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Comparison of dysprosium production from different resources by life cycle assessment



Petra Zapp^{a,*}, Josefine Marx^a, Andrea Schreiber^a, Bernd Friedrich^b, Daniel Voßenkaul^b

^a Institute of Energy and Climate Research—Systems Analysis and Technology Evaluation (IEK-STE), Forschungszentrum Jülich, Jülich D-52425, Germany

^b Institute of Process Metallurgy and Metal Recycling (IME), RWTH Aachen University, Intzestraße 3, Aachen D-52056, Germany

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ABSTRACT

Rare earth elements (REEs) are essential for low carbon technologies. Production of dysprosium (Dy) is mostly induced by rare earth magnets demand (approximately (approx.) 95% of total demand). It is almost exclusively supplied by ion adsorption clays (IACs) of Southern China. Other sources, such as bastnaesite/monazite or eudialyte ores, are also conceivable. Bastnaesite/monazite ores usually show low dysprosium contents. So far, hardly any REEs from eudialyte ores have been processed. The Norra Kärr deposit (Sweden) is one of the largest, highest grade, non-Chinese heavy REE deposits in Europe. Almost all studies on environmental effects of REEs production investigate the bastnaesite/monazite route. Recently, a first life cycle assessment (LCA) of IAC in-situ leaching was published. The present study broadens the scope firstly by including additional beneficiation and separation processes and subsequent production of the single metal dysprosium. Secondly, a comparison of the environmental performance of three production routes from different resources, IAC, bastnaesite/monazite and eudialyte is investigated. The results show that the environmental performance based on eudialyte is the best. The results of IAC and bastnaesite/monazite routes are comparable, but only for low amounts of leaching agent for IACs. For all three minerals freshwater ecotoxicity, human toxicity as well as eutrophication marine and freshwater are important environmental effects. In case of IAC marine eutrophication has the largest share due to in-situ leaching. This paper allows for the first time a straight comparison of Dy production based on three different minerals due to a consistent methodological frame, basic assumptions and parameters.

1. Introduction

Many rare earth elements (REEs) are used in low carbon technologies, today. Among them, especially the more valuable heavy rare earth elements (HREE, gadolinium – lutetium) are critical resources, including both the supply risks and the vulnerability of a system to a potential supply disruption (Erdmann and Graedel, 2011). Modern electrical generators and motors for hybrid and electric vehicles, wind turbine generators or hard disc drives require dysprosium (Dy). Nearly 95% of the total Dy demand accounts for the use in permanent magnets (Hoenderdaal et al., 2013).

Dysprosium, such as most HREEs, are currently almost exclusively supplied by ion adsorption clays (IACs) located in seven provinces in the south of China, distributed over numerous small deposits (Kanazawa and Kamitani, 2006; Yang et al., 2013). IACs are a result of lateritic weathering, predominantly of granites. Suffering strong chemical and biological weathering REEs were adsorbed mainly on the surface of clay minerals at ion state under warm and moist weather. IAC deposits account for approx. 35% of Chinese REE production

(Papangelakis and Moldoveanu, 2014). Together with Chinas biggest REE mine in Bayan Obo (Inner Mongolia) they represent 80% of the world production of REEs (Schüler et al., 2011). In Bayan Obo a bastnaesite/monazite ore is mined with a mining rate of $1.0E + 07$ ton per year. This deposit was formed by hydrothermal replacement of the carbonate rocks of sedimentary origin (Kanazawa and Kamitani, 2006). The ore bodies are different zones with iron rich cores. The main zones are riebeckite, fluorite and dolomite (Drew et al., 1990). Mainly light rare earth elements (LREEs) are processed but also a HRE oxide fraction is produced. As a third option to provide Dy a possible European production based on the mineral eudialyte has been proposed. Eudialyte is a rare, cyclosilicate mineral, which is found in 191 deposits (Friedrichs and Meyer, 2017; Mindat.org). Up to now virtually no eudialyte processing for REEs takes place. However, a huge advantage compared to the other RE minerals is the high share of HREEs (up to 50% of total rare earth oxide (TREO)) in combination with low radioactivity.

This study compares the environmental effects caused by the production routes corresponding to these three minerals, Chinese IACs, Chinese bastnaesite/monazite and Swedish eudialyte, focusing on the

* Corresponding author at: Institute of Energy and Climate Research—Systems Analysis and Technology Evaluation (IEK-STE), Forschungszentrum Jülich, Jülich D-52425, Germany.
E-mail address: p.zapp@fz-juelich.de (P. Zapp).

Table 1
Main parameters of the process chains compared.

Parameter	Ion adsorption clay (IAC)	Bastnaesite/Monazite (B/M)		Eudialyte
Location	China, southern provinces	China, Inner Mongolia, Bayan Obo/Baotou		Sweden, south central, Norra Kärr
TREO in crude ore	0.15%	6.22%		0.59%
TREO in concentrate	Not applicable	Bastnaesite concentrate 55.6% Monazite concentrate 34.1%		2.7%
Beneficiation yield	–	12.6% Zhang and Edwards (2013) 6% Zhang and Edwards (2013)		61.6%
Leaching yield	67.5% ^a	96.6%		96.6%
Solvent extraction yield	97.2%	97.2%		97.2%
HREE in REO	23.9%	1.2%		53.5%
Dy content in REO	2.52%	0.06%		5.26%
ton ore/ton REO ^b	approx. 1015	approx. 220		approx. 290
ton ore/ton Dy ^b	40,873	265,000		5472
t ore/t Dy calculated by using economic allocation	10,846	1230		502
ThO ₂ concentration (ore)	0.005%	0.032%		0.0026%
U ₃ O ₈ concentration (ore)	0.005%	0.002%		0.0018%

^a yield of in-situ leaching and precipitation with ammonium bicarbonate.
^b the values are calculated based on ore concentration and losses along the process chains.

example of Dy. Several studies have approached the topic of environmental consequences related to REE production especially in China in a more general way (Haque et al., 2014; McLellan et al., 2013). For more detailed environmental evaluations of RE processing some life cycle assessment (LCA) studies have been conducted in the last few years (Adibi et al., 2014; Koltun and Tharumarajah, 2014; Sprecher et al., 2014; Zaimes et al., 2015). Almost all of them rely on old data (1990ies) from the Mountain Pass mine (U.S.) or on deduced data for Bayan Obo (Zhao and Navarro, 2014). Additionally, two LCAs considering REO production from IACs have been published recently (Lee and Wen, 2017; Vahidi et al., 2016).

For the first time our approach allows a comparison of the three RE process routes due to consistent frame conditions such as system boundaries, level of detail, inclusion of waste and waste water treatment or allocation procedures. The results are not meant for direct comparison on single processes level (e.g. dry digestion versus roasting), because the type of ores and the ore grades are different at all production sites. Therefore, the entire process chains as described in the following must be taken into account.

2. Dysprosium production

The three different minerals demand different processing procedures. From the beginning of the process chain up to the dissolved RE chloride the processing varies quite significantly. While the processing from IACs is described explicitly in the following, a detailed description of the production from bastnaesite/monazite or eudialyte has recently been published by the authors (Schreiber et al., 2016). Mining activities in Bayan Obo representing the bastnaesite/monazite mineral, beneficiation, cracking and separation in Baotou as well as tailings and sludge treatment are considered. As average value for the various ore bodies located in Bayan Obo a total REO content of 6.22% in the bastnaesite/monazite ore with a share of 0.06% Dy is assumed. Based on a prefeasibility study for the Swedish eudialyte deposit in Norra Kärr (GBM, 2015) a REO content of 0.59% in the ore with a share of 5.3% Dy is assumed. Table 1 presents the most important mineral and process

parameters of the three process chains. In the following, the process chains for ion adsorption clays and bastnaesite/monazite are abbreviated by IAC and B/M.

The REE concentration and the share of elements in the IACs is calculated following a study analysing four Chinese IAC deposits (Bao and Zhao, 2008). The main components are silica and aluminium oxide. The concentration of HREEs is much higher than in B/M ores. Table 2 shows the assumed compositions for all three minerals.

Although the grade of REEs in IAC ores seems low, the ion state of REEs makes extraction and processing easier. While B/M and eudialyte use a classical mining and beneficiation route, for IACs in-situ leaching has become the major technology since 2011, replacing heap leaching and tank leaching due to its better environmental performance (Yang et al., 2013; Zhao and Navarro, 2014). Therefore, this technology is chosen as representative for the study. An overview of the analysed IAC process chain compared to Dy production from the other two minerals is given in Fig. 1. The conventional mining and beneficiation processes (crushing, grinding, separation and flotation) are missing in case of IAC. In contrast to the other two routes, the IAC process chain starts directly with in-situ leaching by ammonium sulphate. The B/M ore from Bayan Obo requires a roasting process using sulphuric acid and the eudialyte mineral is cracked by a dry digestion using hydrochloric acid (Voßenkaul et al., 2017). The RE sulphates from B/M or IAC are converted to RE carbonates by reaction with ammonium bicarbonate before they are converted to RE chlorides by leaching with hydrochloric acid. Further processing of RE carbonates takes place in the same way for all three routes (Fig. 1).

The processes are grouped in the three sections RE concentrate, Dy oxide and Dy metal representing major products along the value chain.

2.1. In-situ leaching of IAC and precipitation by ammonium bicarbonate

Initial to in-situ leaching, injection wells are drilled with an assumed diameter of 0.8 m, a depth of 1.5–3 m and a distance between each leaching hole of 2–3 m (Yang et al., 2013). Then, a leaching solution, using ammonia sulphate as leaching agent, is pumped through

Table 2
Composition of rare earth elements of the different resources (%).

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y
IAC	29.8	13.8	5.9	22.4	3.8	0.35	3.14	0.45	2.5	0.5	1.4	0.2	1.4	0.2	14.1
B/M	24.5	49.3	5.8	17.8	0.9	0.2	0.7	0.08	0.06	–	–	–	–	–	0.1
Eudialyte	8.9	20.2	2.7	11.2	3.1	0.4	3.6	0.7	5.3	1.2	3.7	0.5	3.4	0.5	34.6

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