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LIFE CYCLE ASSESSMENT OF RARE EARTH PRODUCTION FROM MONAZITE

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Abstract

The environmental life cycle impacts of conceptual rare earth production processes were assessed. An average greenhouse gas emission of 65.4 kg CO_2e/kg was estimated for the 15 rare earths produced from monazite, ranging from 21.3 kg CO_2e/kg for europium to 197.9 kg CO_2e/kg for yttrium. The average water consumption of rare earth production was 11,170 kg/kg ranging from 3,803 kg/kg for samarium and gadolinium to 29,902 kg/kg for yttrium. The average gross energy requirement for production was 917 MJ/kg, ranging from 311 MJ/kg for samarium and gadolinium to 3,401 MJ/kg for yttrium. Given the low concentration of HREE in monazite, the high impacts across all categories for yttrium and other HREE are not necessarily representative of HREE sourced from all rare earth resources. Further studies into other rare earth mineral resources (e.g. bastnasite and xenotime) are recommended to improve the overall understanding of environmental impacts from rare earth production.

Introduction

The rare earth elements are comprised of the lanthanide series (atomic numbers 57 to 71) along with scandium (atomic number 21) and yttrium (atomic number 39). The rare earths coexist in varying concentrations in deposits where they must be extracted and separated for commercial use. The physical and chemical properties of rare earths are similar, which not only accounts for their coexistence in deposits, but also demands complex processing for separation and purification.

Demand for rare earth elements is growing due to their use in a number of growing industries and products such as colour screen phosphors, high strength magnets, lasers, chemical catalysts and medical equipment. Recent production data has been reported in Haque et al. [1]. One of the major economic sources of rare earths is monazite, a phosphate based mineral ((Ce, La)PO_4). Monazite features rare earths, thorium and uranium along with radioactive decay products and various impurities such as iron and aluminium in a substitution arrangement of phosphates. Thus monazites have a variable content of rare earths from around 42% in North Korean monazite to around 61% in monazite from certain Australian deposits [2]. The concentration of radioactive substances in monazite also varies; 0.18–0.45% for uranium and 4.5–9.5% for thorium [2].

The environmental impacts of rare earth mining, processing and waste management are poorly understood on a quantitative level. This is due to a lack of systematic impact assessment studies, particularly those that include baseline monitoring prior to resource development. The human health and ecosystem impacts associated with illegal mining of rare earths also have not been properly quantified. There is a recognition of the environmental impacts of rare earth production at local scales. For instance, in-situ leaching is replacing heap leaching of ion-adsorbed rare earth deposits in southern China. However, this is only suitable for specific geochemical and hydrological environments.

Previous analysis of the environmental impacts associated with monazite processing has generally focused on issues relating to the handling of radioactive wastes. Other environmental issues such as the contribution to climate change, water depletion and indirect toxicity issues have received much less attention. Largely, this is due to the relatively small scale of the industry and the importance of addressing and improving local environmental management practices. The environmental impacts resulting from monazite processing has seen some investigation due to the high concentration of radioactive material contained within the mineral (particularly thorium and uranium). The historical disposal of these radioactive wastes has caused long term environmental groundwater pollution in Brazil [3, 4] where wastes from the decomposition of monazite were disposed in (direct contact with) soil. Recently, impacts of the occupational radiation exposure in monazite processing facilities in India have also been investigated [1].

In spite of past environmental studies there is an incomplete understanding of environmental impacts resulting from the processing of monazite for recovery of rare earths. The present study was aimed at improving this knowledge by conducting a LCA of rare earths resulting from this production route. Improving the breadth of the understanding is paramount and a number of impact categories was investigated including gross energy requirement (GER), global warming potential (GWP), water consumption, material resource consumption, toxicity and ionising radiation. Developing improved understanding of these types of environmental impacts associated with rare earth production is critical for downstream evaluations of processes and products containing rare earth minerals.

Methodology

A LCA model was selected as the most suitable environmental tool available to study the environmental effects of rare earth production from monazite. The LCA was conducted based on ISO14040 and ISO14044 [5, 6].

Goal, Scope and Functional Unit

The overall goal of the study was to improve the understanding of environmental impacts resulting from the processing of monazite currently conducted worldwide in the production of rare earth elements. The study, therefore, was specified as a 'cradle-to-gate' LCA, as only the production process was included in the scope. A number of limiting assumptions were made in defining the monazite deposit. These assumptions were necessary to fully specify the processing path followed to produce rare earths and to generate usable results. The boundary and simplified flowsheets are shown in Figure 1. The solvent extraction processes consisted of an organic medium which is mixed with the aqueous rare earth solution in multiple stages (extraction) to selectively extract rare earths into the organic phase. The rare earths are then recovered by further mixing with aqueous solutions of acid (stripping). There were variations in the processing of individual rare earths. The majority of inventory data for the flowsheets were collected from the open literature [7].

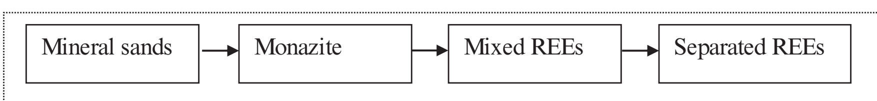

Figure 1: Boundary for life cycle based impact assessment.

Results and Discussion

Grouping and presentation of results

Data relating to global warming potential, gross energy requirement and water consumption have been presented graphically.

In the production stages, mixed REEs were assumed to be formed as oxide or chloride flakes for further separation. Due to the nature of the allocation (by mass), identical results across all impact categories were observed for rare earths sharing flowsheets regardless of individual concentration. For this reason the 15 rare earths will be grouped into nine rare earth groups as listed below under groups:

- Lanthanum (La)
- Cerium (Ce)
- Praseodymium (Pr)
- Neodymium (Nd)
- Samarium (Sm) and gadolinium (Gd)
- Europium (Eu)
- Terbium (Tb) and dysprosium (Dy)
- Holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu)
- Yttrium (Y)

Global warming potential (GWP)

The global warming potential for the production of rare earths from monazite is presented in Figure 2. Tthe production of thermal energy and electricity specified for this study were natural gas and coal, respectively. As the study was aimed at presenting a generalised LCA for worldwide monazite processing, these sources were taken to be the most representative and applicable for the majority of global monazite and rare earth processing facilities. The highest GWP resulting from yttrium production (200 kg CO_2e/kg) is largely due to the large electricity consumption for the production of this rare earth and production of ammonium thiocyanate.

Gross Energy Requirement (GER)

Energy consumption in the production of rare earths is presented in Figure 3. Similarly to GWP, yttrium shows the highest GER (3400 MJ/kg) are due to high electricity consumption and ammonium thiocyanate production. The consumption of coal and natural gas are generally associated with electricity and thermal energy, respectively. However production of chemical reagents also contributes somewhat to the use of these energy resources.

Water consumption

The consumption of water in rare earth production from monazite is shown in Figure 4. One result of interest is the high water consumption associated with production of the inert nitrogen atmosphere for europium production. Nitrogen is required to evacuate oxygen and atmospheric moisture to prevent re-oxidation of europium to elicit good separation of this rare earth. The highest water consumption observed for all rare earths was again yttrium (29,900 kg/kg) due to the high energy and chemical reagent consumption.

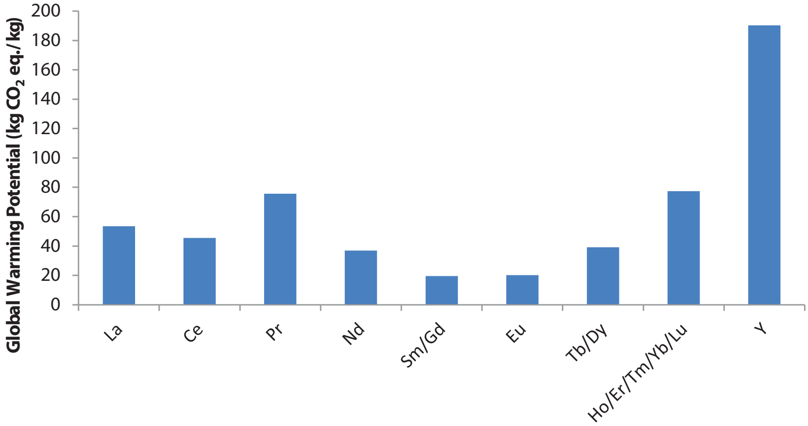

Figure 2: Estimated global warming potential associated with production of individual REEs.

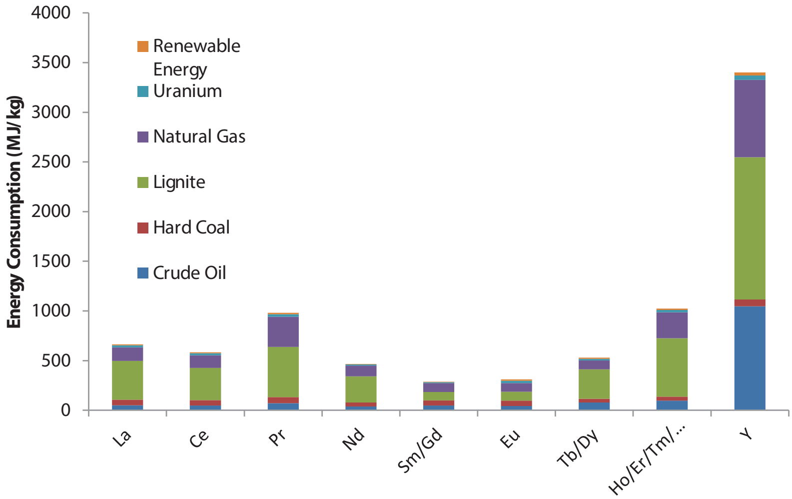

Figure 3: Estimated energy consumption associated with production of individual REEs (in x-axis).

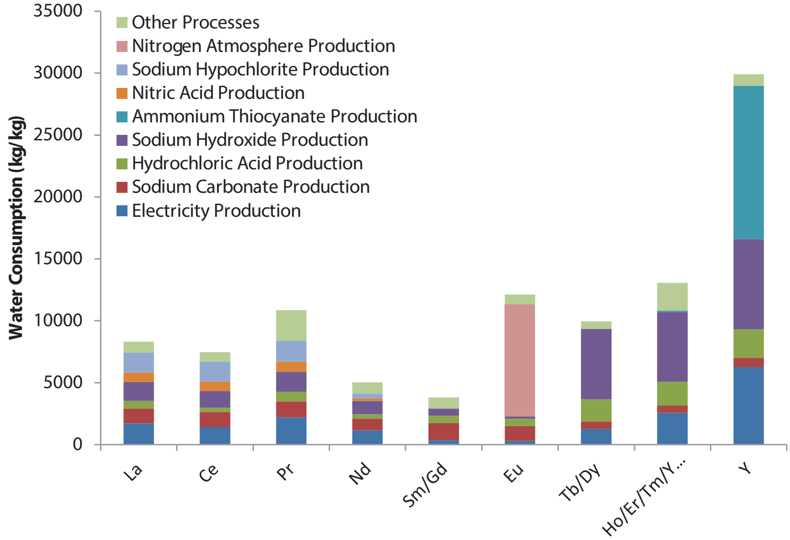

Figure 4: Estimated water consumption associated with production of individual REEs.

<u>Other impacts</u>

Table I contains the LCA results for the remaining impact categories investigated, namely mineral, fossil and renewable resource consumption; solid waste burden (SWB); human, freshwater and marine toxicities; and ionising radiation production.

Table I. Estimated impacts associated with individual REE.

Rare Earth	Resource Consumption	Solid Waste Burden	Human Toxicity	Freshwater Ecotoxicity	Marine Ecotoxicity	Ionising radiation
	kg/kg	kg/kg	kg 1,4 DB_e/kg	kg 1,4 DB_e/kg	kg 1,4 DB_e/kg	GBq/kg
La	960	450	1.31	4.0×10^{-3}	3.4×10^{-3}	7.45
Ce	690	370	1.08	3.7×10^{-3}	3.0×10^{-3}	7.50
Pr	1,360	570	1.67	6.2×10^{-3}	4.5×10^{-3}	7.86
Nd	610	300	0.83	2.7×10^{-3}	2.3×10^{-3}	5.75
Sm-Gd	300	120	0.56	2.7×10^{-3}	1.7×10^{-3}	8.51
Eu	370	120	0.61	2.7×10^{-3}	1.8×10^{-3}	7.43
Tb-Dy	780	330	1.38	3.9×10^{-3}	3.3×10^{-3}	3.62
Er-Ho-Tm-Yb-Lu	2,190	650	2.09	5.5×10^{-3}	5.1×10^{-3}	3.57
Y	3,310	1,560	4.27	1.0×10^{-2}	1.6×10^{-2}	4.63

Resource consumption was taken to be the raw materials used in rare earth production not including water resources. The majority of this impact category was comprised of minerals, soil and rock sourced for production of energy and chemical reagents. Other impact categories were included to further investigate the influence of the lesser occurring resources with properties leading to large impacts in other categories.

Conclusions

The results indicate that rare earth production from monazite produces impacts far greater in magnitude than any other metals currently investigated with a LCA. This is due to the large and complicated flowsheet with high energy consumption associated primarily with numerous solvent extraction stages and high chemical consumption due to the inherent difficulty in separating the individual rare earth elements. The GWP of titanium from the Becher and Kroll process is 35.7 kg CO_2e/kg [8] while results from this study indicate an average GWP of 65.4 kg CO_2e/kg for monazite processing. Similar results are seen for the GER (361 MJ/kg for titanium, 917 MJ/kg rare earth average) and SWB (351 kg/kg for nickel via hydrometallurgical processing [8], 497 kg/kg REs average). It is a reasonable assumption that all other impact categories investigated also display far higher impacts for rare earths than for other commodity metals. This study represents a starting point for further research into investigation of environmental effects resulting from rare earth production. Building a knowledge base of the rare earth minerals may assist in decision making for further development of the rare earth industry, and result in cleaner production of these industrially important metals.

Acknowledgements

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