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Research article

Environmental life cycle assessment on the separation of rare earth oxides through solvent extraction

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ABSTRACT

Over the past decade, Rare Earth Elements (REEs) have gained special interests due to their significance in many industrial applications, especially those related to clean energy. While REEs production is known to cause damage to the ecosystem, only a handful of Life Cycle Assessment (LCA) investigations have been conducted in recent years, mainly due to lack of data and information. This is especially true for the solvent extraction separation of REEs from aqueous solution which is a challenging step in the REEs production route. In the current investigation, an LCA is carried out on a typical REE solvent extraction process using P204/kerosene and the energy/material flows and emissions data were collected from two different solvent extraction facilities in Inner Mongolia and Fujian provinces in China. In order to develop life cycle inventories, Ecoinvent 3 and SimaPro 8 software together with energy/mass stoichiometry and balance were utilized. TRACI and ILCD were applied as impact assessment tools and LCA outcomes were employed to examine and determine ecological burdens of the REEs solvent extraction operation. Based on the results, in comparison with the production of generic organic solvent in the Ecoinvent dataset, P204 production has greater burdens on all TRACI impact categories. However, due to the small amount of consumption, the contribution of P204 remains minimal. Additionally, sodium hydroxide and hydrochloric acid are the two impactful chemicals on most environmental categories used in the solvent extraction operation. On average, the solvent extraction step accounts for 30% of the total environmental impacts associated with individual REOs. Finally, opportunities and challenges for an enhanced environmental performance of the REEs solvent extraction operation were investigated.

1. Introduction

Rare earth metals and alloys play substantial roles in the development to a low-carbon, sustainable economy (Binnemans et al., 2013). Rare Earth Elements (REEs) comprise the lanthanide series of elements in the periodic table i.e. from lanthanum (La) to lutetium (Lu), together with yttrium (Y) and scandium (Sc) which have comparable physical and chemical characteristics (Castor and Hedrick, 2006; Haque et al., 2014). Owing to REEs distinctive structures (their 4f orbitals) and unique chemical/mechanical properties, they have been used in many high-tech products and industries such as hybrid vehicles, wind turbines, optics, fluorescent lightning, catalysts, lasers, rechargeable batteries, military systems, cellphones, and ceramics (Eggert et al., 2008; Fouquet and Martel-Jantin, 2014; Hu et al., 2017).

Mining and extraction of REEs is primarily implemented in China where almost 85% of the global demand is supplied (Hellman and Duncan, 2014). Fig. 1 demonstrates the schematic of major operation steps required to produce individual rare earth elements, mischmetals, and alloys from rare earth reserves. It should be noted that there are two main types of rare earth ores being extracted in China i.e. ion-adsorption clays (predominantly in Southern China) and monazite and bastnasite mixture (predominantly in the Bayan Obo area in Inner Mongolia). At Bayan Obo mine, monazite and bastnasite (with rare earth oxide, or REO, content 4–7%) containing iron ores are mined through open-pit mining. After magnetic separation of iron ores, bastnasite and monazite concentrate with REO content 50% are recovered from tailing via flotation (Zhang and Edwards, 2012). The ore concentrate is roasted with sulfuric acid

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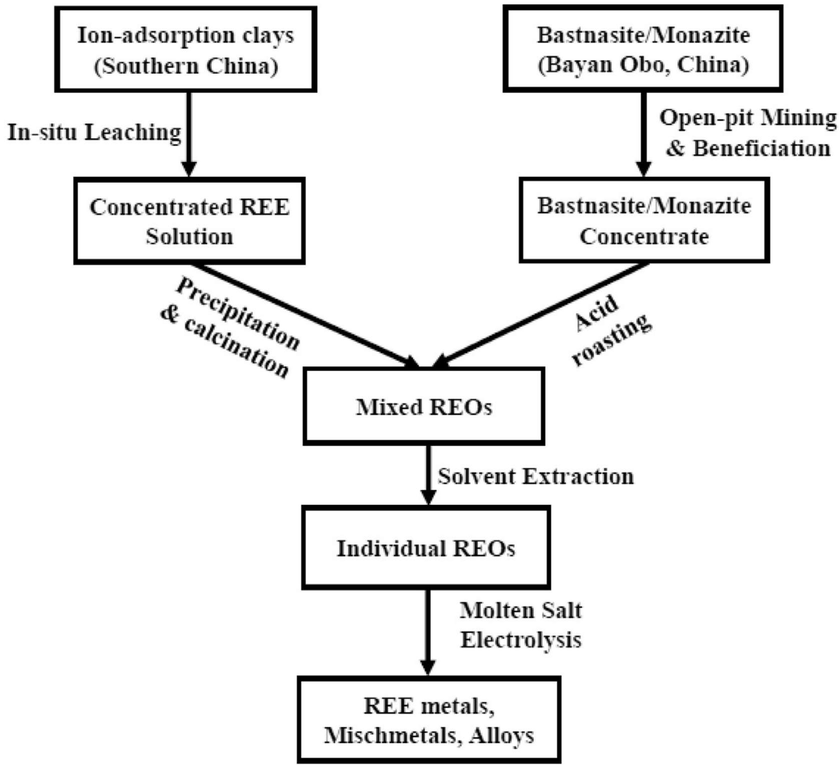

Fig. 1. Schematic of hydrometallurgical processes to produce individual rare earth metals, mischmetals, and alloys.

(called cracking) under 550–650 °C, and residue after roasting is leached with hydrochloric acid to produce rare earth chlorides. To produce individual REOs of purity higher than 99%, the solvent extraction process is then performed and finally, the product goes through molten salt electrowinning to produce metals and alloys. Different from bastnasite and monazite (which are rare earth fluorocarbonate and rare earth phosphate, respectively), ion adsorption clays contain 0.02–1% of REOs but rare earths are in the form of ions. Extraction is usually done through in-situ leaching by ion exchange mechanism (Vahidi et al., 2016). Rare earth ions are precipitated out of the leaching solution by ammonium bicarbonate or oxalic acid and then calcined to produce mixed REOs and finally, solvent extraction and electrowinning processes can be applied to produce rare earth metals and alloys.

It should be noted that all the process steps shown in Fig. 1 involve intensive materials and energy consumption and have significant air/water/solid releases. Despite the fact that REEs are critical to many high-tech and green technologies, REEs production itself carries large environmental impacts. Recently, environmental damage caused by the REEs production has gained significant attention. For instance, due to the different environmental destruction incurred during the REEs production, the Mountain Pass mine located in California which had dominated the REEs market in the 1970s and 1980s closed in 2002 (Zhang, 2013; Fuerstenau, 2013). So, a thorough sustainability assessment can be the first step to minimize the environmental burdens related to REEs production and the most popular method in sustainable product development is Life Cycle Assessment (LCA) (Evans et al., 2009; Golev et al., 2014; Adibi et al., 2014).

A handful of LCA investigations on the production of REEs have been published during recent years and almost all of them used Ecoinvent dataset (Ecoinvent v2.0 and following v2.2 and v3.0) (Althaus et al., 2007; Adibi et al., 2014; Hu et al., 2017). It should be noted that Ecoinvent dataset covers REOs production processes from mining to solvent extraction and while the databases on other processes seem reasonable, the solvent extraction process suffers from insufficient data quality. For example, due to lack of process information with regard to solvent extraction, generic organic chemicals were selected as surrogates and the electricity consumption for the vegetable oils solvent extraction was assumed. Also, the consumption of organic solvent as extractant was approximated according to Mountain Pass production data in the 1980s. Although there are several limitations with the Ecoinvent datasets, as mentioned earlier, they have been widely used in LCA investigations on the REEs products. As an illustration, an LCA of 63 different elements comprising all the lanthanide series was conducted by Nuss and Eckelman (2014) and it was shown that the mining/physical beneficiation steps carry smaller environmental burdens than cracking/solvent extraction steps for REOs production. Based on the Chinese literature regarding the Bayan Obo bastnasite composition, Nuss and Eckelman (2014) re-allocated emissions and materials/energy to all the 15 rare earth oxides by using the default Ecoinvent dataset as well as the REO prices in 2010. In another investigation by Sprecher et al. (2014), a complete LCA on NdFeB permanent magnet production was carried out, and given the emphasis on neodymium element, an economic value based allocation was performed for environmental impacts of the solvent extraction operation.

The goal of this research is to address the limitations and uncertainties associated with the Ecoinvent 3 datasets on the solvent extraction process to produce individual REOs. Material and energy consumption data were gathered from major REEs separation facilities in Inner Mongolia and Fujian provinces in China. Instead of using surrogate, the synthesis and production of common organic extractants were also simulated to compile a unique life cycle inventory for the organic solution. This LCA study improves our understanding about environmental burdens of the solvent extraction operation of REEs and successively, helps us develop new separation techniques with enhanced environmental performance.