Resources, Conservation and Recycling 113 (2016) 1–11

Contents lists available at ScienceDirect

Resources, Conservation and Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

An initial life cycle assessment of rare earth oxides production from ion-adsorption clays

Ehsan Vahidi[a,b], Julio Navarro[c], Fu Zhao[a,b,c,*]

[a] Division of Environmental and Ecological Engineering, Purdue University, West Lafayette, IN, USA
[b] Ecological Science and Engineering Interdisciplinary Graduate Program, Purdue University, West Lafayette, IN, USA
[c] School of Mechanical Engineering, Purdue University, West Lafayette, IN, USA

ARTICLE INFO

Article history:
Received 5 November 2015
Received in revised form 9 May 2016
Accepted 17 May 2016
Available online 1 June 2016

Keywords:
Rare earth elements
Ion-adsorption clays
Life cycle assessment
In situ leaching

ABSTRACT

Rare earth elements (REEs) have found applications in the aerospace, automotive, consumer electronics and lighting industries, among others. A special class of REEs known as heavy rare earths (HREEs) is of particular importance to energy applications. With the growing clean energy technologies incorporating HREEs, it is valuable to examine their environmental emissions and energy requirements. Currently, extraction of HREEs is mainly carried out in China, where they are extracted mainly via open pit mining of bastnasite and/or monazite and leaching of ion-adsorption clays. Leach mining varies significantly from open pit mining technique in that the ores have much lower REE content but REEs stay as cations thus there is no need for physical and chemical beneficiation. To date limited life cycle assessment (LCA) studies have been done on REEs production and all of them are for the bastnasite/monazite route. This paper presents the first LCA of in-situ leach mining of REEs from ion adsorption clays in southern China. The function unit was defined as production of 1 kg of mixed rare earth oxides (REOs) of purity 92%. Ecoinvent 3.0 database was adopted for inventory analysis with material and energy flow information gathered from Chinese literature. To facilitate the use of results in U.S. and EU, TRACI and ILCD in SimaPro 8 were used for environmental impact assessment and cumulative energy demand was also considered as one additional category. The results showed that the environmental impacts for REOs derived from ion adsorption clays are similar in categories such as global warming and cumulative energy demand, but differs significantly in categories of eutrophication and acidification. Since the content of high value HREEs is much higher in ion adsorption clays, when economic value based allocation is used individual REO from in situ leaching has lower environmental impacts across all categories considered. With estimates of HREEs derived from ion-adsorption clays accounting for approximately 35% of the Chinese output, this LCA is a step towards getting a full understanding of the true environmental impact of technologies incorporating HREEs.

1. Introduction

Rare earth elements (REEs) are a body of 17 elements composed of the lanthanide group, atomic numbers (57–71), along with scandium (Sc, 21) and yttrium (Y, 39). REEs are typically grouped in two different categories: light rare earth elements (LREEs, atomic numbers 57–63), and heavy rare earth elements (HREEs, atomic numbers 64–71 plus yttrium 39) (Hurst, 2010). While it is included with the REEs, scandium does not fall into the category of LREEs or HREEs (Jordens et al., 2013). Due to their unique physical and chemical properties, REEs find wide applications in electronic, optical, magnetic and catalytic products (Bradsher, 2009; Greenfield and Graedel, 2013; Chancerel et al., 2015).

REEs are widely utilized in industrial sectors such as petroleum, agriculture, and metallurgy while they are becoming critical in many high-tech applications such as wind turbines, fluorescent lights, mobile phones, liquid crystal screen televisions, hybrid cars, and military systems (Song and Hong, 2010a,b; Adibi et al., 2014). Their importance in the growing field of green energy technology and high energy efficiency applications have led to many governments to classify some REEs as "critical materials" (Bauer et al., 2010; Tse, 2011; United States Geological Survey, 2014; Wübbeke, 2013; Papangelakis and Moldovenau, 2014), and strategies such as material substitution, diversifying supplies, and recycling have

---

[*] Corresponding author at: School of Mechanical Engineering, Division of Environmental and Ecological Engineering, Purdue University, West Lafayette, IN, USA.
E-mail address: fzhao@purdue.edu (F. Zhao).

http://dx.doi.org/10.1016/j.resconrec.2016.05.006
0921-3449/

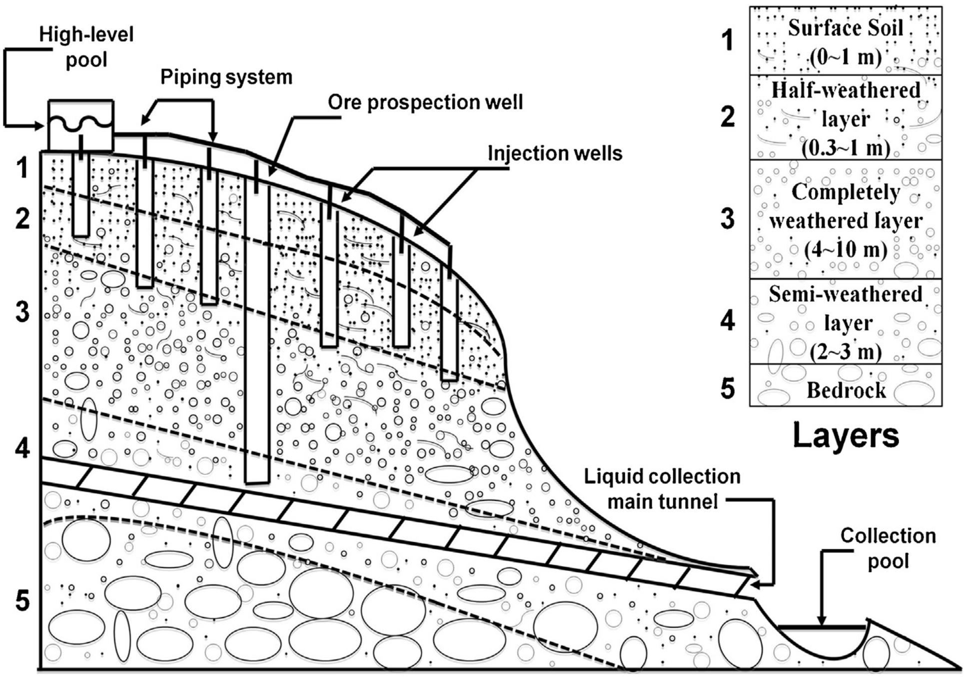

Fig. 1. Typical layers of mining site for ion adsorption clays (adapted from Zou, 2012).

been proposed (Bauer et al., 2010; Machacek et al., 2015; Wu et al., 2014; Ferella et al., 2016).

Extraction of REEs is mainly carried out in China (Hellman and Duncan, 2014), where they are extracted via either open-pit mining of bastnasite and monazite (mainly in the Bayan Obo region in Inner Mongolia) or leaching of ion-adsorption clays (mainly in Southern China) (Kanazaw and Kamitani, 2006). China is currently producing over 95% of the world's total supply from its mines and this dominance may be a cause for concern because growing demand in China for REEs and some export restrictions would negatively affect United States and Europe as major consumers and importers of rare-earth products (Adachi et al., 2010; Kynicky et al., 2012; Jordens et al., 2013; USGS, 2014). According to China's Ministry of Environmental Protection (MEP, 2009) and the Chinese Society of Rare Earths (CSRE, 2002), China has 52 million tons of proved industrial reserves.[1] Compared with bastnasite and monazite, ion adsorption clays only account for a much smaller percentage of total REEs reserve of China (3% vs. 84%) (Schüler et al., 2011).

However, ion adsorption clays have different REE content from that of bastnasite and monazite. As shown in Table 1, for ion adsorption clays REE distribution varies significantly from location to location, but they all seem to have much higher content of some highly valuable HREEs than bastnasite and monazite. In addition, as the name implies, REEs present in ion adsorption clays are in the form of trivalent cations adsorbed on kaolin, which brings the relative ease of extraction (i.e., near the surface and unconsolidated).

Due to these reasons, ion adsorption clays represent an important source of REEs, especially HREEs (Chakhmouradian and Wall, 2012; Walters et al., 2011). In fact, approximately 35% of Chinese production of REEs is coming from ion-adsorption clays (Papangelakis and Moldoveanu, 2014; Yang et al., 2013). Although REEs are critical to many clean energy technologies, the mining, processing, and production of REEs require large energy and material consumption while generating significant air/water emissions and solid wastes. In fact, environmental damage is one of the major reasons cited by Chinese government for imposing export quota.

As the clean energy technology market grows, REEs demand is expected to increase (Binnemans et al., 2013; Hurst, 2010). This calls for a comprehensive examination of the environmental impacts associated with REEs (Li et al., 2014; Liao et al., 2014). To date the most widely used methodology for evaluating the environmental performance of a product or process is life cycle assessment, which holistically takes into consideration of resources consumption and environmental releases along all the life cycle stages (Guinée, 2002).

There have been many reports and studies on the environmental damages caused by the air or water emissions as well as solid wastes from REEs production. However, most of these studies only cover a small portion of the REE life cycle. LCA studies on REEs are very limited and all studies are for the processing of bastnasite (at Mountain Pass, CA) or bastnasite-monazite (at Bayan-Obo, China) (See Navarro and Zhao, 2014 for a review). The datasets in the Ecoinvent database are the first investigation on rare earth oxides where environmental impacts of the Bayan Obo pathway is examined (Althaus et al., 2007). The Bayan Obo pathway was also examined by Koltun and Tharumarajah (2014) where a two-step allocation procedure was proposed to deal with the iron/REE comining issue. Moreover, Sprecher et al. (2014) conduct an LCA on NdFeB magnets, which covers all the process steps involved from ore mining to Nd metal production using Ecoinvent database.

All of the studies discussed above are based on Mountain Pass production data from 1990s or information from Chinese literature on Bayan Obo pathway or a combination. For many process steps, no information is available and surrogates are commonly used. For example, mining of REE bearing ores is approximated by open pit mining of iron ores. Both mass based and revenue based allocation have been adopted to deal with the multi-products issues associated with several REE processing steps. It has also been pointed out that better environmental impact assessment method or indicators may be needed for REE production (Adibi et al., 2014).

While there have been an increasing number of investigations focused on the LCA of REO production from bastnasite and

---

[1] "The part of the reserve base which could be economically extracted or produced at the time of determination" (USGS, 2008).