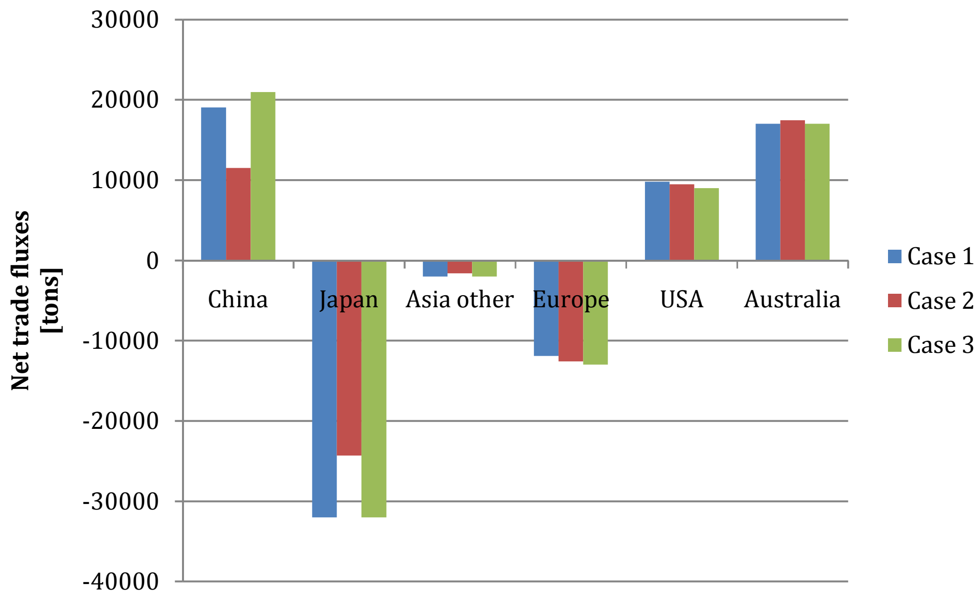
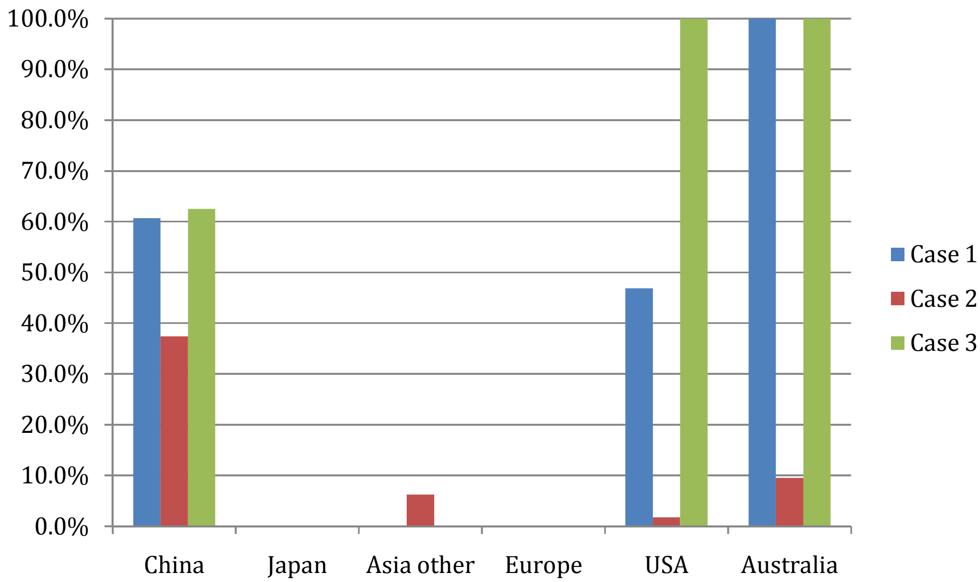


Figure 7: Share of the total consumption produced locally



Conclusion

The global demand for rare earths has been skyrocketing during the past decade thanks to "green" technologies. This trend has shifted the production from OECD countries to China with severe environmental damage. With 95 % of the world supply, China has gained a powerful influence from the fact that no real substitutes exist. Even if former producers in OECD countries are restarting mining, supply is likely to lag demand for the next ten years. A shift of the processing stage to countries having less stringent environmental policies seems likely to happen: Lynas is considering the opening of a processing plant in Malaysia (Avalon Rare Metals, Inc. 2010, Hezri and Hasan 2006)

Based on a spatial modeling of global mining, we examined the effects of different policies on the market's main players. However, the approximations used and the general form of the modeling introduced inconsistencies in our results. Nevertheless, our analysis shows that increased tariffs in Australia and USA can force local consumption without increasing the price significantly. This would be a wise option because unnecessary transportation is avoided. Besides, the high price elasticity of supply with respect to Chinese supply variations confirms the influence of this producer.

This work also points out the difficulty in modeling this market, in comparison with homogeneous markets like coal or copper. Future models may wish to consider different oxides separately, each with their associated production costs. The cross elasticity of demand and supply could then be computed. A more detailed transportation model, as used in Lanz, Rutherford and Tilton (2010), will also correct optimization inconsistencies. If the environmental damages are economically assessable, a concept similar to the carbon leakage rate may be introduced. This would link the costs related to the abatement of 1 gram of CO_2 with the environmental damages made in developing countries. The real effectiveness of environmental friendly cars, for example, could then be quantified with tools like Life Cycle Analysis.

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