Responsible sourcing of rare earth elements

UNIVERSITY OF EXETER

Submitted by Robert Pell to the University of Exeter as a thesis for the degree of
Doctor of Philosophy in Mining and Minerals Engineering

I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University

Signature ....

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Abstract

Rare earth elements (REE) are considered to be critical raw materials due to the combination of their high importance in a range of low-carbon technologies and the concentration of supply, which is dominated in China. The REE industry has a legacy of environmental damage and the mining, processing, and separating out of the REE requires a significant quantity of energy and chemicals. Life cycle assessment (LCA) is a method to quantify the environmental impacts of a product or process and can be applied to the raw materials production sector. This thesis presents how LCA can be applied for REE projects in development. The results can help identify environmental hotspots for a project, and analyse alternatives to help reduce the environmental impacts of REE production.

Mineral processing simulation are commonly used in REE project development and data generated from these studies can be used to carry out a LCA. This approach was presented with the Songwe Hill REE project in Malawi. The mineral processing simulation output data which includes energy and chemical flows is used as the life cycle inventory data (LCI) and calculated with characterization factors to generate life cycle impact assessment (LCIA) results such as global warming potential. This data can inform future engineering studies or process simulations.

REE projects, like all mining projects, can last decades and extract different ore compositions throughout this life-time. A method is presented to generate temporally explicit LCA results. The Bear Lodge REE project, which is in the prefeasibility stage of development and located in the United States, is used as a case study. LCIA results highlight that grade and mineralogy can influence the LCIA results. The relationships between environmental impacts and grade and mineralogy are explored.

Thirdly, a method is presented to include LCA data in the mine scheduling process. LCIA data can form an environmental block model alongside the economic block model for a deposit. These spatially explicit data can then be used as a constraint within long-term mine scheduling simulations. The results indicate that significant reductions in global warming impact can be achieved at a small economic cost.

Finally advances to the current resource depletion impact categories are achieved, advancing the previous methods which neglect socio-economic, regulatory and geopolitical aspects, nor do they include functionalities such as material recycling or reuse that control the supply of raw materials. I examine the economic scarcity potential (ESP) method and make advances based on recent developments in material criticality. ESP criticality scores for 15 REE with the addition of Au, Cu,

platinum-group metals (PGM), Fe and Li are measured and a case study is presented to for the inclusion of REE ESP scores for the materials that form a NdFeB permanent magnet.

This thesis has a focus on utilising LCA in a proactive manner and incorporating it into the planning stages of REE projects to encourage responsible production of REE.

Contents

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Acronym list

- **BGS** British Geological Survey
- **Ce** cerium
- **CSM** Camborne School of Mines
- **DBS** direct block scheduling
- **Dy** dysprosium
- **Er** erbium
- **Eu** europium
- **Gd** gadolinium
- **GWP** global warming potential
- **HREE** heavy rare earth elements
- **IOC** ion-adsorption clays
- **La** lanthanum
- **LCA** life cycle assessment
- **LCC** life cycle costing
- **LCI** life cycle inventory
- **LCIA** life cycle impact assessment
- **LREE** light rare earth elements
- **Nd** neodymium
- **Pr** praseodymium
- **REE** rare earth elements
- **REO** rare earth oxides
- **Sm** samarium
- **Tb** terbium
- **Th** thorium
- **TREE** total rare earth elements
- **TREO** total rare earth elements
- **U** uranium
- **USGS** United States Geological Survey

Declaration

I hereby declare that this thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the thesis.

This thesis includes 3 original papers published in peer reviewed journals and 1 unpublished publication. The main research theme is rare earth elements, life cycle assessment, mine planning and criticality.

The inclusion of co-authors reflects the fact that the work came from active collaboration between researchers and acknowledges input into team-based research.

In the case of chapters 3, 4, 5 and 6 my contribution to the work involved the following:

Thesis chapter	Publication title	Publication status	Student contribution	Co-author name(s)
3	Mineral processing simulation based environmental life cycle assessment for rare earth project development: a case study on the Songwe Hill project	In review	75%	Frances Wall Xiaoyu Yan Jinhui Li Xianlai Zeng
4	Temporally explicit life cycle assessment as an environmental performance decision making tool in rare earth project development	Published (Minerals Engineering Volume 135, May 2019, Pages 64-73)	75%	Frances Wall Xiaoyu Yan Jinhui Li Xianlai Zeng
5	Environmental optimisation of mine scheduling through life cycle assessment integration	Published (Resources, Conservation and Recycling Volume 142, March 2019, Pages 267-276	70%	Laurens Tijsseling, Luke W. Palmer, Hylke J. Glass, Xioayu Yan, Frances Wall, Xianlai Zeng, Jinhui Li,
6	Applying and advancing the economic resource scarcity potential (ESP) method for rare earth elements	Published Resources Policy Available online 25 October 2018	75%	Frances Wall, Xiaoyu Yan, Gwendolyn Bailey

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Chapter 1

Research Objectives and Methodology

1.1 Motivation

Rare earth elements REE are considered by many to be the most critical metals in import dependent countries outside China. This is because China accounts for 88% of the world production [USGS, 2016]. REE also have significant economic importance because of their myriad of uses in modern technology, especially in the low-carbon economy. REE demand is forecast to grow for the short and medium term, and it is likely that mining will have to fill this demand gap.

There is a legacy of environmental damage associated with historic and current REE production [Dutta et al., 2016], and a dissonance is forming between the environmentally damaging supply of REE, and their uses in the low-carbon economy. REE production impacts can include radioactive contamination of terrestrial and aquatic systems, emissions to the atmosphere and waterways, and solid waste that requires management, as well as high levels of energy and material consumption. As new mining projects advance through the development stages it is important to consider the potential environmental impacts that these new projects might have.

Many of the REE projects in the future will have unique mineral compositions and require novel processing flowsheets. There is an opportunity to incorporate environmental life cycle thinking during these development stages; analysing the environmental performance of different production scenarios and processing options. LCA has previously been applied for mining operations and REE production, but has commonly been used as a retrospective tool. The benefits of applying this to projects in development is that LCA analysis can be applied and insights can be used to make an updated project plan. Consequently, a focus of this thesis is applying LCA in the development stages of mining and mineral processing projects.

1.2 Research Objectives

In response to these challenges the objectives of this study are:

1. Establish that LCA can be completed for a REE project using data generated from a REE pre-feasibility study.

2. Develop and apply a temporally explicit LCA for a REE project, highlighting environmental hotspots, and allowing for a consideration of improving the efficiency of the project.

3. Establish if early stage simple LCA can embedded into mine planning and scheduling.

4. Develop a methodology to highlight criticality and supply risk alongside the resource depletion category within LCA.

1.3 Methodology

To fulfil these aims this thesis will introduce the main concepts; REE, LCA, criticality, and mine scheduling. The literature review will also introduce how these topics overlap and can be combined. The main approach of this thesis will be utilising mainstream LCA software (GaBi), to perform LCA for REE projects in the pre-feasibility stage of development. This stage is selected as results generated during this phase can be implemented into project decisions. Particular case studies are selected because they were in the pre-feasibility stage of development, and data was available.

Each chapter introduces the particular methodology applied for that study. Songwe Hill, located in Malawi was used to apply the mineral processing simulation combined with LCA software. Bear Lodge, located in the United States was used as the case study for applying temporally explicit LCA for REE production.

LCA is a well established method to quantify the environmental burdens of a process system and the environmental impacts associated with all the stages of a product's life from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. In this thesis LCA is used to analyse the environmental cost of REE production from both Songwe Hill and Bear Lodge. The LCA software used was GaBi 7.0. Data from this computer based LCA tool developed by PE International was used alongside supplementary data sources such as Ecoinvent.

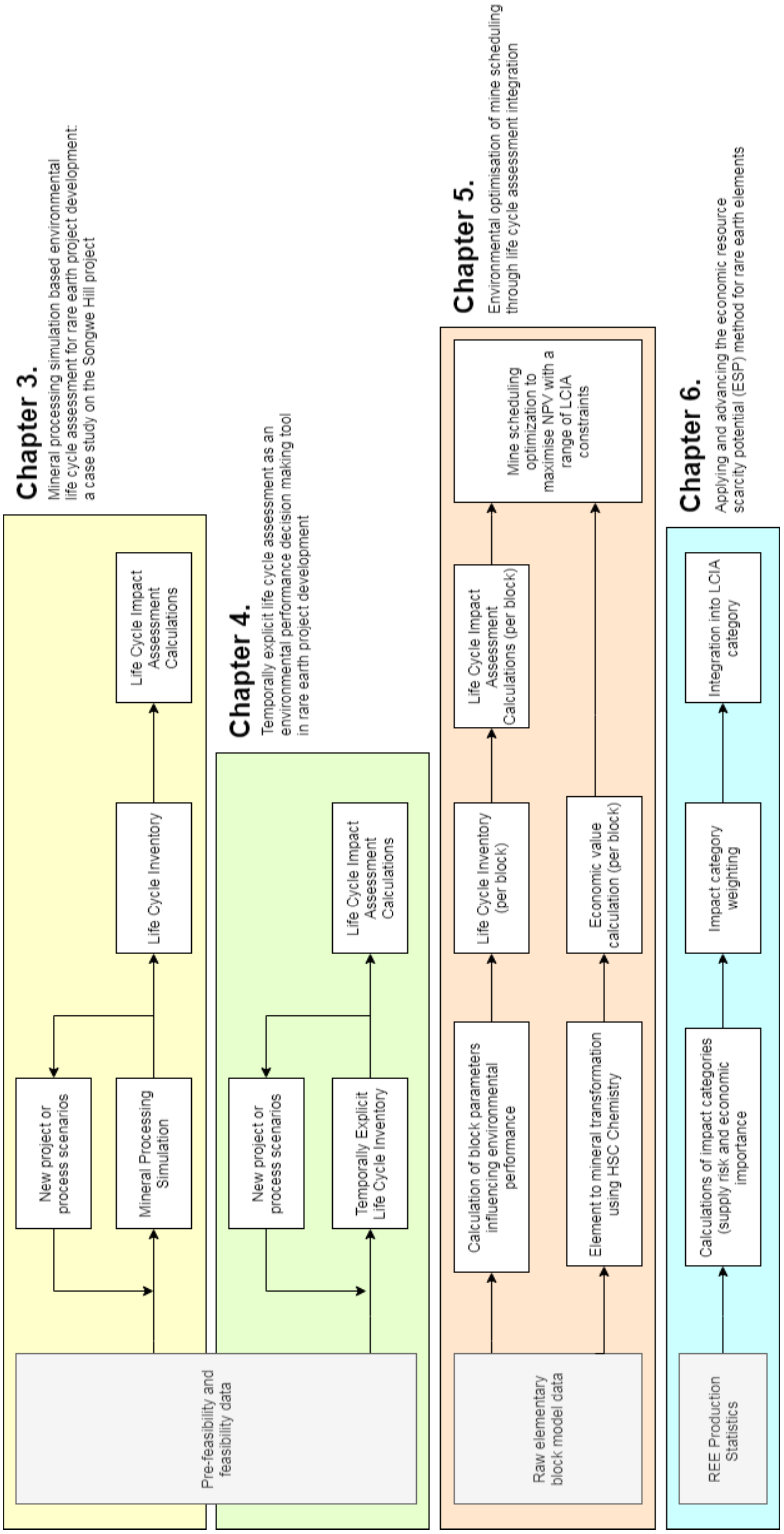

Figure 1.1: Overview of methodologies applied to this thesis

1.3.1 Software

A range of software packages were used to carry out and apply LCA in different project stages. Mineral processing simulations were complete using Outotec's HSC 7.1 and HSC-Sim, chemistry and mineral processing simulation software. The HSC-Sim is a process simulation program where the units are drawn on the flow sheet and the streams are connected according lab derived physical and chemical data. It is possible to have the output of the HSC-Sim stream feed the life cycle inventory data for the GaBi software through the use of a mapping tool in HSC. This allowed for the collection of data directly from the mineral processing simulation, which then allowed the connection of separate processes to create a complete process model in which all the external impacts can be taken into account, such as the transport and energy consumption. SimSched mine planning software was used for the mine planning work and was provided by MiningMath. This software was selected primarily because of the ability to apply environmental constraints in the mine scheduling simulation.

1.4 Thesis Structure

This thesis is presented in eight chapters. Chapter 2 is a literature review of the topics covered in this thesis, introducing REE, LCA, raw material criticality, and mine planning. Chapter 3 examines how mineral processing simulation can be linked with LCA to analyse the relationship between REE geology, mineralogy and environmental impact. Chapter 4 explains temporally explicit LCA, and highlights how impacts can vary over a project lifetime. Chapter 5 applies a method of including early stage LCA in the mine planning phase of a project. Chapter 6 explores REE criticality and highlights how this criticality score can be included as an impact indicator in a LCA.

Chapter 2

Literature review

2.1 Introduction

The REE have been identified as among the most 'critical' metals [Hayes and McCullough, 2018]. A number of technologies central to the transition away from fossil fuels and to a low carbon future require REE to build them. Individual elements or combinations from the family of 17 REE have uses in offshore wind turbines, direct drive motors in electric vehicles, low energy lighting, all computers, and many other applications all around us. This combination of growing demand and the dominant position of China in the production of REE has reinforced their critical status [Graedel et al., 2012].

Mining, processing and separation has caused significant environmental damage, and current methods to extract and separate REE requires a large amount of energy and chemicals[Dutta et al., 2016]. If we are to supply the REE to feed the future needs of low-carbon technologies, we need to develop approaches to ensure REE production is carried out in a responsible way. A number of REE deposits have been identified in recent years in various regions around the world and could be a source of REE for the global market in the coming years. There are a number of technical, economic, and geopolitical challenges associated with the development of these projects. However, it is important that as we examine the possibility of developing these deposits into mines, we consider the environmental impacts associated with the specific projects.

One such method to quantify environmental performance is by using the life cycle assessment approach (LCA). LCA is a tool that can assist decision-makers in evaluating the comparative potential cradle-to-grave, environmental impacts of their actions and for the decision makers and policy makers. LCA also has the advantage of assessing impacts and optimising without the shifting of impacts. For REE projects it can assist in evaluating decisions along the process chain so that decisions made at one point along the life cycle can have consequences elsewhere. LCA enables the estimation of the cumulative environmental impacts, often including impacts that go beyond the boundaries of traditional analyses such as those completed for an environmental impact assessment (EIA). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects and a more accurate picture of the true environmental trade-offs in product or process alteration or selection.

A significant proportion of this thesis relates to life cycle assessment methodologies and how they can be applied in different ways to generate useful data to reduce the environmental impacts associated with REE production. REE are introduced and placed in the global context along with the challenges that exist with responsible sourcing and supply risks.

This chapter is subdivided into four main sections.

- ***Rare earth elements*** (REE) are introduced and reviewed, describing different REE mineralogy, processing options, past and current production, demand, and uses of REE.

- ***Life Cycle Assessment*** (LCA) is introduced as a tool for quantifying environmental performance, providing an overview of LCAs that have been complete for REE production.

- ***Criticality*** is reviewed in a broad context, examining the methods employed for criticality studies and the results for REE in these studies.

- ***Mine Scheduling*** is reviewed, technologies and approaches explored, and put in context of responsible mining

2.2 Rare Earth Elements

The International Union of Pure and Applied Chemistry defines REE as a group of 17 chemically similar elements that includes the 15 elements in the lanthanide group, atomic numbers (57-71), with the addition of scandium (Sc, 21) and yttrium (Y, 39). [Goodenough et al., 2017]. The REE are often classified into light rare earth elements (LREE) and heavy rare earth elements (HREE), however, there is no universally accepted classification into these divisions. Throughout this thesis LREE refers to La, Ce, Pr, Nd, Pm, Sm, and Eu, which possess lower atomic numbers, and HREE to Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu which have higher atomic numbers. Y is grouped with the HREE due to its similar behaviour, ionic radius and charge [Chakhmouradian and Wall, 2012]. The terms rare elements and rare metals are often seen in literature but may refer to groups of elements other than REE. There is no generally accepted definition.

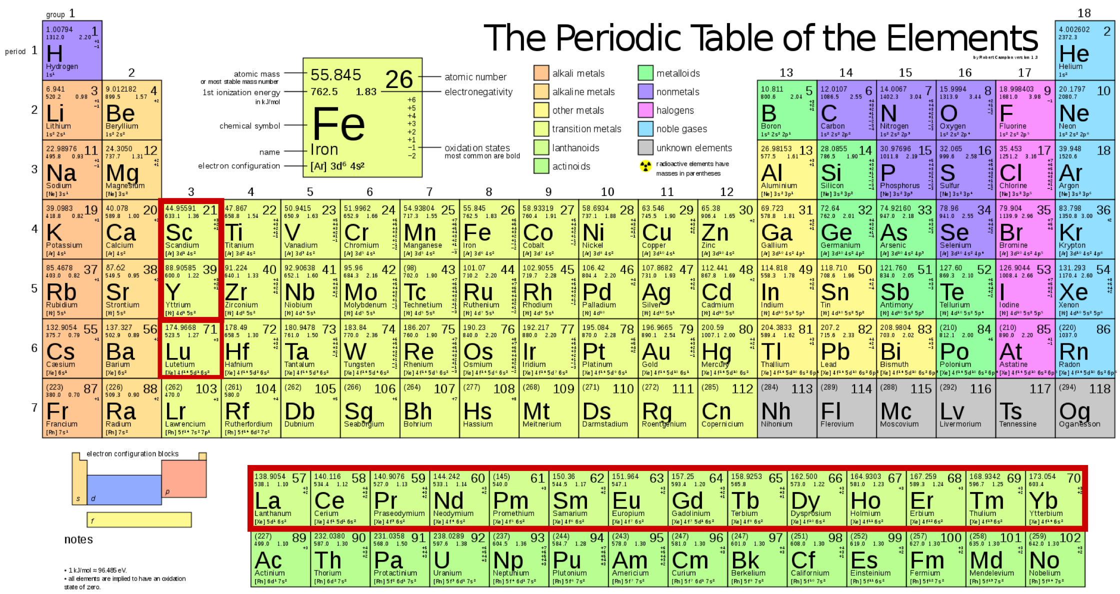

Figure 2.1: Rare earth elements highlighted on the Periodic Table [Daintith, 2014]

REE are not particularly 'rare' in the earths crust but are difficult to separate leading to the misleading name 'rare earths' [Rudnick and Gao, 2013]. The REE upper crustal abundance for Ce is 63 ppm and La is 31 ppm, similar to that of Cu (28 ppm). HREE are less abundant and Tm and Lu, which are the rarest REE, have crustal abundances of 0.30 ppm and 0.31 ppm respectively. These REE are still more abundant than precious metals such as Au (0.0015 ppm) or Ag (0.053 ppm) [Rudnick and Gao, 2013]. The odd atomic number REE are more abundant than the even atomic number REE, a phenomenon called the Oddo Harkins effect. Although REE are relatively abundant in the earth's crust, the fact that they (1) are only found in concentrated forms and (2) that when they are, the other similar REE, either LREE or HREE, will always be present and difficult to separate, mkaes them economically and technically challenging to obtain.

2.2.1 Rare Earth Elements

REE have similar electron configurations, but they also have distinctive physical and chemical properties that enable their use in a broad range of technologies [Crow, 2011, Voncken, 2016]. The number of uses for REE has increased substantially in recent years. In the 1960s the majority of REE were used in television screens, the petroleum industry and computer systems. Today, REE are used in both fluid and auto catalysts, in metallurgy, medical systems, military equipment, and in clean energy technologies such as wind power turbines, electric cars, energy-efficient lighting, and catalytic converters (Table 1.1) [Zhou et al., 2017]. REE markets are commonly divided into nine sectors: catalysts, magnets, polishing, metallurgy, batteries, glass, ceramics, phosphors and pigments, and other applications (Table 1.2.). Additionally the uses can be divided into two broad categories: process enablers and technology building blocks. The process enablers refer to when REE are used in the lifecycle of other materials and components but do not stay with the processed material. The

Table 2.1: Selected uses of REE [Gan and Griffin, 2018]

REE	Application
Lanthanum (La)	Battery alloys, metal alloys, auto catalysts, petroleum refining, polishing powders, glass additives, phosphors, ceramics, and optics
Cerium (Ce)	Battery alloys, metal alloys, auto catalysts (emissions control), petroleum refining, polishing powders, glass additives, phosphors, and ceramics
Praseodymium (Pr)	Battery alloys, metal alloys, auto catalysts, polishing powders, glass additives, and coloring ceramics
Neodymium (Nd)	Permanent magnets, battery alloys, metal alloys, auto catalysts, glass additives, and ceramics
Promethium (Pr)	Watches, pacemakers, and research
Samarium (Sm)	Magnets, ceramics, and radiation treatment (cancer)
Europium (Eu)	Phosphors
Gadolinium (Gd)	Ceramics, nuclear energy, and medical (magnetic resonance imaging, X-rays)
Terbium (Tb)	Fluorescent lamp phosphors, magnets especially for high temperatures, and defense
Dysprosium (Dy)	Permanent magnets
Holmium (Ho)	Permanent magnets, nuclear energy, and microwave equipment
Erbium (Er)	Nuclear energy, fiber optic communications, and glass colouring
Thulium (Tm)	X-rays (medical) and lasers
Ytterbium (Yb)	Cancer treatment and stainless steel
Lutetium (Lu)	Age determination and petroleum refining
Yttrium (Y)	Battery alloys, phosphors, and ceramics
Scandium (Sc)	High strength, low weight aluminum scandium alloys

technology building blocks refer to when REE are incorporated into alloys and compounds to produce a more complex product such as a permanent magnet. In this context REE may be used in small amounts but can be essential for the functionality of the end product [Hatch, 2012].

Whilst the direct value of the REE industry is modest on a global scale at $9 billion in 2016, the value of the downstream products containing REE is at least $1.5-2 trillion US dollars with some estimates placing the worth at $7 trillion [Lima et al., 2018]. In 2011, it was reported that a 59% of REE consumption by tonnage was in the more mature markets which included catalysts, glassmaking, lighting, and metallurgy, and 41% was consumed in the newer high growth markets such as magnets, ceramics and batteries [Charalampides et al., 2015].

REE uses can change depending on the emerging applications. For example early

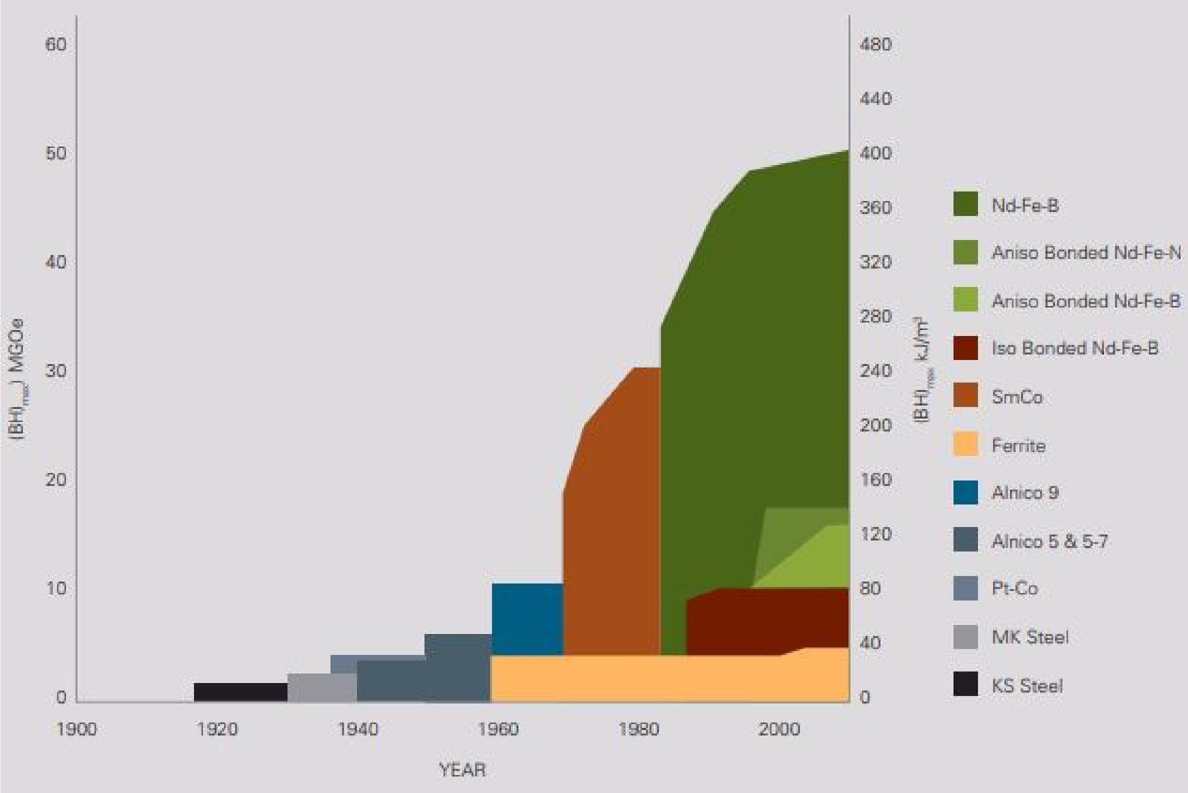

Figure 2.2: The development of magnet making materials, 1900 – 2000. The right hand side Y-axis refers to magnetic strength [ERECON, 2015]

in the 20th century the majority of Nd was used within the glass industry, but by 1984, after the invention and expansion of use of NdFeB permanent magnets, Nd became more useful in a range of modern technologies, and the demand for Nd increased in this area. Today, the share of Nd being used in the glass industry is small at only 360 tonnes, compared to the 18,200 tonnes consumed in the magnet sector (Figure 2.2) [Preinfalk and Morteani, 1989]. This same pattern exists for all the REE, with some applications maintaining functional use whilst substituting individual REE with other REE that are atomic number neighbours [Gupta and Krishnamurthy, 2005].

The green energy and low-carbon sector have been identified as the main drivers of REE demand for the next decade [Roskill, 2019]. For example they are used to increase energy efficiency in energy saving lamps, within LEDs as well as within the electronic motors of hybrid cars. REE can also be used within special alloys that can also contribute to lower weight of a car and therefore lower fuel consumption.

REE can also assist with the reduction of carbon emissions by REE use in energy generation with wind turbines in lieu of carbon based power plants, and REE used in catalysts can reduce noxious tailpipe emissions such as.

2.2.2 REE Geology and Deposits

REE are not found as native metals, but rather are found in a range of minerals including silicates, carbonates, oxides, phosphates, and halides. REE are not major rock forming elements, rather there are processes that concentrate specific REE distributions in residual fluids and are considered accessory minerals [Wall, 2014]. The geology of REE deposits ranges from carbonatite-related deposits such as fresh rocks and laterite, alkaline syenties and granites, weathered silicate rocks with REE ion-adsorption clays [Orris and Grauch, 2002, Wall, 2014, Haque et al., 2014]. There are also hydrothermal deposits, marine, and by-product of placers, bauxite production and waste, and phosphate production for fertiliser [Wall, 2014].

There are over 200 identified REE-bearing minerals [Goodenough et al., 2016], and it is common for a handful of new REE minerals to be discovered each year [Chakhmouradian and Wall, 2012]. Most REE-bearing minerals are rare, the more common bastnäsite, monazite, and xenotime are considered the principal ore minerals and if the ion-adsorption style deposits are included, these deposit types account for 95% of world production [Krishnamurthy and Gupta, 2015]. Most natural REE minerals are dominated by La, Ce, and Nd with a lower amount of HREE [Goodenough et al., 2017]

Bastnäsite is a fluorocarbonate mineral with the basic formula3 [(Ln) (CO3)F] and contains other additions of LREE and a few HREEs [Zepf, 2013]. Bastnäsite is the main ore from Bayan Obo and Mountain Pass. Monazite, a phosphate mineral with the typical formula [(Ce, La, Y, Th)PO4], always contains additions of other LREEs

Table 2.2: Forecast growth in REE demand [Lima et al., 2018]

Application	Growth and logic
Catalysts	Steady growth at 4-6% pa 2016-2020, which Curtin-IMCOA believes may improve with better availability and lower cerium and lanthanum prices.
Glass	As more cerium becomes available at low prices growth could increase to 5-10% pa.
Polishing	Steady growth at 4-6% pa through 2016-2020 due to lower cerium prices. Recycling systems installed during 2011, when prices peaked, have limited recent growth. More recently announcements from China indicate that demand for polishing mobile screens and tablet screens may lead to growth of 10-15% pa.
Metal Alloys	Due to uncertainties associated with Li-ion batteries, Curtin-IMCOA forecasts growth 2016- 2020 will be constrained to a minimal extent. Hydrogen storage applications will increase in medium/ long term. Overall growth at 6-12% pa.
Magnets	Due to limited supply, in spite of ongoing illegal mining in China, forecast growth of 6-12% pa through 2016-2020, which would be greater if legal material were to become available in larger quantities on a long term sustainable basis at reasonable prices. Herein lies a significant opportunity for ROW projects to expand/commence operations – with the support of ROW consumers. The ACREI records that recent growth in this sector has been 14% pa – with growth in China at 16% pa and ROW 12% pa; so this forecast may be considered conservative. The forecasts below are based on recycling of 10-15% through to 2020.
Phosphors	As the new lighting devices, television and computer screens use significantly less rare earths the market is contracting. Pigments for plastics, textiles and cosmetics are a potentially high growth sector. Overall forecast growth rate is zero, but the market could contract further if the current trend of a rapid take-up in changing to LEDs increases.
Ceramics	Steady growth rates at historic rates of 5-7% pa
Other	The use of cerium for water purification is included as a potentially longer term high-growth application, but slower now that major promoter Mountain Pass is closed. Other new applications could include use of Gd in refrigeration. Growth rate of 10-15% 2016-2020, moving to the higher rates of growth in the latter years.

and a to a lesser extent HREEs. This is the principal ore type at the Mount Weld mine in Australia. A major problem when processing monazites is that most monazite ore will contain small amount of Th substituting for REE. Processing produces radioactive residues, which have to be treated accordingly.

REE occur in a number of mineral deposits around the world but are rarely concentrated enough to allow for economic deposits [USGS, 2010]. There are a number of reviews of known mines, deposits, and occurrences [Goodenough et al., 2017, Gupta and Krishnamurthy, 2005, Weng, 2016]. The REE reserves worldwide have been estimated at 140 million tons with China being the largest holder, accounting for 42.3%, followed by Brazil with 16.9% of reserves respectively [USGS, 2016]. Australia, India and the United States also hold large reserves. These studies indicate that there is no shortage of REE in the earths crust to meet demand, however it is also important to consider the fact that not all REE are equally abundant.

REE deposits around the world are highlighted in Figure 2.2. An extended list of economic and non-economic REE concentrations has been developed by [Orris and Grauch, 2002] and more recently a list of economic deposits has been developed by [Weng, 2016]. The deposits can broadly be divided into carbonatite-associated which include weathered carbonatite; alkaline igneous rocks, including alkaline granites; other hydrothermal deposits; ion adsorption deposits; placer deposits and seafloor deposits [Wall, 2014]. REE are also produced as by-products of other minerals and can be recovered from waste.

Within China the resources can be divided into two areas, with the North producing from mixed-type REE ore with minerals such as bastnäsite and monazite. This accounts for 83.7% of China's total production and includes the largest mining region known as Bayan Obo. Bayan Obo was originally developed as an iron ore mine with REE being produced as a by-product. Bastnäsite ores are also exploited in Sichuan.

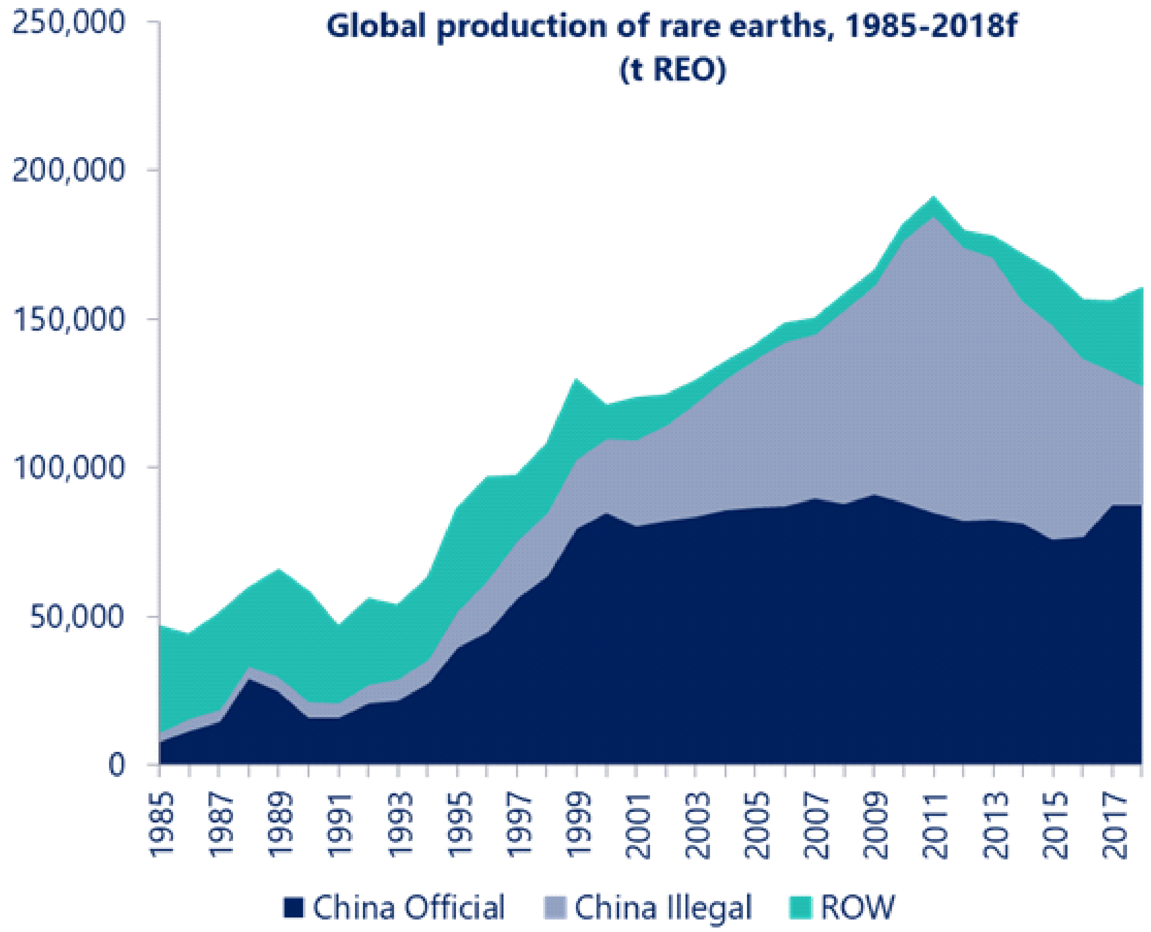

Figure 2.3: Map showing global production of REE deposits (ROW - rest of world) [Roskill, 2019]

The south of China hosts ion-adsorption clays which accounts for 2.7% of total production and is located in seven provinces of Southern China [Yang et al., 2013]. The ion-adsorption rare earth reserves account for around 26% of China's total REE production between 1988 and 2007 [Su, 2009] and was 35% of total production in 2009.

REE mines also exist in Australia, with Mount Weld, in United States with Mountain Pass, in Burundi with Gakara, in India extracting from mineral sands, and in Russia at Lovozero which extracts REE as a by-product from a niobium mine. In Europe, no REE mine exists, however a number of potential geological resources have been identified [Goodenough et al., 2016], with the most important associated with alkaline igneous rocks and carbonatites, and secondary deposits in placers [Goodenough et al., 2016].

2.2.3 REE Markets

REE are also marketed in several forms such as REE chlorides, metals, carbonates, oxides. REE production has increased significantly since 1960s as indicated in Figure 2.3. The United States produced a majority of the REE for the world market from 1965 until the 1980s, at which point China entered the market and dominated the production of REE until the present. The current average annual production of REOs is estimated at between 130,000-140,000 for the year 2017 [USGS, 2016]. This production comprised of China (85%), Australia (10%), and the remained of production coming from Malaysia, Brazil, India, Russia, and Vietnam [USGS, 2016]. It is estimated that between 20-40% of the Chinese domestic market is supplied from illegal production in southern China [Liu and Heyde, 2015, Packey and Kingsnorth, 2016]. Almost all demand is met through primary production and as noted, China dominates production, but also dominates consumption. For example in 2014 China consumed 119,000 t out of the 130,000 t produced [USGS, 2016].

REE are considered as 'strategic' or 'critical' materials for a number of economies [Hayes and McCullough, 2018]. This is because REE are important to economies, and have important uses in defence, combined with the fact that there are few substitutes for the material. These factors combined with the fact that the majority of REE are sourced from a small number of foreign countries.

Table 2.3: Selected REE Deposits classified by deposit type and with associated mineral resources and REO grades [Weng et al., 2013]. (CAR=carbonatite, IOCG=iron oxide copper gold, ALU=alluvial, ALK=alkaline, PEG=pegmatite)

Project	Deposit Type	Mt ore	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Y	%LREE	%HREE
Mt Weld CLD, Australia	CAR	14·9	23,233	46,262	5,020	17,639	2,374	516	1,060	88	243	29	58	10	29		739	9·61	0·12
Mt Weld Duncan, Australia	CAR	9·0	12,029	19,047	2,297	8,653	1,369	372	963	126	614	92	198	19	87	10	2,501	4·47	0·36
Olympic Dam, Australia	IOCG	9,940																0·4	0·03
Asharam (Eldor), Canada	CAR	422·7	3,609	6,731	724	2,575	329	77	181	18	72	10	21	2	13	2	13	1·42	0·02
Charley Creek, Australia	ALU	805·3																0·02	0·01
Nolan's Bore, Australia	CAR	47·3	4,900	12,500	1,500	5,300	600	100	300	20	80	10	20	30	20	3		2·52	0·05
Norra Kärr, Sweden	ALK	58·1																0·59	
Toongi-Dubbo, Australia	ALK	73·2															1,400	0·75	
Bayan Obo, China	CAR	1,460																3·8	56·9
Kvanefjeld, Greenland	ALK	619															900	1·06	
Strange Lake, Canada	ALK & PEG	492·5	1,200	2,700	300	1,100	200		200	50	320	70	220	30	220	32	2,200	0·58	0·31
Buckton, Canada	SLE	496·7	47	82	11	39	8	2	6	1	6	1	4	1	4	1	39	0·02	0·01
Eco-Ridge MCB, Canada	PLA	37·4	368	698	70	225	39	2	26	4	17	3	7	1	6	1	7	0·14	0·01
Eco-Ridge HWZ, Canada	PLA	49·2	197	371	37	119	20	1	12	2	7	1	3		2		5	0·08	0·01
St Honore-Niobec, Canada	CAR	1,058																1·73	18·35
Round Top, USA	G&R	1,033·8	24	95	12	34	12	0	12	4	36	9	37	8	64	10	280	0·019	0·045
Mountain Pass, USA	CAR	16·7																7·98	1·33
Bokan-Dotson, USA	G&R	6·7	550	1,650	210	800	210	20	220	40	240	50	130	20	100	10	1,550	0·37	0·21
Araxá, Brazil	CAR	28·3	11,801	20,780	1,909	5,826	627	141	288	30	121	17	33	2	17	0	474	4·14	0·07
Songwe Hill, Malawi	CAR	56·5	2,864	5,193	556	1,908	279	73	174	21	101	17	39	5	28	4	474	1·10	0·07

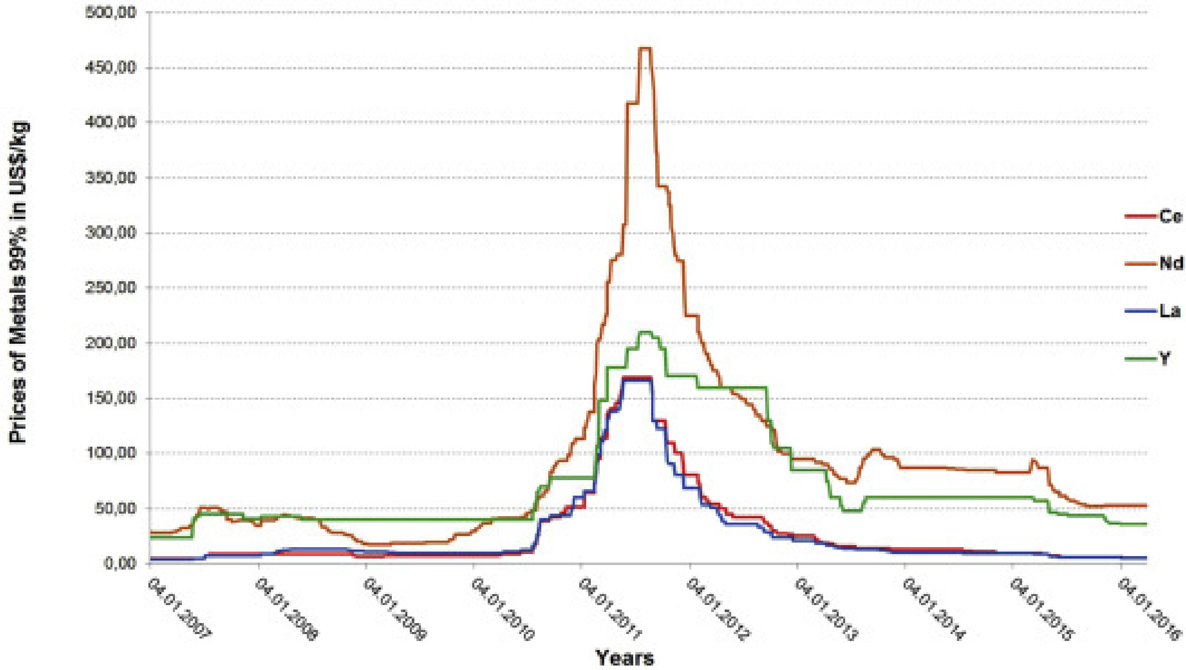

Figure 2.4: REE prices during the last 10 years for selected REE
[Xu et al., 2018]

2.2.3.1 The 2010/2011 Price Spike

A significant price spike (Figure. 2.4) in the REE market occurred in 2011 in response to China imposing export restrictions on REE whilst being the dominant producer [Massari and Ruberti, 2013]. The world was alarmed that global high-tech market might suffer from the supply restriction [Nakamura, 2011]. The price spike was relatively short-lived but resulted in greater attention from REE import dependent countries to look at their supply chains. During this time over 400 REE mineral deposits outside of China were evaluated for development [Hatch, 2012].

Following the export restrictions, China was accused of using REE as a political instrument and in 2014 were found to have violated WTO trade rules [He et al., 2015, WTO, 2014].

There have been claims that the Chinese government uses its monopolistic position in the REE to develop China's economy [Campbell, 2014, Wübbeke, 2013]; however, this has been strongly denied by Chinese officials claiming that the political measures implemented, such as the restriction of exports of REE, were in response to environmental issues [SCIO, 2010].

in 2016 the government of China commenced the consolidation of the REE mining industry. The number of REE mining and smelting-separation companies was reduced from over a hundred to six, in an effort to better manage and plan REE production and reduce the environmental impact of the industry. For example the Ministry of Land and Resources of the People's Republic of China decreased the REE mining rights from 113 to 67 in 2012 and today eight mining companies own 99.97 of the total REE reserves in China [Rao, 2016]. In reaction to this consolidation, there have been increased levels of illegal production within China. In 2016 illegal mining has been estimated at 40% of China's production (Figure. 2.5) [Rao, 2016].

2.2.3.2 The Balance Problem

Individual REE have a specific set of uses and, therefore varying demand; but the natural abundance of the different elements in ore does not match market demand [Goodenough et al., 2017]. The different ores have varying concentrations of individual REE and the potential for these different ores to meet future market needs has been explored [Goodenough et al., 2017].

There is a high demand for La and Ce, and these elements form the majority of production [Binnemans, 2014]. There are predicted supply shortages for Nd, which is considered one of the drivers of market optimism and forecast demand growth, owing to their use in EVs, wind turbines. The natural abundance of REE has been identified as a major challenge for REE suppliers [Binnemans, 2018]. The global annual production of between 130,000-140,000 tons of REE does not clearly provide us with data for the availability of the individual REE (Figure. 2.5).

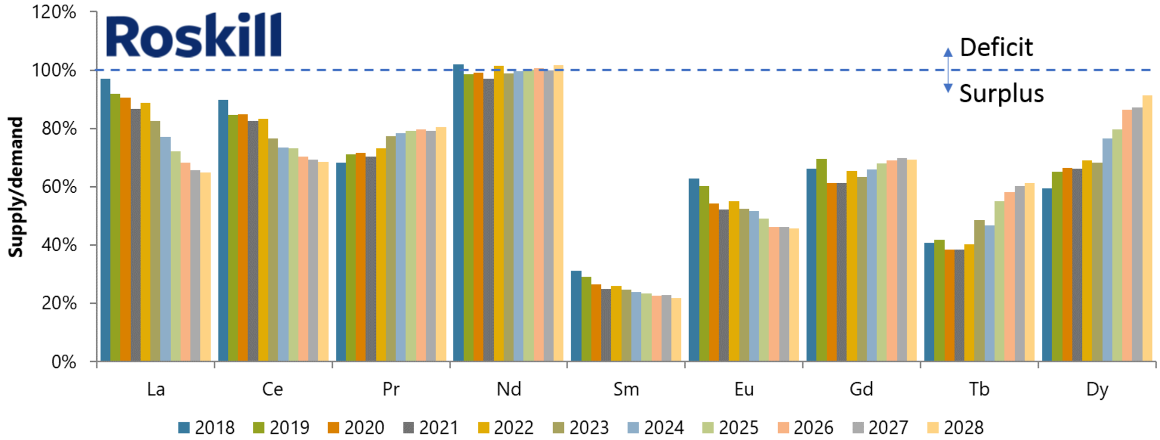

Figure 2.5: Global Rare Earths supply-demand balance by element– December 2018 report (t REO) [Roskill, 2019]

There are efforts to solve the balance problem through diversification of resources that are exploited, with an emphasis on deposits with a REE balance that matches demand. Secondly, increased recycling rates, and thirdly substitution of REE with high demand with REE atomic number neighbours that have similar functional uses but lower demand. Finally, new uses are being explored for abundant REE.

2.2.3.3 Recycling

REE recycling is currently very limited with less than 1% of all REE being recycled [Binnemans et al., 2013]. Recycling is mostly limited to permanent magnets and polishing compounds with a lesser amount from batteries and lamps [USGS, 2016]. This is because REE are used in small amounts in the majority of their end-use applications, and there are challenges with the collection, extraction and recovery of the constituent materials within end-products [Jowitt et al., 2018, Li et al., 2017]. A number of countries, such as Japan, have a greater reliance on recycled REE as they may not have significant natural resources and the recycling taking place today includes the direct recycling of manufacture scrap or residues, urban mining of end-of-life products, and the recycling of solid and liquid industrial wastes [Jowitt et al., 2018, Graedel et al., 2012].

REE recycling has the potential to combat the so-called “balance problem”. For instance, primary mining of REE ores for Nd generates an excess of the more abundant elements, La and Ce. Therefore, recycling of Nd can reduce the total amount of REE ores that need to be extracted [Binnemans et al., 2013]. A significant improvement in the recycling of REE is required with a fully integrated recycling route [Jowitt et al., 2018]. However, even with increased recycling rates, it will not fill the growing demand gap and so it is expected that virgin REE will be required for the coming decades [Roskill, 2019]. The time delay before REE can re-enter the market also needs to be considered. This will be different depending on the application, but as an example the average life expectancy of a wind turbine, which may contain a large tonnage of Nd is 20 years [Ziegler et al., 2018].

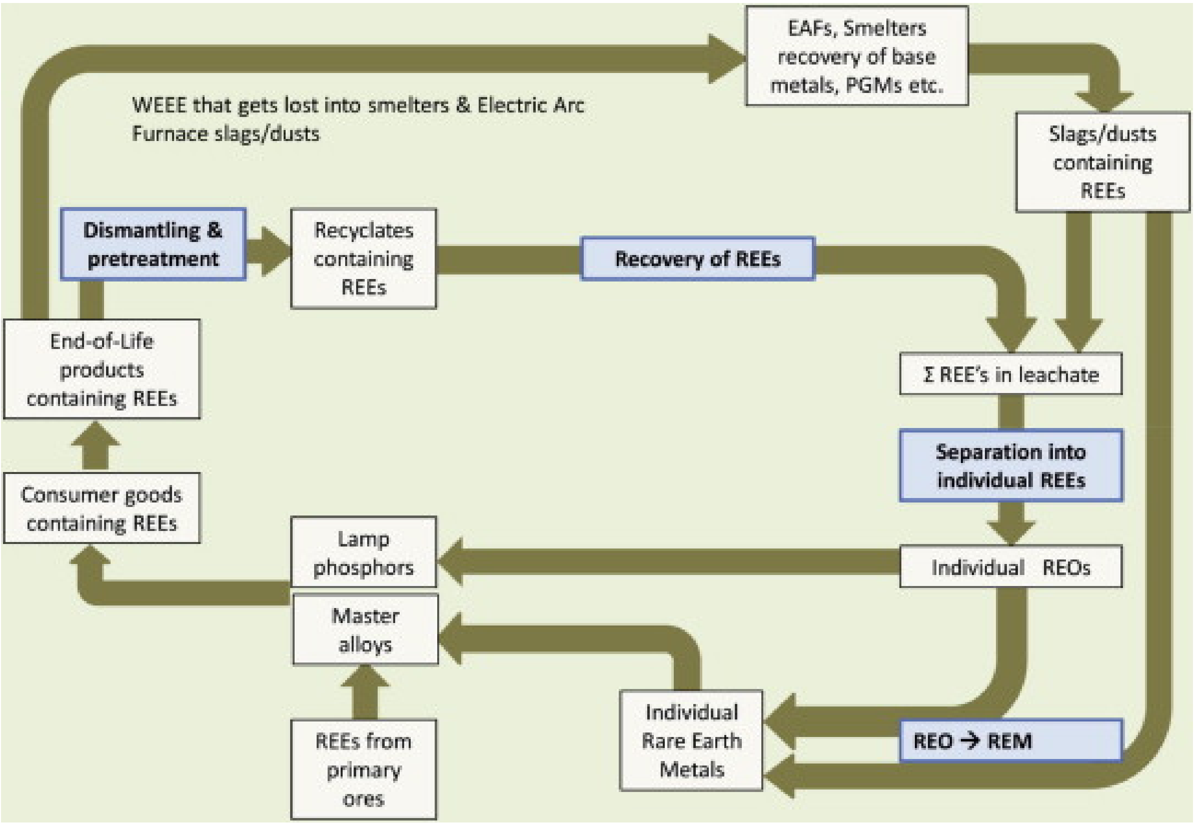

Figure 2.6: Closing the loop in the life cycle of rare earths in major technological applications [Binnemans, 2014]

2.2.4 REE mining, mineral processing, and metallurgy

REE deposits are unique, with a unique combination of minerals. For example Bayan Obo, which is the largest REE mine in production contains bastnäsite, monazite, fluorite, magnetite, barite, dolomite, aegirine, calcite, quartz [Fan et al., 2016]. There are no REE projects around the world which have identical mining stages and process flowsheets due to the distinct nature of REE deposits and mineralogies but there are common process flow stages that are shared by a number of projects. These stages include mining from the ore deposits, crushing and grinding the ore, cracking the minerals to produce mixed REO concentrates, before separation and purification of the oxide concentrates (Figure. 2.7). Only three major REE bearing minerals are exploited commercially; bastnäsite, monazite, and xenotime, plus the addition of ion-adsportion clays.

The REE production chain is complex and often involves a number of stakeholders but can be divided by four phases: mining, mineral processing, cracking, and REE separation. Not all of these stages will be on-site and may be in different countries entirely. REE are sold in various forms, including as mineral concentrates, as mixed rare earth oxides (REO), individual oxides, carbonates, purified metals, or metal mixtures (Figure. 2.7). A single operation may produce a number of different saleable products in these formats.

2.2.4.1 Mineral Production

Mining projects will go through different technical reports prior to production. The type of study depends on the location of the project. This usually starts with an order-of-magnitude study. This is usual an initial financial appraisal of a project, and commonly only requires a single person to carry out this study. This may include an elementary mine plan and will dictate whether further investigation such as an

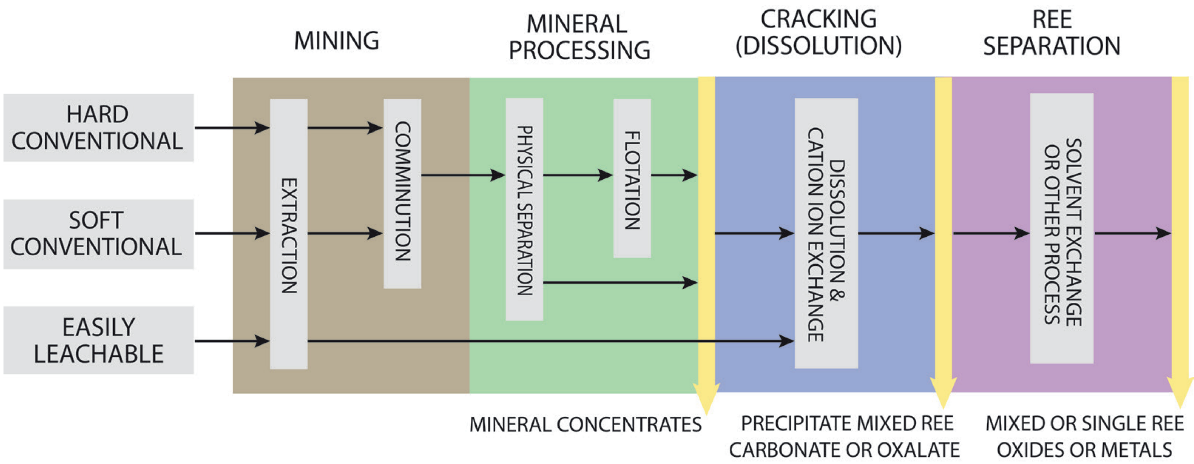

Figure 2.7: Summary of mining and processing routes for REE deposits. Ores are divided into three types: hard conventional, such as igneous carbonatite and alkaline igneous rocks; soft conventional, such as mineral sands; and easily leachable, which includes ion-adsorption clays [Wall et al., 2017]

exploration project with an indicated mineral resource will be made. These studies often use similar projects from around the world to predict processes and mine plans, and are considered to be accurate to 40-50% [Stones, 2016].

If the project is deemed economic, a preliminary feasibility study or pre-feasibilty study will be carried out and complete due diligence work to determine whether to proceed to a detailed feasibility study. Pre-feasibility studies are considered to be accurate to 25-30%. Estimates about process efficiencies are typically obtained by factoring known unit costs and estimated gross dimensions or quantities once conceptual or preliminary engineering has been completed. These studies are often carried out by a small group of technical people with multidisciplinary skills [Stones, 2016].

Detailed Feasibility Studies are normally the highest order and most important because they are the litmus test for proceeding with a project. Typically, Detailed Feasibility Studies are the basis for capital appropriation and provide the budget figures for the project. They may be completed with a financial accuracy of 10% provided that a significant portion of the formal engineering is completed. In some cases, Detailed

Studies are completed to an accuracy of 15% with quantities derived from general arrangement drawings only. When the engineering is later sufficiently advanced, a second estimate is made to an accuracy of 10% to provide confirmation and firm budget numbers.

2.2.4.2 Mining

Mining of the REE containing material is most commonly completed using conventional open-pit methods. The largest REE mine in the world is the open-pit Bayan Obo located in Inner Mongolia, China, where minerals such as bastnäsite are mined as a co-product of iron ore. The basic process involves drilling, blasting, and hauling of rocks for stockpiling or downstream processing. Underground mining is not commonly used for REE but has been applied to the Russian Lovorezo project. Another method is in-situ leaching for of the ion-adsorption type deposits and will be described in section 2.2.5.1 [Wall et al., 2017].

2.2.4.3 Mineral Processing

REE mineral processing refers to the physical separation of the grains containing the valuable REE minerals from the gangue minerals. Some ore types don't require this stage of mineral processing and instead moves straight to whole-ore leaching. This is applied if physical beneficiation is not suitable for REE ores because of the fine-grained structure or a low starting grade of REE [Krishnamurthy and Gupta, 2015].

The output of the mineral processing will be a REE mineral concentrate and the waste material known as tailings. The objective of the mineral processing stage is to separate the REE-bearing minerals from their associated matrices. This is challenging due to the similar chemical composition, magnetic behaviour, specific gravity, and electrostatic conditions of the valuable REE containing ore and the gangue materials [Hussein, 2016]. The mineral processing stage will generally include comminution followed by a combination of gravity, magnetic, electrostatic and froth flotation separation techniques [Jordens et al., 2014].

Comminution is required to reduce the size of particles through crushing and grinding. It is important that the ore is not ground beyond the liberation size because this will consume additional energy and could result in reduced recovery or grade for the downstream processes. Following the ore size reduction, material is classified by size for further processing. This can be achieved by the use of high-frequency vibrating screens, and hydrocyclones. Deslimining is often required as a REE minerals can be lost in the size fraction produced during the comminution phase [Krishnamurthy and Gupta, 2015].

The next stage requires the separation of REE-bearing minerals from the gangue mineral to produce a concentrate. Froth flotation separates mineral particles based on their hydrophobicity [Hussein, 2016]. Once the REE ores are liberated they are mixed with water to form a slurry. A chemical known as a collector will be added to make the REE minerals hydrophobic, whilst the gangue minerals stay hydrophilic [Krishnamurthy and Gupta, 2015]. Gravity separation uses the difference in density or specific gravity to separate mineral particles. The process involves that addition of water to the ore particles to form a slurry which then flows into a gravity separator. Layers or channels of particles form based on their specific gravities.

Magnetic separation exploits the differences in magnetic susceptibility to separate mineral particles. For example bastnäsite, monazite, xenotime, and eudialyte are paramagnetic, meaning that they have slight attraction to magnetic fields. Common gangue minerals such as barite, calcite, dolomite, quartz, and zircon are diamagnetic, meaning they are slightly repelled by magnetic fields. There are both wet and dry magnetic separation processes depending on factors including particle size, and multiple stages may be employed depending on the range of magnetic susceptibilities of the minerals in the ore.

Electrostatic separation uses the differences in conductivity between minerals to achieve separation [Higashiyama and Asano, 2007]. This process tends only to be used when other separation options are not feasible [Jordens et al., 2013]. This is because comminution processes tend to be a wet process and the energy requirements to remove moisture from the ore for electrostatic separation could be energy intensive.

2.2.4.4 Extractive Metallurgy

The extraction of the REE from the REE-mineral concentrate is carried out to produce a high-purity (around 90%), mixed-REE concentrate. The approaches used during this stage use hydrometallurgy and pyrometallurgy. Hydrometallurgy uses low-temperature reactions in an aqueous fluid to recover valuable components in the ore. The processes include leaching, solution concentration and purification; and product recovery by precipitation as compounds [Gupta and Krishnamurthy, 2005].

Following mineral processing, REE-bearing minerals need to be 'cracked'. The cracking stage uses acids and alkalis to leach REE from the mineral into a pregnant leach solution. Concentration and purification is carried out to remove impurities that have been leached into the pregnant leach solution along with the target REE. Common impurities that are associated with REE include Fe, Al, and Th [Xie et al., 2014]. There are two approaches which are commonly used; double-sulfate precipitation to produce REE sulfates and a combination of impurity removal and direct solvent extraction of REE. The output from the concentration and purification is a high-purity REE chemical concentrate as a mixed-REE carbonate, chloride, hydroxide, or oxide with a purity of greater than 90%. The concentrate will then be sent to a solvent extraction facility for separation into high-purity +99% individual REE [Gupta and Krishnamurthy, 2005].

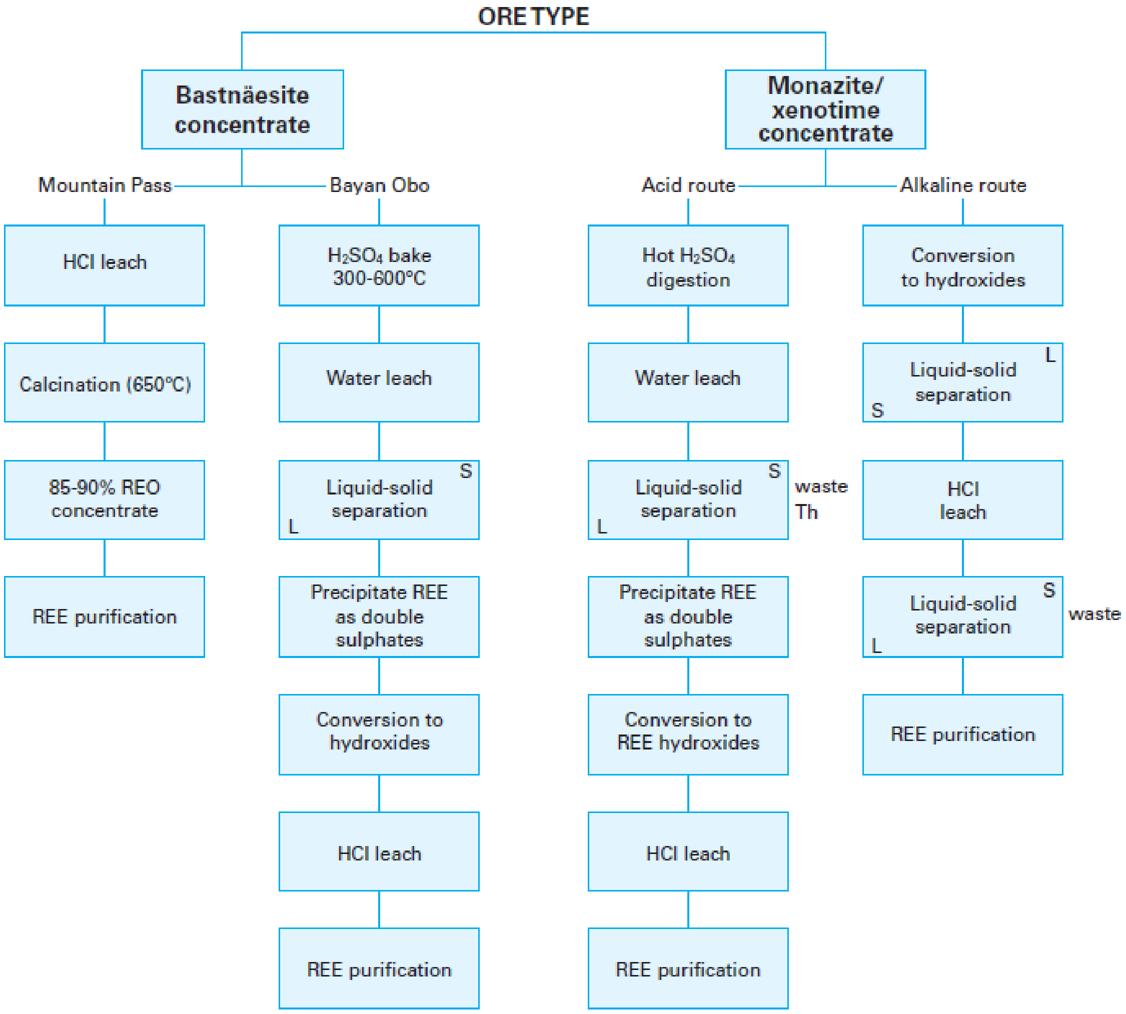

Figure 2.8: Processing routes for extracting REE from concentrates of three major REE-bearing minerals(Mountain Pass refers to processing route prior to 2002 closure)

[Walters et al., 2013a]

2.2.4.5 Purification and Separation

The REE concentrate will then require further purification and separation depending on the final product desired. There are a number of processes for separating individual REE from naturally occurring REE mixtures. The process exploits the small differences in basicity resulting from decrease in ionic radius from La to Lu [Krishnamurthy and Gupta, 2015]. The basicity differences influence the solubility of salts, the hydrolysis of ions, and the formation of complex species, and these properties form the basis of separation procedures by fractional crystallization, fractional precipitation, ion exchange, and solvent extraction [Krishnamurthy and Gupta, 2015]. Solvent extraction is a commonly used hydrometallurgical process in industry, whereby a leaching solution of dissolved elements will be forcibly mixed with an immiscible organic solvent and this will extract an element or group of element and will usually be completed in a series of mixer settlers [Xie et al., 2014].

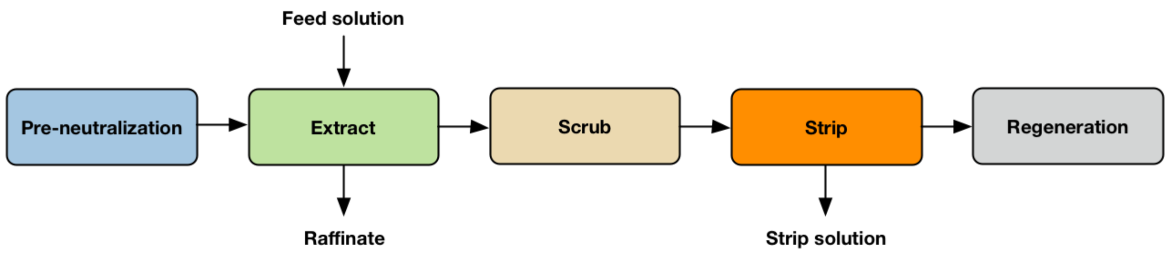

Figure 2.9: Process of solvent extraction circuit for the separation of REE [Metals, 2018]

2.2.4.6 Metal Formation

The formation of the REE in metal forms uses REO from the ore processing and separation operations. These oxides are extremely stable and their reduction to metal is energy and materials intense. Reduction, deals with the techniques for converting the pure rare earth oxide intermediates to the metals. Chemical as well as electrochemical reduction methods have been used and the variety in the actual processes has come about because of the different physical properties of the individual rare earth elements. The processes are not described in detail here as they are processes further downstream than are considered in this thesis.

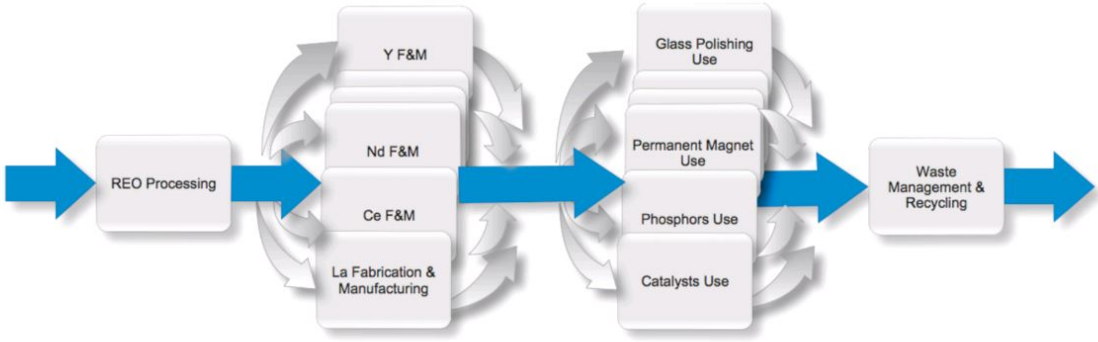

Figure 2.10: Life cycle of the REE on a global level
[Du and Graedel, 2011]

2.2.5 Environmental Impacts of REE Production

REE are an important non-renewable resource for the world market, but their extraction and processing has produced a legacy of negative environmental impacts in Brazil, China, India, Malaysia, and the United States. The production of REE through mining, mineral processing, REE separation and metal formation can cause environmental impacts. For example mining can cause ecological destruction, pollution, soil erosion [Liu and Diamond, 2005, Guo, 2012, Vahidi et al., 2016]. Mining and mineral processing of REE can also generate large amounts of waste which may include high levels of radiation. The mineral processing and purification stages can require high amounts of energy and can also be chemically intensive as well as producing significant amounts of waste products [Koltun and Tharumarajah, 2014]. Tailings are also produced in the production of REE from the uneconomic fraction of an ore. Mixtures of crushed rock and processing fluids from mills, washeries or concentrators that remain after the extraction of REE. These tailings can interact with the environment in a number of ways [Kossoff et al., 2014].

A commonly cited environmental challenge with REE production is the co-generation of radioactive material [Koltun and Tharumarajah, 2014]. The waste material from REE mines, known as tailings can contain hazardous waste which commonly contain

Th, a radioactive element. Different mineralogies of REE ore have different radiation doses (Figure. 2.11) and this has often been the single issue that has prevented certain deposit types from being exploited [Mudd et al., 2016]. For example xenotime in Malaysian placer deposits contains two percent U and 0.7 % Th [Walters et al., 2013b]. This is also the reason why processing of beach sands containing monazite has been banned in Australia, China, and Europe [Curtis, 2009].

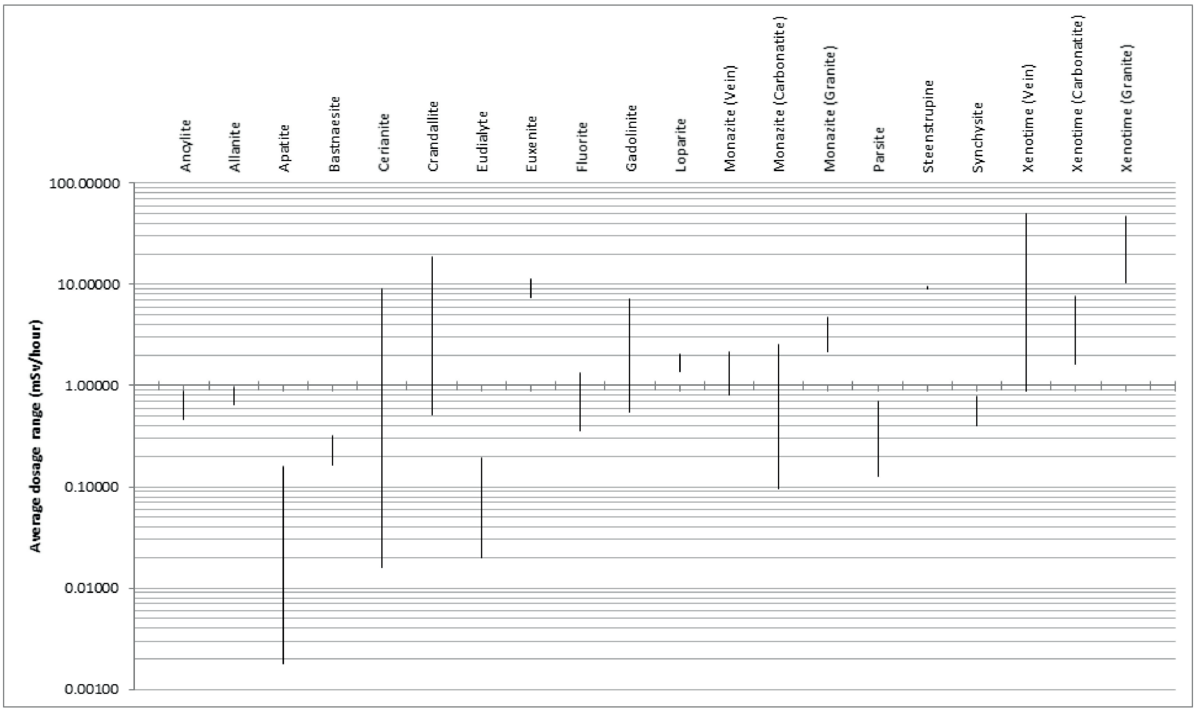

Figure 2.11: The calculated radiation dosage ranges in mSv/hour zero metres from the radiation source (i.e. the mineral concentrate). The ranges are between the lowest and highest dosages based on the weight percent constituent of uranium and thorium in the mineral [O'Callaghan, 2012]

Air emissions from REE processing can include sulfur oxides, hydrogen chloride, hydrogen fluoride and dust which contain radioactive elements. Whilst water systems can be polluted and contain heavy metals, acids, fluorides, and large amounts of ammonium [Schüler et al., 2011]. In the 1990s at Mountain Pass, United States 3,000 litres of wastewater was generated every minute. This wastewater contained low concentrations of Th and U, which was being piped to evaporation ponds. Th and Ra collected as scale inside the pipe and pipe failures led to pipeline spillages of millions of litres of hazardous waste into the desert. This waste had much higher levels of Th and Ra than the low concentration in the Mountain Pass deposit [Lima et al., 2018].

Other waste streams that have the potential to contaminate land and water systems include fluorine. This was calculated for a Chinese deposit, which produces 8.5 kg of waste per tonne of REO, and 13 kg of dust. The common use of concentrated sulfuric acid during high-temperature calcination was also estimated to produce between 9,600 and 12,000 m^3 of waste gas containing dust concentrate, hydrofluoric acid, and sulfur dioxide, and produces 75 m^3 of acidic wastewater and 1 tonne of radioactive waste residue [Lima et al., 2018].

China has been the largest producer of REE since the 1960s and has often operated with limited environmental regulations resulting in significant environmental damage to areas near mining operations and processing facilities [EPA, 2012]. It was reported that there has been a divergence between price and value due to the neglected environmental costs associated with REE production [SCIO, 2010].

The largest REE mine in the world, Bayan Obo, has 11 km^2 of tailing impoundment which has radioactively contaminated the surrounding soil, groundwater and vegetation. For example it was soil quality from the 24 sites in the mining area, and the 76 sites in the mine tailings area had average concentration of Cr, Cd, Pb, Cu, and Zn higher than background. It was identified that the region had moderate potential ecological risk, but low ecological risk in the tailings region. The contaminated hot-spots were primarily located near mining-related high-pollution plants [Pan and Li, 2016].

In China, REE separation and refining used a method known as saponification until recently which has generated significant volumes of harmful wastewater [EPA, 2012].

Figure 2.12: Photograph of the Baotou tailing dam
[Li et al., 2013]

2.2.5.1 Ion-adsorption deposits

The ion-adsorption rare earth resources in Southern China are the major supply source of the HREE for the world market. The surface mining and heap leaching of these deposits has caused serious environmental damage [Yang et al., 2013]. The methods of extraction for these deposits has changed over time, initially it involved traditional surface and mountaintop mining combined with heap leaching techniques which evolved to in-situ leaching methods. It has been estimated that the production of 1 t of REO from the ion-adsorption deposits using the heap leaching methods require 300 m^2 vegetation and topsoil excavation, and produced 2000 t of tailings, which were disposed into nearby valleys and waterways. This process also produces 1000 t of wastewater which can contain high concentrations of ammonium sulphate and heavy metals [Su, 2009]. Since 2012, the Chinese central government placed a ban on surface mining and heap leaching and promoted in-situ leaching [Walters et al., 2013b].

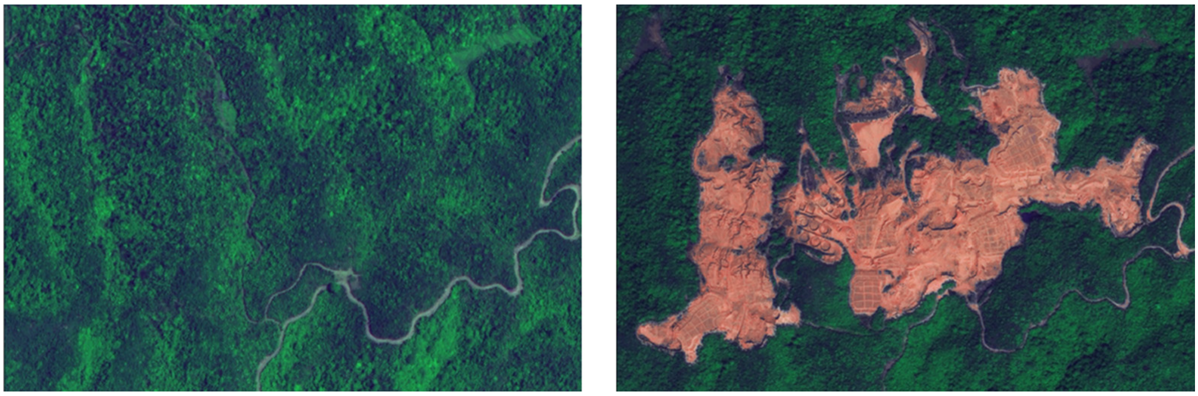

Figure 2.13: Satellite images of a rare earth mining site in Ganzhou, China, on April 2005 (left) and February 2009 (right)
[Yang et al., 2013]

The scale of ion-adsorption type deposit exploitation, and the removal of topsoil has changed the topography and soil composition of the region, leading to increasing frequency and magnitude of flooding events. This has caused a permanent loss of ecological habitat. Other impacts cited include regional air pollution and human health issues [Yang et al., 2013] There have been reports of uncontrolled illegal mining accounting for approximately 40% of the Chinese domestic market and 30% of the global market in 2016 [Packey and Kingsnorth, 2016].

Despite the negative environmental impacts associated with the legacy of production from ion-adsorption style deposits, such ores consume less energy for production as they do not require beneficiation, unlike hard rock deposits (Table 2.4) [Wall et al., 2017].

Table 2.4: Examples of REE deposits and qualitative analysis of their mining and processing [Wall et al., 2017]

Ore type	Energy for crushing and grinding	Difficulty of beneficiation	Chemicals	Radioactivity	Amount of rock to be moved	By-products
Carbonatite	Medium - High	Variable 10 m	Flotation - medium	Medium	Low	Not usually
Weathered carbonatite	Medium	10 m and finer	Flotation - medium	Low - Medium	Low	Not usually
Alkaline rock	High	Variable 1 m and finer	Variable	Variable	High	Co-products common
Ion adsorption clay	None	Beneficiation not needed	Leaching so can be high	Low	Low	None
Mineral sand (placer)	None - low	10 - 100 m	Low	High	High	from TiO_2 zircon etc production
By-product of igneous apatite	High	100 m - mm	Medium	Low	High	from fertiliser manufacturer
Red mud	Bauxite processing	n/a REE from red mud	Medium	Low	High	From Al production

2.3 Life Cycle Assessments (LCA)

LCA is a tool used to assess the environmental impacts associated with all stages of a product, process, or activity. An important aspect of LCA is the fact that it can evaluate indirect impacts that occur in the development of a product, or a process system over its entire life cycle [ISO, 2006]. The International Organization for Standardization (ISO) defines LCA as a method which:

> ”...addresses the environmental aspects and potential environmental impacts through a product’s life cycle from raw material acquisition through production, use, end-of-life treatment recycling and final disposal.” [ISO, 2006]

The purpose of conducting an LCA is to better inform decision-makers by providing information or data from a life cycle perspective, which otherwise may often not be considered. A wide range of environmental impacts can be captured into a single integrated framework in a scientific and quantitative way. The holistic approach also generates results on how decisions made at one stage in the life cycle might have consequences somewhere else. This recognition of how choices effect the environmental performance of product or process ensures that a balance of potential trade-offs can be made, and it is possible to avoid burden shifting (e.g., reducing air emissions to create further water resource impacts).

The purpose of a LCA described by [ISO, 2006] is to assist in;

1. identifying opportunities to improve the environmental performance of products at various points in their life cycle,

2. informing decision-makers in industry, government or non-government organisations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),
3. selecting relevant indicators of environmental performance, including measurement techniques, and
4. marketing (e.g. implementing an eco-labelling scheme, making an environmental claim or producing an environmental product declaration).

LCA has been developed as "primarily a steady-state-tool" that does not consider spatial or temporal dimensions [ILCD, 2010]. However, a number of strategies have been developed to include time-dependent LCA [Pell et al., 2019a, Levasseur et al., 2010, Dyckhoff and Kasah, 2014] as well as spatially explicit LCA and recently with the inclusion of both dimensions [Maier et al., 2017]. The importance of the temporal dimension in relation to mining and mineral processing was highlighted by [Molinare, 2014] with reference to copper production.

LCA can serve multiple purposes within academia and industry. For example LCA has been identified as a useful tool in assessing environmental impacts from different process simulations [Reuter et al., 2015, Molinare, 2014, Pell et al., 2019a].

The LCA approach uses a quantitative method and has been internationally recognized and defined in the ISO standards 14040 (ISO, 2006a) and 14044 (ISO, 2006b). The methodology has developed since the 1970s, with the formation of the Society for Environmental Toxicology and Chemistry (SETAC) in 1993, when they released a standardized methodology for conducting LCA. It is also possible to include social considerations (social life cycle assessment), and economic criteria (life cycle costing), and together with environmental LCA they can be used to produce a life cycle sustainability assessment (LCSA) [Ekener et al., 2018]. This thesis only considers environmental LCA.

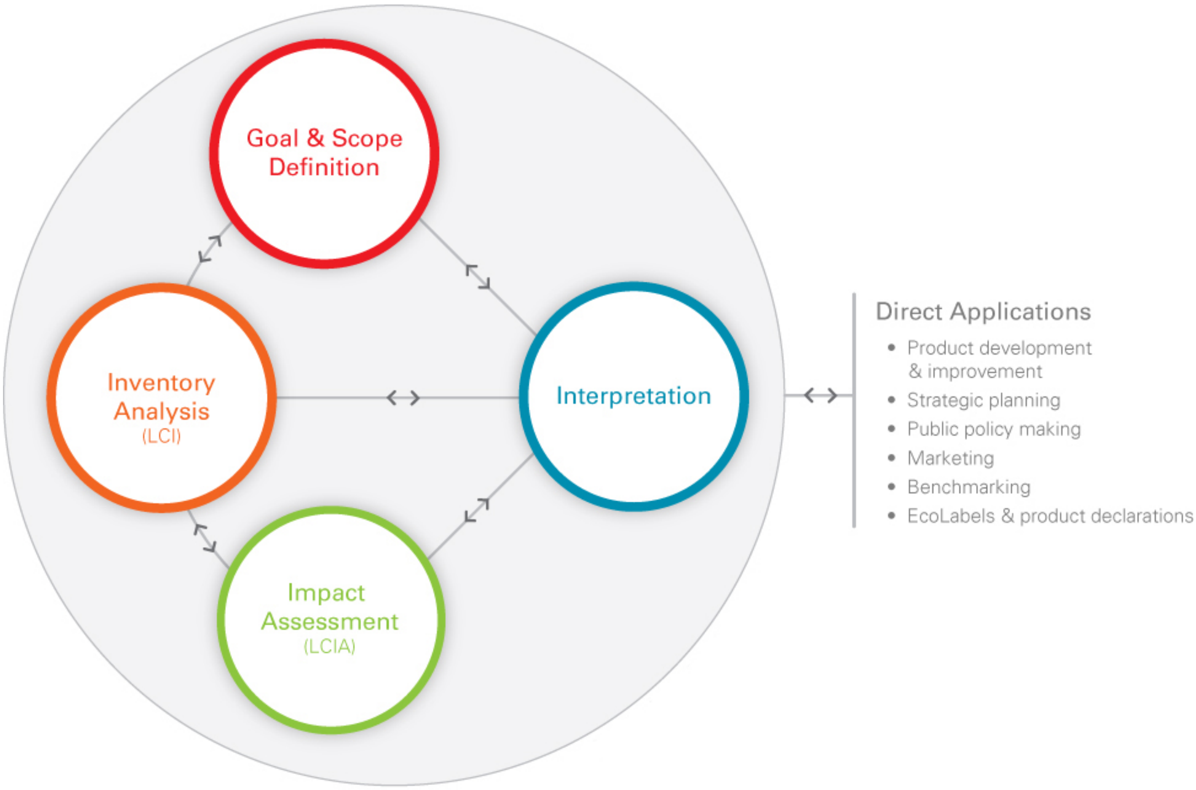

Figure 2.14: The four stages to a LCA
[ISO, 2006]

There are a number of publications which provide detailed instructions and technical guidance to conduct an LCA such as [Huijbregts et al., 2004, Curran, 2006, ILCD, 2010]. A brief introduction into LCA is made, introducing the goal and scope definition phase, the inventory analysis, the impact assessment and the interpretation (Figure.2.15) as outlined by the international standards [ISO, 2006].

2.3.0.1 Goal and Scope

This stage determines the purpose and intent of the study. The methodology, system boundaries, cutoff limits, and functional unit that are selected during this phase and these choices can have a large impact on the final results [ILCD, 2010]. The environmental impact is measured with reference to the functional unit and is defined by ISO as the:

"...quantified performance of a product system for use as a reference unit"

The system boundary clarifies what is included and what is excluded in the study. The choice of what is included in study depends on the intended application; the audience; the assumptions made; data and cost constraints; and cut-off criteria [PE International, 2014]. A process flow diagram is commonly used to highlight the system boundary. In theory, all elementary flow inputs and outputs should be measured, however, in reality it is only necessary to included inputs and outputs which impact the overall conclusion of the study.

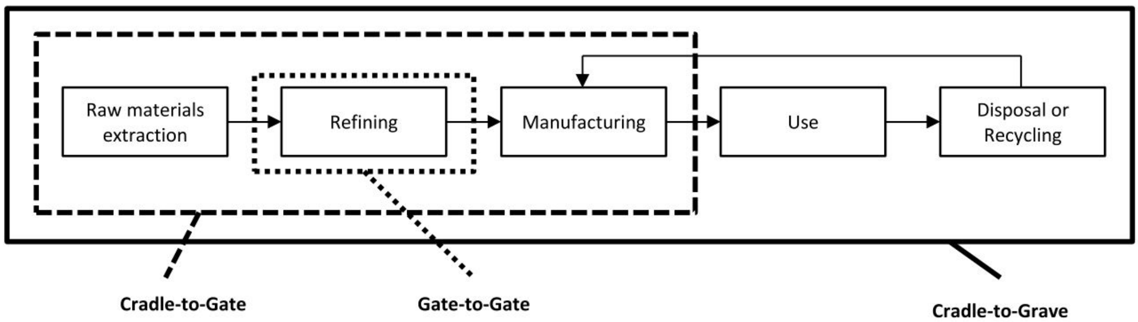

Figure 2.15: Life cycle phases for a generic product, illustrating cradle-to-gate, gate-to-gate, and cradle- to-grave system boundaries.
[ISO, 2006]

LCA should include as much information as available in order to meet the goal of the study. This means that all unit processes that contribute to the overall impact should be included, however unit processes are often excluded due to lack of data and according to ISO 14044 standards, this should be disclosed in the final report. It is also important to consider that LCA is an iterative process which means that adjustments may be made to the goal and scope in response to the assessment [ISO, 2006].

2.3.0.2 Life Cycle Inventory

The compilation of the material and energy inputs and emissions and wastes generated for the product system is completed during this stage. This includes flows to and from unit processes, known as intermediate flows, and flows into the system from nature, known as elementary flows. The full material energy, waste and emissions, flow data of the product system in a LCA study is known as the life cycle inventory (LCI). LCI data is often collected from multiple sources, and the level of detail required for a specific study is outlined during the goal and scope of the study.

There are two main methods for LCI generation based on the desired study goal. Attributional LCI refers to collecting data for all the physical flows relevant to an environmental impact into or out of the life cycle system boundary. In contrast consequential LCI generates data from the consequences of actions made, highlighting how flows relevant to environmental impacts will change in different scenarios. There are studies which may have a goal of performing only an inventory analysis and interpretation, this is known as a LCI study and is covered under [ISO, 2006].

2.3.0.3 Impact Assessment

The life cycle inventory data is used with characterization factors to calculate the amount and significance of the potential environmental impacts to form the life cycle impact assessment (LCIA) [ILCD, 2010]. The LCI data are assigned to impact categories and their impacts are quantified according to characterization factors. There are often a number of impacts occurring at various spatial locations and impacting different impact categories. Because of this, the models used within impact assessment are often a more simplistic calculation of more sophisticated models.

The impact assessment method should be defined during the goal and scope phase of a LCA, and the methodology clearly and transparently defined. For some impact categories, such as global warming and ozone depletion, there is a strong consensus on the characterization factors, however for others there are a number of competing calculation methods available. The resulting impact models have been developed for relative comparisons, however they have not been designed for predictions of risk [ILCD, 2010].

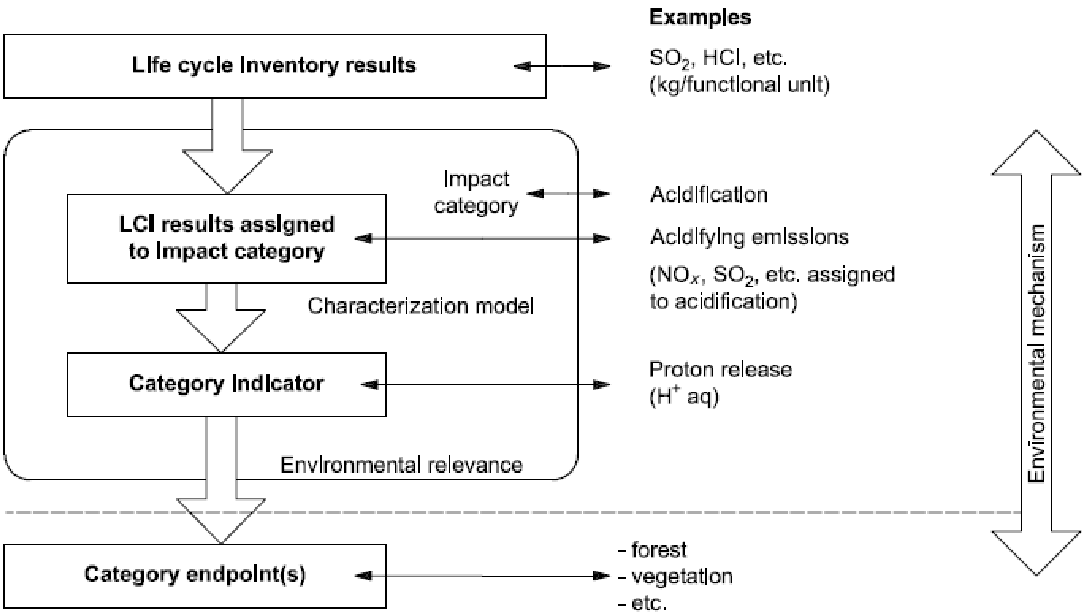

Figure 2.16: The process of impact category calculation from the LCI data [ILCD, 2010]

A key concept within LCIA is that of a stressor. A stressor refers to conditions that may lead to an impact. For example, if a product or process is emitting greenhouse gases, the increase of greenhouse gases in the atmosphere may contribute to global warming, or a process that results in the discharge of excess nutrients into bodies of water may lead to eutrophication. A life cycle impact assessment (LCIA) provides a systematic procedure for classifying and characterizing these types of environmental effects.

Midpoint modelling is often used to indicate the relative potency of the stressor at a common midpoint within the cause-effect chain. Analysis at a midpoint can be useful as it minimizes the amount of forecasting and effect modeling incorporated into the LCIA, thereby reducing the complexity of the modeling and often simplifying communication. Midpoint modeling can minimize assumptions and value choices, reflect a higher level of methodological consensus in the LCA community, and can be more comprehensive than model coverage based on endpoint estimation.

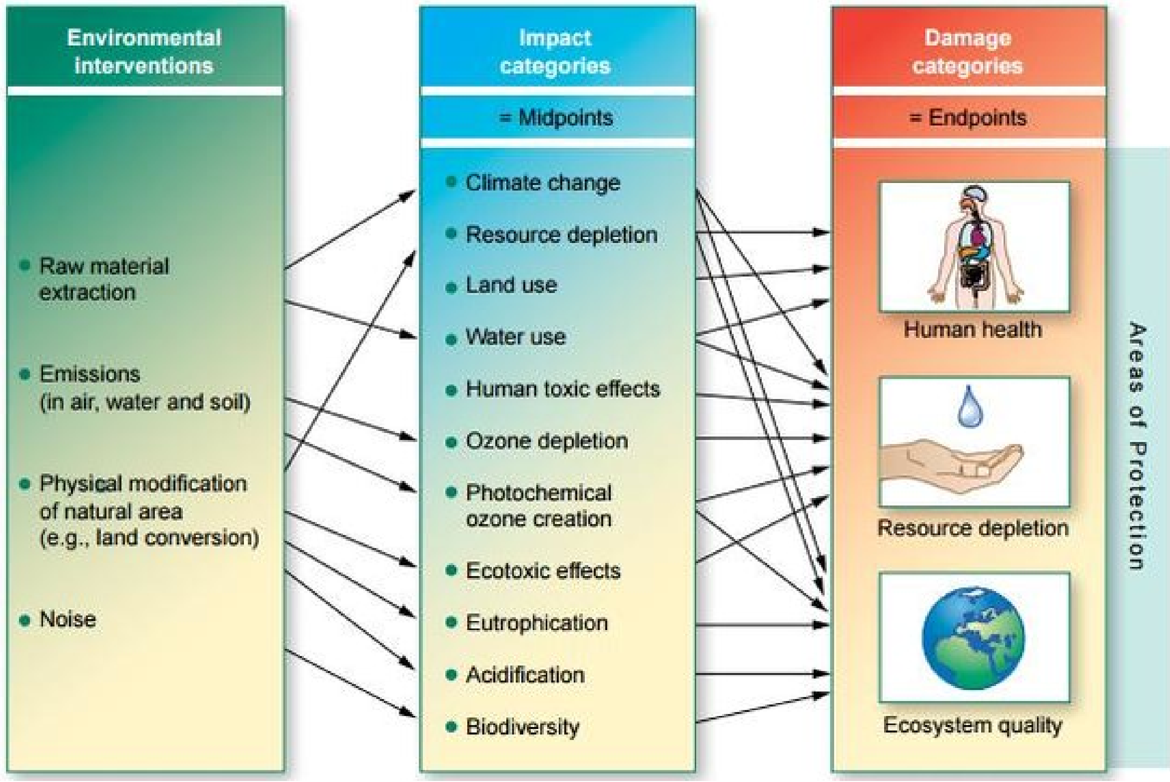

Figure 2.17: The process of impact category calculation from the LCI data [ILCD, 2010]

Weighting refers to the process of adjusting or aggregating indicator results across impact categories to produce a single score. The weighting process is implemented and is calculated using different methods, such as those agreed by an international panel or through the judgement of the economic value of the impact.

An optional step of LCA depending on the goal and scope of the study is to carry out normalisation. This refers to calculation of the magnitude of the impact results relative to available reference information [Norgate and Haque, 2010]. The reference could for example be related to the average individual person in a community over a given period of time. For example global warming impact per person. This process is used with the aim of better understanding the relative magnitude of each indicator result of a product system being assessed.

2.3.0.4 Interpretation

The outcome of the study can be used to inform decision making. A systematic technique can be used to evaluate and check information from the results of the LCI and the LCIA, and communicate them. Interpreting results of an LCA can often be complex, as it may involve a number of scenarios and a number of assumptions may have been made during the study. These must be highlighted in the final results as well as the limitations of the study.

2.3.0.5 Uncertainty and sensitivity

There is a necessity for an analysis of the uncertainties involved in caryring out an LCA to help focus research efforts and also to provide support in the interpretation of LCA study results [Heijungs et al., 2009].

There are three types of uncertainty that can be considered within a LCA study; parameter uncertainty, scenario uncertainty, and model uncertainty [Guldbrandsson and Bergmark, 2007]. Parameter uncertainty relates to the statistical uncertainty in the input data which can be assessed through the use of analysis such as Monte Carlo simulation. Scenario uncertainty refers to the subjective choices that are made, for example regarding allocation or cut-off criteria. These subjective choices can have a significant impact on the results and the level of this impact can be explored through sensitivity analysis. Model uncertainty refers to the level of understanding of the system being measured. This is particularly difficult to quantify especially when applying LCA to emerging or novel technologies.

2.3.0.6 Limitations of LCA

LCA can have limitations based on the method applied, the assumptions within the study, and with impact coverage. LCA relates to the regular production, use and end-of-life management and does not cover accidents, and it is possible and recommended to carry out complimentary environmental based risk assessments alongside LCA.

Data quality is an important assessment element of an LCA study and LCI data quality can have a significant impact on results and when completing a comparative LCA. Low data quality may lead to high uncertainty in the results making it impossible to clarify the superior environmental choices. LCIA impact calculations also have different levels of quality, with many competing calculation methodologies. This needs to be considered when evaluating LCIA results.

The process of weighting to create a single environmental score may assist in communicating impacts, but this method is non-scientific and requires value judgments. LCA results can be used to make environmental claims and the LCA methodology allows for flexibility to omit data or adjust the system boundary which may generate favourable results.

2.3.1 LCA Studies for Rare Earth Production

A number of LCA studies have been completed for REE projects in recent years. Figure 2.18 below highlights these academic studies on REE projects, with the first study being carried out in 2008. There are a range of methodologies and impact assessments used for these studies and have identified specific challenges with applying the LCA approach to REE production. When comparing REE LCA studies it is important to consider whether functionally-equivalent systems are being analysed. For example it is stated in ISO 2006 that:

> Comparing the results of different LCA or LCI studies is only possible if the assumptions and context of each study are equivalent [ILCD, 2010].

This is a particular challenge with REE production because of both the large range of elements considered, and the fact that each deposit has a specific balance of individual REE. Each REE project will also have a range of final products from REE ore, REO, to combined misch-metals. The system boundaries can often be different for each study. The system boundaries are drawn to support the goal of the study and the inclusion or exclusion of individual processes and life cycle stages can have a large effect on the LCA results [PE International, 2014].

One of the challenges with LCA studies for REE production is that they are commonly *cradle-to-gate* studies, meaning that the LCA covers the stages from raw material extraction (the 'cradle') to the point of shipment of the final product (the 'gate'). However, REE projects have a wide range of final products which can include REE containing ore, to REO or separated REE (Figure. 2.18). This combined with the fact that there are different relative proportions of individual REE depending on the deposit and processing. The range of results for the single impact category global warming presented in (Figure.2.18).

LCA results have varied within the studies, even when comparing the same project (Figure. 2.18). Some studies have indicated that the mining and beneficiation stage of REE production is not a significant contributor to the overall impacts, but rather the separation of the REO and reduction to REE have a greater energy demand and material requirements that contribute more to environmental impacts [Arshi et al., 2018].

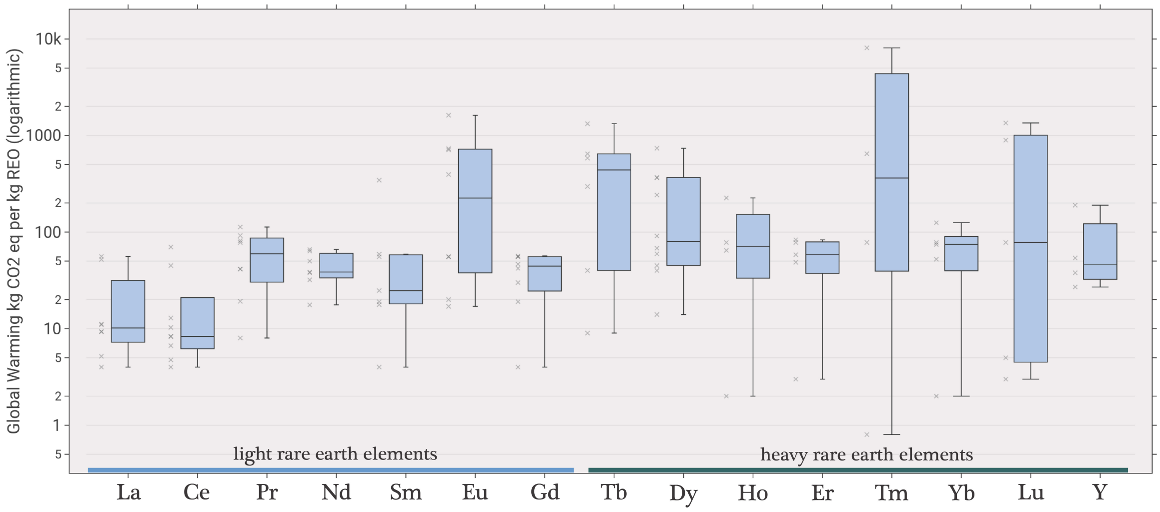

Figure 2.18: Meta-analysis of LCA studies on REE production with global warming impact (kg CO_2 eq. per kg REO)

2.3.1.1 System boundaries and allocation

REE production requires a number of stages which include different types of mining, beneficiation and refining plant configuration to recover various REO or concentrates. These processes are driven by mineralogy, ore grades, recovery rate and targeted by/co-products of the project. In order to allocate for the various products that come out of a REE project, market allocation is often utilised as presented (Equation 2.1.). This process allocates the environmental footprints of all the individual REE and co-products [Weng, 2016, Pell et al., 2019b].

$$Xi = \frac{Ei * Ri * Ci * P}{\sum(Ei * Ri * Ci * P)} \tag{2.1}$$

[Weng, 2016]

Where:

- Ei: Unit values of the commodity i (eg dollares per tonne)
- Xi: Environmental footprint contribution of Commodity i (%)
- Ci: Ore grade of commodity i (%)

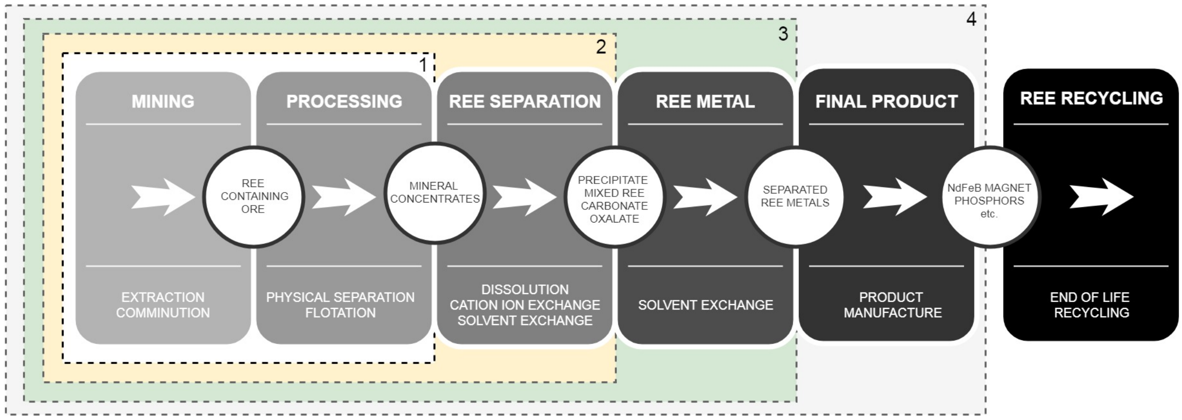

Figure 2.19: REE life cycle and the end products included within LCA

- Ri: Recovery rate of commodity i (%)
- P: Annual production capacity of the project (t ROM/y)

Author	Year	Project	Country	Mineralogy	Impact Assessment	Allocation	Stages included
Arshi et al	2018	Bayan Obo, South China Clays	China	Monazite, Bastnäsite, IOC	TRACI, ILCD	Mass & Economic	4
Browning et al	2016	N/A	Australia	Monazite	N/A	Mass	3
Haque et al	2014	Bayan Obo	China	Bastnäsite	N/A	Mass	3
Ikhlayel	2017	N/A	China	Monazite, Bastnäsite	CML 2001	Mass	3
Jin et al	2016	N/A	N/A	N/A	TRACI	Mass	4
Koltun and Tharumarjah	2014	Bayan Obo	China	Monazite, Bastnäsite	Eco-indicator 99	Economic	3
Lee and Wen	2017	Bayan Obo, Sichuan, South China Clays	China	Monazite, Bastnäsite, IOC	CML2002	Mass	4
Lee and Wen	2018	Bayan Obo, Sichuan, South China Clays	China	Monazite, Bastnäsite, IOC	N/A	Eco-cost	4
Lima et al	2018	Araxa	Brazil	Monazite	IMPACT2002+	Mass	2
Marx et al	2018	Bayan Obo, Mount Weld, Mountain Pass	Australia, China, USA	Monazite, Bastnäsite	ReCiPe 1.08	Mass & Economic	4
Navarro and Zhao	2014	Review	Global	N/A	N/A	N/A	N/A
Pell et al	2018	Songwe Hill	Malawi	Synchysite	TRACI	Mass	2
Pell et al	2018	Bear Lodge	USA	Bastnäsite	TRACI	Mass	2
Schreiber et al	2016	Bayan Obo, Norra Kärr	China, Sweden	Monazite, Bastnäsite, Eudialyte	ILCD	Mass & Economic	3
Sprecher et al	2014	Bayan Obo	China	Monazite, Bastnäsite	ReCiPe 1.08	Mass	4
Vahidi and Zhao	2017	Bayan Obo, South China Clays	China	Monazite, Bastnäsite, IOC	TRACI	Mass & Economic	3
Vahidi et al	2016	South China Clays	China	IOC	TRACI	Economic	2
Weng et al	2017	26 Projects	Global	Numerous	ReCiPe 1.08	Economic	3
Zaimes et al	2015	Bayan Obo	China	Monazite, Bastnäsite	TRACI, IPCC	Mass	2
Zapp et al	2018	Bayan Obo, South China Clays, Norra Kärr	China, Sweden	Monazite, Bastnäsite, IOC, Eudialyte	ReCiPe 1.08	Mass & Economic	2
Wulf et al	2017	Bayan Obo, Mount Weld, Mountain Pass	Australia, China, USA	Monazite, Bastnäsite	ReCiPe 1.08	Economic	4

Figure 2.20: Review of life cycle assessment studies for rare earth production

Mass based allocation causes issues if it is applied to REE production. This is because the mass of a a low value REE, such as La or Ce in a project does not determine whether it is economically feasible. It is often the lower volume of higher value REE such as Nd or Dy. To overcome this, a combination of economic and mass based allocation is used [Arshi et al., 2018, Koltun and Tharumarajah, 2014, Weng, 2016]. However as Figure. 2.21 and 2.22 indicates, REE price fluctuates in relatively short time-frames. This means that if an identical study was complete using economic allocation 2010 and 2018, the attribution of impacts on the different REE would be significantly different.

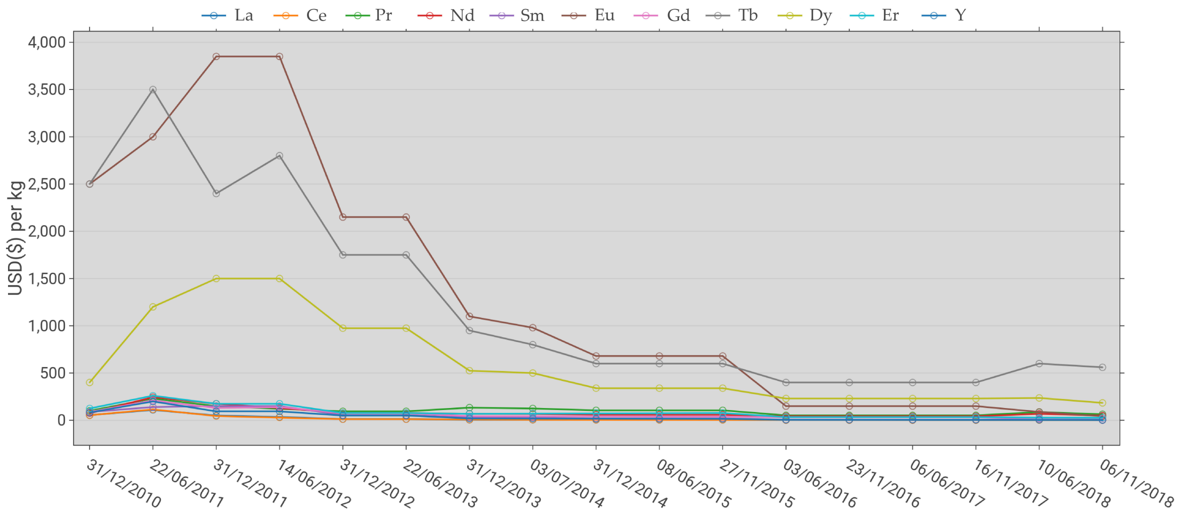

Figure 2.21: The changing economic price of individual REE over time

One of the limitations of the economic allocation procedure is that there is a temporal change to the value of REE (Figure 2.18).

A number of REE LCA have cited challenges with obtaining good quality data, and as described in the limitations of LCA, many studies have made different subjective choices and assumptions. This is an area that would require further research and the development of a framework and rules pertaining to commonly used chemicals.

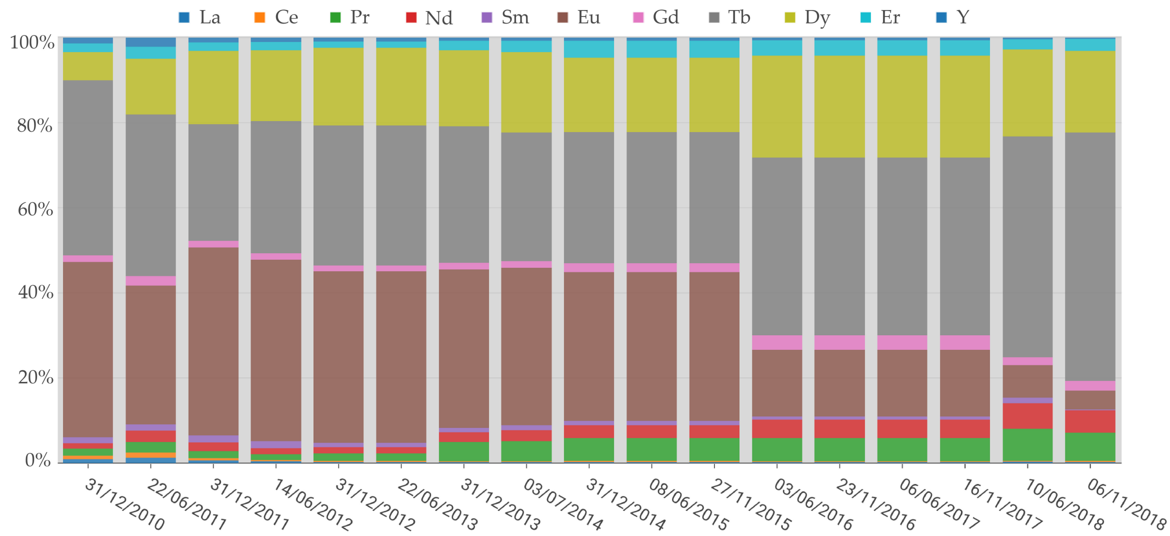

Figure 2.22: The change in relaitve value of individual REE over time

2.4 Criticality

Mineral criticality is a subjective concept that has developed over many decades. The term 'criticality' has been used with reference to raw materials since at least 1939, when the United States of America government issue the "Critical Material Stockpiling Act", followed by comparable acts in the US and Europe [Buijs, 2012, Achzet and Helbig, 2013]. There has been a vast amount of published literature on this topic in the last decade [Erdmann and Graedel, 2011, Buijs, 2012, Sonnemann et al., 2015, Graedel and Reck, 2015], following the Natural Resources Council introduction of a material criticality assessment methodology in 2008 [NRC, 2008]. This report defined the path forward on criticality, highlighting its distinction from material scarcity and how criticality can be useful for raw material strategy. It has also been stated that understanding criticality is important to enhance supply chain resilience. Understanding how substitution of the critical material or by augmenting the supply through changes in the mining and recycling [Binnemans, 2014, Binnemans, 2018]. Although there is no commonly accepted definition of raw material criticality the aims can be described as:

> "... capturing both the supply risks on the one hand and the vulnerability of a system to a potential supply disruption on the other [Erdmann and Graedel, 2011]

A number of criticality methodologies exist and the criticality analysis frameworks vary widely in terms of the procedures for aggregating factors into final scores and how the factors are weighted. This was supported by a recent review of criticality studies which noted the wide divergence in methodology [Erdmann and Graedel, 2011]. Criticality studies also vary in terms the threshold at which raw materials become critical, and these are often subjectively decided (Figure. 2.23). The differences

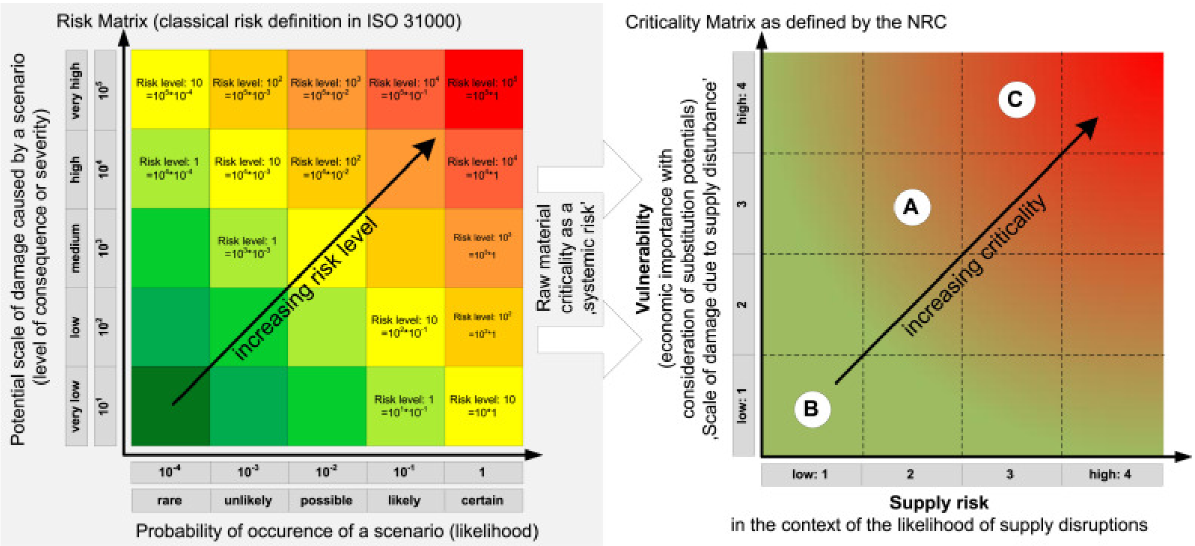

Figure 2.23: The criticality concept showing a 2-dimensional space where raw materials can be located in terms of their risk to supply disruption and the economic impact of said supply disruption

[NRC, 2008]

in approaches can in part be explained by the different aims of studies and what particular economic systems are being examined. Economic systems can range from a single corporation [Duclos et al., 2019] to a sector, or even national and regional economies [NRC, 2008] and criticality studies may also look at a range of materials, from single elements [Rosenau-tornow et al., 2009], to a handful of metals from the same geological family [Nassar et al., 2015] or elements that have a use in a single end technology [Nuss and Eckelman, 2014].

Despite the range of methodologies and factors influencing the criticality scores, there is a common approach to displaying results with a two-axis approach. Supply risk presented on a horizontal axis, and the impact of damage or vulnerability to that supply risk on the vertical axis. These two dimensions are considered independent of one another and raw materials are only deemed to be critical if they posses both a high supply risk and have a high value, or have high importance. Most studies use a weighted average with subjective rankings of the importance of each category. Finally, the corresponding target values are aggregated either linearly, or in a matrix, or in a 3-

dimensional way which will generate a final criticality value [Achzet and Helbig, 2013]. An exception to this was made with the development of a criticality vector magnitude, whereby the distance from the origin to a metals location in criticality space was made [Graedel et al., 2012]. There was also a development of a a single criticality indicator by multiplying the two factors creating convex contour lines [Glöser et al., 2015].

Criticality studies are dynamic and so are subject to changes in demand and supply conditions [Mccullough and Nassar, 2017]. For example, the EU criticality analysis in 2014 indicated that some materials lost their criticality status comparing to the assessment in 2010 (European Commission, 2014a, 2010). For example an increase in demand for a new technology or supply restriction can impact national secutriy and economic health [Sprecher et al., 2017]. Criticality can also be influenced by increased reliance on foreign supply [Fortier et al., 2018]. This was highlighted during 2010 when foreign dependence of REE was used as leverage for a political agenda with the REE following a dispute between Chinese and Japanese governments [Ting and Seaman, 2013, Mancheri and Marukawa, 2016].

Criticality studies are also site specific. A material critical for the United States may not be critical for China, and this is the case for REE as although the economic value of REE is still very high in China, the fact that they account for over 90% of production means that there is a very low risk of supply disruption. This is also the case for industries, with certain materials being essential for specific technologies but not others. Graedel proposed that different frameworks should exist for different studies looking at global, national, or company levels [Graedel et al., 2012].

Some studies have included environmental issues within criticality studies [Achzet and Helbig, 2013]. The basis for the inclusion is that environmental issues can be considered as a supply risk. However, Graedel indicated that environmental issues should be considered as a separate third-dimension as the environmental issues should be considered during material selection [Graedel et al., 2012, Graedel and Reck, 2015]. Using this third dimension relies on LCA data, and this data can vary in accuracy as is the case with REE [Nuss and Eckelman, 2014].

A review of criticality frameworks and criticality analysis was carried out to review the most common criticality factors [Achzet and Helbig, 2013]. These are presented in Table 2.5.

Table 2.5: Forecast growth in REE demand [Lima et al., 2018]

Factors of vulnerability	Factors of supply risk
Substitutability	Country concentration of production
Value of products affected	Country governance
Future demand/supply ratio	Depletion time
Value of the utilised materials	By-product dependency
Spread of utilisation	Company concentration in mining corporations
Change in demand share	Demand growth
Import dependence	Import dependence
Target groups demand share	Recycling/recycling potential
Strategic importance	Substitutability
Ability to innovate	Volatility of commodity prices
Change in imports	Exploration degree
Company concentration of production	Production costs in extraction
Consumption volume	Stock keeping
Mine production change	Market balance
Recyclability	Mine/refinery capacity
	Future market capacity
	Investment in mining
	Climate change vulnerability
	Temporary scarcity
	Risk of strategic use
	Abundance in earth's crust

2.4.0.1 REE in criticality studies

For markets outside China, REE are considered to have issues associated with security of supply [Nassar et al., 2015]. Concerns over the availability of REE have been frequently discussed in literature in recent years, with publications highlighting the dominant position of China in both production [Belva, 2010] and in consumption

[USGS, 2016]. There have also been risks associated with supply disruption highlighted in studies [Graedel and Nassar, 2017, USGS, 2016]. Political changes have occurred in recent years in response to this. Most recently with President Donald Trump signing the 2019 National Defence Authorization Act, banning the U.S. Department of Defense from acquiring rare earths or rare earth containing magnets from China, Russia, Iran, and North Korea.

REE have been designated as critical by a committee of the U.S. National Research Council, stating that they have very high concern [NRC, 2008]. The British Geological Survey (BGS) produced a risk list for 2012 and 2015 examining the relative risk of 41 elements or element groups needed to maintain the UK economy and lifestyle [BGS, 2017]. The methodology included factors such as location of current production and reserves, the political stability of these locations, and the percentage of the companion metal fraction. The list only examined supply risk and not factors of vulnerability. REE placed in the top position for both years. The Committees of the European Commission gave REE a critical designation in the 2010, 2014, and 2017 as highlighted in (Figure. 2.24). This study separated HREE and LREE and highlighted that HREE, being almost exclusively produced in China, had a higher supply risk than LREE.

A study was carried out using the methodology developed by Graedel to incorporate a range of factors and group it into a 3-dimensional framework which includes factors of vulnerability, factory of supply risk, with the additional environmental risk axis [Graedel et al., 2012]. The results present a detailed overview of the factors influencing the criticality score for the individual REE and can be seen in Figure.2.25.

A review of criticality studies was completed by [Hayes and McCullough, 2018]. The results indicated that of the 56 elements evaluated in the study, REE were most

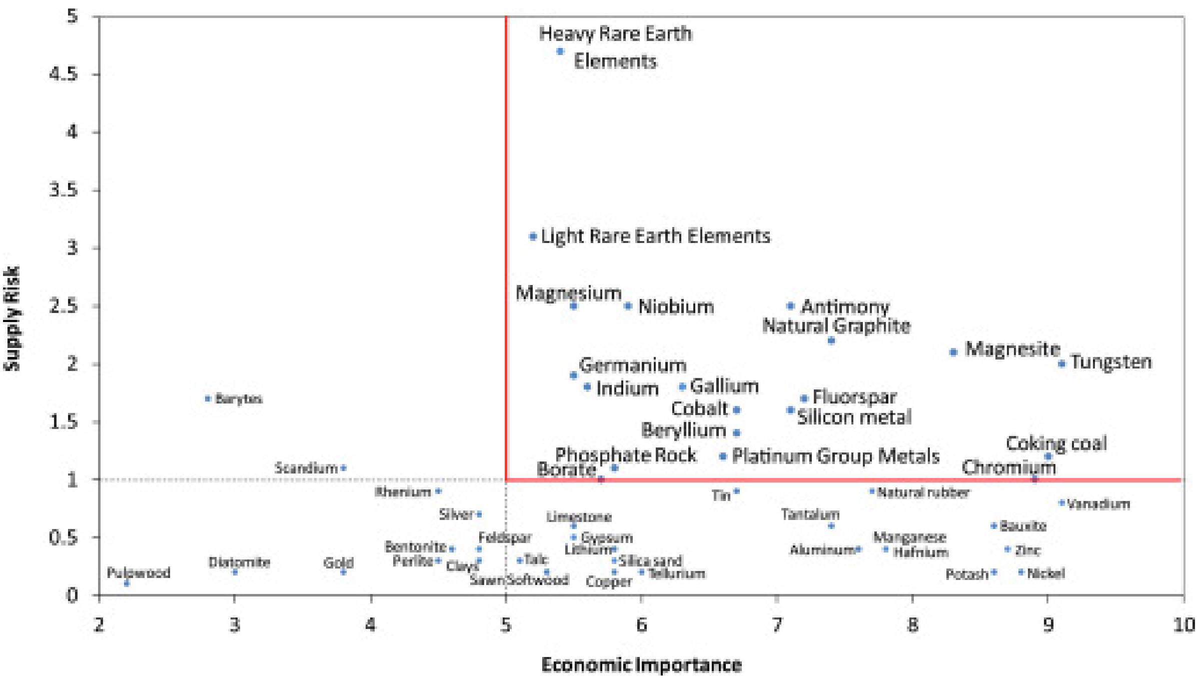

Figure 2.24: The TERP framework to structure supply risk factors grouped according to different factors

[Dewulf et al., 2016]

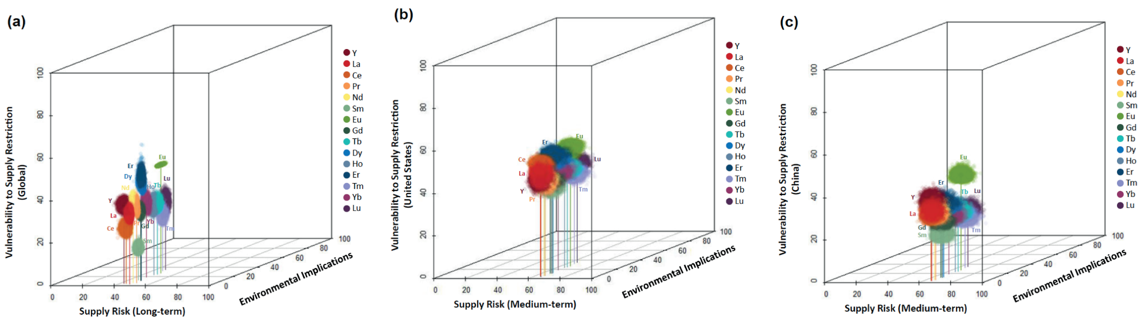

Figure 2.25: Locations of REEs in criticality space: (a) global level; (b) national level, for the United States; and (c) national level, for China. Figures are created using the Scatterplot3d package (Ligges and Machler 2013) in the R language and environment for statistical computing

[Nassar et al., 2015]

commonly recognised as critical, alongside the platinum-group metals (PGM), and indium.

2.4.0.2 Limitations of criticality studies

A limitation of criticality studies is the fact that a subjective decision is made during the process, whether it is the indication at which point an element becomes critical, or how the individual factors are weighted in terms of importance. A number of studies also fail to present their methodologies in a clear and transparent way. A list of other limitations were presented by [Buijs, 2012]:

- Studies show a bias towards technology minerals by emphasising high-tech applications and the role of market power of producers in smaller markets
- They lack predictive power beyond the short term
- They have a tendancy to overstate the economic impact of a possible supply disruption of 'critical minerals'
- They often fail to distinguish between short-term and long-term problems
- They take insufficient account of the the diversity and particular characteristics of the resource markets that are analysed
- They focus exclusively on risks related to the mining and export of raw materials but disregard the larger production chain (e.g. refining, transport and trade in semi-products).

It has been claimed that many criticality studies fail to reflect the dynamic nature of raw material risk, with most studies assuming that each indicator has the same impact on raw material criticality for every raw material. There are also areas of criticality studies which are difficult to quantify. For example, political risk or accident risk could be considered at least partially subjective and resource markets are dynamic especially when it comes to technology metals, such as REE that are produced in lower volume. The balance between supply and demand and the sources of supply can change quickly. In conclusion, criticality studies can be useful for decision makers from policy and industry. The methods employed should be clearly defined and the limitation of criticality assessments understood.

2.5 Mine Scheduling and Project Development

Mine scheduling is an important step in the mining process, where the extraction of ore is sequenced to maximise the value of the project whilst meeting physical and economic constraints. The process has been defined in an open-pit context as:

> ”Specifying the sequence of blocks extraction from the mine to give the highest NPV, subject to a variety of production, grade blending and pit slope constraints” [Whittle, 1999]

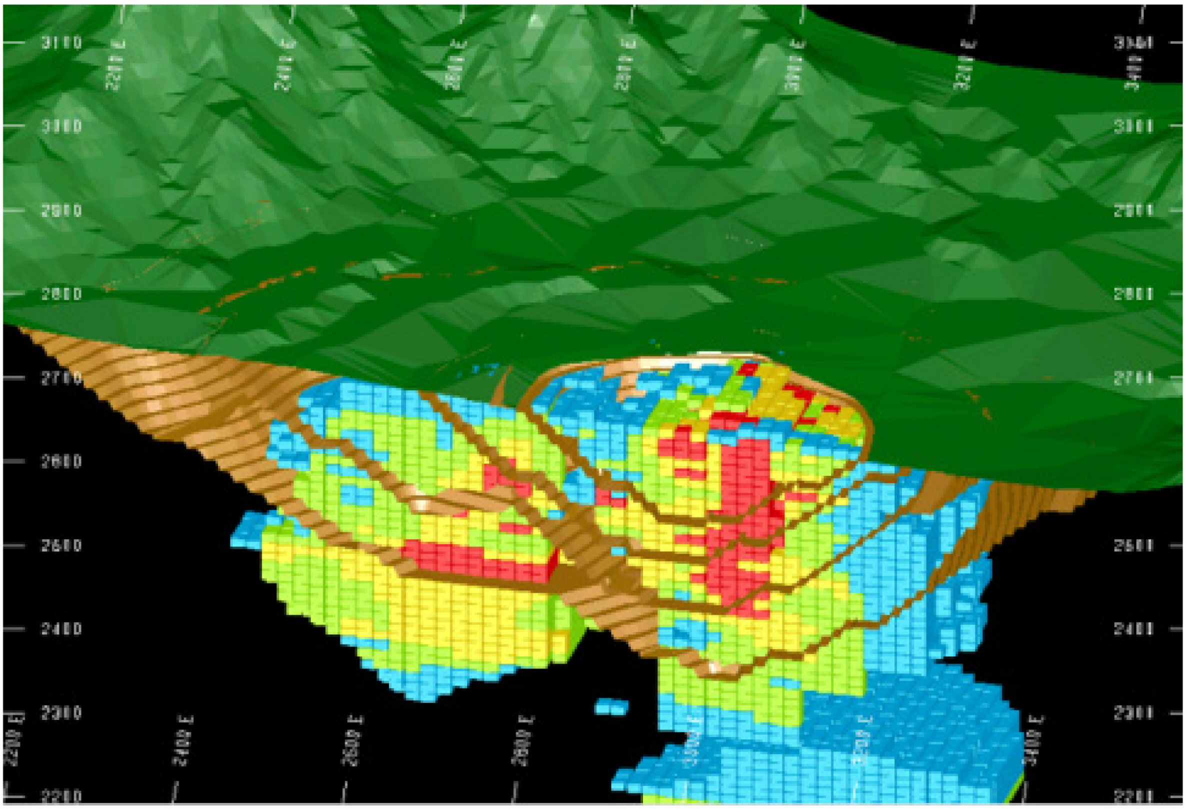

Figure 2.26: A 3-D block model representing an ore deposit
[Dagdelen, 2001]

A block model is generated to represent the deposit (Figure.2.26). A block model is regularised, three dimensional array of blocks used to represent properties and characteristics of an ore body. Block dimensions will be selected based on exploration drilling patterns, ore body geology and mine equipment size. Each block will be assigned a grade using estimation techniques which can include inverse distance weighted interpolation, weighted moving averages and kriging [Osanloo et al., 2008]. It is then possible to give each block an economic value based on financial and metallurgical data, and more recently environmental data has been included [Pell et al., 2019a]. The economic future value of the block can be calculated by discounting the original value to time zero using a discounted rate. Estimation of block properties represents one of the largest sources of technical risk in mine planning [Davis and Newman, 2008]. Uncertainty with respect to ore grade and tonnage can negatively impact the economic performance of an operation.

The efficient extraction of mineral deposits is becoming more important with diminishing grades and deeper deposits and one way to increase efficiency is to improve mine production scheduling. Different models have been developed to solve the complex problem since the 1960s [Dagdelen, 2001]. The nested pit approach is the most commonly applied method in the mining industry which was introduced by Lerchs and Grossmann [Lerchs and Grossman, 1965].

2.5.0.1 Classical mine planning

Classical mine production scheduling determines the final pit limit before defining the nested pits. The sequencing, which sets out the time period at which an individual block will be extracted is determined as well as the destination for each extracted block. This is calculated based on the grade which can included the expenses and cost of the block. All blocks above this grade are considered as ore and below considered waste. The final stage of scheduling is to calculate how much material should be extracted in particular time periods [Dagdelen, 2001].

The scheduling problem was originally solved by dividing the problem into sub problems. The approach predicts the production capacities in the mining system and estimates for related costs and commodity prices. The analysis of the ultimate pit limits are defined once the economic parameters of the system are known and it is then possible to select pushbacks, to divide the deposit into the smallest pit with the highest value per ton to the largest pit with the lowest value per ton. The cutoff grade is defined and the process is indicated as in (Figure. 2.29). Undiscounted value is used to determine the pit limit as the timing of material extraction cannot be known until the material to be removed has been identified, a production rate established, and the order of mining or mining sequence established.

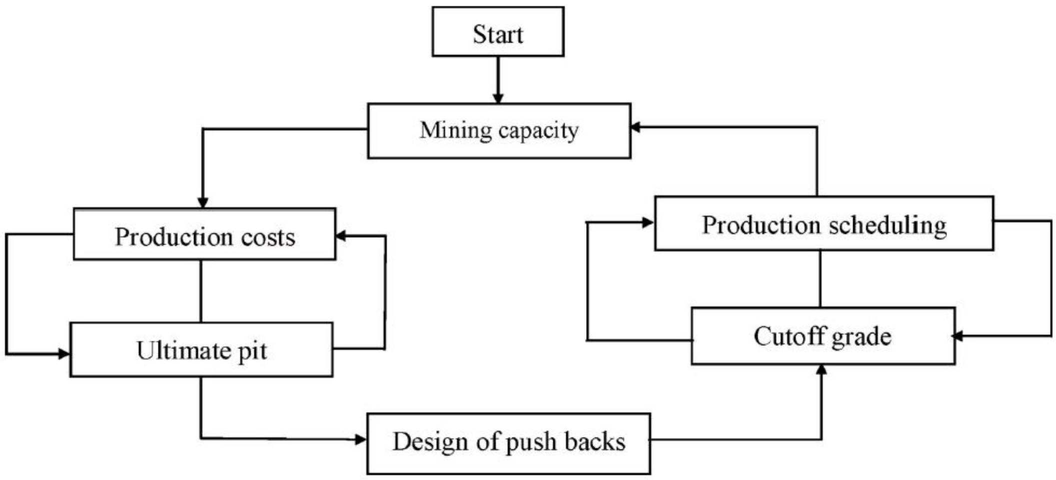

Figure 2.27: Traditional mine scheduling by using circular analysis [Lerchs and Grossman, 1965]

The Lerchs-Grossman algorithm is most commonly applied to determine the pit limit [Lerchs and Grossman, 1965]. The algorthm produces a mathmatically optimuum solution of maximising the pit value. Non-optimizing heurestic approaches are also commonly used such as floating cone algorithms.

The pit limit analysis is usually carried out using commercial software and requires an economic block model, and is constrained by the maximum allowable pit slope. The objective of this stage is to maximise the undiscounted value of the pit. This is calculated using the principle that each block will be mined if its value is greater than the cost of its own mining and processing, and covers the cost of the overlying sub-economic blocks that must be mined to access the ore.

Sub-pits are generated in the model, known as nested pits. The reason for the development of nested pits is to generate areas that go from the most profitable to the least profitable or break-even material. This information is useful to determine the starting point for the mine, and in what sequence to mine the pit to produce the highest value NPV. The nested pits are generated at the same time as the pit limit using the same algorithm and methods, but the commodity sale price or processing cost is varied.

The order in which the pit expands is known as the mining sequence and is determined by the pushback parameters. The time at which each block is extracted. The major challenges of solving the mine scheduling problem was described by [Whittle, 1999].

> ”The pit outline with the highest value cannot be determined until the block values are known. The block values are not known until the mining sequence is determined; and the mining sequence cannot be determined unless the pit outline is available.” [Whittle, 1999]

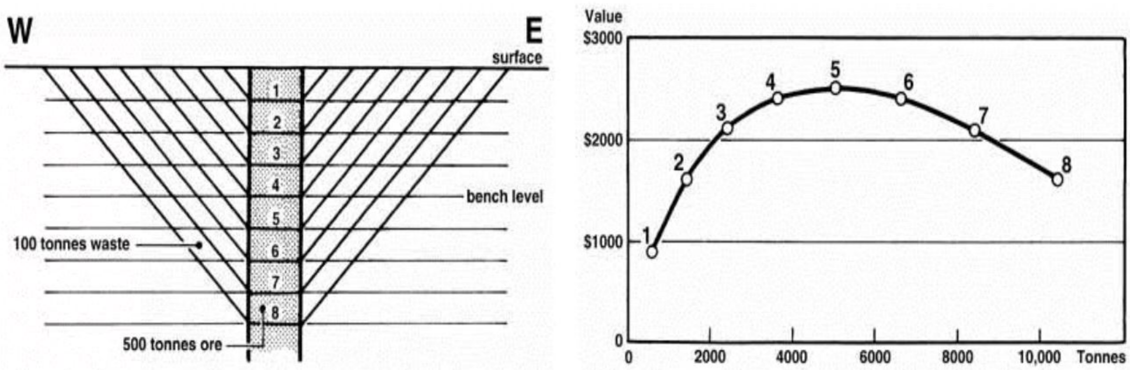

Figure 2.28: Pushbacks and mine sequencing
[Whittle, 1999]

2.5.0.2 Direct block scheduling

A Direct Multi-Period Scheduling (DBS) has the advantage over the classical method in being able to apply correct discount factors to cash flow over production years resulting in present value forecast assessments [Almeida, 2013]. DBS uses heuristic models based on simulated annealing to analyse each block independently, and uses Tabu search to find a group of solutions that are near optimum [Almeida, 2013].

DBS is a surface constrained method to carry out long-term production scheduling of an orebody. DBS can be used to complete scheduling of mining of blocks directly from the block model whilst remaining within operational constraints. The algorithm uses operational and physical constraints at the block resolution to produce the optimum long-term production schedule which also includes the final pit. This means that many steps that are used in the traditional process are skipped [Navia-vásquez et al., 2017]. For example there is no need to run a pit or cut-off grade optimziation first as these are executed simultaneously from the block model. This is achieved by assigning revenue and cost values to each block in addition to the traditional model attributes. The method considers each block present in the model as a single unit for each mine period.

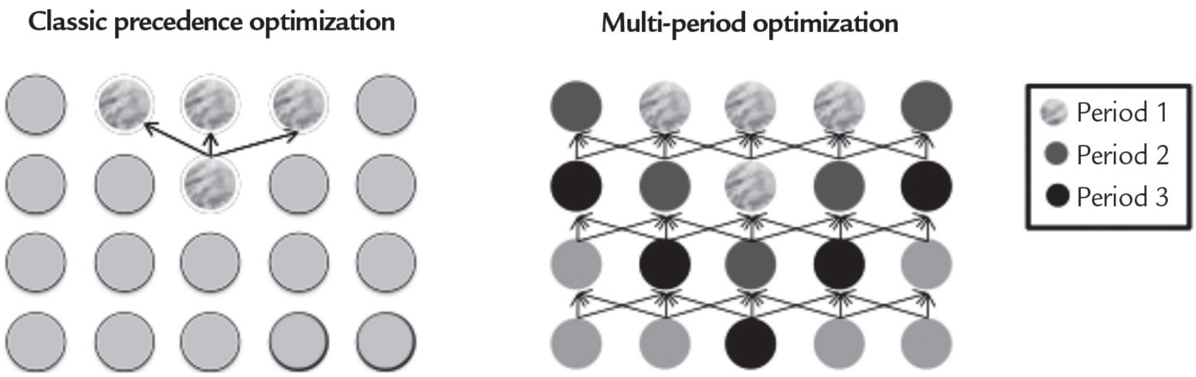

Figure 2.29: Traditional mine scheduling by using circular analysis [Navia-vásquez et al., 2017]

DBS is a useful approach to generate the same order of NPV generated as the

Lerchs-Grossmann approach, whilst using the correct discount factors and considering integer blocks mined in each period. The NPV of DBS can be create a similar NPV but in a shorter time period [Almeida, 2013]. The appliction of the adequate discount factor is more significant for limiting blocks thererfore there is a trend for the classical methodology to overestimate reserves and underestimate ore grade.

It is also to integrate environmental parameters with DBS. For example a constraint such as CO2 emission alongside the other standard constraints can be included. This work is presented in Chapter 5.

Chapter 3

Mineral processing simulation based environmental life cycle assessment for rare earth project development: a case study on the Songwe Hill project

There is increased pressure on mining companies to consider the environmental impacts that their project might have during the development phase and explore a range of options that could minimise these impacts. Mining life cycle assessments quantify the environmental performance of production based on a single value average over the life of the project. This approach fails to consider environmental impact variation which may occur over the life of the project. It is potential to use data developed during engineering studies for the pre-feasibility stage of a mining project to carry out a LCA and produce LCIA data on a temporal basis, such as per month or per year. Having a greater temporal resolution for the LCA enables companies to identify relationships between grade and ore composition early on in a project, giving companies time to reflect and make informed decisions from these environmental results.

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Research article

Mineral processing simulation based-environmental life cycle assessment for rare earth project development: A case study on the Songwe Hill project

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A R T I C L E I N F O

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A B S T R A C T

Rare earth elements (REE), including neodymium, praseodymium, and dysprosium are used in a range of low-carbon technologies, such as electric vehicles and wind turbines, and demand for these REE is forecast to grow. This study demonstrates that a process simulation-based life cycle assessment (LCA) carried out at the early stages of a REE project, such as at the pre-feasibility stage, can inform subsequent decision making during the development of the project and help reduce its environmental impacts. As new REE supply chains are established and new mines are opened. It is important that the environmental consequences of different production options are examined in a life cycle context in order that the environment footprint of these raw materials is kept as low as possible. Here, we present a cradle-to-gate and process simulation-based life cycle assessment (LCA) for a potential new supply of REE at Songwe Hill in Malawi. We examine different project options including energy selection and a comparison of on-site acid regeneration versus virgin acid consumption which were being considered for the project. The LCA results show that the global warming potential of producing 1 kg of rare earth oxide (REO) from Songwe Hill is between 17 and 87 kg CO_2-eq. A scenario that combines on-site acid regeneration with off-peak hydroelectric and photovoltaic energy gives the lowest global warming potential and performs well in other impact categories. This approach can equally well be applied to all other types of ore deposits and should be considered as a routine addition to all pre-feasibility studies.

1. Introduction

Rare earth elements (REE) are a group of 17 elements composed of the lanthanide group, atomic numbers (57–71), with the addition of scandium (Sc, 21) and yttrium (Y, 39). REE are used in a range of electronic, optical, magnetic and catalytic applications because of specific and unique physical and chemical properties that the different REE possess (Adibi et al., 2014; Voncken, 2016). For example, neodymium (Nd) is an essential constituent of NdFeB high strength permanent magnets that are often used in electric vehicles. This application in electric vehicles, which is currently experiencing significant growth, has contributed to an increased demand for REE (Fishman et al., 2018). A number of REE deposits have been identified around the world that could potentially fulfil the future demand outlook (Goodenough et al., 2017). There is additional incentive to develop production outside China to reduce production concentration. China currently is the majority producer in all stages of the REE value chain. This combination of high economic importance, such as the need for Nd for the electric vehicle market, with an increased risk to supply disruption due to market concentration, has led to many governments and organisations to classify REE as ‘critical’ materials (Graedel et al., 2015; Nassar et al., 2015; Pell et al., 2018).

As REE projects are being explored in different parts of the world and are financed, they move from exploration through to project feasibility. REE production can be material and energy intensive and has been linked with high environmental damage (Sprecher et al., 2014; Wall et al., 2017). Life cycle assessment (LCA) is an established and widely applied method to holistically evaluate the environmental impacts of any product systems (Yan et al., 2011). The results generated from the LCA approach can be useful in quantifying the total environmental costs of REE production and are complementary to traditional environmental evaluations such as environmental impact assessments. A number of LCA studies have been applied to REE projects with different REE-containing minerals and with projects in various stages of development. Bayan Obo, the world's largest source of light REE (bastnäsite ore), has been studied a number of times (Zaimes et al.,

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2015; Koltun and Tharumarajah, 2014; Arshi et al., 2018; Du and Graedel, 2011; Haque et al., 2014; Sprecher et al., 2014). Vahidi et al. (2016) and Lee and Wen (2016) completed LCAs for a number of ion adsorption deposits, a major source of heavy REE also located in China. Marx et al. (2018) compared the REE production from Mt Weld in Australia with Mountain Pass, USA, and Bayan Obo. Predictive LCA studies have also been completed for REE projects. Weng et al. (2016) carried out a broad comparative study of 26 different operating and potential REE projects, which was discussed by Pell et al. (2017). Schreiber et al. (2016) used a predictive LCA to measure the environmental performance of REE production from the REE mineral, eudialyte, at Norra Kärr in Sweden. Their paper examined how changing physical and chemical parameters of the deposit, and changing processing methods through the life of a project can influence the environmental impact. This method was also applied by Pell et al. (2019a) for the Bear Lodge project in USA. The results highlighted the environmental impact changes over the life-of-mine and the positive relationship between decreasing grade and increasing global warming impact. This work also highlighted that this relationship is not consistent among the different mineralogies at the deposit.

A major limitation of current LCA methodology for REE production is that it is difficult to compare results across studies because of variation in system boundaries used, source and quality of life cycle inventory (LCI) data, different allocation procedures, and the use of different databases and life cycle impact assessment (LCIA) methods. In particular, most LCA studies use simple average black-boxes to represent high-level aggregated processes when compiling the LCI such as with Weng et al. (2016). Although the results from these studies can be useful for communicating aggregated impacts to non-specialist audiences, using this approach may not provide the resolution needed to identify particular impacts as it cannot capture the details and interconnected nature of materials processing systems.

Carrying out an LCA at the early stages of a project can inform choices that are made later during the development of the project even though the LCA results might have relatively high uncertainties (see Fig. 1). Some work has even examined the inclusion of LCA in long term mine scheduling which takes place at a very early stage of a mining project (Pell et al., 2019b). The approach presented in this paper highlights how early-stage LCA based on a scoping or pre-feasibility study can be realised by generating a mineral process simulation-LCA model. This can be used to inform choices of processing routes, energy sources and waste management and can be continuously updated throughout project development. Recent studies, aiming to develop an indicator framework for the environmental sustainability benchmarking of metallurgical industry products, have already highlighted that it is possible to integrate detailed mineral processing simulations with LCA (Rönnlund et al., 2016a, 2016b; Reuter et al., 2015).

Once a model has been developed it is possible to update processing efficiencies, update grade and mineralisation data following drilling campaigns, or replace specific modules to reflect changes in the project. Fig. 1 highlights the advantage of including environmental data early in the project development stage. The planning phase offers the greatest opportunity to minimize the environmental, capital and operating costs of the ultimate project, while maximizing the operability and profitability of the venture. But the opposite is also true: no phase of the project contains the potential for instilling technical or fiscal disaster into a developing project that is inherent in the planning phase. At the start of the conceptual study, there is a relatively unlimited ability to influence the cost of the emerging project. As decisions are made, correctly or otherwise, during the balance of the planning phase, the opportunity to influence the cost of the job diminishes rapidly. The ability to influence the cost of the project diminishes further as more decisions are made during the design stage. At the end of the construction period there is essentially no opportunity to influence costs.

Quantifying the flows of ore and waste through the mining and mineral processing stages of a project using simulation has evolved and improved in quality in recent years (Reuter, 1998; Abadías Llamas et al., 2019). A common tool that is used to plan and optimise mineral processing is mineral process simulation software. The data generated from this type of software, such as energy, material and chemical

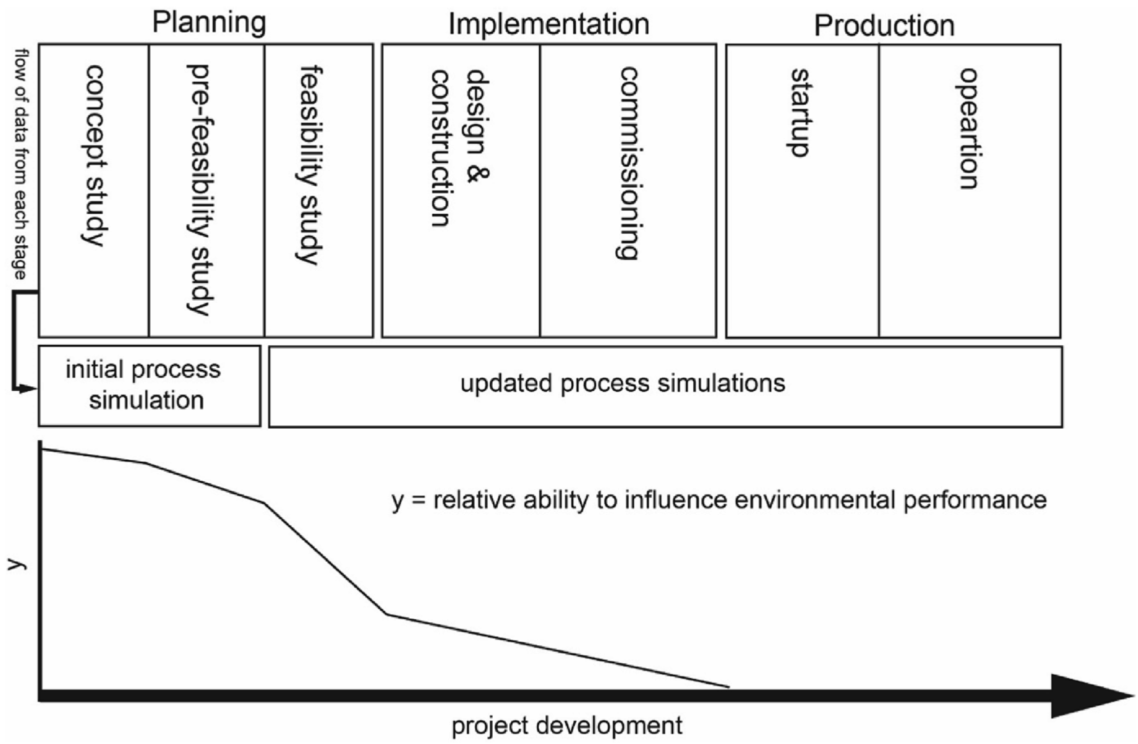

Fig. 1. Relationship between project stage, data availability for process simulations and the impact on LCA results reliability and the ability for those findings to impact project development (adapted from Schoonwinkel et al., 2019)

requirements and process efficiencies, can be used to generate data for the LCI (Reuter, 1998). This study aims to carry out a simulation-LCA for REE production by using mineral processing software, HSC Sim, directly in combination with an LCA software GaBi (Commercial software GaBi® 7.0 Pro). This approach allows for an easily updated LCA as the project moves through development, ensuring a consistent system boundary whilst generating robust and reliable LCI data based on elementary flows generated from HSC Sim that are balanced in terms of mass and energy. Simulation-based LCA has been adopted using other simulation programmes such as Aspin plus and applied to a range of process design scenarios (Righi et al., 2018).

The simulation-LCA approach is a useful tool to analyse and compare detailed process options in REE production, helping to unpack potential trade-offs between resource and environmental efficiency and identify the hotspots for intervention. Most exploration projects produce publicly available information even at the early 'pre-feasibility' stage. We show that it is possible to use this information to quantify environmental impacts using simulation-LCA so that projects can be compared and mining companies can refine and optimise their proposed methods to reduce environmental impacts. We use the Songwe Hill project as a case study to demonstrate the new simulation-LCA method developed.

The rest of this paper is organised as follows; Section 2 explains the materials and methods used in this study describing the case study process and highlighting the simulation-LCA process and the different scenarios compared. Section 3 presents the results for the six scenarios and also examines the results of best performing scenarios in detail. Uncertainty analysis is also included in this section. The paper concludes with Section 4, which suggests how a simulation-LCA during the pre-feasibility stage of a project could be used in the future to enhance environmental evaluations and management in REE project development.

2. Materials and methods

2.1. The case study

The REE project investigated is Songwe Hill, a carbonatite REE deposit in the Chilwa Alkaline Province of southern Malawi (Garson, 1962; Croll et al., 2014; Broom-Fendley et al., n.d.). The ore minerals are synchysite-(Ce) and fluorapatite in ferroan calcite and dolomite carbonatite. The proposed ores are have a total rare earth oxide (TREO) grade of 1.62%. The deposit is light-REE enriched but with a relatively high proportion of Nd and higher proportions of heavy-REE than in most carbonatites (Broom-Fendley et al., n.d.).

Based on the pre-feasibility study, the project is forecast to have an 18-year mine life with an annual production of 2841 tonnes (Croll et al., 2014). Songwe Hill plans to mine and process REE ore to form a mixed REO concentrate, which is then removed from site (Fig. 2). The downstream separation of the individual REE from the mixed REO is usually done by solvent extraction (a processed summarised in Wall et al., 2017; Krishnamurthy and Gupta, 2015) but beyond the scope of this study.

2.1.1. Mining

Songwe Hill will be mined using a conventional open pit mining method employing drill, blast, truck and shovel (Croll et al., 2014) Loading and hauling will be a 24 h operation, with ore mining will be carried out during the day shift. The overall dimensions of the final open pit will be 650 m north to south, by 450 m east to west and the final pit will be 300 m deep. The mine is predicted to operate for 312 days a year, operating two 11 h shifts per day, averaging seven operating hours per shift. All waste material will be delivered by truck to the waste dump and no backfilling of the open pit is planned.

2.1.2. Beneficiation

Solid ore particles will be reduced in size by crushing and milling to increase the surface area of the solid ore particles and allow a greater degree of liberation of the ore from the gangue material. Ore-bearing material is then upgraded using flotation.

2.1.3. Leaching and dissolution

A calcite leach is carried out to dissolve the calcium in the calcite and ankerite. Re-pulped slurry is then transferred to the REE leach stage whereby hydrochloric acid (HCl) and flocculant are added. Thickener underflow material is pumped to the HCl REE filter where the filter cake is re-pulped with sodium hydroxide is to convert REE phosphates, fluorcarbonates and other refractory REE minerals to acid soluble phases. The thickener overflow is pumped to the purification circuit. Filter cake from caustic conversion is re-pulped with recycled HCl and transferred to the REE dissolution stage. The REE dissolution stage solubilises the REE minerals ready for purification. The purification circuit receives material from the REE leach thickener overflow the REE dissolution thickener overflow and the residue leaching thickener overflow and the pH is adjusted to 1.5–2 with limestone. The purpose of this phase is to remove iron and phosphate.

2.1.4. Precipitation

REE-containing fluid from the purification stage is initially precipitated by a gradually increasing the pH with the addition of sodium hydroxide in sequential agitated tanks. Thickener overflow and REE precipitate filtrate is sent to waste neutralisation, whilst filter cake from this stage is re-pulped with caustic solution before being pumped to caustic conversion stage 2. The slurry is then pumped through agitated tanks with the addition of sodium hydroxide. Thickener underflow is filtered and moves onto a conveyor towards the Ce removal stage. The filter cake is dried at 150 °C to oxidise Ce (to Ce^{4+}), making it insoluble in later leaching. Dried cake then is mixed in agitated tanks where selective leaching of REE oxides occurs using HCL. The thickener overflow and filtrate travels to final REE precipitation and the underflow is filtered re-pulped and agitated in the residue leaching phase. Thickener underflow from this stage is discharged into the waste Ce product. REE-containing solution from the Ce removal thickener overflow is precipitated with increasing pH in a series of agitated tanks. The final underflow is filtered, dried and bagged for shipping and is the final product in this LCA.

2.1.5. Waste management

This stage includes the transport and storage of tailings that come from the beneficiation stage and thickener underflow from the waste neutralisation.

2.1.6. Acid generation

There are three HCl regeneration circuits; they involve reacting high strength calcium chloride with 98% concentrated sulphuric acid to produce high strength HCl and insoluble gypsum. Sulphuric acid is produced on-site by pumping molten sulphur through a pressure leaf filter and burning it in a furnace producing a hot gas flow containing 11% sulphur dioxide. Cooled gas is ducted and sulphur dioxide is converted to sulphur trioxide and is then passed through absorption towers that absorb sulphur trioxide to form sulphuric acid. Steam from this process is also used to generate power, which is included in the LCI. We have also included a comparison of virgin acid consumption on-site.

2.1.7. Energy scenarios

The energy supply options for the Songwe Hill project are listed below and included in the LCA. It is important to note that some energy is produced from the acid regeneration circuit. The first scenario, which uses energy from a coal fired power station, is reliant on the development of the Kam'mwamba power station. This is a proposed 300-MW (MW) coal-fired power station planned for the Kamwamba area in

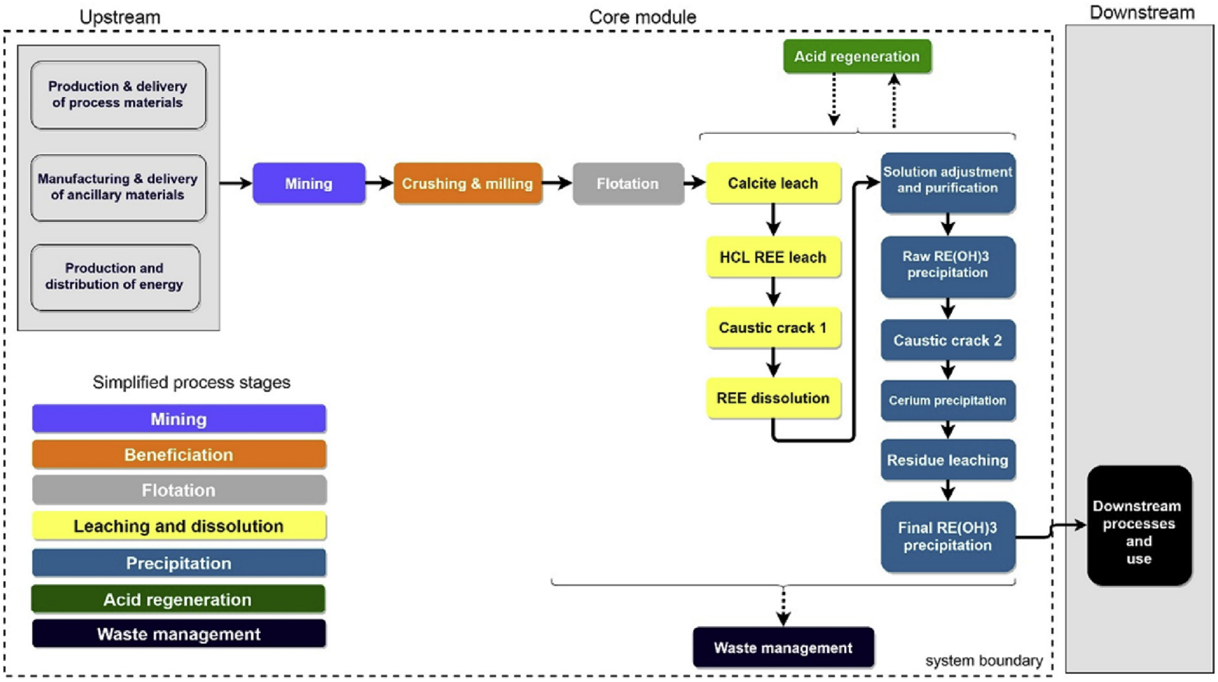

Fig. 2. Songwe Hill process flowsheet with the system boundary for life cycle assessment.

Zalewa, Malawi, forecast to start by 2022. The second scenario, although included in the comparison is not a realistic option for the project. This is because although the current grid power in Malawi is hydroelectric, the amount that can be generated is limited and it is not a reliable source of energy during peak hours. The other scenarios explore combining off-peak grid with storage solutions and other energy sources.

1. Coal fired power station
2. Grid power (hydroelectric)
3. Grid (off-peak) and battery storage
4. Grid (off-peak) and heavy fuel oil
5. Grid (off-peak) and diesel
6. Grid (off-peak) and solar and storage

The energy storage was assumed to be carried out using 75 kWh lithium-ion stationary batteries and includes the environmental impacts associated with the formation of the batteries (Vandepaer et al., 2017).

2.2. Goal and scope

A LCA was performed to quantify the environmental impacts of REO production from Songwe Hill according to ISO, 20040 (2006a, 2006b) standards. The cradle-to-gate study had the goal to compare the environmental costs of different acid and energy scenarios. The LCA model was created using GaBi 9.0. The functional unit of the investigation is the production of 1 kg REO. The technical system boundary for the production of REO has been highlighted in Fig. 2.

Scenarios measuring the environmental impact associated with TREO produced and individual REE are presented. Individual REE impacts are allocated using a combination of economic and mass based allocation, placing greater impact on the elements with higher economic value (Koltun and Tharumarajah, 2014). This is the economic allocation procedure recommended for REE in this scenario by Schrijvers (2017).

The results have been grouped into six main stages: mining, beneficiation, leaching and dissolution, precipitation, acid generation, and waste management (Fig. 2). The life cycle of REO production in this study only considers the operational stage and does not include the impacts associated with exploration, building of the production site or the production of equipment used at the mine site, consistent with other REE LCA studies (Haque et al., 2014; Lee and Wen, 2016; Wulf et al., 2017).

2.3. Life cycle inventory and simulation

The LCI data for the mining stage were collected through Mkango Resources Ltd and from scientific literature. Data, such as energy and material flows for the mineral processing, were acquired by process simulation using the HSC Chemistry 8.0 software (www.outotec.com). Initial data and individual process efficiencies for this process simulation were provided by Mkango Resources. The link of data generation from process simulation to the LCI is shown in Fig. 3, which also highlights how it is possible to change process efficiencies and scenarios. This method has been taken from Reuter et al. (2015).

Some data, such as the specific flocculant and fatty used at Songwe Hill, were unavailable in the LCA database and were replaced with similar substances, as noted in the supplementary information. Waste and discharge streams were assumed at national discharge standards for the industry and through estimates made in the pre-feasibility study (PFS). Background data from the GaBi database and ecoinvent 3.0 were used.

2.4. Life cycle impacts assessment

Assignment of impacts for the 1 kg of REO from Songwe Hill was carried out using the TRACI 2.1 impact assessment methodology with ILCD impacts included in the supplementary information. GaBi software (GaBi 2018) is used to derive the indicator scores. Eight impact categories from TRACI 2.1 have been used in this study following the five impact category suggested in the white paper developed by PE International for the harmonisation of LCA methodologies for metal production (PE, 2014), with the addition of ecotoxicity, human toxicity (cancer), and human toxicity (non-cancer) because of their relevance to REO production (see Table 1) (see Table 2).

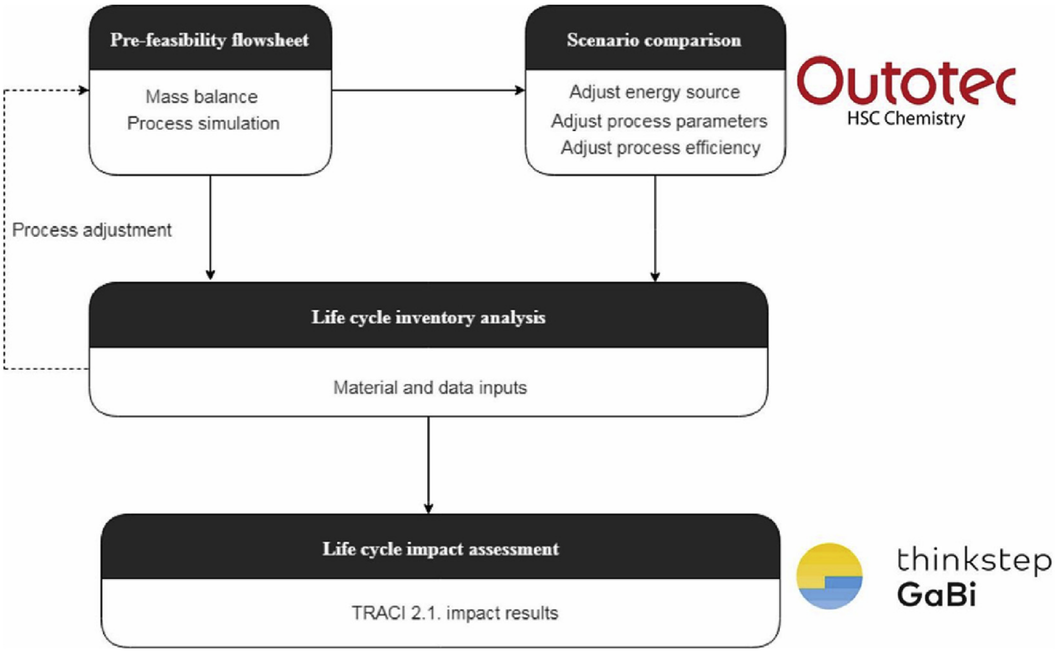

Fig. 3. Process of integration of HSC Sim simulation (www.outotec.com) with GaBi LCA software (Reuter, 1998, 2015).

Table 1
Production of individual REE element, recovery rate and value (value data obtained from metalprices.com).

Element	Recovery	Production (tonnes/year)	Value (US$/kg)
Lanthanum	55%	1075	18.54
Cerium	9%	341	17.89
Praseodymium	57%	227	101.35
Neodymium	57%	756	81.19
Samarium	60%	114	47.26
Europium	59%	27	1314.78
Gadolinium	58%	62	64.22
Terbium	56%	7	1235.91
Dysprosium	58%	35	584.46
Yttrium	58%	165	40.48
Holmium	57%	6	N/A
Erbium	57%	13	85.30091
Thulium	56%	2	N/A
Ytterbium	56%	10	N/A
Lutetium	53%	1	N/A

3. Results

The different stages of production are analysed in terms of impact on for the eight LCIA categories measured. A major contributor to all categories is the inclusion of on-site acid regeneration and the use of a low carbon energy source. On-site acid regeneration is economically important for the Songwe Hill project, but it was possible to explore whether this had a detrimental environmental impact. An initial comparison of on-site acid regeneration versus virgin acid consumption, which included transportation of the acid to the project (assumed at 1000 km), use, and waste management, shows that acid regeneration has a lower impact in acidification, ecotoxicity, global warming, human toxicity (cancer), human toxicity (non-cancer), and smog air. The scenarios had an equal impact for particulate air, and virgin acid consumption had a higher impact for the eutrophication impact category (Fig. 4.). For this reason further comparison of energy sources was made using the assumption of on-site acid regeneration. The detailed results for this comparison is shown in the supplementary information. The detailed results for this comparison is shown in the supplementary information (see Fig. 5).

3.1. Energy source

Fig. 6 compares the environmental performance of the eight LCIA categories for six different energy supply scenarios. The first scenario, which is the use of coal as the primary energy source, has the highest environmental impacts for all categories measured, with a global warming potential of 81.35 kg CO_2 eq per kg REO produced. In contrast the second scenario, which refers to hydroelectric power, only produced 17.03 kg CO_2 eq per kg REO. The hydroelectric combined with battery storage produced 18.64 kg CO_2 eq per kg REO and hydroelectric combined with heavy fuel oil and combined with diesel produced 27.04 and 21.09 kg CO_2 eq per kg REO, respectively. The combination of

Table 2
TRACI life cycle impact assessment categories used in this study with descriptions (US EPA, 2008; Hertwich et al., 1999).

Impact category	Description
Acidification	Increased concentration of hydrogen ions (H+) within the local environment
Ecotoxicity	Environmental toxicity potential from site-specific parameters
Eutrophication	Enrichment of an aquatic ecosystem with nutrients that accelerate biological productivity and an undesirable accumulation of algal biomass
Global warming	Average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere
Particulates (human health)	Collection of small particles in ambient air which have the ability to cause negative human health effects
Human toxicity (cancer)	Human toxicity potential from site-specific parameters that can be cancer causing
Human toxicity (non-cancer)	Human toxicity potential from site-specific parameters that are non-cancer causing
Smog	Formation of ground level ozone caused by various chemical reactions which occur between nitrogen oxides (NOx) and volatile organic compounds (VOCs)

information.

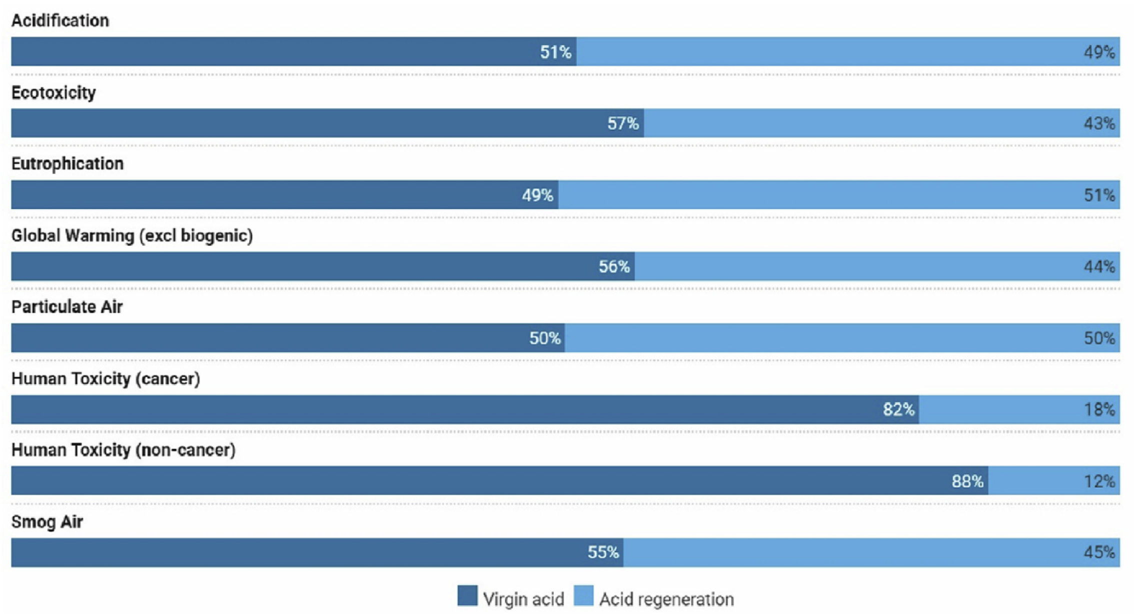

Fig. 4. Share of impact for virgin acid consumption versus on-site acid regeneration.

hydroelectric with solar and storage had the second lowest global warming potential producing 18.20 kg CO_2 eq per kg REO.

3.2. *Allocation results from lowest impact scenario*

The high economic value of Nd combined with the high proportion in the deposit is highlighted with the combined economic and mass based allocation procedure (Fig. 6). The higher value HREE are produced in low volume, meaning that their relative contribution to the impact is reduced and conversely despite the fact that La is produced in high volume, it has a low economic value. Allocation for the other scenarios and impact categories are included in the supplementary information.

3.3. *Contribution analysis*

The best performing scenario which would be realistically used at Songwe Hill was selected for further analysis as shown in Fig. 7. The scenario ensures a reliable supply of energy, whilst having a low impact in all the impact categories measured. Fig. 7 shows the share of the production stage on the eight impact categories assuming acid regeneration and the combination of off-peak hydroelectric energy combined with solar and energy storage. The major contributor in all categories other than particulate air is the precipitation phase of production. The contributors to the precipitation impact categories are explored in section 3.3.1. The leach and dissolution phase also has a substantial contribution to the acidification, global warming, and both human toxicity impact categories. The particulate air formation is dominated by the mining stage.

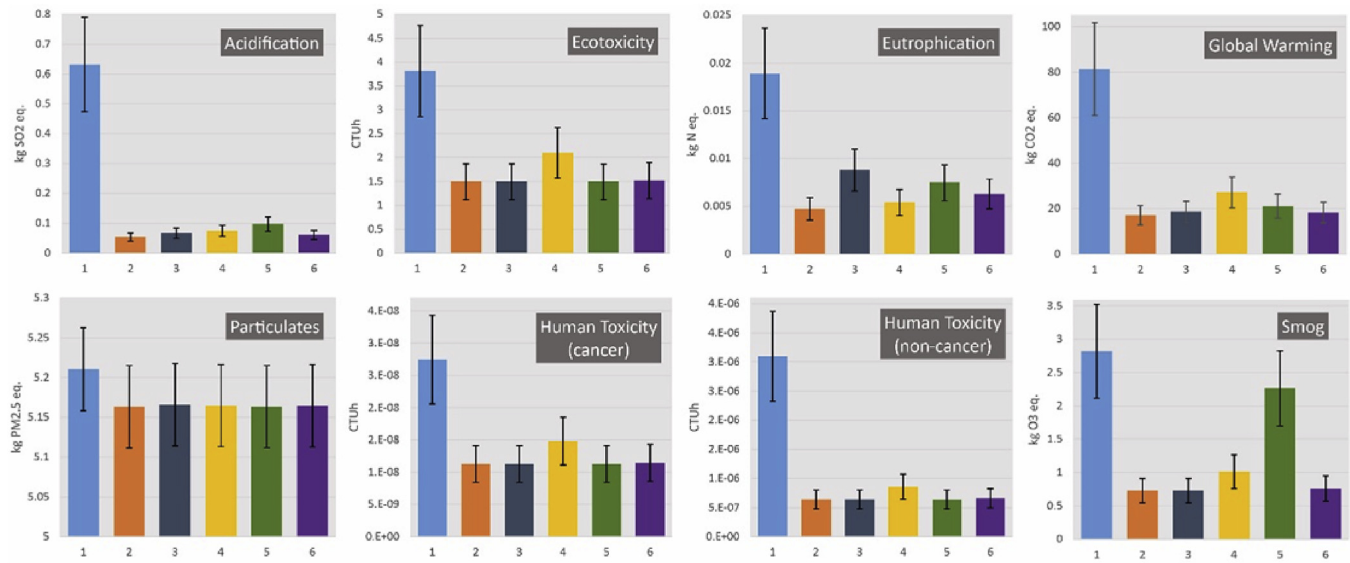

Fig. 5. Environmental impacts of 1 kg of REO produced at Songwe Hill for six energy scenarios. 1 Coal fired power station, 2 Grid power (hydroelectric), 3 Grid (off-peak) and battery storage, 4 Grid (off-peak) and heavy fuel oil, 5 Grid (off-peak) and diesel, 6 Grid (off-peak) and solar and storage. See explanation in section 2.1.7.

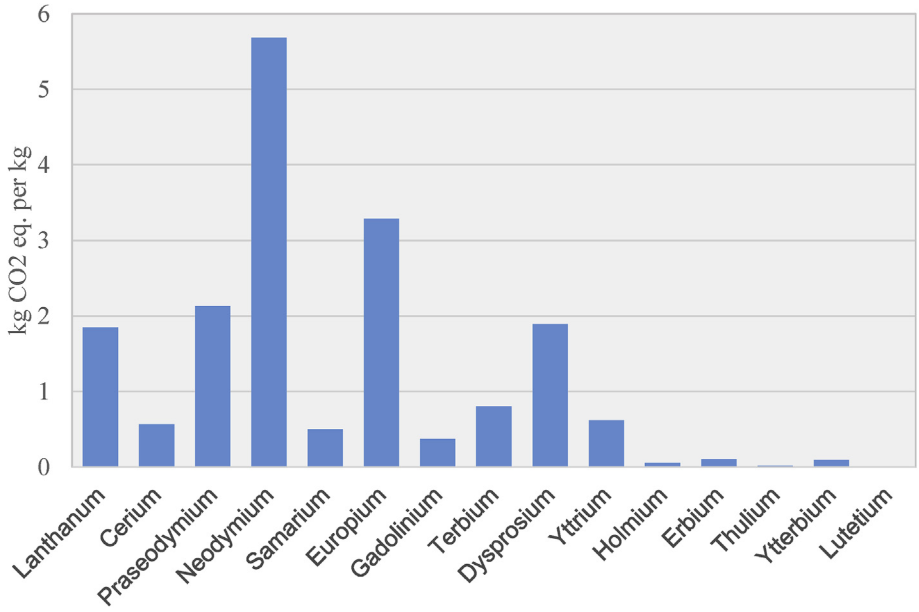

Fig. 6. Global warming potential (inc. biogenic) with allocation for the individual REE at Songwe Hill.

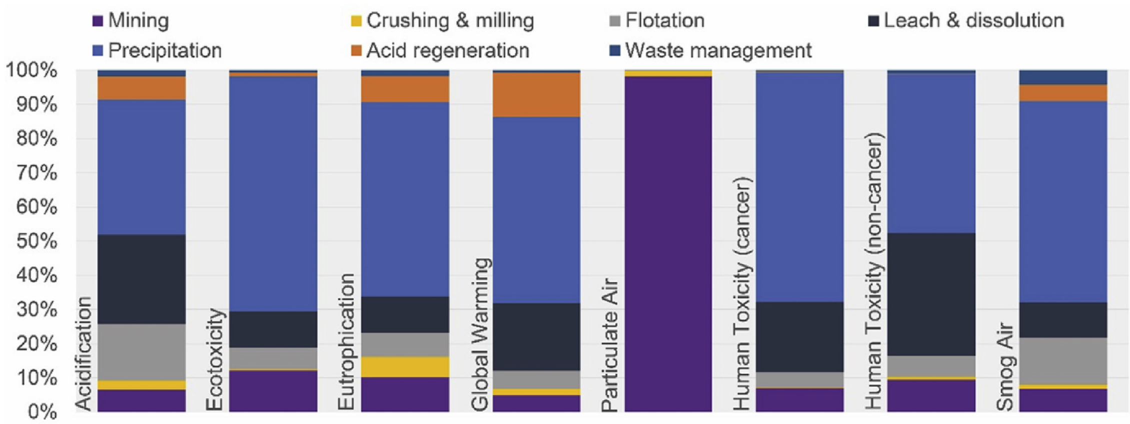

Fig. 7. Contribution analysis of eight TRACI 2.1 impact categories for rare earth oxide (REO) production assuming acid regeneration and energy supplied through a combination of hydroelectric, solar and energy storage.

3.3.1. Contribution to precipitation process

Fig. 8 presents the contribution to the precipitation stage of REO production. The solution adjustment and purification contributes between 20 and 40% for the acidification, global warming, particulate air and both human toxicity (cancer and non-cancer). The caustic crack 2 stage contributes between 30 and 50% for the acidification,

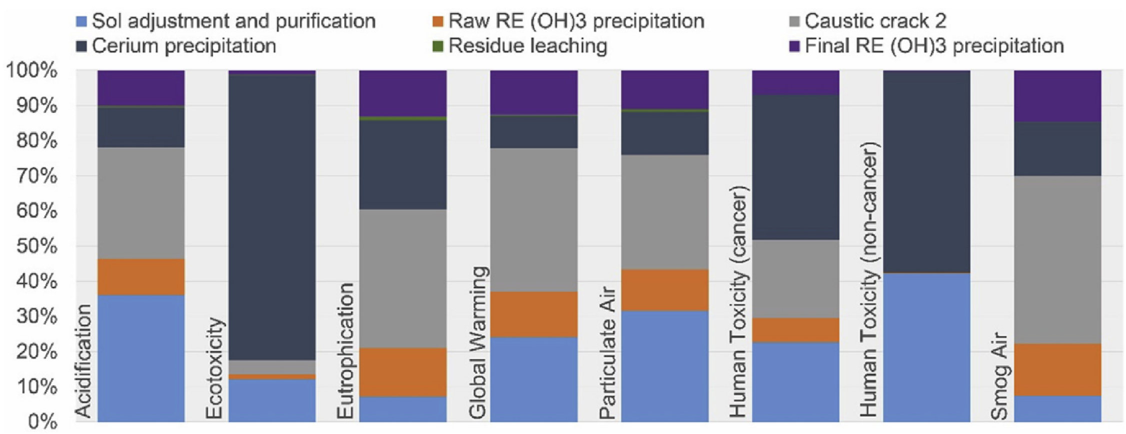

Fig. 8. Contribution of selected major inputs to precipitation stage impact categories assuming acid regeneration and energy supplied through a combination of hydroelectric, solar and energy storage.

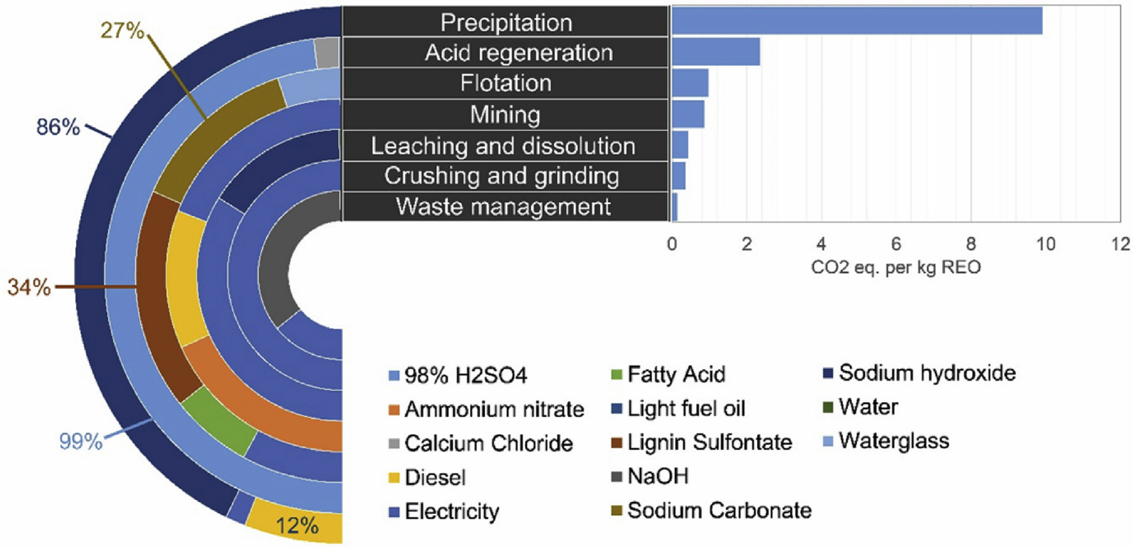

Fig. 9. Material and energy flow contribution to global warming impact in each proposed production stage at Songwe Hill.

eutrophication, global warming, particulate air, and smog air. The Ce precipitation stage has a significant contribution of over 80% to the ecotoxicity impact category and a more moderate contribution of 35–55% for both human toxicity (cancer and non-cancer) impact categories. The raw RE $(OH)_3$ precipitation, final RE $(OH)_3$ precipitation, and residue leaching have relatively small contributions to each impact category, not exceeding 15%.

Fig. 9 presents the percentage contribution to the global warming impact from the main material and energy flows. Energy consumption is a significant contributor in the mining, crushing and grinding, leaching and dissolution, and waste management stage. Sodium hydroxide contributes 31% to the global warming impact in the leaching and dissolution and 86% in the precipitation stage. Sulphuric acid is the major contributor during acid regeneration, accounting for 96% of the global warming impact for that stage.

3.4. Results compared to other REE projects

Fig. 10 compares the performance of Songwe Hill to other selected LCA studies of REO production. It is important to note that a direct comparison is not necessarily a fair comparison of the environmental performance of these projects because of different system boundaries and different LCIA methods (as shown in Table 3). It is important to understand the limitation in direct comparisons between studies due to ranges in functional equivalency. This is particularly challenging with REE due to the large range of elements considered and the fact that each deposit has a specific balance of individual REE, combined with the fact that each project has a range of final products. The system boundaries can also differ resulting in the inclusion or exclusion of individual processes which can impact the final results. Songwe Hill is also the first REO production route that has been modelled using process simulation to generate LCI data. The comparison has used acid recycling and energy scenario six, which was off-peak hydroelectric combined with photovoltaic and energy storage.

Songwe Hill has a lower impact indicator score for acidification, ecotoxicity, and eutrophication, smog air, and human toxicity compared to studies carried out at Mountain Pass, Bayan Obo and the Ion adsorption deposits. Songwe Hill had the worst environmental impact indicator scores in the ozone depletion and particulate air categories. This is due to the inclusion of a number of emissions calculations from the National Pollution Inventory to generate LCI data in the mining phase. This is further supported by the fact that the mining phase is the

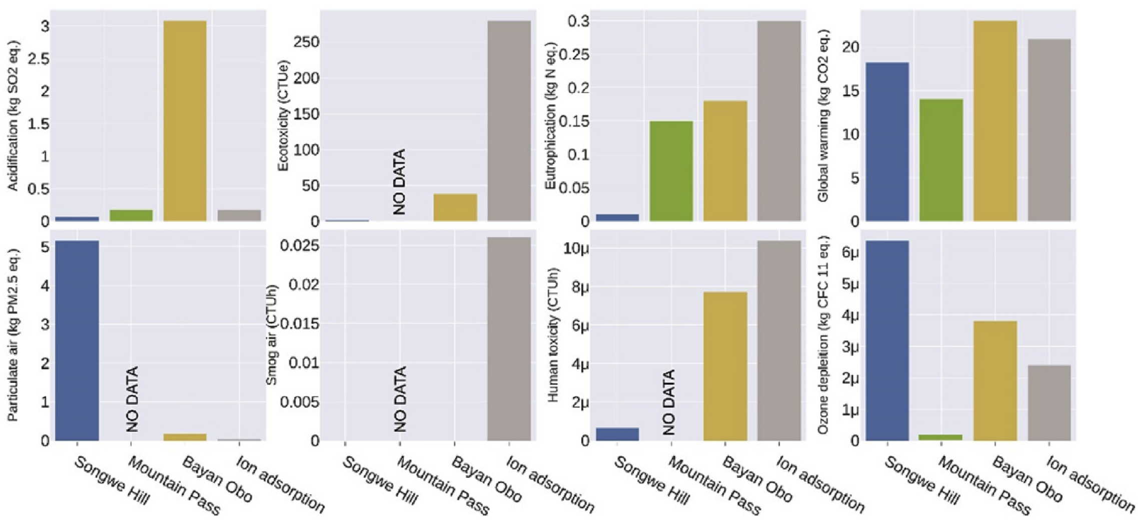

Fig. 10. LCIA results for Songwe Hill, Mountain Pass, Bayan Obo and Ion adsorption deposits.

Table 3
Selected projects used for comparison of REO production.

Project	References	Functional unit	Software	LCIA method	Database	Project stage
Songwe Hill	This study	1 kg REO	GaBi	TRACI	Ecoinvent 3	Prefeasibility
Mountain Pass	Nuss & Ecklemen	1 kg REO	SimaPro 8	ReCiPe	Ecoinvent 3	Production
Bayan Obo	Zaimes et al. (2015)	1 kg REO	N/A	TRACI	Ecoinvent 3	Production
Ion adsorption	Vahidi et al. (2016)	1 kg (90–92% purity) REO	SimaPro 8	TRACI	Ecoinvent 3	Production

majority contributor to the particulate air category (Fig. 7).

3.5. Data quality and uncertainty analysis

The use of data generated by process simulation for the LCI means that it is important to understand the uncertainty in this process, and therefore the uncertainty in the results generated by using this data. The process simulation relies on lab-scale studies that are used to generate a compliant prefeasibility report. Data quality indicators were produced alongside the LCI and is included in the supplementary information. These indicators are based on the classification system of the American Association of Cost Estimation and is the same approach as Marx et al. (2018). The LCI data uncertainty for the project as a whole was −28% to +34%. This is due to much of the data falling into data quality category 3 which represents calculated, modelled, stoichiometric, calculated, up-scaled data and has a data deviation of −20% to +30% (Bull, 2012). Monte Carlo simulation is completed and presented in Fig. 11, considering the uncertainty in the LCI quantities data and the impact calculations using the process described by Ivanov et al. (2018).

4. Discussion

The study evaluates the environmental impact of REO production from a life cycle perspective at Songwe Hill. Analysis indicates that overall Songwe Hill performs favourably compared other REO production LCA studies. The precipitation stage has the greatest contribution to a number of environmental impact categories, with impacts mostly attributed to sodium hydroxide consumption.

Carrying out an LCA during the pre-feasibility stage of a project would allow the results generated to influence decision making in project development. The LCI data required can be generated through process simulation. The on-site acid regeneration had lower life cycle environmental impacts in seven of theht impact categories measured. When comparing the energy scenarios, the option of using the Kam'mwamba coal fired power plant that is under development in Malawi performed poorly in all impact categories. If Songwe Hill uses this energy the project would have high environmental impact scores. The second scenario, purely hydroelectric, performed well in all categories. Unfortunately, this scenario is unrealistic as the power is not consistently available during peak hours. From the final four scenarios investigated, the sixth scenario, which included off-peak hydroelectric combined with photovoltaic and energy storage, had the lowest environmental impact in the acidification, global warming, and human toxicity categories.

As the project moves through to the feasibility stages, there is increased the certainty in both the geology and the project processes and infrastructure, the LCA can be updated and used in the subsequent decision making the granularity of the approach used, it is possible to assess the contributions of individual processes (Fig. 9).

The study used a combination of mineral processing simulation software to generate LCI data. The advantage of this approach is that as a project moves through development stages and refines the process flowsheet, the simulation can quickly and efficiently integrate these changes into the LCA model. Updated mineral processing simulations can feed into the LCA model allowing for project changes to be examined in terms of environmental performance, whilst maintaining a consistent system boundary and more reliable LCI data (Fig. 1). In order to develop this into a process that is easy to adopt for mining companies and allows for comparison across projects, a harmonisation of methodologies for particular commodities needs to be made. In other sectors, such as with product manufacturing it is through the development of product category rules (PCR), which refers to the calculation rules for the underlying LCA of a product or process, as well as provides

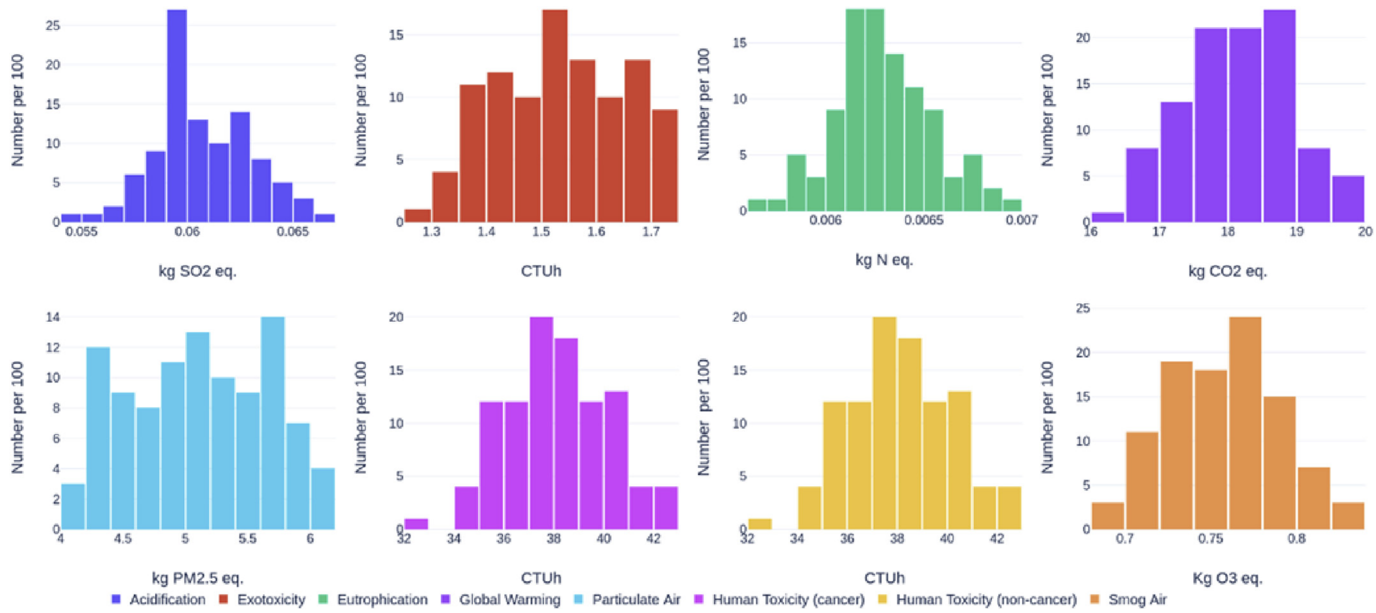

Fig. 11. Monte Carlo simulation of LCI data and impact category calculation on each impact category.

information and the format for presentation in an environmental product declaration (EPD). There is currently a lack of PCR for specific commodities such as REE, which would provide clarity for future LCA.

5. Conclusions

This study presented an approach to include mineral process simulation linked LCA during the early stages of project development, such as following a pre-feasibility study. The results indicate that the lowest global warming impact would be obtained using hydroelectric power as an energy source with the inclusion of on-site acid regeneration. However, use of hydropower for off-peak energy combined with photovoltaic power and energy storage is the best solution in terms of global warming impact while providing reliable power on-site.

The process simulation-LCA method has the advantage of being easily updated during the life of a project as new data becomes available. For example, as new drill data uncovers more information about the mineralogy and grade of the deposit, this data can be fed into the process simulation software which in turn can generate LCI data such as energy and material requirements for the process flowsheet which will update the LCIA results. This approach also ensures the generation of robust and reliable environmental impact results due to the closed mass and energy balance LCI data and consistent system boundary definition. This method could be developed as a standard approach for LCI generation for PCR in the future and can ultimately, better inform decision making during the development of a project and help reduce its life cycle environmental impacts.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jenvman.2019.109353.

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Chapter 4

Temporally explicit life cycle assessment as an environmental performance decision making tool in rare earth project development

There is increased pressure on mining companies to consider the environmental impacts that their project might have during the development phase and explore a range of options that could minimise these impacts. Mining life cycle assessments quantify the environmental performance of production based on a single value average over the life of the project. This approach fails to consider environmental impact variation which may occur over the life of the project. It is potential to use data developed during engineering studies for the pre-feasibility stage of a mining project to carry out a LCA and produce LCIA data on a temporal basis, such as per month or per year. Having a greater temporal resolution for the LCA enables companies to identify relationships between grade and ore composition early on in a project, giving companies time to reflect and make informed decisions from these environmental results.

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Temporally explicit life cycle assessment as an environmental performance decision making tool in rare earth project development

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ABSTRACT

The study shows that a detailed LCA can be carried out for a proposed mining project as soon as Prefeasibility (PFS) data are available. The prefeasibility study is one of the key early steps in bringing a deposit towards production and results are often publically available. This study applies the technique to a rare earth deposit because rare earth element (REE) consumption is increasing owing to their use in low-carbon technologies such as electric vehicles and wind turbines. It is therefore particularly important to understand the environmental impacts of the raw materials. A number of REE deposits are under development to give additional supply and many possess novel mineral compositions and will require different processing methods than previously used. Assessing the environmental performance of the production of REE during the development of projects offers significant insights into how to improve the sustainability of a project. In this study we used life cycle assessment (LCA) to quantify the environmental impacts for producing rare earth oxide (REO) from the Bear Lodge Project, United States. The Life Cycle Impact Assessment results were produced for each year over the life of the project, generating insight about the relationships between ore composition, grade, processing method and environmental impacts. The environmental impacts vary significantly during the life of a project and a temporally explicit LCA can highlight these.

1. Introduction

Rare earth elements (REE) are a group of 17 chemical elements composed of the 15 lanthanoids (lanthanides) as well as scandium (Sc) and yttrium (Y). REE can be subcategorised depending on their atomic number into light rare earth elements (LREE) (e.g., La, Ce, Pr, Nd, Sm, and Eu), and heavy rare earth elements (HREE) (e.g., Y, Gd, Tb, Dy, Ho, Er, Tm, Yb, and Lu). The similar physical and chemical properties of the individual REE means that they are often found together as elemental constituents of their host minerals (EPA, 2012). REE possess unique nuclear, metallurgical, chemical, catalytic, electrical, magnetic, and optical properties (Voncken, 2016). They have a broad and expanding range of uses in military and medical applications, communications, and petroleum refining, lighting, and renewable energies. The elements are considered important for many emerging alternative energy technologies, improving the performance of hybrid cars, wind turbines, rechargeable batteries and biofuel catalysts. The REE are marketed in many forms, such as mineral concentrates, mixed REOs, individual oxides, carbonates, purified metals, or metal mixtures (the so-called 'misch' metal).

China produces a majority of REE, accounting for 85% of global REE supply (USGS, 2017). However, this figure is likely lower than the genuine value as it does not include the share of illegal production, which was predicted to be around one third of official production (Mancheri et al., 2013). This high concentration of production in combination with REE's high economic importance in the low-carbon economy has led to a number of studies identifying REE as critical raw materials (Nassar et al., 2015; Mancini and Camillis, 2013; BGS, 2017; Pell et al., 2018). Country concentration of proven reserves of REE is more dilute than production. China had an average of 39% of total world reserves from 1995 to 2015 (Chen et al., 2018). There are also a mismatch between individual REE production and demand. This is known as the 'balance problem' (Binnemans, 2014).

REE are widely dispersed around the world in a diversity of deposit types but are generally found in low concentrations, limiting the amount of known economic deposits to around 200 (Goodenough et al., 2017). To date only the minerals bastnäsite-(Ce), monazite-(Ce), and xenotime-(Y) have been commercially recovered in large quantities

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from carbonatite-related deposits, granite-related deposits and mineral sands (Wall et al., 2017). The environmental challenges associated with REE production are closely linked to the geology of a deposit, the methods of extraction and processing employed, and the controls that are put in place to mitigate environmental impacts (Koltun and Tharumarajah, 2014).

One major environmental challenge linked with REE production is the co-extraction of radioactive elements. Thorium, and to a lesser extent U, are often incorporated in the lattice of the REE minerals or occur as separate but associated thorium-bearing minerals (Wall et al., 2017). Other acidic and chemical waste can also be produced such as hydrogen fluoride (HF) and acidic waste water (Wall, 2014; Arshi et al., 2018). REE extraction and processing can release emissions such as hydrogen fluoride (HF) and acidic waste water as well as produce solid waste (Wang et al., 2017). The processing and separation of REE can be chemically and energy intensive partly due to the similar physical and chemical nature of the lanthanoid elements, making them difficult to separate (Wall et al., 2017).

In this study, life cycle assessment (LCA) is used as a quantitative method to assess the environmental impacts during the mining and processing of mixed REE product (cradle-to-gate). LCA is a useful tool to evaluate the environmental performance of projects based on their flowsheets. The combination of simulation with LCA has been presented in recent studies, highlighting that it has the potential to be employed early in a project to assess the performance of specific process choices (Rönnlund et al., 2016a, 2016b, Reuter et al., 2015). The purpose of this work was to develop an indicator framework for the environmental sustainability benchmarking of products produced by the metallurgical industry. This approach has not yet been applied to REE production, however a number of LCAs have been completed for active REE mines, with a majority of work on the mining and processing of bastnäsite ore at Mountain Pass, USA or the bastnäsite-monazite ore at Bayan-Obo, China (Althaus et al., 2007; Du and Graedel, 2013; Haque et al., 2014; Sprecher et al., 2014). Vahidi et al. (2016) completed an LCA of a number of the ion-adsorption REE production routes from Seven Southern Provinces of China. Lee (2016) also completed an LCA for an ion adsorption clays, comparing their production to Bayan Obo and production in Sichuan, China. The results indicated that production from Sichuan had lower environmental costs among the categories measured compared to Bayan Obo. It was also noted that there was considerable potential to mitigate impacts across these production chains. Marx et al. (2018) completed a comparative study of NdFeB production from Mount Weld, Australia, Mountain Pass, USA, and Bayan Obo.

Weng et al. (2016) completed a broad comparative LCA of 26 different operating and potential REE projects, including Bear Lodge. Energy requirements and global warming potential were the only impact categories considered in this study. The study concluded that lower REE grades significantly increase the environmental impact of REE production, and that REE production causes higher environmental impacts than common metals. The study is a useful comparative approach, but due to its inconsistent inventory data, it was not a consistent LCA, as noted in the response to this paper (Pell et al., 2017).

This study is the goes beyond previous studies by introducing temporally explicit LCA for REE production. This has been applied to other industrial applications (Maier et al., 2017) but to the authors knowledge this is the first time this approach has been applied for any mining project. This allows insight into the drivers of different environmental impacts during REE production such as changing ore grade, changing processes or other project specific variables. This study also attempts to clarify the importance of LCA integration in the early development stages of a mining project. This approach has been adopted in the product development stage of many companies outside the mining industry but is often carried out as a retrospective measurement for raw material projects (da Luz et al., 2018).

Mining projects move through different stages of development to determine whether the mineral resource can be mined economically. The first stage is known as the order of magnitude study. If successful this will move to a preliminary feasibility study (PFS). During this stage, data about many processes are created and the reports are often published to the public. During this stage, geology of the site, ore deposits, resource estimates, mining and processing methods, waste management, and energy and infrastructure estimates are made. This data can be used to perform an early stage LCA. International Mineral Resource and Ore Reserve reporting codes do not quantify the levels of accuracy or uncertainty with PFS, however some research has reviewed the accuracy of these studies (McCarthy, 2003; Snowden et al., 2002) indicating that at a 90% confidence level, the cost accuracy of a PFS study is ± 15–25% and has over 20% of the engineering study complete. In contrast a feasibility study has a more detailed mine plan, a cost accuracy of ± 10–15% and around 50% of the engineering study is complete (Noppe, 2014).

The advantage of carrying out a LCA during the PFS, even in the context of higher uncertainty, is that it can inform mining companies about particular processes that have high environmental impacts in a life cycle context. This information can be useful during this stage as it allows companies to explore alternative process options as a project moves towards the higher certainty feasibility stage. This is examined in this study with the comparison of a gravity and magnetic separation stage with a flotation stage from data in the PFS and from a scientific study from Cui and Anderson (2017).

2. Research methodology

The Bear Lodge Project is a proposed mining and processing operation in Wyoming USA, which includes Bull Hill Mine located in the Bear Lodge Mountains, Crook County and the processing facility, located in Upton, Weston County. Bear Lodge is currently in the PFS stage and is one of the main REE prospects in the USA (Pre-feasibility Study Report, 2014).

The deposit is carbonatite, part of which is weathered, that contains bastnäsite-(Ce), synchysite-(Ce), monazite-(Ce), cerianite-(Ce) and ancylite-(Ce) as the REE-carrying minerals. The project is LREE-enriched with a total rare earth oxides (TREO) grade of 4.7 wt% (Fig. 1). A notable advantage of the Bear Lodge project is the high percentage of Nd in the REE composition of the ore, at 18% compared to 12% at Mountain Pass for example. For this reason, Bear Lodge has been suggested as a project particularly suitable to support the U.S. REE demand from the U.S. wind energy growth targets (Cui and Anderson, 2017).

The project is forecast to have a 45-year life of operation, with mining for the first 38 years and production from a high grade stockpile for the last 7 years. For the first nine years the mine will produce between 3.5 and 3.9 million tonnes per year and between 4.5 and 4.7 million tonnes during peak mining during years 15–28. The hydrometallurgy plant will be in operation for 45 years with a feed of 152,000 tonnes per year of upgraded material for the first nine years of operation, and from year 10 the plant would be expanded receiving a feed of 191,000 tonnes per year (Pre-feasibility Study Report, 2014).

The annual TREO production and average grade per year are shown in Fig. 1 alongside the ore composition. The different ore compositions represent variations in mineralogy of the deposit. These compositions have different TREO grades as well as different precipitation efficiency (Pre-feasibility Study Report, 2014) (see Table 1)

2.1. Goal and scope

The objective of this research is to assess the environmental impacts by applying a process-based LCA model to REO production at Bear Lodge, USA according to ISO 14044 guidelines (ISO, 2006). Different processing options have been compared and LCIA has been completed for different temporal stages of the project (Figs. 2 and 3). The functional unit for this study is 1 kg of mixed REO produced. The REO

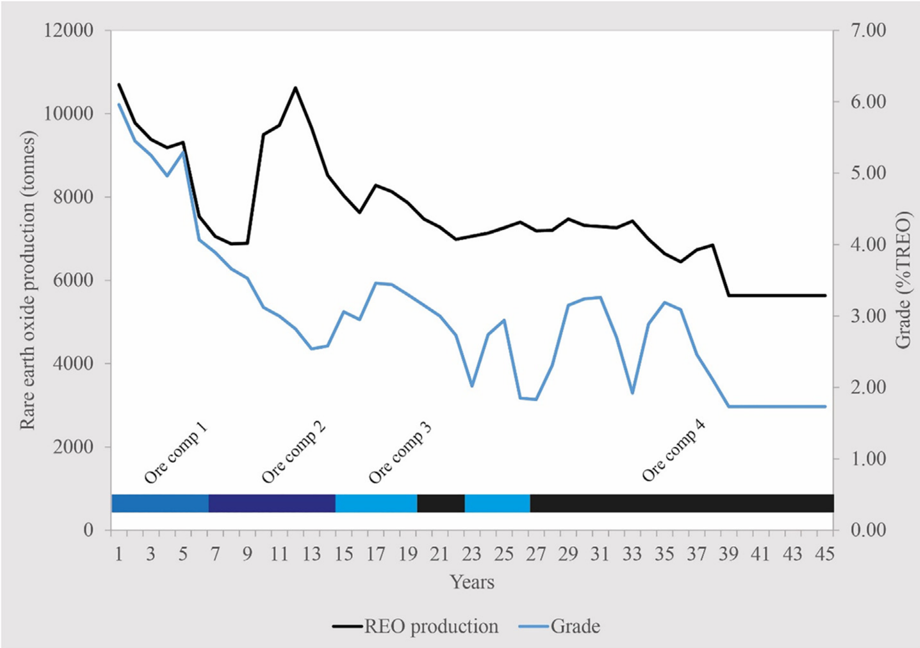

Fig. 1. REO production, grade, and ore composition change during production at Bear Lodge (Pre-feasibility Study Report, 2014).

production process consists of a number of inter-related component processes, which have been broken down into subsystems connected by flows. The LCA system boundary is cradle-to-gate and includes the mining, beneficiation, hydrometallurgy, waste management, and transport. This LCA does not take into account the downstream processing of the mixed REO into separates individual elements and manufacture to final products. The TRACI 2.1 impact assessment method (Bare et al., 2012) was selected in this study and the calculations were performed using the LCA software GaBi 6.

An additional comparison between an alternative beneficiation flowsheet as proposed by Cui and Anderson (2017) and the current flowsheet indicated in the Pre-feasibility Study Report (2014). A temporal environmental comparison is completed using the LCA approach as described within the manuscript.

A distinction between this study and previous papers is that the temporal dimension of the project is explored, using annual production data, geology and ore variation, and process performance predicted for the PFS. Using this approach allows for an analysis environmental impacts over the life of mine.

2.2. Life cycle inventory

The Life-Cycle Inventory (LCI) was created using a combination of data from the Bear Lodge PFS Study (Pre-feasibility Study Report, 2014), GaBi, Ecoinvent (Wernet et al., 2016) databases as well as calculations from literature. Data that were not available in these reports were estimated using the equations given here in the supporting information. The background data, e.g. electricity mix, were specific to US where possible. Some data such as chemical production data were not country specific due to the limited data availability of some processes. Information about the data source and quality is shown in Table 2. Dust emission data is from the Ambient Air Quality Modeling Protocol (IML Air Science, 2014) and includes the stated pollutants of concern, namely particulate matter smaller than ten microns in size (PM10) and particulate matter smaller than 2.5 µm in size (PM2.5), carbon monoxide (CO), sulfur dioxide (SO_2) and oxides of nitrogen (NOx).

2.2.1. Mining

The Bear Lodge mine will use a conventional open-pit drill and blast method, with a focus on near-surface, oxidised sections of the deposit. The Bull Hill and the Whitetall Ridge areas of the deposit will be mined. The Bull Hill deposit has a higher grade but the Whitetall Ridge deposit is 2.5 times more enriched in heavy REE.

2.2.2. Beneficiation

The physical upgrade plant would produce a REO pre-concentrate using a series of crushing, washing, screening, and separation steps. On average, the physical upgrade plant recovery is expected to be 92.8% in years 1–9 and 87.9% over the life-of-mine. There process is different depending on the ore type and the stage of the project. There is also a novel method which includes wet high-intensity magnetic separation (WHIMS) and flotation.

2.2.3. Crushing and screening

From years 1–9 Bear Lodge will process high-grade ore which is expected to have a 4.7 wt% REO content. All the run of mine ore is initially crushed and screened to 3360 µm. The specific beneficiation steps that are employed from this point depend on the ore composition. Bear Lodge has allocated four crushing, screening, and separation

Table 1
Headgrade of the different ore compositions at Bear Lodge.

	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	MgO %	CaO %	Na_2O %	K_2O %	MnO %	TREO g/t
Comp 1	22.8	6.69	18.0	1.01	8.76	0.36	4.92	7.94	8.94
Comp 2	32.3	9.73	13.6	1.44	9.21	0.31	7.50	4.44	5.20
Comp 3	40.3	12.4	12.9	1.12	5.11	0.27	9.72	3.03	2.99
Comp 4	45.4	14.2	13.0	1.15	0.93	0.30	11.1	3.21	2.52

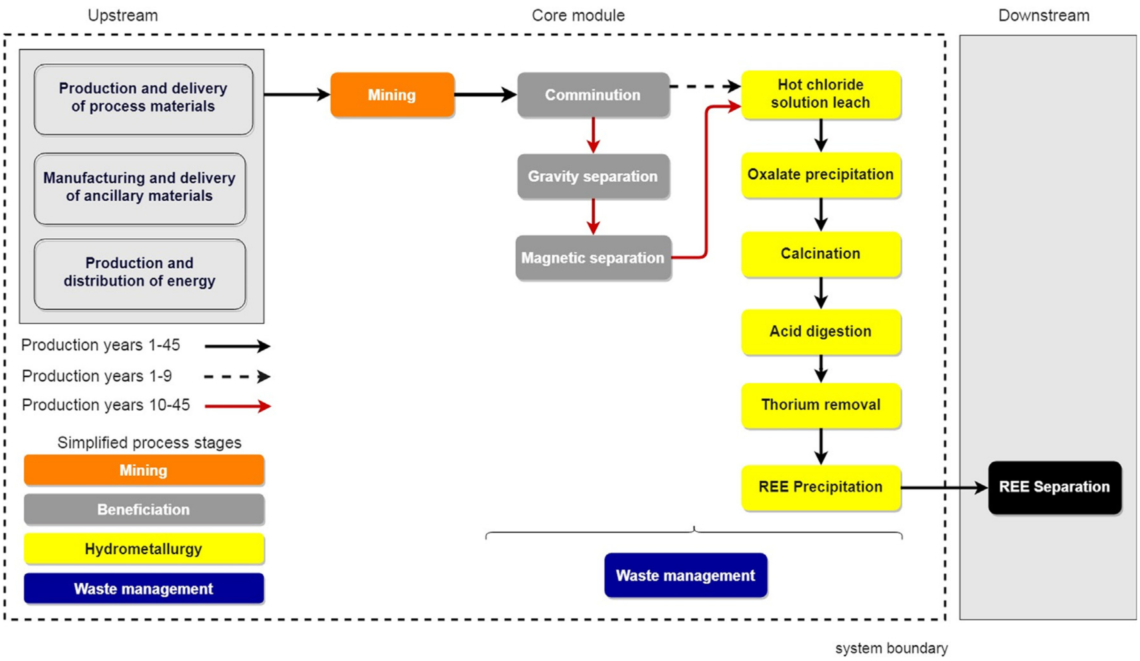

Fig. 2. The system boundary and proposed flowsheet at Bear Lodge REE project proposed by Pre-feasibility Study Report (2014).

processes. Ore composition 4 is crushed and screened to a 297 µm and is then thickened. Ore composition 1 and 2 is crushed and screened to 100 µm. Oversized material is sent to a spiral gravity classifier, where light material is sent to a pre-tailings belt filter and is dewatered. The heavy material is sent to the 297 µm grinding mill. Ore composition 3 is crushed and screened to 100 µm. Oversized material is sent to a magnetic separator. Magnetic material is sent to the spiral gravity separator. Liquids are recycled during this stage, and the final solid concentrate is stored in bins prior to transport to the Hydromet plant.

2.2.4. *Crushing, screening, magnetic and gravity separation*

From year 10 of the project gravity and magnetic separation will be included in the beneficiation phase. Testwork completed by SGS produced a concentrate grade of 6.64% REO at 86.4% recovery from a feed grade of 4.5%.

2.2.5. *WHIMS and flotation*

Cui and Anderson (2017) proposed a method which included comminution to minus 100 mesh, followed by WHIMS, conditioning, rougher and cleaner flotation. The WHIMS stage removes the iron content to reduce the interference of iron during the flotation process. The proposed method will produce a concentrate grade of 11.2% REO at 61.2% recovery.

2.2.6. *Hydrometallurgy*

The hydrometallurgy process uses hydrochloric acid to leach the

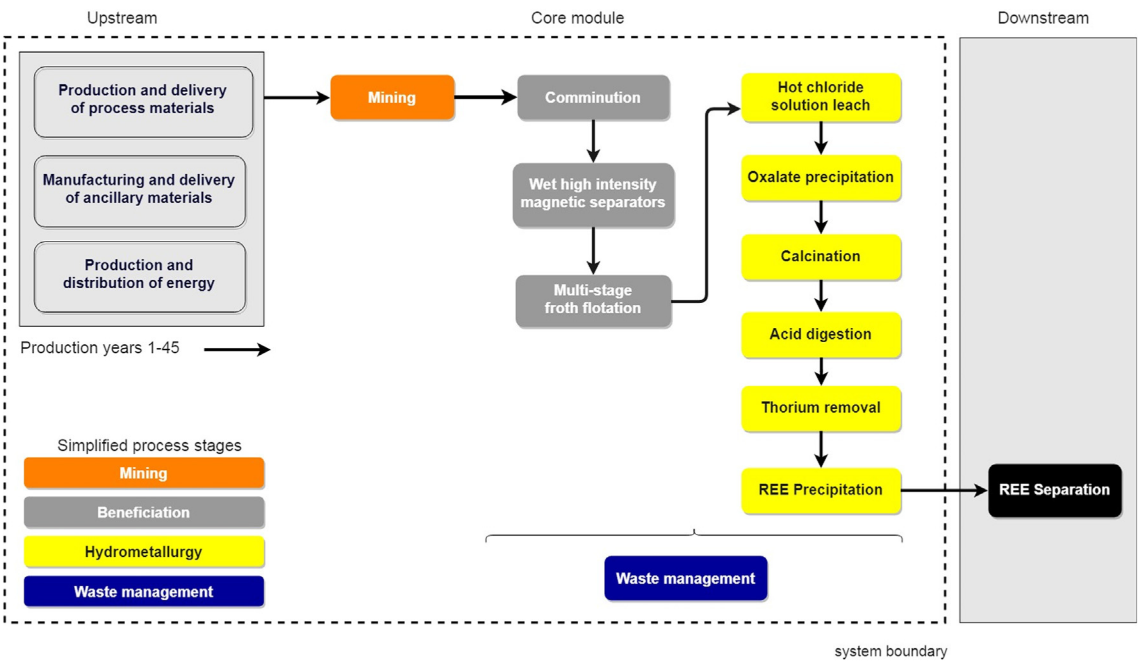

Fig. 3. The system boundary and proposed flowsheet at Bear Lodge REE project proposed by Cui and Anderson (2017).

Table 2
Life cycle inventory inputs for 1 kg REO produced at Bear Lodge (Pre-feasibility Study Report, 2014).

Input	Unit	Low	High
Diesel	MJ	10.70	17.94
Electricity grid	MJ	15.89	58.05
Diesel generator	MJ	3.15	4.42
ANFO	kg	0.00	0.05
Process Water	L	42.40	42.48
Steel	kg	0.12	0.12
Flocculant	kg	0.58	1.41
Lime	kg	0.01	0.01
Limestone	kg	9.27	17.24
Sodium hydroxide	kg	0.00	0.02
Natural gas	MJ	3.09	5.87
Ammonia	kg	0.83	0.85
Hydrochloric acid	kg	4.24	12.86
Oxalic Acid	kg	2.46	5.58
Nitric Acid	kg	2.18	2.24
Hydroxamic Acid	kg	0.02	0.03
Strontium Nitrate	kg	0.33	1.19

REE from the ore. Rare earth oxalates are then precipitated from the pregnant leach solution by the addition of oxalic acid and converted to REO in a kiln. Thorium and other impurities are removed by a nitric acid leach and double hydroxide precipitation method. A bulk REO powders of > 97% purity is formed as the final product.

2.2.7. Waste management

Waste management involves the movement and storage of waste rock from the mining operation and the management and storage of waste as tailings from the beneficiation and hydrometallurgy stage. The waste rock facility for storage of overburden and mine waste is recountered and managed during the operation of the mine. Non-hazardous waste produced from Hydrometallurgy phase is dewatered and neutralised before being transported by truck to the tailings storage facility. Thorium and uranium will be removed to ensure radionuclide levels below 0.05% and lime stone and quicklime will be added to neutralise the material. The tailings storage facility is a zero discharge facility and non-contact surface water runoff will be diverted around the facility. During the life-of-mine 15.8 million tons of waste will be produced for the tailings storage facility and it is designed to operate as a dry stack facility. Thorium hydroxide residue is contained and transported to a third-party disposal facility.

3. Results

3.1. Environmental impacts per 1 kg of REO produced at Bear Lodge

The results of the LCIA for producing 1 kg of REO from Bear Lodge are listed in Table 3. The results generated are based on the average for production over the life of mine according to processes described in the PFS report (Pre-feasibility Study Report, 2014). The global warming impact was 12.1 kg CO_2 eq. compared to 14 kg CO_2 eq. in Sprecher's study at Mountain Pass (Sprecher et al., 2014). The acidification impact at Bear Lodge in this study is 0.06 kg SO_2 eq., lower than that at Mountain Pass (with an impact of 0.063 kg SO_2 eq. to 0.17 kg SO_2 eq.). It is important to understand the limitation in direct comparisons between studies due to ranges in functional equivalency. This is particularly challenging with REE due to the large range of elements considered and the fact that each deposit has a specific balance of individual REE, combined with the fact that each project has a range of final products. The system boundaries can also differ resulting in the inclusion or exclusion of individual processes which can impact the final results.

3.2. Temporally explicit environmental impacts over life-of-mine

The assessment results for the project can be broken down by each year of production. The impacts have been categorised into the four stages of production and shown in Figs. 2 and 3. The grade fluctuates during the life of mine, with a general decreasing trend. There is a positive relationship between global warming impact and decreasing grade. The global warming impact is lowest in the first year of production at 8.66 kg CO_2 eq. per kg of REO produced and highest in year 26 of production at 16.3 kg CO_2 eq. per kg of REO. This figure, which is almost double that of the first year indicates how much environmental impacts can change over time depending on the changing grades and physical properties or processes employed at an operation.

The termination of mining at year 38 is seen in Fig. 4 with the beneficiation feed drawing from stockpiles. During the last 7 years the global warming impact remains relatively static, with small reductions in kg CO_2 eq. owing to reducing waste management impacts. The

Fig. 5 presents the relationship between the annual average grade of the ore extracted, the ore composition and the global warming impact. There is a positive correlation with decreasing grade and global warming impact. The lower grades global warming impact scores have a greater range of impact. The different ore compositions relationship between grade and global warming potential can also be seen and have been isolated in smaller figures above the main figure.

The mining phase contributes between 2.2 and 4 kg CO_2 eq. per kg REO until year 33. From year 34 until year 38 mining is reduced and from year 39 until year 45 no new mining is carried out which is the cause of the reducing impact of the mining phase during these stages. The mining stage is influenced by a number of factors, with the most important one being the stripping ratio during each year of production. Beneficiation has a small contribution to the global warming impact category during the first 9 years of production as a simple process of crushing and grinding occurs as highlighted in Fig. 1. From year 9 until year 45 beneficiation includes gravity and magnetic separation and this results in a higher global warming impact during these years. The hydrometallurgy phase appears to steadily increase its global warming impact over the life of mine. Waste management is relatively stable with increases in global warming due to lower grades.

The contribution to the global warming impact category during the beneficiation phase (Fig. 4) and the hydrometallurgy phase (Fig. 5)

Table 3
Life cycle impacts for the production of REO from Bear Lodge (this study), Mountain Pass (Nuss and Eckelman, 2014), Bayan Obo (Zaimes et al., 2015), and Ion adsorption (Vahidi et al., 2016) with TRACI characterization (note that lowest impact values from these studies are used).

Environmental impact indicator	Unit	Bear Lodge	Mountain Pass	Bayan Obo	Ion adsorption (China)
Acidification	kg SO_2 eq.	6.00E−02	1.70E−01	3.08E+00	1.70E−01
Ecotoxicity	CTUe	1.45E+00	N/A	3.76E+01	2.79E+02
Eutrophication	kg N eq.	1.30E−02	1.50E−01	1.80E−01	3.00E−01
Global warming	kg CO_2 eq.	1.21E+01	1.40E+01	2.30E+01	2.09E+01
Human health	kg PM2.5 eq.	1.60E−02	N/A	1.70E−01	2.59E−02
Carcinogenic	CTUh	1.30E−08	1.30E−08	2.27E−06	3.00E−02
Non-carcinogenic	CTUh	1.20E−06	1.20E−06	7.70E−06	1.04E−05
Ozone depletion	kg CFC 11 eq.	2.40E−09	2.30E−09	3.80E−06	2.40E−06

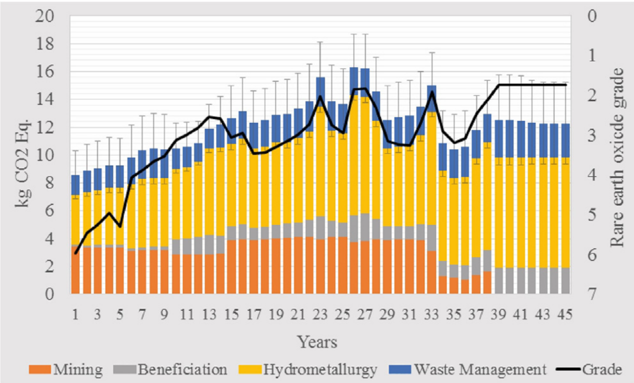

Fig. 4. Global warming impact (kg CO_2 eq. per kg REO) and reversed average grade (%TREO) during five different stages of the life of mine.

have been included. A majority of the contribution during beneficiation is due to electricity consumption during the crushing, classifying, grinding and gravity separation and the magnetic separation. The impact is around 0.2 kg CO_2 eq. during the first 9 years of production and then increases substantially to between 0.8 and 1.9 kg CO_2 eq. for the rest of the life of mine once further beneficiation has come online, and fluctuates between 0.8 and 1.9 kg CO_2 eq. The fluctuation is due to the changing grade and mineralogy, which impacts the energy requirements for the crushing grinding and classifying.

The hydrometallurgy phase has a higher impact on global warming when compared to the beneficiation phase due to the high direct energy consumption and the embodied carbon footprint associated with the chemicals consumed. The volatility in impacts over time is also less than the beneficiation phase. This is due to the fact that the hydrometallurgy has an input of mixed stockpiled concentrate which has more consistent physical and chemical properties. It is however still possible to see the changing grade and mineral composition in the results with particular high peaks in global warming impact during years 26 and 34 of production. These relate to low points in grade during the mining phase during similar time periods.

Assuming the overall environmental impact of all categories is 100% Fig. 6 highlights the contribution of each TRACI impact category by process over the life of mine. The largest contributor to the ecotoxicity, eutrophication, human health (particulate air formation), resources, and smog air is mining during the early stages of the project. This contribution decreases over time until the mining ends at year 39. Acidification is dominated by the hydrometallurgy phase followed by the beneficiation phase, which increases its contribution over time.

Compared to other LCA studies on REE production, Bear Lodge has a low contribution to eutrophication from the mining and waste management. Water borne emissions are often a major contributor to eutrophication, especially with REE production in China from the ion-adsorption clays in Southern China[23]. Bear Lodge claims it will have zero-discharge tailings storage facility, which explains the limited impact during this stage.

The temporally explicit LCIA data can be used to evaluate

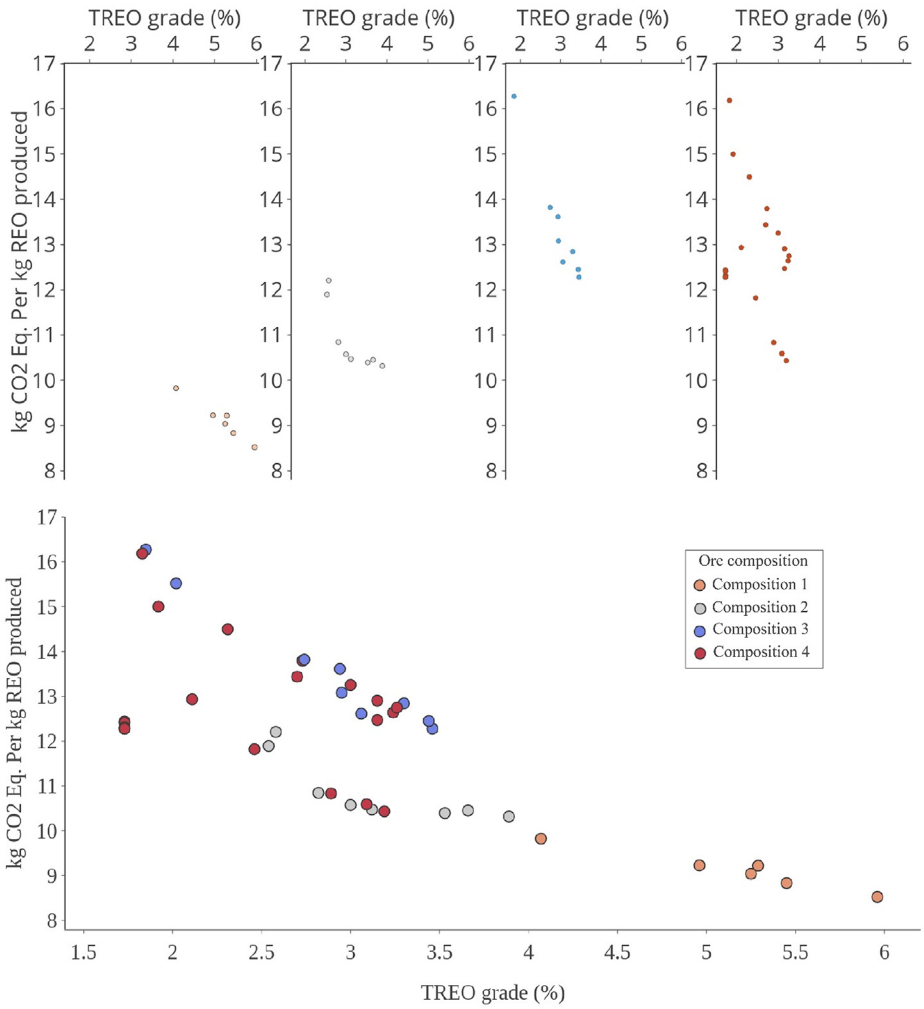

Fig. 5. Global warming impact relationship with grade and ore composition.

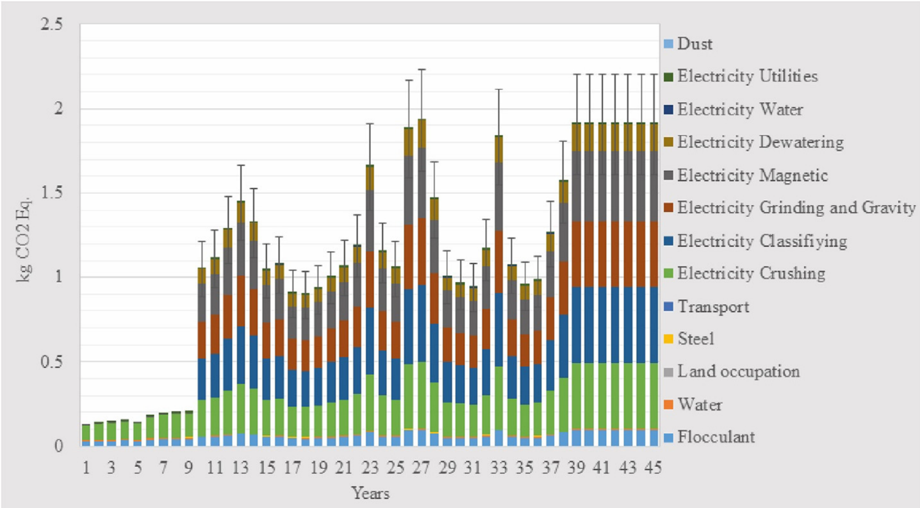

Fig. 6. Beneficiation contribution to global warming impact over life of mine.

processing options at the project or advise on whether specific remediation approaches should be implemented during the life of the project. For example the results indicate that the hydrometallurgy stage is the largest contribution to global warming impact. As other beneficiation options may be available and this in turn could reduce the hydrometallurgy contribution, different process options have been explored.

3.3. Beneficiation process comparison

The mineral processing route proposed by Cui and Anderson (2017), Fig. 2, has been examined by using a separate LCA study, completed on the single process of processing with a functional unit of 1 kg of REO contained in the produced concentrate. It is important to note that the grade and recovery of ore achieved in each processing approach is different. The physical upgrade method proposed in the prefeasibility would produce a grade of 6.64% REO with a recovery of 86.4% whilst the flotation approach would produce a concentrate grade of 11.2% REO at 61.2% recovery. It is also important to consider the fact that the downstream hydrometallurgy impacts have not been included in this calculation, but it is likely that improved grade would lower the environmental costs during the hydrometallurgy stage.

The results are presented in Table 4 comparing the performance of the two beneficiation methods over the life of the mine and the average impacts per kg REO produced during the years 10–45. This was done as the first 9 years of beneficiation of the high grade ore using the conventional method has a low impact in all categories measured and outperforms the method proposed by Cui and Anderson (2017). This is highlighted in Fig. 7 which shows the percentage performance of the beneficiation method proposed in the Pre-feasibility Study Report (2014) against the WHIMS and flotation method proposed by Cui and Anderson (2017). It is likely that the method proposed by Cui and Anderson could be employed from year 10 once the high grade ore has been processed (see Fig. 8).

During the years 10–45, the flotation method has a lower environmental impact for the acidification, eutrophication, human health, human toxicity, ozone depletion, and smog impact categories. The flotation method has a slightly worse result in the global warming category with 0.933 kg CO_2 eq. produced per kg of contained REE compared to the crushing, grinding, gravity and magnetic separation which has an impact score of 0.85 kg CO_2 eq. Fig. 7 highlights the relative performance in each LCIA impact category through the project life (from left to right of each colour). This shows that many of the impact categories have a small percentage difference apart from the smog formation impact category. The method proposed by Cui and Anderson performs much worse in this area. This is due to the higher embodied impacts of the chemicals used in the method proposed by Cui and Anderson. The impact scores and the higher grade achieved would indicate that the method proposed by Cui and Anderson if applied in the production of REE at Bear Lodge from years 10 until year 45 would reduce the overall impact in many categories. However, further research needs to be done to understand how improved grade in the concentrate would impact the material and energy requirements in the hydrometallurgy phase (see Fig. 9).

Table 4
Life cycle impacts for the two beneficiation processing options of Pre-feasibility Study Report (2014), and Cui and Anderson (2017) at Bear Lodge using mass based allocation for 1 kg REO with the TRACI characterization.

Impact category	Unit	Pre-feasibility Study Report (2014)	Cui and Anderson (2017)	Pre-feasibility Study Report (2014)	Cui and Anderson (2017)
Acidification	kg SO_2-Eq	1.70E−03	1.70E−03	2.00E−03	1.62E−03
Eco-toxicity	CTUe	1.68E−02	2.26E−02	2.00E−02	2.16E−02
Eutrophication	kg N-Eq	1.00E−04	1.10E−04	1.00E−04	1.00E−04
Global Warming INC	kg CO_2-Eq	7.04E−01	9.80E−01	8.49E−01	9.34E−01
Global Warming (Non-INC)	kg CO_2-Eq	7.03E−01	9.81E−01	8.48E−01	9.34E−01
Human Health	kg PM2.5 eq.	1.00E−04	1.30E−04	1.70E−04	1.20E−04
Human toxicity	CTUh	1.19E−10	1.98E−10	1.41E−10	1.91E−10
Human toxicity (Non-Cancer)	CTUh	8.68E−09	8.69E−09	1.01E−08	8.11E−09
Ozone depletion	kg CFC 11 eq.	4.77E−10	4.69E−10	5.13E−10	4.17E−10
Resources	MJ surplus energy	4.37E−02	1.10E+00	4.45E−02	1.13E+00
Smog	kg O_3 eq.	2.39E−02	2.23E−02	2.76E−02	2.10E−02

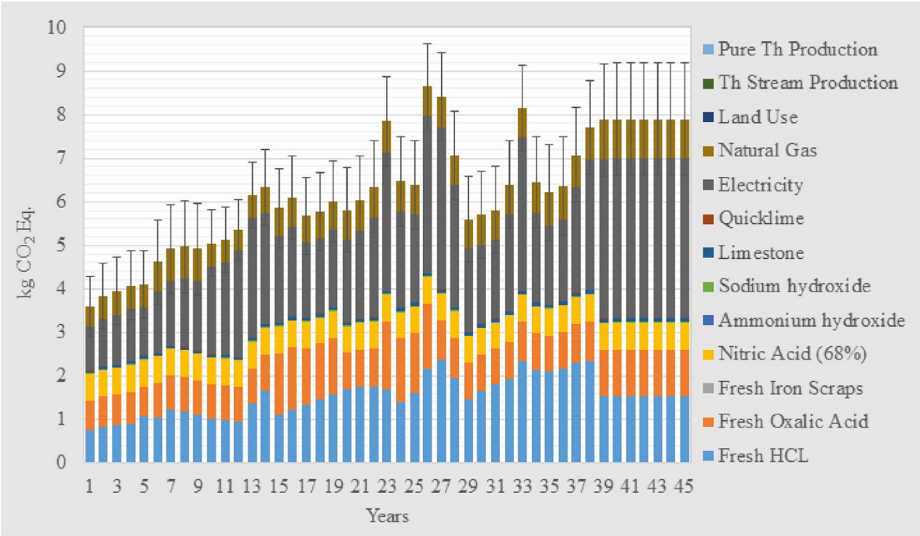

Fig 7. Hydrometallurgy contribution to global warming impact per kg REO over life of mine.

4. Discussion

This is the first cradle-to-gate LCA to examine the life cycle environmental impacts of REE over different stages of production of a mine life. It has shown that even with limited data during the early stages, it is possible to highlight the specific environmental challenges during a project lifespan. This provides an opportunity to both mitigate against these impacts and research alternative processing options, which has been highlighted here in the comparison of the two beneficiation options for the Bear Lodge project. The results indicate that there is potential for the WHIMS and flotation method to be employed from years 10–45.

LCIA impacts against different temporal stages of the Bear Lodge REE project were investigated, examining relationships between impact categories and changing grade, processing options and material and chemical consumption. The results highlight that a predictive LCA at a project scale can be a useful tool in identifying environmental hotspots and advising on processing options. Another important consideration is the fact that it is possible for outside agencies to carry out a detailed LCA and quantify environmental impacts with publicly available data, either to assess an individual project or to compare projects. There are country specific guidelines to disclose details of mineral projects such as National Instrument 43-101 or Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC). The data used here were acquired from the Pre-feasibility Study Report which was generated according to National Instrument 43-101 guidelines. This is a step that most exploration projects progress through and so provides an opportunity for public awareness of the environmental impacts or projects.

The LCIA methods and data selected for this work are not all equivalent. For example there is a strong consensus and a catalogue of research on impacts such as global warming, whilst greater uncertainty on other categories such as those used for toxicity calculations are considered as interim and results should be taken with this in mind (Rosenbaum et al., 2008; Hauschild et al., 2008).

The results generated from the LCA are useful, however it is important to understand the role that LCA has to play in the context of risk assessment. LCA may generate data about the environmental performance of a process, but it may fail to indicate whether a particular process choice has an increased spatially and temporally explicit risk to the environment, such as a tailing dam failure or groundwater seepage of ions and cations. LCA is useful in evaluating global impacts while

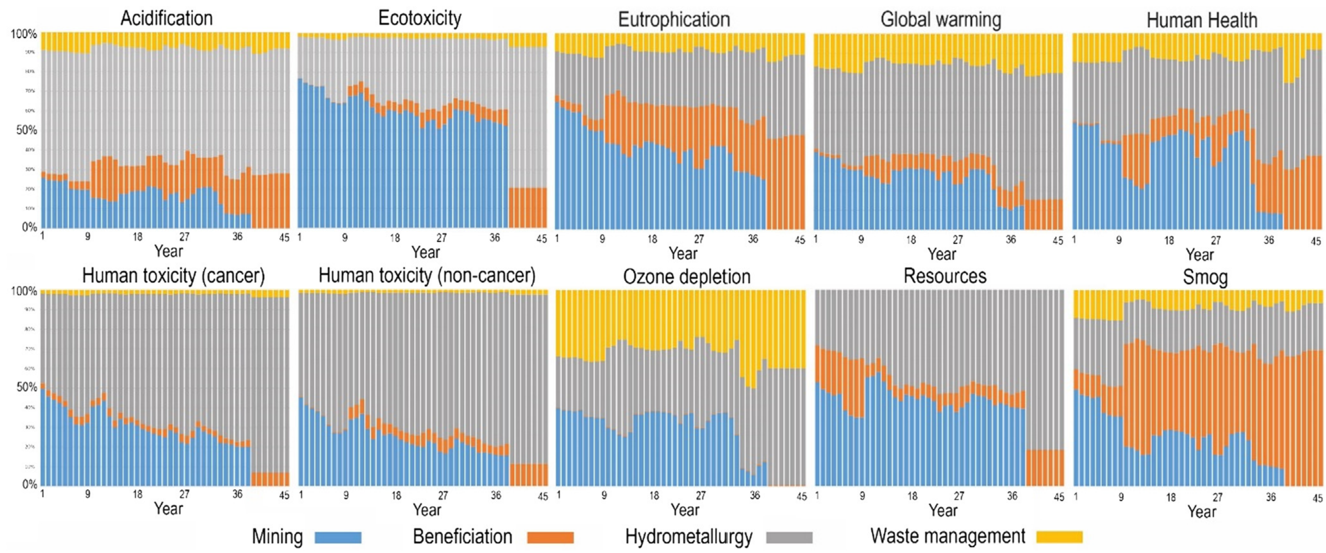

Fig. 8. Share of production process on total impact of 1 kg of REO production over the life of mine with project life moving left to right for each impact category.

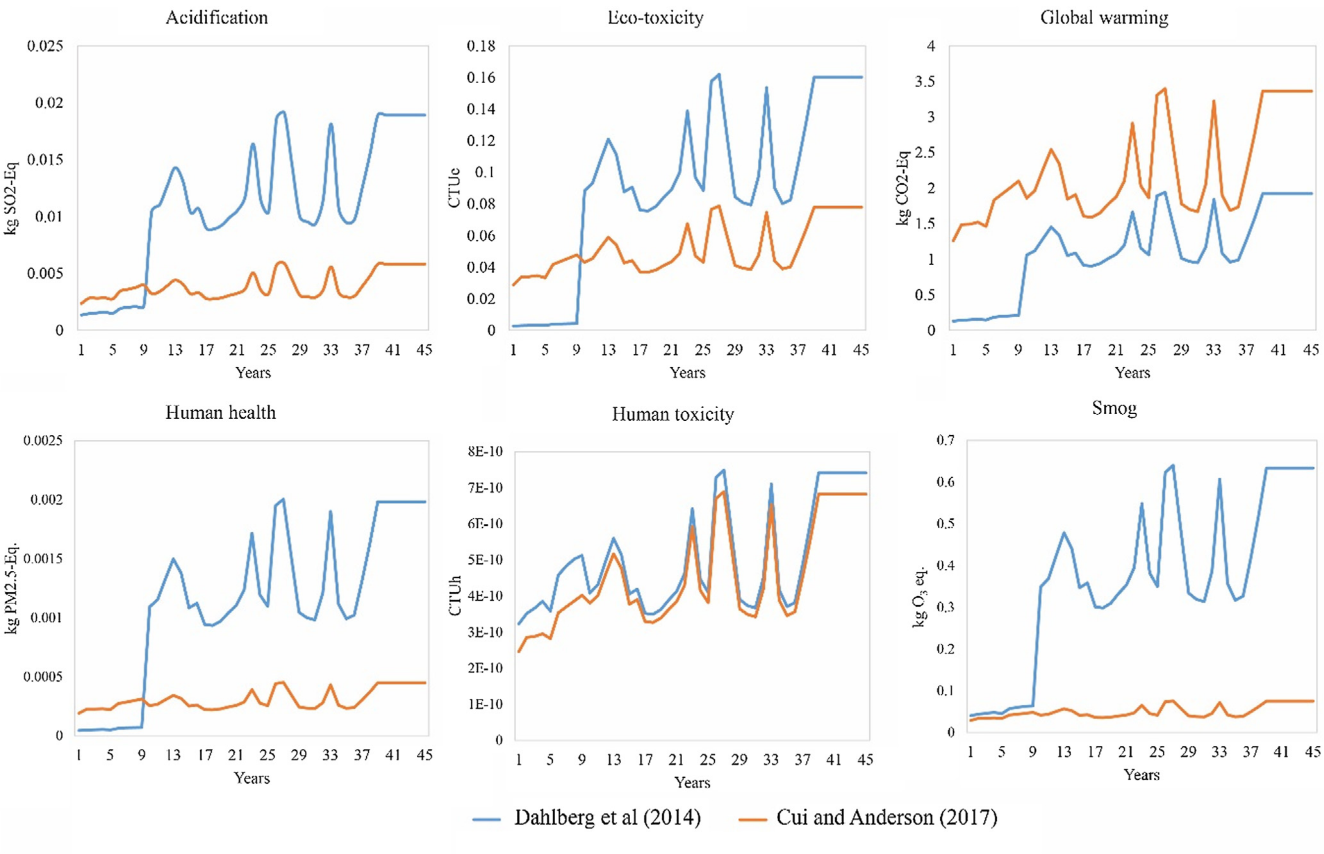

Fig 9. Comparison of using either the Pre-feasibility Study Report (2014) or Cui and Anderson (2017) beneficiation flowsheets on six TRACI impact categories over the life of mine.

quantitative risk assessment (QRA) is a more suitable approach when assessing local impact assessments. QRA integrates a range of data across a broad range of disciplines including source characterisation, fate and transport, modelling, exposure assessment, and dose-response assessment. Instead it is advised that the results of both assessments are considered before decisions about a change in process choice is made (Linkov et al., 2017).

4.1. Uncertainty analysis

The uncertainty analysis carried out in this project does not consider the accuracy of the process choices described in the PFS and whether these processes would feature if the project moves into production. The uncertainty of the data is based on the data quality indicator classification system of the American Association of Cost Estimation (Bull et al., 2012), a method suggested by Arshi et al. (2018). This refers to the uncertainty of the LCI data for each stage of production (see Table 5).

Table 5
Data quality of the four stages of production (data quality 3 is calculated, modelled, stoichiometric calculated, up-scaled data, data quality 5 is roughly estimated data).

Stage	Data quality	Deviation
Mining	3	−20 to +30
Beneficiation	3	−20 to +30
Hydrometallurgy	3	−20 to +30
Waste management	5	−50 to +100

5. Conclusions

The results highlight that a predictive temporally explicit LCA at a project scale can be a useful tool in identifying environmental hotspots and advising on processing options that could improve the environmental performance of a rare earth project. Adding a temporal dimension provides a greater opportunity to explore the relationships between the properties of the deposit, the mining and mineral processing methods and the environmental impacts. The results indicate that there is a positive relationship between decreasing grade and global warming impact, but there are also patterns that exist between the ore composition and the global warming potential.

The beneficiation approaches compared generated different environmental impacts over time. The beneficiation process presented in the Pre-feasibility Study Report (2014), which included crushing, grinding, magnetic and gravity separation had a higher average impact over the life of mine for the acidification, eco-toxicity, human health, human toxicity, and smog, whilst the flotation approach presented by Cui and Anderson had a lower global warming impact.

Applying the LCA methodology higher uncertainty in this stage of a project for both the geology of the deposit and the mining and mineral processing methods that will be used is offset by the fact that high impact areas can be explored and changes can be implemented as a project moves through development into the feasibility stage.

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Notes

The authors declare no competing financial interest.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.mineng.2019.02.043.

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Chapter 5

Environmental optimisation of mine scheduling through life cycle assessment integration

Interest in mine scheduling has primarily concerned the mathmatical challenge of extracting the ore in a sequence which maximises NPV. The increased awareness of global warming and the policy changes that have been adopted because of this, such as carbon taxes, makes predictive modelling of changing carbon price scenarios important. Developing a model which can consider both aspects of maximising NPV whilst allowing for different carbon pricing scenarios was the motivation for this chapter.

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Full length article

Environmental optimisation of mine scheduling through life cycle assessment integration

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ABSTRACT

Life cycle assessments (LCA) are useful to quantify the environmental costs of mining projects, however the application of LCA is often a retrospective environmental measurement of operating mines. This paper presents a novel methodology of carrying out a LCA to generate life cycle impact assessment data that can form an environmental block model of a deposit. These spatially explicit data can then be used as a constraint within long-term mine scheduling simulations. The results indicate that significant reductions in global warming impact can be achieved at a small economic cost. For example using an environmental constraint it was possible to achieve 91.9% of the global warming impact whilst achieving 95.9% of the net present value compared to the baseline. Different constraints and economic scenarios are explored and multi-criteria decision analysis is carried out. This approach enables environmental considerations to be included in strategic mine planning. This is important because mining will continue to form an important part of our society for the foreseeable future. Integrating environmental considerations into the earliest stages of mine planning can assist in driving environmentally responsible raw material extraction.

1. Introduction

This study proposes that environmental data for mining activities can be calculated using Life Cycle Assessment (LCA) and then included in mine scheduling simulations. A methodology to incorporate this approach in mine scheduling has been developed using a case study of an iron deposit located in the Iron Quadrangle, Brazil. The aim is that this is a generally applicable methodology that can be applied for other commodities.

Mining is an essential part of society, providing raw materials for consumer goods and supporting industrial development (Carvalho, 2017) and will remain so for the foreseeable future (Elshkaki et al., 2018). However, the mining industry can cause environmental degradation, impacting landscapes, water resources and air quality. On a global scale the mining sector currently represents around 2.7% of worldwide energy use contributing to significant greenhouse gas (GHG) emissions (IPCC, 2007). As demand for raw materials rises, the quality and grades of ore deposits is decreasing, and as a result it is predicted that global warming emissions will increase (Norgate and Haque, 2010). In order to maintain current levels or reduce this for the future requires improved efficiency through the adoption of new and enhanced techniques within the mining industry. Mining companies can also reduce economic risk from improved environmental performance as governments and consumers demand increased social and environmental responsibility (Wall et al., 2017).

LCA is one of the most promising methods to quantify the environmental performance of mining operations (Durucan et al., 2006; Blengini et al., 2012). It is an objective method that measures the environmental burdens of a product or process over its lifetime, considering the additional embodied impacts of materials or energy that are consumed in the studied process (ISO, 2006). LCA follows ISO 14040 and ISO 14044 standards (ISO, 2006). A key feature of LCA is that it measures the indirect impacts of a process, such as the environmental impacts associated with the fuel production, which may energies a process. Other life cycle approaches exist alongside LCA, such as life cycle costing (LCC), which takes into account the internal and external financial costs of a product system with a similar approach to LCA (Guinée, 2002) and social life cycle assessment (SLCA) which considers social aspects associated with a product system. SLCA and LCC can be integrated with LCA to form a life cycle sustainability

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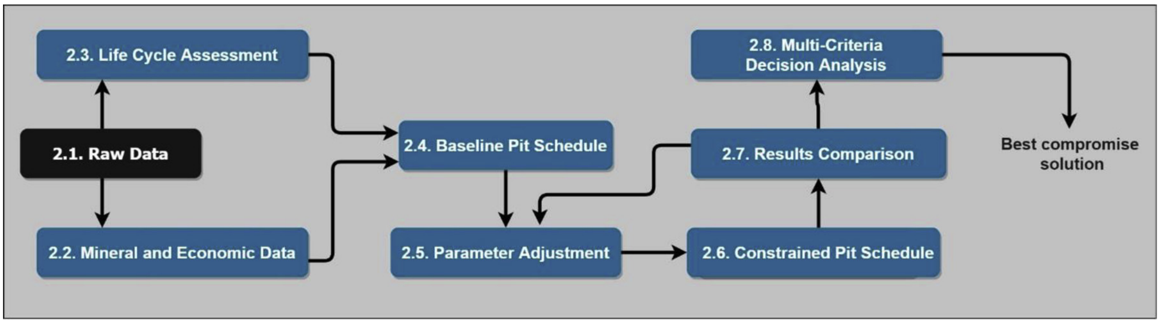

Fig. 1. Methodological framework for incorporation of life cycle impact assessment data in mine planning.

assessment (Finkbeiner et al., 2010).

The LCA approach has more commonly been used for policymakers and researchers, (Scott Matthews et al., 2014) but has recently gained traction from the mining companies themselves. Norgate and Haque (2010) carried out a mine-to-gate LCA of an iron ore mine, and found that to produce 1 kg or iron ore 11.9 kg CO_2 Eq. was emitted, with the greatest impacts associated with the loading and hauling stage. Ferreira and Leite (2015) also carried out a LCA for iron ore production from Brazil. This study examined the environmental costs of producing iron ore concentrate and highlighted that the use of grinding media as a major contributor to environmental impacts. Chaulya (2006) used a different approach, visiting three iron ore mines to measure particulate emission rates and develop formula for different surface activities. Physical properties of the ore can impact emission rates during mining activities and these, alongside other data such as spatial location form the basis of the calculations for the LCA in this paper. Energy consumption and emissions calculations are made using equations from the National Pollution Inventory (NPI, 2008) and Chaulya (2006).

LCA can be used to identify options for environmental improvements in a mining operation (Awuah-Offei and Adekpedjou, 2011). A challenge with current of LCA in the mining industry is that it has been applied in a reactive way, assessing the impacts of current operations (Vahidi et al., 2016; Arshi et al., 2018). This is helpful to develop a Life Cycle Inventory (LCI) and a baseline of impacts, however there is an opportunity to expand the use of LCA integration in mine planning and process design. The proactive approach has been used since 1993 (Keoleian, 1993) and has been applied in the chemical processing, manufacturing and building design industries (Azapagic and Clift, 1999; Steinø et al., 2013) but not as far as we know within the mining sector. There have also been advances in LCA to produce spatially and temporally explicit impact data (Maier et al., 2017) which have yet to be applied to mining.

The design stage of a product or process can determine its environmental impact over its lifecycle (Baumann et al., 2002) and so is an important intervention point to achieve environmental goals (Graedel and Allenby, 1998). Designing products or a process with the environment in mind and to assume some responsibility for the product's environmental consequences as they relate to specific decisions and actions is known as eco-design. In the context of mining, mine planning can be considered an aspect of process design and offers the opportunity to apply eco-design during this phase. Mine planning refers to the process of selecting particular material for extraction and designating the order and time of extraction to minimise cost or fulfil a specific business target. This process can occur well in advance of operation and can be updated throughout the life of the mine. It usually involves generating geological data by drill holes or other sampling methods. From these data, a block model can be formulated that contains data about the location and mineral composition of each 'block' in the deposit. Ore and waste blocks have to be selected based on their economic value and sequenced to ensure that products have a consistent marketable grade. For iron ore deposits, this includes a consistent iron content but also consistent levels of contaminants such as silica, alumina and phosphorus.

Pit optimization has been an important stage of mining project development. Traditionally, the approach for this included a series of steps to plan the mine known as nested pits. This was introduced in 1965 and remains the most commonly used approach in the mining industry (Lerchs and Grossman, 1965). However, a limitation of this approach is that it may fail to optimize the economic value of the whole pit. The approach known as Direct Multi-Period Scheduling or Direct Block Scheduling (DBS) advances this and applies the correct discount factors to cash flow over production years (Almeida, 2013; Souza, 2018). The Direct Block Scheduling approach can be used to maximise the economics of a deposit but also to fulfil particular business targets. Consideration of particular targets other than directly economic is known as 'strategic mine planning'. These targets can continuously evolve and change and in the context of this paper the target examined is global warming potential. Integrating DBS and LCA allows environmental considerations to be included in mine planning in a proactive way. This paper presents how this can be achieved and examines the environmental-economic relationship of mine planning using DBS.

2. Materials and methods

Environmental LCA data can be integrated into the mine scheduling process (Fig. 1) so that it is possible to explore scenarios and change constraints after initial results generation. The method is based on the Optimum LCA Performance (OLCAP) method described by Azapagic and Clift (1999) to meet the needs of the mine scheduling approach. The best compromise solution is based on the subjective values of the user. For example, it could place preferential importance on the environmental performance or the economic performance. The case study and data used in this study is from an iron ore deposit located in Brazil. This site was selected as the deposit is large and contains a relatively simple mineral composition.

2.1. Raw data

In order to evaluate the quality and quantity of potential ore within a deposit, a variety of direct and non-direct methods can be employed, including surface sampling, sub-surface drilling and geophysical techniques (Moon et al., 2006). The minimum information requirement of deposit knowledge is an average grade of element of interest and the number of tonnes that contain this grade. The distribution of grade and tonnes across the deposit is also critical for mine planning and is commonly estimated using linear interpolation methods such as Ordinary Kriging, data from drilling and other sampling methods. In this study, data on the orebody were obtained from diamond core drilling where intact core is recovered and then sampled for grade and chemical composition. Depending on the precision and accuracy required, either a mass spectrometry or an X-ray fluorescence method is subsequently used to determine the chemical composition of a representative sample of the core. A stringent quality assurance/ quality control procedure is applied consisting of preparing and analysing blanks, standards, duplicates and possibly certified reference materials to ensure data quality (Abazalov, 2017). The authors performed Kriging Neighbourhood Analysis to produce an unbiased estimate of the various elements present across the deposit at the mining block scale (Vann et al., 2003). This produced data for Fe, Si, P, Al, Mn, and SiO_2 grades at the deposit. These data have a spatial co-ordinate with x, y and z values. The data with its spatial location together forms the block model.

2.2. Mineral and economic data

Each block is assigned an economic value and a waste value, based on the elemental grades and tonnage of the block. The waste value is calculated by multiplying the tonnage of the block, which is found by multiplying specific gravity with the dimensions of the block, with the mining cost per tonnage. The mining cost per tonne is defined at $8/t. This can be seen in Eq. 1 where WV is defined as Waste Value, T as tonnage and C_m as mining cost.

$$WV = T \bullet C_m \tag{1}$$

The economic value is calculated by considering the economic value of the iron in the block and by subtracting the mining costs, processing costs and penalties for phosphorus content. The economic value of the iron is calculated by multiplying the Fe grade with the block tonnage at an iron ore price of 108 $/t under an 85% recovery. The mining costs and processing costs are set at $8/t and $6/t respectively and the phosphor penalty is $4/t. This is shown in Eq. 2 where EV is defined as Economic Value, $\%_{Fe}$ as the iron content in the block, P_{Fe} as the price per ton of iron ore, R_{Fe} as the recovery for iron ore, C_p as processing costs, $\%_P$ the phosphor grade and P_P as the penalty per ton of phosphorus.

$$EV = T \bullet \%_{Fe} \bullet P_{Fe} \bullet R_{Fe} - T \bullet (C_m + C_p) - -T \bullet \%_P \bullet P_P \tag{2}$$

The SimSched software resolves during the calculation process if a block is waste or ore by evaluating what maximizes the NPV at that point in time: mining and processing that block or mining and sending it to the waste dump (SimSched, 2018).

2.3. Life cycle assessment

2.3.1. Goal and scope

The goal and scope of this LCA was to measure the global warming impact of mining and transporting a single block at the case study iron ore mine. The cradle-to-gate LCA had a functional unit of one block at the drop-off location at the mine and does not include crushing, grinding or other processing. The economic value was excluded from the functional unit as this will be included in the pit-scheduling in a later stage. The system boundary of the LCA includes electricity and diesel inputs and the associated dust and exhaust emissions at the mine site (Fig. 2).

2.3.2. Life cycle inventory analysis

For the mining activity, data were predicted for the production and consumption of the following inputs: diesel in mining equipment, explosives, exhaust and dust emissions from vehicles and ore and waste loading and dumping. The input variables that are central to the differences in environmental performance for the extraction of each block were; silt content, block hardness, the specific gravity and tonnage of each block and its location in deposit.

The equations used have been included in the supplementary information and follow the approach used by Chaulya (2006) for particle emissions and NPI (2008) for emissions from equipment, diesel and electricity consumption. All parameters other than the physical properties of the block remained static. This included environmental conditions and the equipment used. Diesel equipment is used unless stated otherwise and was selected based on what is consistent with regulations for the region.

2.3.3. Life cycle impact assessment

The results in this study examine the global warming potential (GWP) midpoint indicator using the TRACI 2.1. life cycle impact assessment methodology. The data for diesel, explosives, and energy use and emissions was obtained from the GaBi database. The electricity was assumed to be the average grid mix from Brazil. The LCA was carried out using GaBi 6.0 software. The inputs and outputs included in the LCA have been listed in Table 1. The data included represents the major contributors to the global warming potential impact, which is supported by previous LCA studies for mining operations (Awuah-Offei and Adekpedjou, 2011).

We have additionally included results for acidification and human health in the supplementary information. Global warming was included as the single impact as this is the approach due to the simplicity in comparison and the nature of this study was primarily to investigate the methodology.

2.4. Baseline pit schedule

Simsched Direct Block Scheduler software developed by MiningMath uses an operations research based algorithm to consider long term scheduling of the orebody (Souza, 2018). The blocks within the block model are directly scheduled on an annual basis, whilst satisfying constraints that are operational (e.g. annual throughput or stockpiling constraints) and desired constraints, such as product grade or maximum annual environmental impact. The overall goal of the simulation is to maximize the overall NPV of the project.

Essential parameters are three dimensional indices of the blocks, at

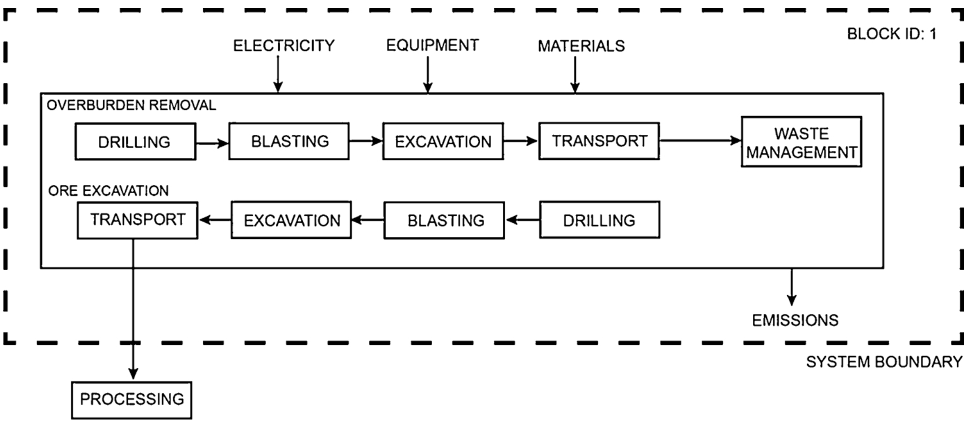

Fig. 2. System boundary of LCA for each block of iron ore mining.

Table 1
Calculations included for the life cycle inventory block data (Chaulya, 2006; NPI, 2008).

Process	Item	Description	Unit
Drilling	Electricity	Input	MJ
Blasting	Explosives	Input	kg
Excavation	Diesel	Input	MJ
Loading	Diesel	Input	MJ
Hauling	Diesel	Input	MJ
Ore Dump	Diesel	Input	MJ
All	Dust	Output	kg
All	Carbon dioxide	Output	kg
All	PM2.5	Output	kg
All	PM10	Output	kg

least one elemental grade, specific gravity, slope angle and a discount factor. The software allows for additional data per block in the model, such as global warming potential (GWP). The software also allows the annual GWP to be constrained, either over the whole life of mine or during a pre-defined period.

A schematic overview of the software execution method is shown in (Fig. 3). Direct Block Scheduling linearizes the optimization problem, after which Linear Programming (LP) is used to execute the model. Following that, Mixed Integer Programming combined with proprietary heuristics converts the continuous LP model into an integer and non-linear solution. Following that, the software verifies the feasibility and, if feasible, it verifies whether that solution has actually maximized the NPV. If the initial solution defined by Direct Block Scheduling is not feasible, certain constraints will be relaxed by the model in order for the program to find a solution. Constraints such as the slope angle are not relaxed by the software, as this may lead to an unsafe scheduled solution (SimSched, 2014). Limitations are that the program only gives a long term planned optimization and additional software packages or programming is required to define a short term plan. The calculation only includes capex and only limited operating expense is included in the NPV of the schedule. It is not a deterministic software, meaning that the changing the parameters will influence the final result in a direct way.

In this study, the calculated GWP per block and elemental content depending economic values were assigned to all the blocks within the block model. After the software has ran the optimization, a mining schedule, the economic performance of the operation, tonnages of metal produced and the annual environmental impact are provided. By constraining the annual environmental impact in the settings of the optimization it is possible to optimize the mining schedule whilst limiting the annual output of CO_2.

2.5. Parameter adjustment

The first pit scheduling simulation was carried out without environmental constraints, forming the baseline for the study for comparison of further simulations. In the software set up additional constraints were added that put a maximum on the annual output of kg CO_2. As constraint the second and third quartile of the annual output of the baseline simulation were chosen. This would allow to see what level of constraint generates a significant reduction in environmental output and at what economic cost. The constraints are seen in Table 2, with 629 Mt being the second quartile and 735 Mt the first quartile.

The Fe economic value was also adjusted for scenarios 4–9, where the basic Fe price of \$108/t was increased by 1%, 3% and 4% respectively. The rationale behind providing additional value for Fe in scenarios with global warming thresholds is as described in the introduction. Mining companies may see an economic value to reduced CO_2 emissions. For example, premium prices have been attached to reduced carbon emissions and in some regions carbon has been taxed (International Council of Mining and Metals, 2013). By introducing increased economic value of Fe it is also possible to see the appropriate additional value a company could theoretically charge for a reduced carbon emission product.

2.6. Constrained pit schedule

The process described in the baseline ore sequencing was followed but with the inclusion of the environmental constraints listed in Table 2 with scenario 2 and 3. Added economic value of the block was also simulated under Q2 and Q3 constraints with scenario 4–9. This was completed to understand the increased block value that would be required to match the baseline under constrained environmental conditions.

2.7. Results comparison

Data generated from the constrained pit schedule can be compared in terms of environmental impact and the associated NPV impact. These

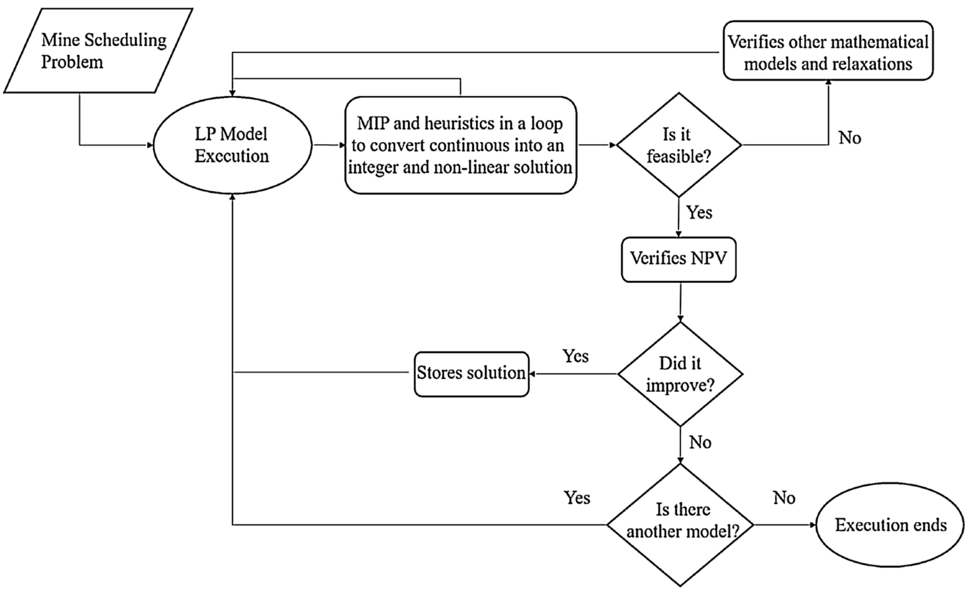

Fig. 3. Schematic overview of the simulation as performed by the software (SimSched, 2018).

Table 2
Parameter scenarios used in this study.

Scenario	Name	Net Present Value	Fe Value ($/t)	Global Warming (kg CO2 per annum)
1	B	Maximum	Standard -$108	None
2	Q3	Maximum	Standard -$108	735 Mt
3	Q2	Maximum	Standard - $108	629 Mt
4	Q3-1	Maximum	Standard * 1% - $109	735 Mt
5	Q2-1	Maximum	Standard * 1% - $109	629 Mt
6	Q3-3	Maximum	Standard * 3% -$111	735 Mt
7	Q2-3	Maximum	Standard * 3% - $111	629 Mt
8	Q3-4	Maximum	Standard * 4% - $112	735 Mt
9	Q2-4	Maximum	Standard * 4% - $112	629 Mt

data were used in the multi-criteria decision analysis. From this stage of results comparison, it is also possible to visualise relationships and make constraint adjustments for further simulations.

2.8. Multi-criteria decision analysis

The comparison of scenarios was done using the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) method (Olson, 2004). This approach arranges the scenarios among the alternatives providing the distance to the ideal, and the worst possible solution. It is also possible to include the relative weights of criterion importance. The intermediate results and calculations for this process is included in the supplementary information.

3. Results

3.1. Environmental and economic block models

Fig. 4 provides a 3D model of both the economic value in the deposit and Fig. 5 a 3D model of the global warming impact of the deposit. These data were used as described in the methodology to schedule the pit, selecting which blocks to be extracted and in which order. The economic block model highlights that there are high value zones which have been calculated by Eq. 1 in the methodology. The global warming block values indicate a zone of high global warming blocks near the base of the deposit. This is partly because these blocks will require further transportation to be removed from the pit.

The major contribution to global warming is during the waste rock removal and transportation (Fig. 4). Other major contributing impacts are the excavation of the overburden, the excavation of the ore, the disposal of the overburden and the ore transportation. The ore transportation has a clearly defined spiking trend throughout the blocks which represents the relative distance of that block to the ore drop-off point which is assumed at the surface and on the west edge of the pit. Other more subtle trends can be seen, which indicate both changes in distance of required transport or areas where there is increased/decreased ore or waste product.

3.2. Baseline results

The mine scheduling simulation with no environmental constraints produced annual CO_2 Eq. emissions that ranged between 600,000 and 800,000 tonnes. There is an increase in CO_2 Eq. emissions from year 21, reaching a peak at year 35 followed by a steady, fluctuating decline until year 88. The emissions reflect the simulated mining extraction during these periods to create the highest NPV. The cumulative NPV value in Fig. 5 shows the optimization of the target cut-off grade. The NPV value reached for the baseline was $64,989 million at year 91 (Fig. 6).

3.3. Introducing constraints

By introducing annual CO_2 Eq. constraints to the mine schedule simulation both the annual and cumulative global warming potential emissions and NPV are effected. The annual and cumulative emissions for the Q3 constraint, which limits the global warming impact to three quarters of the average global warming value, can be seen with Fig. 7. The annual CO_2 Eq. emissions are similar to the baseline, fluctuating by

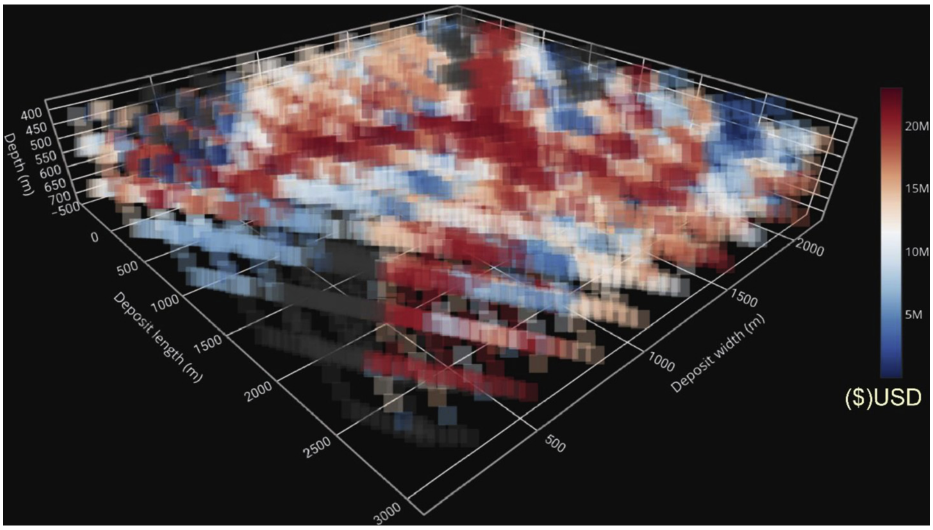

Fig. 4. Economic block model (available 3D model at https://plot.ly/~rp416/165/environmental-optimisation-of-mine-scheduling-through-life-cycle-assessment-inte/).

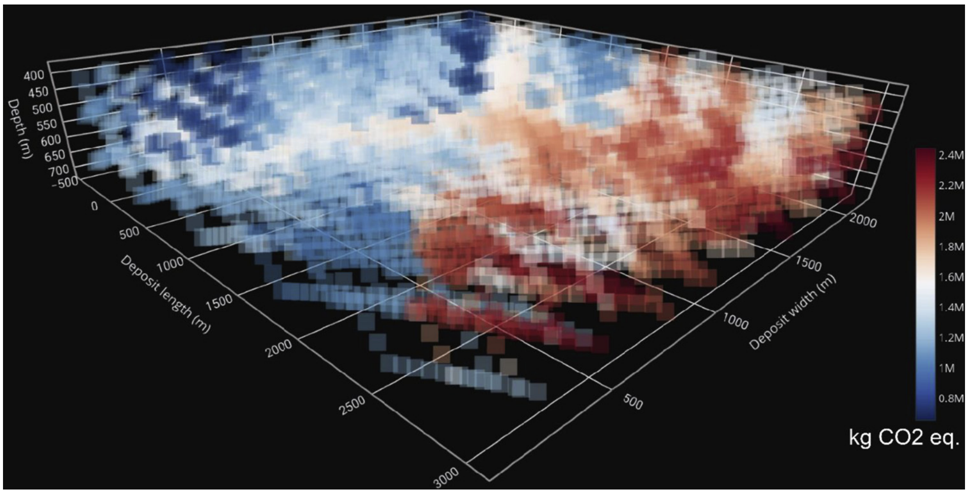

Fig. 5. Carbon footprint block model with global warming impact value for block (right).

around 100,000 tonnes above or below the baseline. The cumulative emissions indicate that CO_2 Eq. emissions are higher under this constraint until year 41. From years 41 to 53 the cumulative emissions reduce relative to the baseline and from years 54 to 81 the emissions increase to the point of reaching baseline levels. There is a final drop at the end of life to that finalises the cumulative global warming reduction of the Q3 scenario by 176,116 tonnes compared to the baseline. This reduction in CO_2 Eq. emissions came at a reduction in NPV of $355.9 million.

By contrast the Q2 constraint has a much more significant reduction in CO_2 Eq. emissions on an annual and cumulative basis. The Q2 constrained simulation reduced cumulative emissions of CO_2 Eq. by 4.9 million tonnes compared to the baseline scenario. This reduction in global warming emissions came at an NPV cost of $2.6 billion. This is due to the higher constraint limiting the extraction of higher impact blocks. The NPV and GWP impact rate is not linear as shown in these constraint scenarios. For example the Q3 scenario produced NPV at 99.45% of the baseline whilst having a GWP impact of 99.7% of the baseline. The Q2 scenario produced NPV at 95.9% of the baseline whilst having a GWP impact of 91.9%. This indicates that an optimal solution may be possible by exploring constraints and different economic values (Fig. 8).

3.4. Coupled CO_2 thresholds and economic criteria

As described in the introduction some mining companies adopt voluntary environmental standards and carbon dioxide emission limits as well as selling raw material product at a premium price because of a reduced global warming footprint (Tole and Koop, 2013). Some regions, such as in Canada have also introduced carbon taxes. Either way this leads to an economic incentive to reduce CO_2 emissions. Placing the Q3 and Q2 thresholds with economic value increase for Fe by 1%, 3%, and 4% allows us to evaluate at what value increase is required to maintain baseline NPV whilst reducing GWP impact. Fig. 9 highlights CO_2 Eq. emissions for the six scenarios with increased Fe value.

From the baseline of 64.99 million tonnes of CO_2 Eq emissions, the reduced cumulative CO_2 Eq. emissions from the Q3 scenarios are 0.23 million tonnes for Q3-1, 0.21 million tonnes for Q3-2, and 0.31 for Q3-4. The Q2 scenarios reduce the CO_2 Eq. emissions substantially more with Q2-1 saving 4.98 million tonnes, 4.98 million tonnes for Q2-3, and 1.63 million tonnes for Q2-4. This last scenario adjustment of 4% increased Fe value

Fig. 9 reflects a similar structure to Fig. 7 for annual production with high fluctuation from years 1 to 11 and towards the end of the project life and the lowest annual emissions seen during years 31 to 61. This indicates that the underlying simulation is only making small changes to selecting and ordering block extraction. These small changes can significantly impact the cumulative CO_2 emissions. There are three strands of performance for cumulative CO_2 emissions. All Q3 scenarios perform in a similar way with regards to CO_2 emissions. Q2-1 and Q2-3 also perform in a similar way. This suggests that these CO_2 constraints don't impact the DBS simulation by much. The 4% economic value

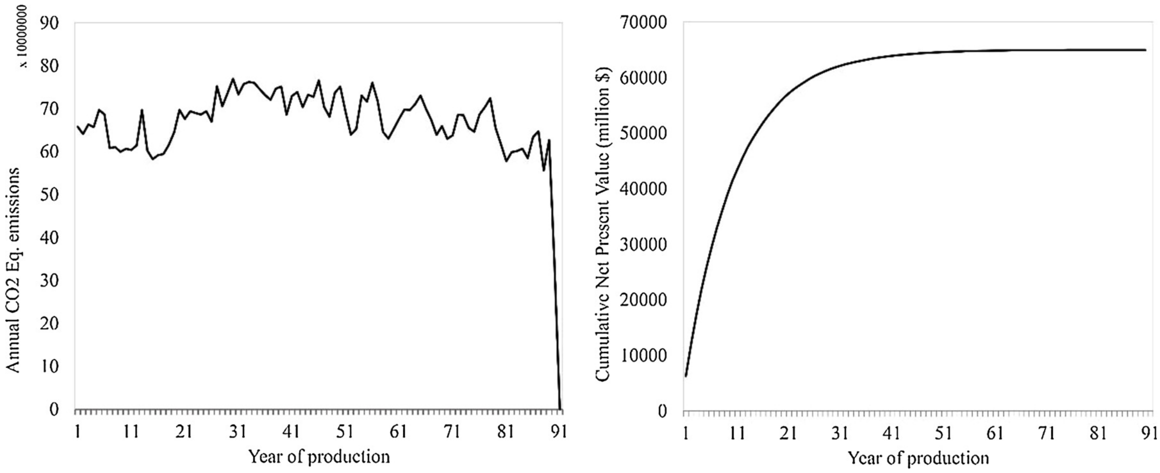

Fig. 6. Baseline annual CO_2 Eq. emissions (left) and cumulative NPV (right) from SimSched software.

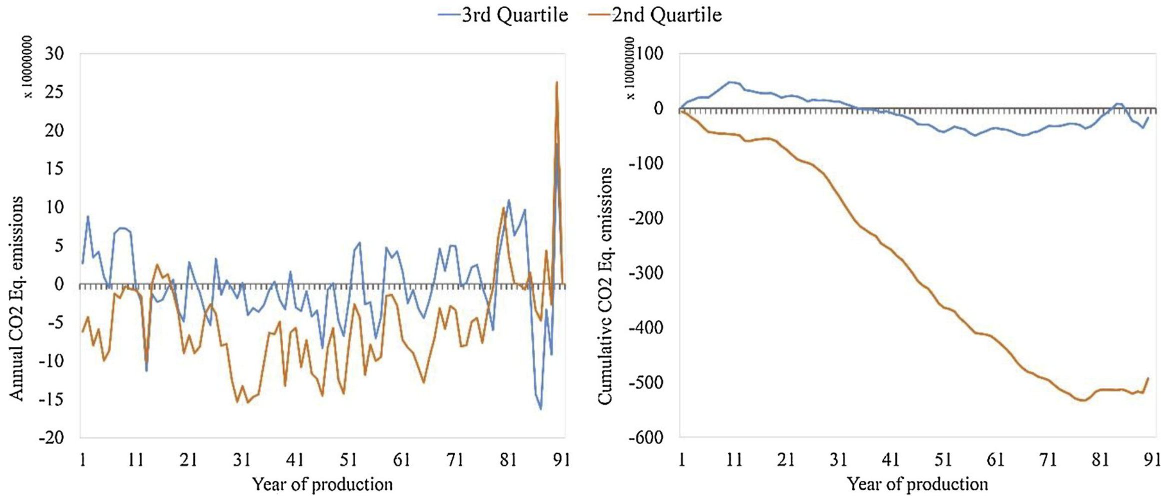

Fig. 7. CO_2 Eq. emissions relative to the baseline for two threshold scenarios on an annual basis (left) and cumulatively over the life-of-mine (right).

increase for Q2 substantially increases the cumulative CO_2 emissions compared to Q2-1 and Q2-3. This is due to the increased economic value of Fe making new areas of the deposit economically feasible to extract even within the CO_2 emission thresholds.

The NPV performance of these scenarios are compared to the baseline in Fig. 10. The best performance is by Q3-4. This would be expected as the economic value of the blocks is increased and there is a limited constraint on the simulation. This is followed by Q3-3 and Q2-4. This indicates that the additional constraint of Q2-4 is roughly equal to a 1% increase from Q3-3 whilst significantly reducing CO_2 emissions. The worst performing scenario was Q2-1 followed by Q2-3. These scenarios had higher emission constraints and only 1% and 3% increase in the economic value of each block.

The Life Cycle Impact Assessment (LCIA) scores for the different scenarios indicate that the CO_2 Eq. emissions range from 8.22 to 8.38 per tonne of iron ore extracted at the mine. These values are within the range of Norgate and Haque (2010) who calculated a CO_2 Eq. of 11.9 per tonne of Fe concentrate and Ferreira and Leite (2015) who calculated 13.32 kg CO_2 Eq. per tonne of Fe concentrate. However, both studies included the iron ore treatment, specifically the grinding, which accounted for 31.53% of the impact. The mining stages accounted for around 2.78 kg CO_2 Eq. per tonne.

Table 3 also presents the economic cost per kg of CO_2 Eq. saved from the baseline scenario. The negative values means that the scenario would make money. This is because the additional value given to the block in these scenarios means that it outperforms the baseline in terms of economic performance.

3.5. Multi-criteria decision making analysis

The range of scenarios were compared for performance in both the GWP impact and the NPV category. The Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) was used for decision making analysis and results are shown in Fig. 11. Three different scenarios rating the relative importance of NPV and GWP are compared. Scenario 8 which represented 3rd quartile for constrained GWP and the maximum added value of 4% performed best when a weighting of 75% was given for NPV and 25% for GWP. This was followed by scenario 9 and then 6. The worst being scenario 3. This highlights that the best performing scenarios with high economic weighting have a low environmental constraint and a higher Fe value.

When NPV and GWP weighting were equal scenario 7 performed the best. This scenario had the higher GWP constraint (Q2) and had a Fe increased value of 3%. This was followed by scenario 9, and then 8. The worst performing scenario being scenario 2. Placing equal weighting on NPV and GWP leads to closer TOPSIS scores. The Q2 GWP constrained scenarios slightly outperforming the Q3 scenarios for the same Fe values.

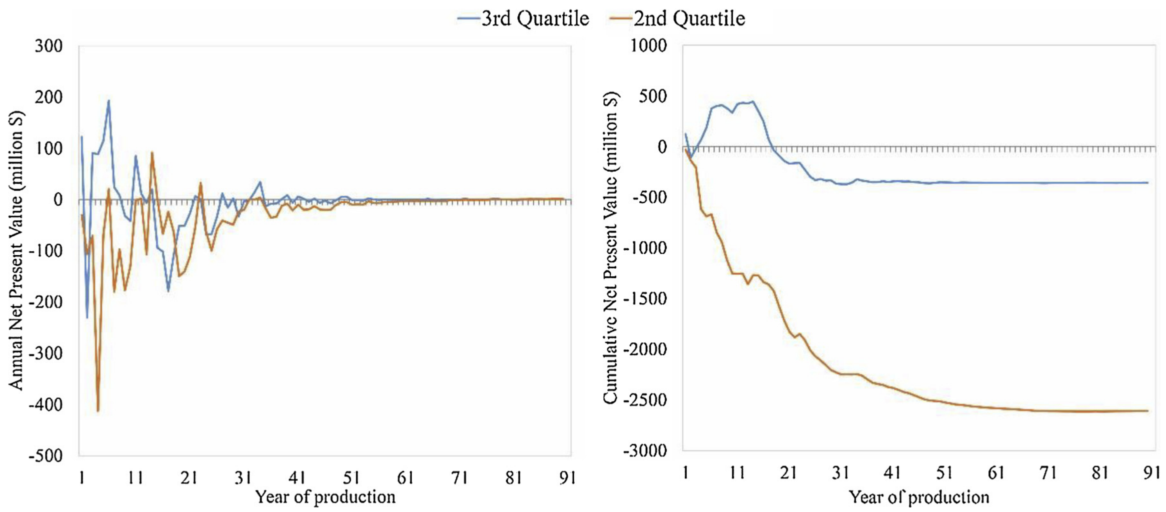

Fig. 8. Net present value relative to the baseline for two threshold scenarios on an annual basis (left) and cumulatively over the life-of-mine (right).

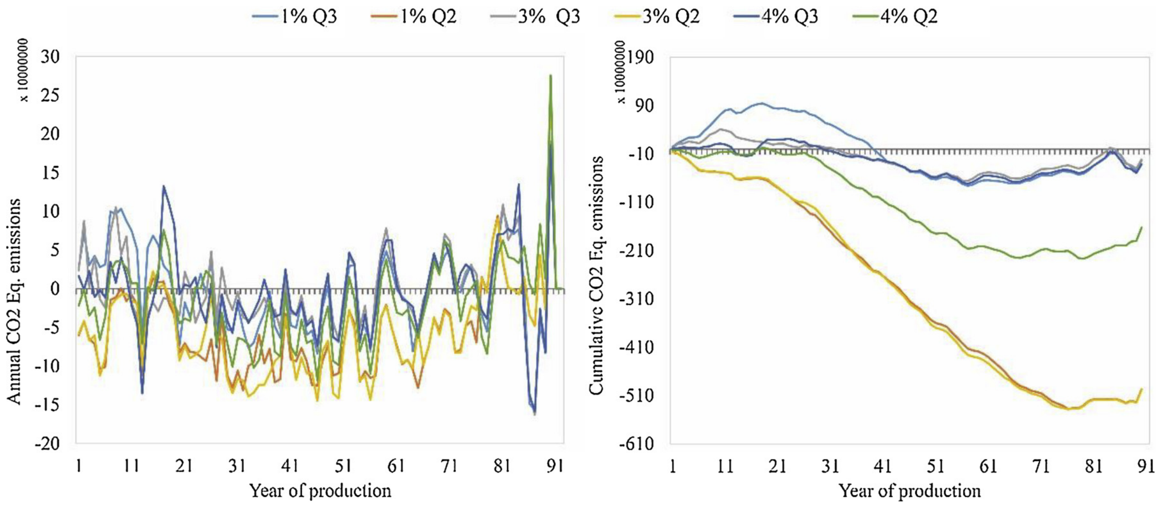

Fig. 9. CO_2 emissions relative to baseline.

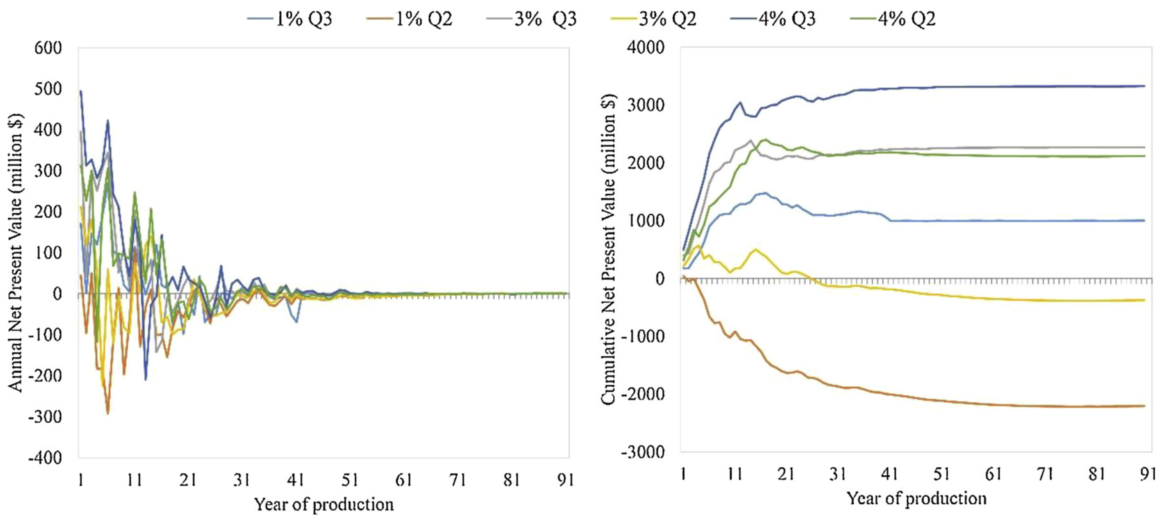

Fig. 10. Net Present value relative to baseline.

Table 3
Environmental performance and cost of improvement for the different scenarios.

Scenario	B	Q3	Q2	Q3-1	Q2-1	Q3-3	Q2-3	Q3-4	Q2-4
$ Per kg CO_2Eq saved	0	2.02	0.53	−4.22	0.44	−10.54	0.08	−10.67	−1.30
kg CO_2Eq. per tonne Fe	8.38	8.37	8.22	8.36	8.23	8.36	8.24	8.36	8.31

4. Discussion

The calculations used to predict CO_2 Eq. emissions are taken from literature and not specific to the study site. It would be possible to improve the quality of the data gathering samples at the site and include site-specific environmental conditions such as wind speed, rainfall, and silt content. The process developed in this study is a first attempt at including environmental considerations in mine planning. The approach does not need to be static. As a project is developed and understanding of the geology increases, environmental calculations or measurements can be updated to include more accurate results to inform future decisions in both long-term and short-term mine planning. The same approach could be used in short-term mining planning with greater detail to evaluate the impacts of equipment selection and mining and hauling schedules. Gathering further data about equipment performance and changing environmental conditions during different stages of production could enhance the accuracy of the results from the calculations used to generate the LCI data. The approach could also be adjusted and applied for governments and institutions if applied to economic scarcity models when deciphering the real price of resource dependence and resource extraction costs. Using an approach which considers the normally externalised environmental costs within the model could develop the Hotelling Model, the Real Price Model or the Extraction Costs model (Hotelling, 1931; Norgaard, 1990).

In this study, GWP has been placed as a static cost to a mining operation. However it is possible to treat carbon in the same way as NPV, with greater reductions in GWP today being more important than the same in 50 years. This was explored in Bauer et al. (2013) and the approach could be used in the simulation. Another variable that could be explored is changing technology during the life of the mine. For example, mining equipment transitioning to electric vehicles and reducing exhaust emissions. The energy source may also change over the life of mine, which would in turn effect environmental impact. During the life of a mining operation, environmental conditions could

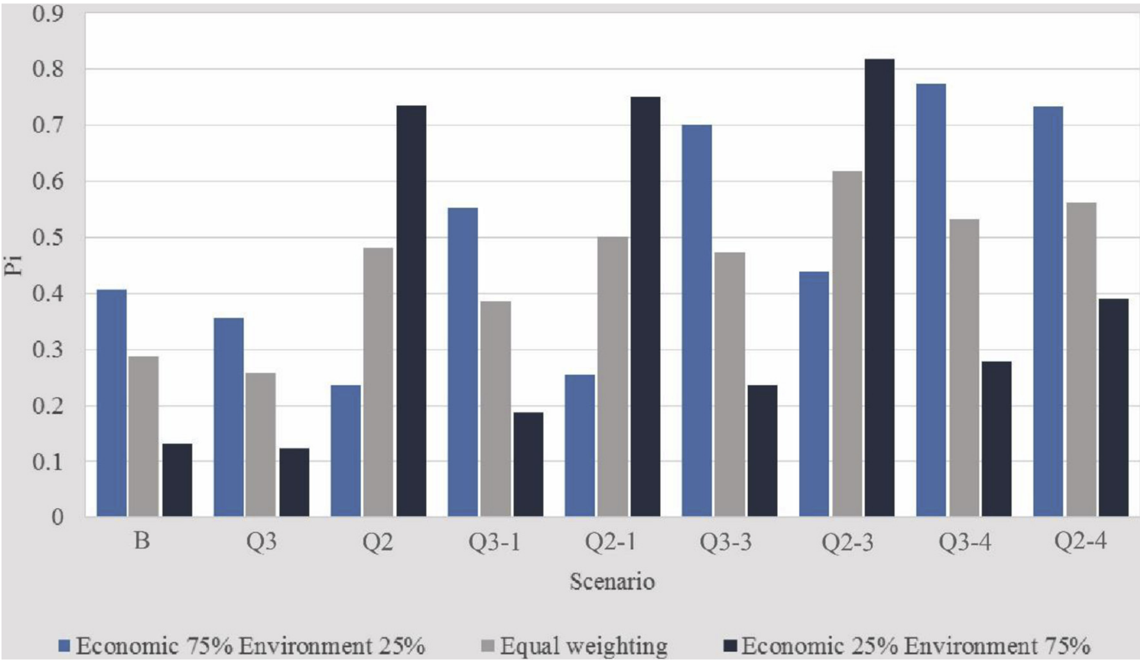

Fig. 11. Results of the TOPSIS multi-criteria decision analysis with different weight for economic and environmental criteria.

significantly change. These temporal variables were deemed as beyond the scope of this work but could be a useful area for future research.

Although this has been applied to GWP, the approach could be replicated for other impacts categories. This could include particulate matter formation which is particularly important as this can cause health problems for both mine workers and local populations and water impacts using approaches developed by Northey (2018). The measured impacts also only include those which are caused by the mining operation. The processing stages in iron ore production have been measured to have a high impact (Ferreira and Leite, 2015; Gan and Griffin, 2018). A LCA of the crushing and grinding, processing, and transportation of the materials and included alongside the mine planning optimisation to optimize the process in a holistic way as is done with geometallurgy. Incorporating these different stages of production would fit the parametric LCA approach which has been used in the architecture and design sector (Skalna, 2018).

5. Conclusion

This study presents a method to include environmental considerations in long-term mine scheduling simulations. The results show that it is possible to reduce GWP impacts by introducing GWP constraints but this will cause a non-optimal economic performance. By exploring GWP constraints and adjusting the economic value of the ore it is possible to determine the economic cost required to reduce CO_2 emissions under different scenarios. For example the results showed that with no adjustment to the economic value of the ore, the cost of reducing CO_2 emissions for the Q3 scenario was US$2.02 and US$0.53 for Q2.

In a LCA context, the approach was able to reduce CO_2 emissions. The baseline produced 8.38 kg CO_2 Eq. per kg ore extracted and Q2-1 was able to reduce this to 8.23 kg CO_2 Eq. per kg ore extracted. With the results it was possible to carry out multi-criteria decision analysis using TOPSIS to incorporate economic and environmental performance. The challenge of subjectivity remains with this method, but under equal weighting was Q3-3 performed best. Q3-3 also performed best in the higher environmental weighted scenario, whilst Q3-4 performed best in the higher economic weighted scenario.

The approach presented in this study has the potential to assist in decision making for mine planning, including environmental data during the planning stage and has the potential to be applied throughout the mine life to short term mine planning and include the processing stages of the operation.

Acknowledgements

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.resconrec.2018.11.022.

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Chapter 6

Applying and advancing the economic resource scarcity potential (ESP) method for rare earth elements

Improving LCIA categories is important if we are to improve our future policy on responsible resources management. This is especially true for the resource depletion category within LCIA. For example REE are physically available in the earths crust, however economic and geopolitical forces mean that they are considered 'critical' by a number of studies. The motivation of the work in this chapter is to highlight the specific risks that individual REE have in terms of supply and identify how these risks could be included alongside more traditional resource depletion calculations.

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Applying and advancing the economic resource scarcity potential (ESP) method for rare earth elements

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ABSTRACT

A number of studies have identified rare earth elements (REE) as critical metals due to their high economic importance combined with a high risk of supply disruption (Du and Graedel, 2011; Nassar et al., 2015; Schneider et al., 2014). The current methods used to calculate resource depletion in life cycle assessments (LCA) neglect socio-economic, regulatory and geopolitical aspects, nor do they include functionalities such as material recycling or reuse that control the supply of raw materials. These are important factors in determining criticality and are the controlling factors on REE availability rather than geological availability. The economic scarcity potential (ESP) method introduced by Schneider et al. (2014) provides a framework to calculate criticality. This paper reviews the ESP method and advances the method based on recent developments in material criticality. ESP criticality scores for 15 REE with the addition of Au, Cu, platinum-group metals (PGM), Fe and Li are measured. The results highlight that Nd and Dy are the most critical REE, owing mainly to the high demand growth forecast for these two elements. A pathway is presented for incorporating these calculated scores into the ReCiPe life cycle impact assessment (LCIA) method of a LCA.

1. Introduction

Life cycle assessment (LCA) is an important tool to quantify the environmental performance of a product or a process such as rare earth element (REE) production. A LCA can detail potential impacts that this process will have on human health, natural environment and natural resources. However there are limitations and problems for assessing abiotic resource depletion during a life cycle impact assessment (LCIA) (Drielsma et al., 2016). Abiotic depletion potential has been used as an indicator, calculating future exhaustion of resources based on current production levels. Advances were made to this approach by Vieira et al. (2016) with the surplus cost potential method, which calculates the increased cost of extracting raw materials due to depleting resources providing a cost per unit of metal extracted in the future. Both methods are useful in understanding the long-term availability of resources but fail to consider a range of factors which control the supply of critical raw materials. In order to correctly assess the criticality of materials, it is necessary to have an indicator that takes into account several impact categories for supply risk and economic importance rather than just resource depletion. Otherwise, the assessment categorizes cerium (which is as abundant in the crust as copper) as highly critical along with dysprosium, praseodymium and the other heavy REE. This paper examines how an alternative method to assess mineral resource inputs can be devised and used for critical metals such as the REE.

Rare earth elements include the lanthanides and the chemically similar elements yttrium (Y) and scandium (Sc). The elements are often divided into two groups, the light rare earths elements (LREE) and heavy rare earth elements (HREE). The LREE include La, Ce, Pr, Nd, and Sm. The HREE include the elements from Eu to Lu in the Periodic Table as well as Y. The REE have strategic importance, with uses in a number of emerging low-carbon technologies. Specific physical properties of individual REE are necessary for efficient electric vehicles, and direct drive wind turbines, such as Nd in NdFeB high strength magnets. The addition of Dy is used to maintain the performance of these magnets at high temperatures. Other REE such as La and Ce are used in catalysts for fluid catalytic cracking of crude oil and production of transportation fuels; and Ce and La are used as emissions catalysts in petrol fueled vehicles. Total industrial demand of REE, excluding Y, is small with an estimated use of 159,500 t in 2016 (USGS, 2016), but REE have a large positive economic contribution to downstream industries. One of the major challenges of REE supply is 'the balance problem'; the misbalance between the economic market demand and the supply of individual REE Du and Graedel (2011). There is often high demand for REE that are minor constituents of a REE ore (such as Pr), while the demand for the major constituents (such as La and Ce) may be much lower.

The security of supply of REE has been a concern for import-dependent industrialized countries with ambitions to advance their low-carbon economy. China currently dominates the production of REE, excluding Y, accounting for 88% of total REE production in 2016 (USGS, 2016). There is a history of supply disruption of REE exports,

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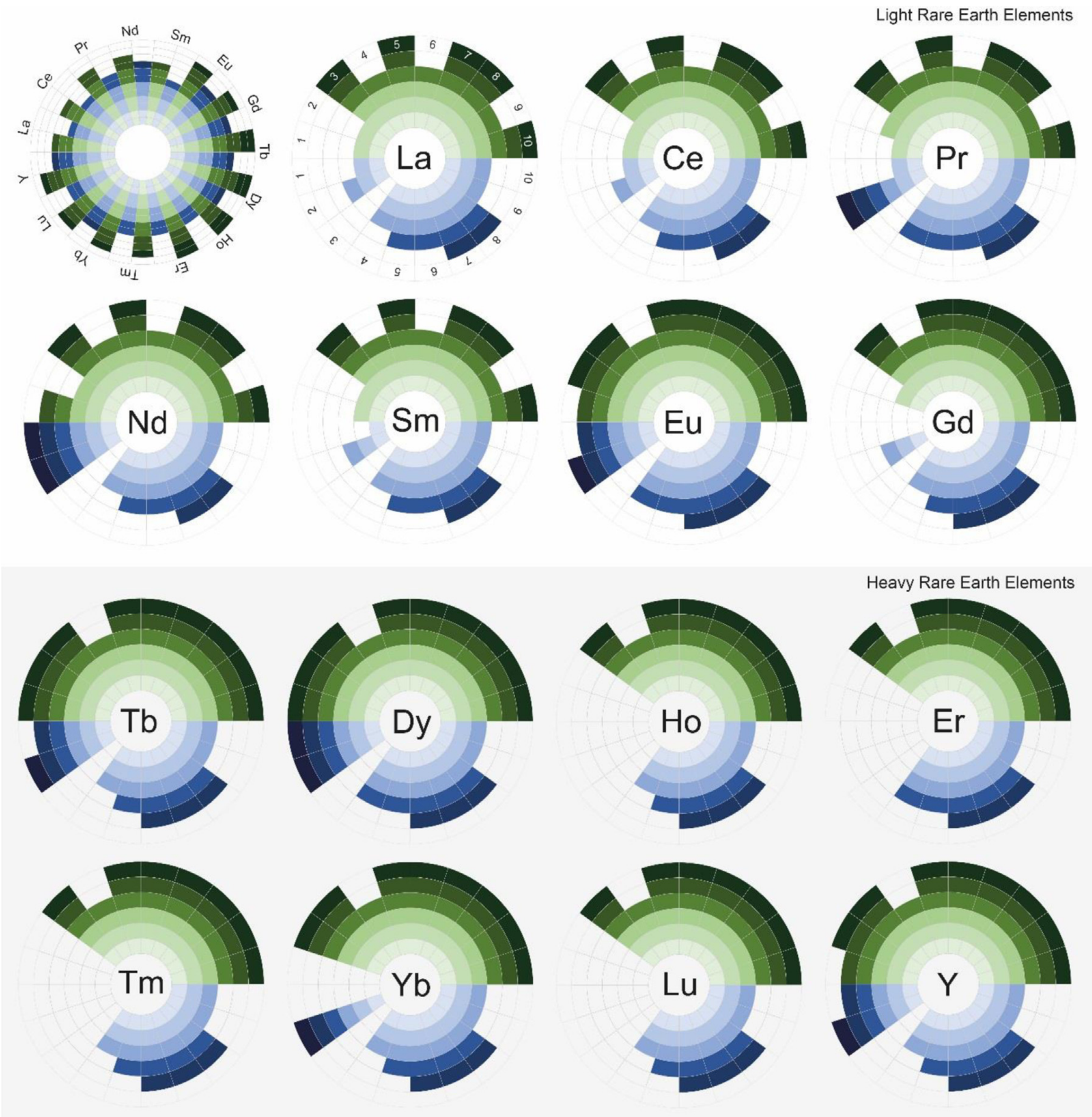

Fig. 1. Criticality assessments for individual REE based on supply risk (green top half of each) and economic importance (blue bottom half) at various scales from national to global in a medium term time scale. White space means that the REE was not included in the criticality study (NRC, 2008; Erdmann and Graedel, 2011; Nassar et al., 2015; BGS, 2015; Moss, 2013; Coulomb, 2015; Glöser et al., 2015) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

this has fueled increased attention into the future availability of such elements. From 2007–2009 China reduced export quotas of REE by 25% (Binnemans and Jones, 2015). This resulted in significant price increases following the export restrictions which were put in place by China (Mancheri, 2015). Concerns about the future supply of REE and the monopolistic nature of production combined with the growing economic importance of downstream products has led to a number of studies identifying individual REE, or REE as a single group, as critical materials (NRC, 2008; Erdmann and Graedel, 2011; Nassar et al., 2015; BGS, 2015; Moss, 2013; Coulomb et al., 2015; Glöser et al., 2015).

A number of projects exist in various stages of development around the world that if moved into production would diversify the supply of REE. For example mining projects are in the prefeasibility or feasibility stage in Europe, with Sweden's Norra Kärr project; in Africa with Malawi's Songwe Hill, Namibia's Lofdal, and South Africa's Zandkopsdrift; in North America with Canada's Ashram, and Nechalacho, USA's Bear Lodge; Australia's Nolans, Dubbo Zirconia project; South America has projects such as Araxá and Serra Verde, both in Brazil. However, there are a number of barriers making production outside China challenging. China currently possesses excess production capacity within the country, suppressing prices and reducing the chances of projects outside China from accessing funding. There is also a lack of proven processing technologies for the unconventional mineralogy in some of the new prospects and a lack of efficient and clean technology for separating and converting rare earth oxides to metals and alloys (USGS, 2016). These factors mean that a large amount of time and capital are required to bring in new operations online and diversify the supply.

Downstream uses of REE are often considered to have positive environmental impacts when they are used in generating clean energy or replacing conventional combustion engines in cars (Fishman et al., 2018). However, the mining, isolation and recovery of REE has a number of environmental and social impacts throughout the life-cycle (Zaimes et al., 2015, Koltun and Tharumarajah, 2014, Arshi et al., 2018, Du and Graedel, 2011, Haque et al., 2014, Sprecher et al., 2015).

REE production and processing requires a large amount of energy and chemicals, and can produce greenhouse gas emissions, chemical pollutants, hazardous mine waste and wastewater, which can contain radioactive material and can cause extensive land transformation. Chemicals used in the refining process have been involved in REE bioaccumulation and pathological changes in local residents (Li et al., 2013). Contaminants associated with REE production, which include radionuclides and heavy metals, have been identified as having negative impacts on human, plant and livestock health (Rim, 2016).

It is important to understand and manage the environmental and social costs associated with REE production as we progress to a low-carbon economy and renewable energy generation, which is likely to require more metal and mineral raw materials per unit energy produced. When considering the sustainability of the raw materials that are produced for the low-carbon economy, it is important to consider risks to supply disruption, which could include market imbalances or governmental interventions such as export bans.

The aim of this paper is threefold. (i) To show that individual REE have unique supply risks and economic importance and therefore different levels of criticality. (ii) To provide a more appropriate impact category within LCIA for resource scarcity of critical metals (iii) Explain how criticality can be included in LCA frameworks and see what results would look like.

2. Review of REE criticality studies

A variety of methodologies can be used to determine raw material criticality. The approaches may vary but share a common aim to define the supply risk of a raw material and its relative importance to the economy. The criticality calculation methodology typically contains an evaluation of the level of supply risk and the impact of said supply risk in a two-dimensional matrix (NRC, 2008; Erdmann and Graedel, 2011; Graedel et al., 2015). Environmental impacts can be used to create a third axis (Graedel, 2015).

Criticality studies are context dependent and can be carried out on a range of scales and for a range of stakeholders, which can be anything from a single company or technology, to a national or multi-national economy (Graedel et al., 2012). For example, a criticality study from the perspective of a country will be different from that of a company, and short-term risk of raw material criticality may not be the same in the medium or long-term. Criticality studies are connected to the concept of risk theory in a holistic way, including economic, societal or environmental risk (Helbig et al., 2016; Frenzel et al., 2017). A wide variety of factors are often considered in criticality assessments, including geological deposits, geographical concentration of deposit or processing facilities, social issues, regulatory structure, geopolitics, environmental issues, recycling potential, substitutability, and sustainability (Achzet and Helbig, 2013; Erdmann and Graedel, 2011).

Eight studies that include criticality of REE have been reviewed (Fig. 1). Each study had a different context, with various spatial scales, from national to international and looked at different areas of the economy. For example Nassar et al. (2015) looked at the criticality of REE associated with the global economy, whilst Coulomb examined the criticality of REE in the context of the low-carbon economy. Where possible the studies looked at a medium-term time perspective of criticality.

All but one study (BGS, 2015) included two-dimensions typical of criticality studies which could be translated into supply risk and economic importance. Fig. 2 shows the supply risk of the REE on the left hand side of each box and to the right shows economic importance of the REE from these studies. The relative criticality scores are normalized and given a colour scale between 1 (non-critical) to 6 (extremely-critical). The terms used in the study also varied meaning that this approach includes subjective judgement of the criticality scores. The white categories indicate gaps in the criticality study.

2.1. Life cycle impact indicators for abiotic resource depletion

The concept of the Area of Protection was founded in the early 1990s by the Society of Environmental Toxicology and Chemistry (Fava et al., 1993). It is used in the LCA community to identify classes of endpoint category indicators that society deems important to protect, and allows a linkage between damages because of environmental intervention and societal values. The Area of Protection are divided into the protection of: Human Health, the Natural Environment and Natural Resources (Finnveden, 1997; Udo de Haes et al., 1999). Te ILCD handbook defines these natural resources and that challenge as;

> "The concern of natural resources is the removal of resources from the environment (and their use) which results in a decrease in the availability of the total resource stock, as non-renewable (usually abiotic) resources are finite"

This definition and the depletion of abiotic resources is a much disputed category within LCA as it crosses the economy-environment system boundary in combination with the fact that there are different ways to define the depletion problem, and there are different ways of calculating these depletion definitions (Van Oers and Guinée, 2016).

For example Van Oers and Guinée (2016) stated that the environmental impact of LCA should not strive to take into account the different aspects of a criticality assessment due to the varying temporal and spatial nature of each study. However this can be overcome with a clear definition during the goal and scope phase of a LCA and matching the criticality calculation to what is being measured. For example if the environmental performance of a mining project is being measured, it is possible to complete the criticality calculation for the life of the mining project with criticality scores in a global context.

Different approaches can be used to determine the decreasing availability of resources. Different approaches have distinct visions or cultural perspectives for abiotic resource depletion (De Schryver et al., 2018). The cultural perspective theory which has categorised visions on resource depletion as either individualist, hierarchist and egalitarian is explored is incorporated into different LCIA methodologies.

One approach to resource depletion which aims to remove the cultural perspective from the process is through the use of entropy or exergy as a basis for characterization, which considers the efficiency of extraction. A thermodynamic approach which can capture resources is a useful approach as is it has an established scientific basis. Exergy is a measure of available energy, whilst entropy in this context refers to the dispersal of energy within a system.

A common method that has been used and is considered individualist uses resource scarcity for the basis of characterization. This method calculates the long-term depletion of non-renewable resources. The depletion of resources is calculated and considers future resource scarcity as a result of current consumption. The impact from resource use is then calculated as an impact on human welfare due to reduced availability, increased competition, and limited accessibility driven by social and geopolitical factors (Finnveden, 2005; Sonnemann et al., 2015). These approaches have shortcomings. Firstly, calculations of physical resource availability or 'depletion potential' used in LCIA rely on a fixed stock paradigm, as described by Tilton and Skinner 1987. The idea that there is a finite quantity of a resource, often described as a crustal abundance, fails to calculate the reuse or recycling rate of these materials and considers that materials are lost after use. There is also no clear definition for undiscovered resources (Vieira et al., 2016). The alternative method used is the opportunity cost paradigm, which states that if physical quantities reduce, or are more difficult to access, prices will increase and innovations and alternatives to that material will be sought, reducing demand. LCIA practitioners have used both methods which have very different views on natural resources and can significantly alter LCIA results. In the fixed stock method, any use of natural resources results in reduced availability for the future, whereas in the opportunity cost view, natural resources are viewed as flows that

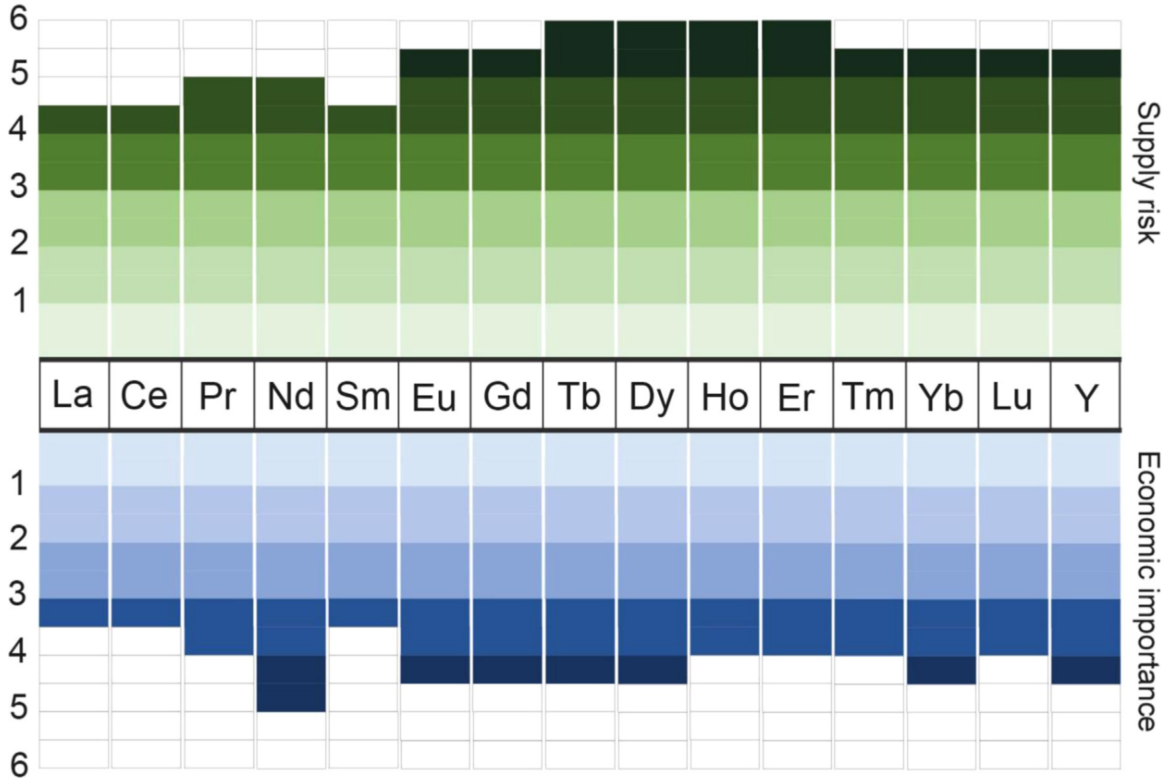

Fig. 2. Normalized average of the combined REE criticality studies from Fig. 1.

need to be managed to meet human demands (Drielsma et al., 2016).

Different methods have different visions and methodologies. Many of these methods that are currently employed to not consider the socio-economic, regulatory and geopolitical aspects or functionalities such as material recycling or reuse.

3. Materials and methods

The abiotic depletion potential method (Van Oers and Guinée, 2016) and the surplus cost potential method (Vieira et al., 2016) are used for comparison in this paper. The latter has been integrated into the ReCiPe methodology (Huijbregts et al., 2016). This method to calculate metal depletion provides scores for 75 mineral resources providing impact scores in relation to 1 kg of Cu. Fig. 3 provides a comparison of five mineral resources and categorizes rare earth elements as a single group.

LCIA is a step in a LCA which translates data such as emissions or resource uses from LCA studies to an easily understandable smaller number of impact scores. The method of calculating these scores is referred to as characterization, and the results will produce an environmental impact per unit of stressor (e.g. per kg of resource). Schneider et al. (2014) identified that economic aspects of resource supply are neglected in current LCA methodologies and attempted to overcome this by introducing the economic resource scarcity potential

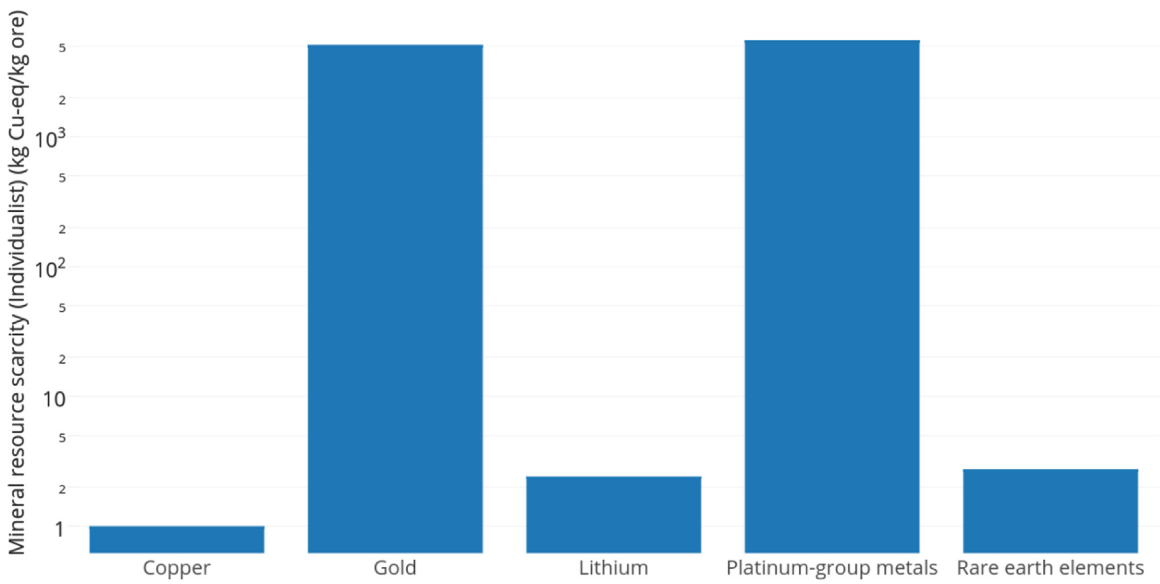

Fig. 3. Mineral resource scarcity results (individualist) using the surplus cost potential approach.

(ESP) model.

Various data that contribute to scarcity of resources are included, expanding the Area of Protection for natural resources to include economic or socially derived scarcity. The factors that are included in ESP include reserves, recycling, and country and company concentration of mining activities, economic stability, demand growth, trade barriers, and companion metal fraction. Drielsma et al. (2016) highlighted that this method assesses short term availability of resources, and is a useful tool in identifying disruptions that may arise in this timeframe. Drielsma et al. (2016) also argued that the Area of Protection for natural resources is altered using this method as the ESP method aims to protect the product system being measured rather than the resources themselves. For example, the protection of the value that a resource has when being used rather than the resource itself.

Current LCIA methods, such as the ReCiPe approach only take into account geological availability and the increased cost of accessing raw materials in the future. The surplus cost potential method fails to take into account resource criticality. Additional methods, such as the ESP approach, would be a useful step to incorporate criticality factors into the life cycle sustainability assessment framework which would better represent impacts on the Area of Protection for Natural Resources (Sonnemann et al., 2015). The ESP method put forward by Schneider (2014) allows for a new characterization factor for resource use impact assessment. Using these characterization factors and a framework to incorporate criticality into the life cycle sustainability assessment context by Sonnemann et al. (2015) allows for integration of the ESP method into the LCA.

3.1. Methodology of ESP calculations

The factors that impact resource availability were suggested by Schneider et al. (2014) and have been highlighted in Table 1. Equal weighting was used for all impact categories initially replicating the method used by Schneider (2014). This was followed by a comparison of results if the economic importance impact category was increased to represent 50% of the total ESP score. Production data were obtained by combining the USGS data with other project scale information. Individual REE data were obtained from individual companies, and when not possible were estimated from literature. All sources of information and origins of data used in the study are included in the Supplementary information.

Table 1
Overview of impact categories, indicators and thresholds used in the ESP calculations (Thresholds are based and on data from Schneider et al. (2014) DOJ and FDT (2010), The World Bank Group (2012), UNDP (2011), Rosenau-Tornow et al. (2009).

Impact category	Category indicators	Threshold
Supply risk		
Reserve availability	Reserve/Annual production	Low < 0.4 < high
Recycling	New material content (%)	Low < 0.5 < high
Mining country concentration reserves	HHI index	Low < 0.15 < high
Production bottleneck (country concentration)	HHI index	Low < 0.15 < high
Production bottleneck (company concentration)	HHI index	Low < 0.15 < high
Governance stability	WGI[1]	Low < 0.25 < high
Socioeconomic stability	HDI[2]	Low < 0.12 < high
Trade barriers mine production	Share of mine production under trade barriers (%)	Low < 0.25 < high
Companion metal fraction	Production as companion metal (%)	Low < 0.2 < high
Trade		
Economic importance		
Average production and cost per kg	$ per kg	Low < 0.1 < high

The data incorporate 10 impact categories and can be aggregated to provide a single ESP value (Eq. (2)). Each category has been described in a glossary in the Supplementary information. This allows for the comparison of the 15 REE studied as well as providing a comparison with Au, Cu, PGM, Fe and Li. Other elements were selected because they offered a range of supply risk and economic importance scores in previous criticality studies. They are used for comparison with the REE and to give a context to how REE perform. The criticality in the context of this paper is within a "global economy" and so not specific to a particular technology or group. This also allows for integration within the ReCiPe LCIA as this is on a global scale. It should be noted that it is possible to adjust the context through weighting the results or changing the thresholds. Thresholds used in this study are shown in Table 1 with justification for their values.

The aggregation of the supply risk and economic importance impact factors is given equal weighting. Individual category indicator results (impact factor x LCI) give an indication for the magnitude of the risk. However, the results only provide a comparison of the resources studied. A greater number of resources used for this method will allow for a more comprehensive estimation of supply risk and provide a better basis for decision making.

As noted by Schneider (2014), to produce a supply risk perspective for the resource availability requires each category indicator to be placed in relation to a target. This method is described in detail by the distance-to-target method by Frischknecht et al. (2008). The resulting impact factors (I) provide a threshold, above which high risk of supply disruption is expected. This was calculated for comparison for the 15 REE together with gold, copper, platinum group metals (PGM), iron ore and lithium (i) and each impact category (j). The ratio of current to critical flows is squared allowing large impact values (above the target value) to be weighted above proportional (Frischknecht and Büsser Knöpfel, 2013; Drielsma et al., 2014). The indicators are scaled from 0 to 1, with order being inverted when necessary to ensure high score corresponds to high risk. All values below the value of "1" are deemed uncritical and have no impacting score.

$$I_{i,j} = Max\left\{\left(\frac{indicator\ value_{i,j}}{threshold_{i,j}}\right)^2; 1\right\} \tag{1}$$

$$ESP_i = \prod_j (I_{i,j}) \tag{2}$$

The resulting economic scarcity potential score for each element which includes the impact categories from both supply risk and economic importance is a dimensionless quantity determined by the ratio of the current indicator value to the determined threshold linked to the LCI.

4. Results

The performance of individual REE compared to Au, Cu, PGM, Fe and Li has been calculated and highlighted in Fig. 4.

4.1. Reserve availability

The 15 REE included in the study had a lower score for reserve availability than Au, Cu, PGM, Fe and Li. These other metals had higher impact scores because of their high level of production relative to REE; being produced in thousands or millions of tonnes per annum compared to REE which have a total production of the 126,000 t in 2016. This, combined with the large reserves of REE, calculated as 120,000,000 (USGS, 2016) t based on their continued availability and typical metallurgical recoveries means the reserve availability of REE is higher than the other metals in the study leading to a low impact score. Of the REE, Y, Gd, Tb, Dy and Ho had the highest impact score whilst Ce and La had the lowest. These results can be explained by the fact that HREE

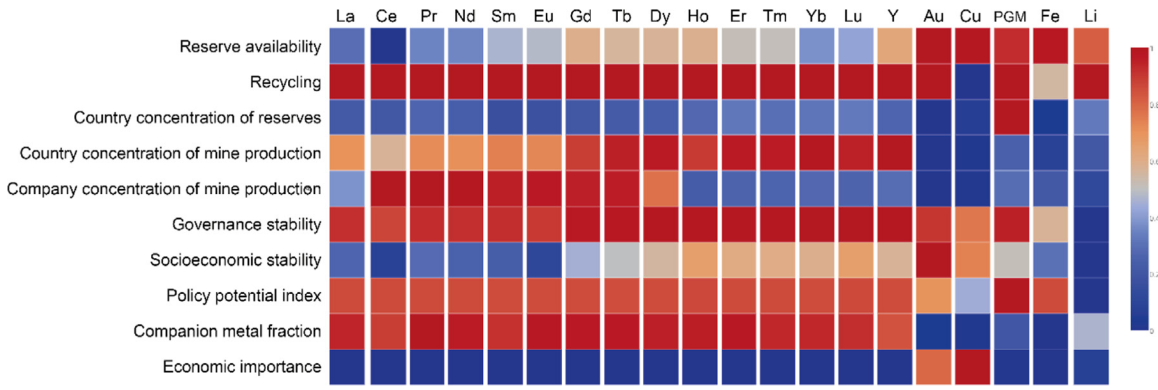

Fig. 4. Individual impact category scores for 10 categories. Data based on (Buijs et al., 2012; NRC, 2016; Graedel et al., 2015; Nassar et al., 2015; Angerer et al., 2009).

are less abundant in the earth's crust and also less abundant in REE deposits, whilst consumption of some of these elements remains relatively high, such as Dy and Tb in permanent magnets. Er, Tm, Yb and Lu are not abundant in deposits but are exploited at very low rates leading to a moderate impact score.

4.2. Recycling

More work needs to be carried out to quantify the rate of recycling of different REE because the published data used for the calculations in this study does not represent the quantity of recycled material reentering the system.

4.3. Country concentration of reserves

The country concentration of reserves impact score was high for PGM compared to the other raw material in this study. This is because of the dominance of South Africa in holding the reserves of PGM. In contrast reserves of Au, Cu and Fe appear the most widespread as they have the lowest score in this category. The REE had moderate scores in this area with slightly increasing impact scores of the HREE because of the dominance of China in holding much of the HREE reserves. The country concentration of reserves indicated that although the reserves of rare earths are relatively widespread, there is a high concentration of Sm and Eu in China, whilst Ho, Er, Tm, Yb and Lu in reserves is more geographically widespread.

4.4. Country concentration of production

The impact score for the country concentration of production was high for all REE compared to Au, Cu, PGM, Fe and Li owing to the dominance of REE production from China. The HREE had the highest impact score for this section. Li was highest scoring in this category for the non-REE.

4.5. Company concentration of mine production

The company concentration of mine production impact category displays the dominance of Northern Rare Earth (Group) High-Tech Co., Ltd, China even when put in in the context of other raw materials, with Ce, Pr, Nd, Sm, Eu, Gd, Tb having the highest scores for this section. The lower impact score for the LREE can be explained by production from Lovozerskiy GOK in Russia, Mount Weld in Australia and mineral sands in India, which are all LREE-enriched deposits.

4.6. Governance stability

The impact scores were high for the REE, with highest scores being seen with the HREE that are produced almost exclusively in China. Li had a low impact score in this category is explained by its production in Australia and Chile. PGM and Au had high scores in these categories highlighting that there are risks associated with the stability of governments in regions where these materials are mined.

4.7. Socioeconomic stability

Au was the highest scoring element, followed by Cu and then the Ce, Pr, Nd, Sm, Eu, Gd, Tb. The low socioeconomic stability of the countries producing Au are highlighted as well as the moderate socioeconomic score of China. For REE the lowest impact scores were Ce and Eu. This is owing to the combination of elevated levels of production of these elements from Mt Weld, Australia and Australia's higher performance in government stability and socioeconomic stability.

4.8. Policy potential index

The 15 REE studied had a high score for the policy potential index. However it is PGM that had the highest score in this category, whilst Fe had a similar score to the REE. The policy potential index impact score was the highest for Tb, whilst Ho had the lowest score. Many of the REE received moderate scores in this impact category indicating that there was only a small amount of variation in the impact scores for the REE.

4.9. Companion metal fraction

REE have a high risk associated with the fact that they are commonly exploited as a by-product of each other and of other raw materials (such as iron ore at Bayan Obo, China) among others. The other raw materials used in comparison had low impact scores in this category indicating that they are commonly extracted as the main component at a mine. The companion metal fraction impact scores were relatively similar to each other. Pr had the highest score whilst Y had the lowest.

4.10. Economic importance

In the economic importance category the REE have a low score. This category is dominated by Cu and to a lesser extent Au. These are the two raw materials that have the greatest economic importance during the raw material extraction phase. Of the REE, Nd had a markedly higher economic importance impact score than the other REE. This is owing to the use of Nd in NdFeB magnets, which are predicted to drive demand growth until 2022 (Roskill, 2016). Dy and Pr were calculated as having the next highest economic importance scores. All other REE have low economic importance scores.

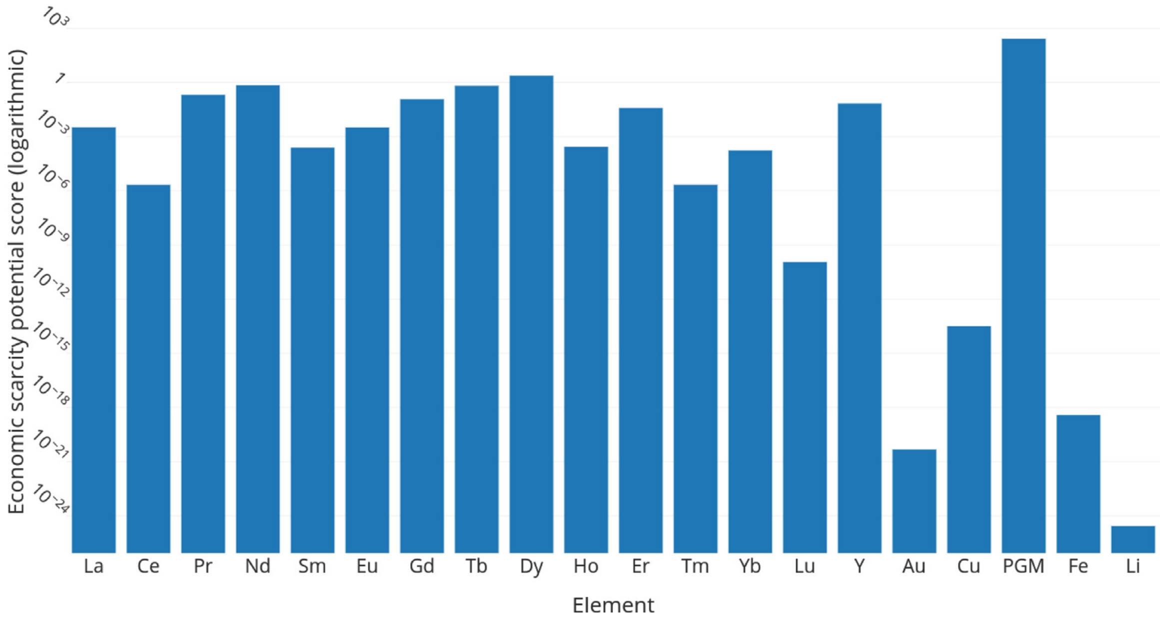

Fig. 5. Individual economic scarcity potential scores for 10 categories, each of which has equal weighting.

4.11. Overall ESP

The final ESP results are presented on a logarithmic scale to better display the relative performance of individual elements. The ESP scores displayed in Fig. 5 show how the REE compared to Au, Cu, PGM, Fe and Li. Giving equal weighting to each category and using the methodology described above resulted in PGM having the highest ESP score and so these elements are considered the most critical in this context. The factors driving the PGM score up are the high policy potential index score, the high governance stability score as well as a high country concentration of reserves. Dy scores second highest for ESP. It is interesting to note that as a greater number of raw materials are included in the study, the relative performance of elements can change, as in this case where Dy has overtaken Nd in terms of relative ESP score. This is because the economic importance was an important factor in driving Nd's ESP score up in the REE comparison, but as more raw materials are added with a greater economic importance, this distinction becomes less important. Nd is the next highest scoring element, followed by Tb, Pr, Gd and Y. Au, Cu, Fe and Li all have lower ESP scores than the REE.

The economic scarcity potential approach used in this study provides results that greater reflect the reality of resource availability until 2021 when compared to the abiotic depletion potential or surplus cost potential approach, which are more suited to understanding the long-term availability of resources. It considers socio-economic, regulatory and geopolitical aspects or functionalities such as material recycling or reuse in the calculations rather than geological availability. This is an area that is currently missing in the LCA approach but has an impact on low-carbon technology development and proliferation. Nd and Dy are the highest scoring REE using this approach, highlighting the need to broaden the supply chain for these two elements in particular, whilst Ce has a low economic scarcity potential score and is overproduced. New uses of Ce, which is cheap because of the oversupply, would help to even up requirement for REE and help supply of Nd and Dy.

A simplified calculation was used for economic importance, looking only at demand growth, production volume and value of material produced. Improvements could be made to this calculation. A novel empirical approach has been presented by Mayer and Gleich (2015) which looks at risk associated with future price increases of raw materials. The approach which uses a compounding framework to calculate net present values and volatility is a potential avenue to include under these calculations which may provide more realistic economic importance impact scores.

The method used in this study only looks at the impact categories associated with the mining and dissolution phase and fails to consider the larger production chain of final products which can be in a number of forms such as rare earth oxides, misch-metals or separated metals and transport. Future work could look at the different processing stages and see how this would alter the economic scarcity potential scores for different elements. Recent work has examined the role of primary processing (first post-mining stage) in the supply risk of critical metals (Nansai et al., 2017). Understanding the role of different processing stages in raw material availability is an important area of research, especially for REE production which has a long and complex production chain. Future work should cover all elements from the periodic table using the economic scarcity potential approach to calculate scores for the global economy for the short to medium term. Using improved economic importance calculations would make the approach a useful addition to the LCIA results. Annual updates on production would allow the method to be up to date and have practical use.

4.12. Adjusting the weighting of economic importance

Criticality studies are context dependent. The ESP results above use an equal weighting for each impact category. However, it is possible to adjust the level of an impact category or categories to represent a different context. Fig. 6 shows this with the blue bars indicating the results of the ESP scores with equal weighting for the impact factors. The orange bars calculate the ESP score by giving all the supply risk impact categories (reserve availability, recycling, country concentration of reserves, country concentration of mine production, company concentration of mine production, governance stability, socioeconomic stability, trade barriers to mine production, companion metal fraction) equal weighting and giving the economic importance impact category the same weighting as the combined supply risk impact categories.

The results indicate an increased ESP score for Au and Cu, which is the highest scoring element in this context, because of their high economic importance score. A small reduction in the ESP score for PGM, which is the second highest scoring element, and Li which has a small reduction in ESP score. Fe has a large decrease. The REE have a substantial decrease in their ESP score owing to their relatively low economic importance using the simple calculation in this study when compared to the other elements. Nd is highest scoring of the REE,

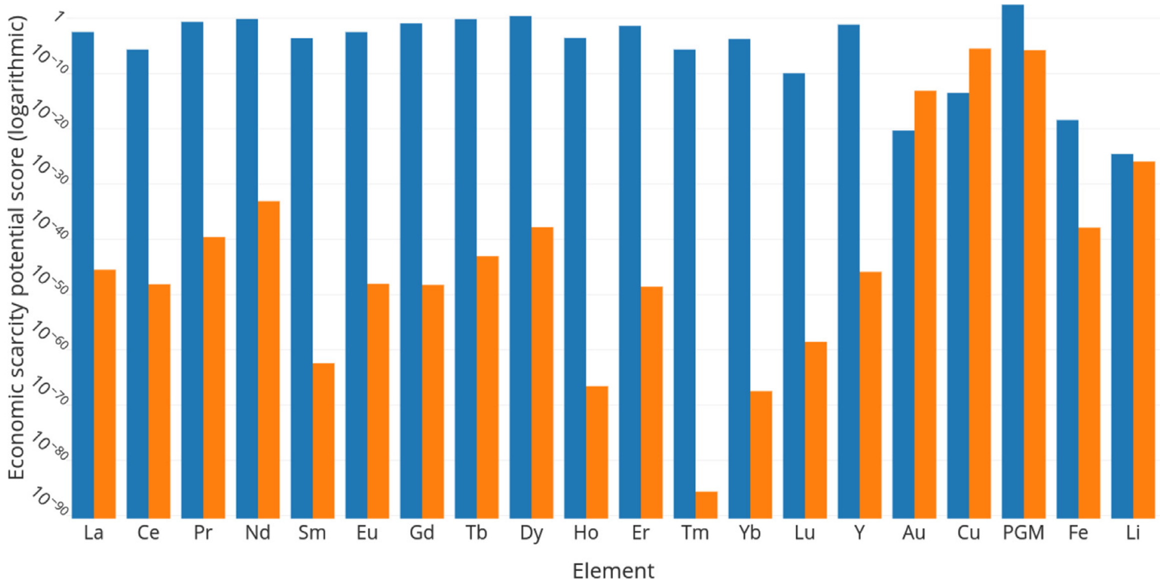

Fig. 6. Economic scarcity potential scores for calculated using 10 categories for each individual element. Blue bars are ESP scores with equal weighting for the impact factors. The orange bars calculate the ESP score by giving all the supply risk impact categories (reserve availability, recycling, country concentration of reserves, country concentration of mine production, company concentration of mine production, governance stability, socioeconomic stability, trade barriers to mine production, companion metal fraction) equal weighting and giving the economic importance impact category the same weighting as the combined supply risk impact categories.

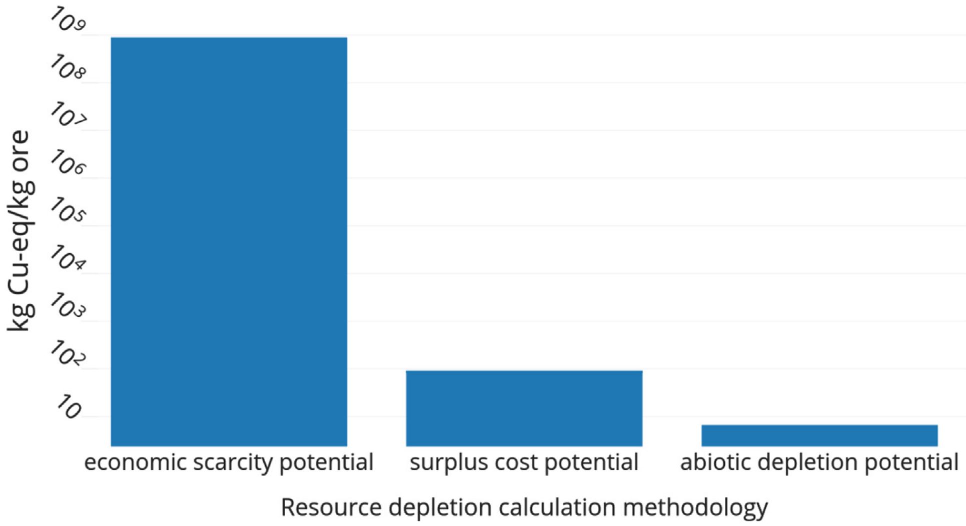

Fig. 7. Comparison of resource depletion calculation methodology on the results for the components of NdFeB magnet.

Table 2
Composition of virgin NdFeB magnet (Jin et al., 2016).

Element	Weight %
Fe	66.88
Nd	18.0
Dy	6.15
Pr	4.6
Cu	0.18

followed by Dy owing to their relative high economic importance compared to other REE.

Increasing the weighting of economic importance (Fig. 6) highlights the flexibility of criticality studies. For example, giving equal weighting Cu was considered one of the lowest scoring elements in comparison, but when economic importance was increased to 50% of the total ESP score it became the highest scoring element in the study. Criticality studies can be used to compare the relative levels of criticality of raw materials in different scenarios, but these need to be clearly defined. This study used a global spatial scale for the whole economy and used a medium term time scale, but it is possible to adjust the criteria for a number of scenarios. The weighting of the impact categories will be different depending on the context of the study. For example a study of the criticality of raw materials for the low-carbon economy, would give a higher economic importance to the raw materials used in the relevant technologies than has been given in this study. A valuable area of research would be to develop understanding of appropriate weighting for the impact categories under different scenarios. Understanding the importance of different processes of raw material availability would be a useful step in developing a robust method and would be important in its successful integration into the LCA approach.

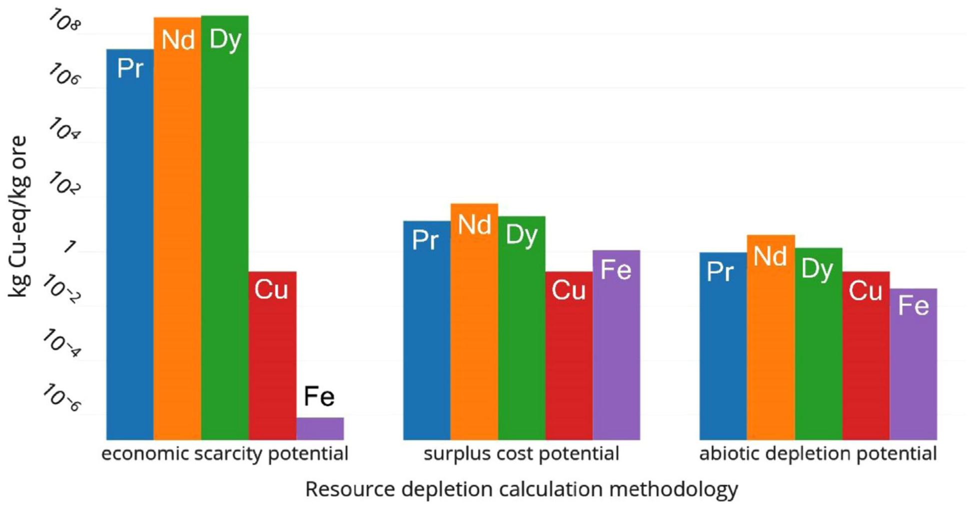

Fig. 8. Elemental contribution to resource depletion calculation scores for economic scarcity potential, surplus cost potential, and abiotic depletion potential for components of NdFeB magnet.

4.13. Integration into LCA

The scores of the individual elements will be calculated against the reference element of copper. Fig. 7 provides a simulation of resource depletion results using three different calculation methodologies (economic scarcity potential, surplus cost potential, abiotic depletion potential) with the example using a 1 kg NdFeB magnet. Simplified inventory data were used (Jin et al., 2016), and is shown in Table 2. A comparison of results is highlighted results using the abiotic depletion potential approach, the surplus cost potential approach and the economic scarcity potential approach.

The results show that there is an increased score (kg Cu-eq/kg ore for the economic scarcity potential calculation method. This is because the REE components, Pr, Nd and Dy have a high economic scarcity potential score as elements. Cu is the reference value for all methods which explains the equal score with each method. Fe has a lower score using the economic scarcity potential approach as it has been calculate to have low criticality. Fig. 8 highlights how the economic scarcity potential approach places greater emphasis on elements that have higher criticality scores and are more susceptible to supply disruption in the short to medium term. This information could prove useful in comparative LCA when examining the environmental performance of a product and process and provides and additional metric for which to compare. Such as scenario could exist when comparing the environmental performance of two mining operations. Results for environmental performance could be included alongside criticality data for a better comparison.

5. Conclusions

The ESP approach is particularly useful when trying to understand the availability of critical metals. This is important as they play a key role as raw materials for the low-carbon economy. This is important as they play a key role as raw materials for the low-carbon economy. This paper aimed to compare the performance of individual REE and put it in context with other raw materials. The results indicate that REE need to be considered as distinct elements with different criticality associated with each of them. For example Dy and Nd had the highest economic scarcity potential scores, whilst Lu and Ce had the lowest of the REE. One of the reasons for Ce having a low score is its overproduction. The excess availability and low criticality means that companies have an opportunity to find new uses for Ce. For example the Critical Materials Institute have developed aluminum-cerium alloys (Sims et al., 2016). The high scores for Nd and Dy are due to the increase in demand of NdFeB magnets in hybrid and electric vehicles until 2026 (Goodenough et al., 2017). Whilst projections for Sm, Tm and Lu suggest that growth and production volume will remain low, keeping the economic importance of these elements low. All REE have higher economic scarcity potential scores than Au, Cu, Fe and Li, whilst PGM had the highest score of all the elements included in the study. The high score for PGM was due to its concentration of reserves and production in South Africa, which has a low score in the governance stability and policy potential index. Although further work needs to be done and more elements need to be included in the method before its integration into LCIA results, this study provides a guideline for the approach.

A major challenge for this approach, as with all raw material studies is the availability of data. An inconsistent amount of data are available for the calculations of the economic scarcity potential impact categories. There is a lack of reliable production data for the REE, and this would also be the case for other raw materials. USGS and BGS are useful sources of data, and they are clear about the uncertainty of some production data. For example the high level of illegal mining in REE in China has been ignored (Rao, 2016).

The development of economic and supply risk indicators that can fit alongside or within LCA should be further explored and methods such as the approach shown here can be considered complimentary to other resource depletion methods currently employed.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.resourpol.2018.10.003.

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Chapter 7

Discussion and Future Research

The aim of this research is to improve the environmental performance of REE production. LCA studies were carried out and the results highlighted environmental impacts at both the Songwe Hill project in Malawi, and the Bear Lodge project in the United States. The LCA studies enable the comparison of environmental impacts from different process choices such as energy use, and the processing technology employed for these projects. LCA can be used early in project development to examine the impacts of specific project choices, and from this analysis the refining of project choices can lead to significantly reduced environmental impacts.

The LCA results indicated that a large contribution to a number of the impact categories was a combination of electricity and HCl, oxalic acid, and nitric acid at Songwe Hill, and acid consumption is a major contributor to the LCA impacts such as global warming and acidification was the acid consumption. This is because of the embodied energy and impacts associated with its production and use. These results would indicate that energy choice, with a low embodied impact, can reduce the environmental impact of REE projects. Recycling opportunities and trade-offs for HCl and oxalic acid also offered potential for significant impact reduction. Reducing virgin acid consumption through acid regeneration can be energy intensive and so consideration of that embodied impact of that energy source is important.

Four papers addressed different aspects of the aim. Firstly by determining whether LCA approaches are suitable for REE projects in the prefeasibility stage of development. Secondly to develop a process that considers the temporal variation of impacts for REE production. Thirdly, to create a method to integrate LCA driven environmental considerations in mine planning. Finally to include supply risks in the LCIA framework.

7.1 Comparison of deposits, projects and mines

The comparison of different REE projects using the LCA approach is challenging due to the range of end-products, lack of consistent cross-project data, and co-products. Although it can be a useful approach to compare across project, the work in this thesis has indicated that applying LCA at a project scale to compare project options has significant potential to reduce environmental impacts.

The approaches developed could also be applied to other commodities. For example novel Li resources are being explored and as new processes are developed to extract and process Li containing ores or brines, project scale predictive LCA could be a useful tool to assess the life cycle impact of different project choices.

7.2 Integration LCA at the pre-feasibility stage

Chapter 3 had the aim to determine at what stage of a REE project adequate data exist to complete a LCA and generate LCIA results to support the environmentally sustainable development of a project. This question is important as the decision made during the early stages of product system have the greatest contribution to their environmental profile [Weitz et al., 1999]. Chapter 3 explored this, successfully completing a LCA from pre-feasibility data and concluded that once a project moves into the pre-feasibility stage adequate data and understanding of the processes involved in a REE project to complete a LCA. Completing a LCA during this stage of a project has the limitation of greater data and process uncertainty, but also has the advantage of greater opportunity to contribute to environmental improvement through process change. This relationship is highlighted with Figure 7.1. and is known as the eco-design paradox. An LCA should be understood as a rigorous scientific modeling exercise, not a comprehensive accounting of the exact environmental impacts, and so uncertainty arising from the data from pre-feasibility stage shouldn't prevent the exploration of the relationships between material and energy flows and related impacts for REE projects.

The data quality generated from the pre-feasibility will be relatively low as at that stage of a study, it will typically have completed around 5% to 15% of the engineering tasks, and cost estimates will have an accuracy of around 25% to 30%. The aim of a pre-feasibility is to pin point areas within the project meriting further attention [Chernaik, 2010]. With this in mind, the LCA approach is ideally suited to identify environmental hotspots that may require further consideration. As a project moves through development a feasibility study will be completed, which will firm up the processes for the project and will typically 25% to 50% of the engineering tasks complete cost estimate accuracy of 10% to 20%. For example, study of new drill core produces more information about the mineralogy and grade of the deposit, this data can be fed into the process simulation software which in turn can generate LCI data such as energy and material requirements for the process flowsheet which will update the LCIA results. This approach also ensures the generation of robust and reliable environmental impact results due to the closed mass and energy balance LCI data and consistent system boundary definition. This method could be developed as a standard approach for LCI generation for PCR in the future and can ultimately, better inform decision making during the development of a project and help reduce its life cycle environmental impacts.

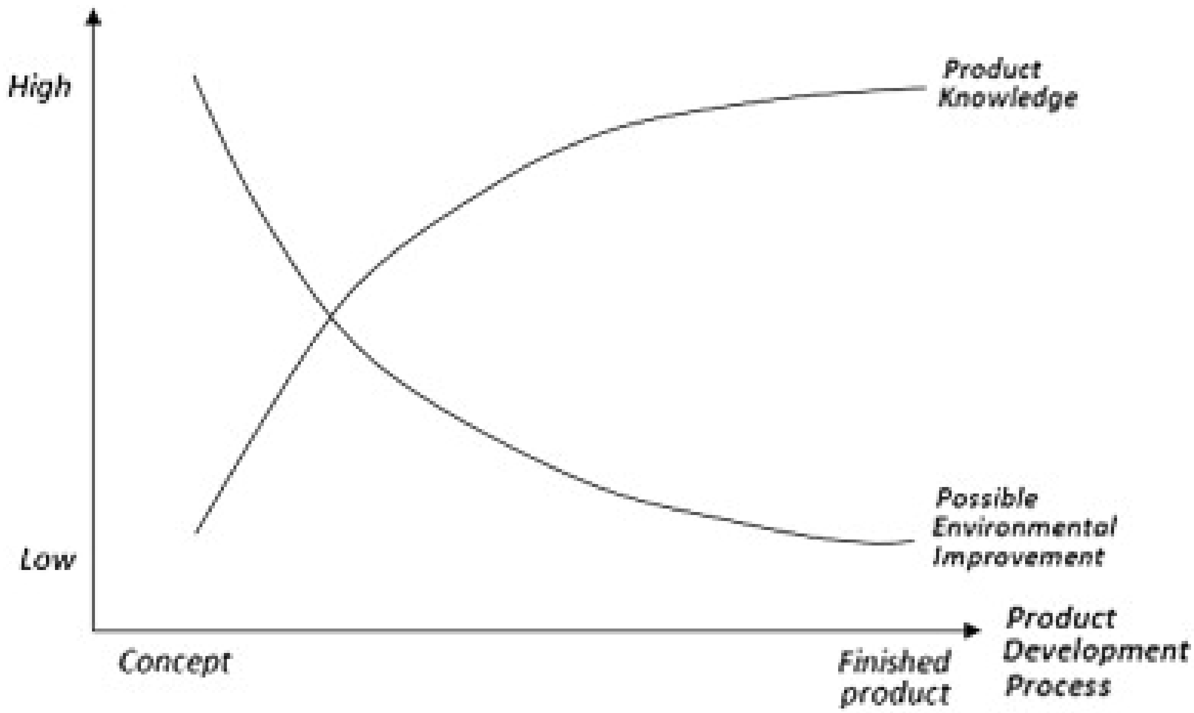

Figure 7.1: The Eco-design paradox from product design applicable to mining project development [Poudelet et al., 2012].

Chapter 3 used mineral processing simulation data from the Songwe Hill project to generate LCI data. The incorporation of LCA into the development stage of REE projects as a predictive tool through process-simulation LCA has been highlighted in recent studies [Reuter et al., 2015, Rönnlund et al., 2016a, Rönnlund et al., 2016b]. Utilising mineral processing simulation linked LCA is advantageous due to the fact that any updates made during project development will not require significant economic cost or time. The mineral processing simulation linked LCA approach also has the advantage of ensuring a consistent system boundary, incorporating all the energy and material flows of the system measured.

The predictive LCA approach has been explored through eco-design for products and the process is highlighted in Figure 7.2., but this approach has not been widely adopted in the development of mining projects.

The environmental mine engineering study, (EIS) may cost approximately 2.5% of the total pre-production capital cost. For project it might include dust control, noise attenuation, recycling, reclamation, and reduction of visual impact. This stage does not include a LCA approach to quantify the life cycle environmental costs

7.3 Temporally explicit LCA and REE projects

Chapter 4 explored temporally explicit LCA and uses the case study of the Bear Lodge REE project to highlight the fluctuation of different LCIA over its mine life. Mining projects can produce material over long time periods, exploiting different geological regions, mineralogies, and using different mining and mineral processing techniques. LCA in contrast generally produces a static environmental score for a process or product [Heijungs et al., 2009]. A time-frame or horizon is commonly defined in the goal and scope of an LCA study, but little regard is given to the sensitivity of the chosen number, and in mining the environmental impact arising may last decades or centuries as is seen with acid mine drainage.

By completing a temporally explicit LCA, environmental hotspots from a certain year of a project can be seen, highlighting risk stages and allowing for a consideration of improving the efficiency of the project. Adding a temporal dimension provides a greater opportunity to explore the relationships between the properties of the deposit, the mining and mineral processing methods and the environmental impacts.

It also allows the consideration of changes over time from the resource and energy flows. For example over a mining project which may extend for several decades, the energy mix used to power to operation may change as the de-carbonisation of the energy supply occurs, or a new resource policy is implemented. There is also a need to consider the changing environmental scenarios at different times. For example background concentrations of a particular substance may be different in the future and an additional contribution to this may have a more substantial impact. Put simply, the same emission at different points in time may cause different environmental pressures and impacts.

The Bear Lodge study used the temporal approach but maintained a static energy mix and assumptions on future atmospheric conditions, however it was possible to identify a positive relationship between decreasing grade and global warming impact, as well as relationships between changing ore composition and the global warming potential. From this information it was possible to highlight the time horizons that had a higher level of impact and those with a low impact.

The Bear Lodge study used a year for the temporal resolution of the LCA study, however with sufficient computing power this approach could be scaled to explore the relationship between changing mineralogy and LCA impacts in real time. For example by using the approach presented, it could be possible to analyse material in a processing circuit using quantitative mineralogy analysis and use mineral processing simulation or equipment measurements to calculate the impacts associated with changing mineralogy.

7.4 Embedding LCA into mine planning and scheduling

The consideration of the environmental impacts at one of the earliest stages of a mining project was the motivation behind the development of the framework to integrate mine planning and LCA. The approach has similarities to the mineral processing simulation LCA, with the mine planning approach having the additional option of applying constraints to each new simulation. This allowed for a comparison of the environmental-economic performance for different scenarios.

This approach can also be applied throughout the mine life to short term mine planning and include the processing stages of the operation. The LCA data is generated from physical, chemical and geographic properties of the block so relies on a number of assumptions. However, the model is developed in a way that as more data about environmental impacts, the model can be updated.

7.5 Criticality as a LCIA category

The chapter explored the development of an economic and supply risk indicators, originally presented by [Schneider et al., 2014]. The paper presented that it is possible to fit the results from this approach alongside or within LCA as a complimentary indicator to other resource depletion methods.

REE are considered to be ’critical’ metals as described in the literature review, because of their high economic importance in many modern technologies, and specifically within the low-carbon economy. However, the current LCIA categories fail to consider supply risk or criticality. This is explored in Chapter 4, and the results indicated that all REE scored highly for ESP compared to Au, Cu, Fe and Li, whilst PGM had the highest score of all the elements included in the study. The limitations of the current resource depletion impact category has been highlighting, noting in particular that models for resource availability in the future lack accuracy.

An impediment for its adoption in LCIA is the fact that the ESP method includes areas of subjective judgement. Some criticality approaches have been carried out without the need for subjective decision making [Mccullough and Nassar, 2017]. There is also a challenge with the scale and application of the ESP study and how it would be harmonized to fit in the LCA approach. Another major challenge for this approach, as with all raw material studies is the availability of data. There is an inconsistent amount of data are available for each commodity and so the calculations of the economic scarcity potential impact categories are simplified. For example there is a lack of reliable production data for the REE, and this would also be the case for other raw materials. USGS and BGS are useful sources of data, and they are clear about the uncertainty of some production data. For example the high level of illegal mining in REE in China has been ignored and has been predicted to be as high as 40% (Rao, 2016).

7.6 Integrating LCA into mining project stages

The techniques developed throughout this thesis have presented ways to incorporate LCA into the pre-feasibility stages of development. However, it is possible to carry out simple qualitative type LCA as soon as desk studies are completed. Knowledge of regional geology and predicted processes and energy consumption can be estimated and environmental challenges can be identified at the front-end of a project **??**. As the project advances, more of the geology and engineering is known and the LCA approach can move to a more quantitative process and follow specified frameworks. It is important to consider that LCA can be used as a predictive tool and as a measurement tool, so that mining companies can measure their LCA performance and predict future changes.

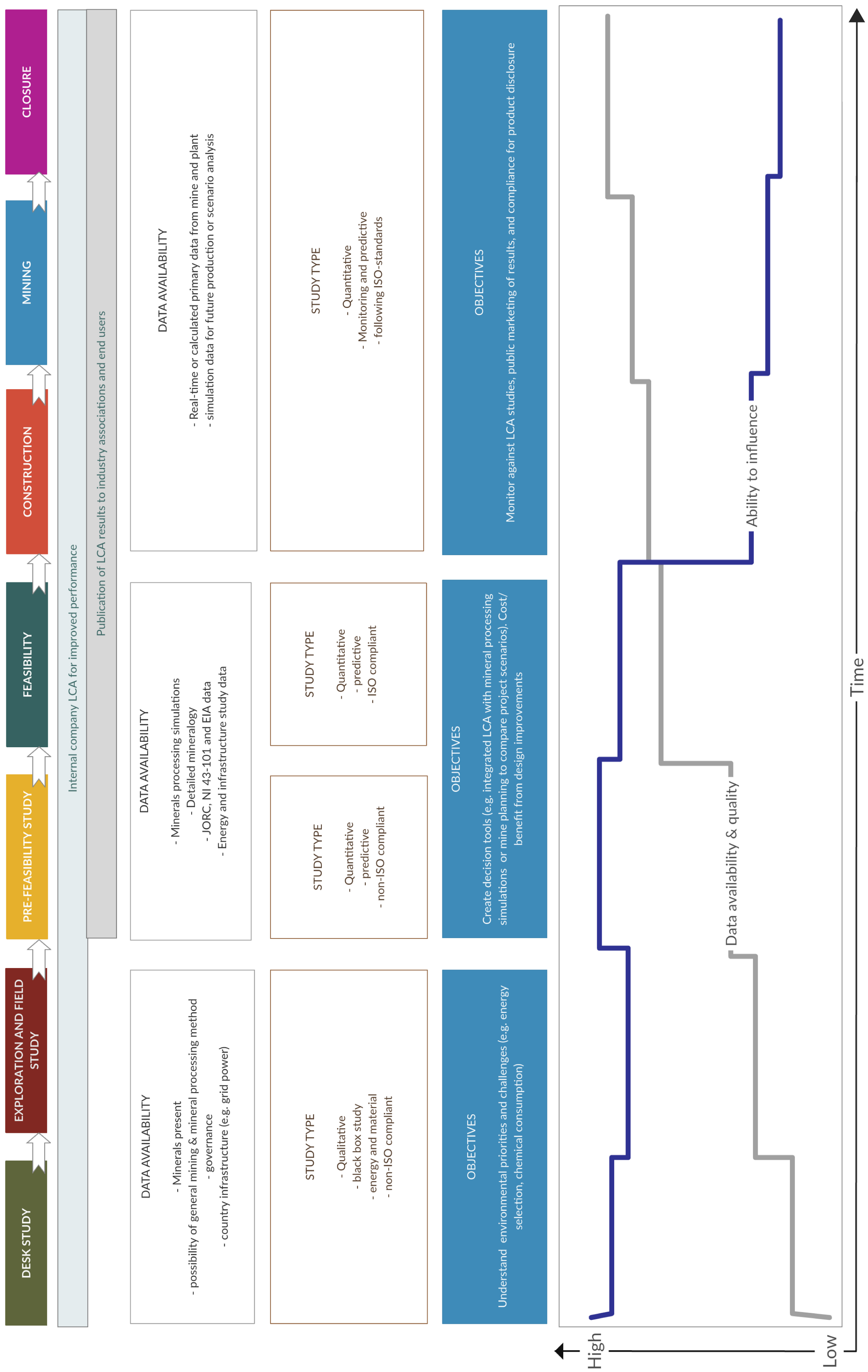

Figure 7.2: Stages of LCA integration into mine project development

7.7 Mining and mineral processing in the context of REE lifecycle

The mining, mineral processing, and processes required to form a REO have been explored in depth in this work. The downstream processes to form end-products such as separated REE metals [Arshi et al., 2018, Marx et al., 2018, Vahidi and Zhao, 2017]. The relative contribution to different impact categories are presented in Figure 7.3. For example Nd and Pr can be produced separately, or as an alloy (didymium), using an oxy-fluoride molten salt electrolysis process and this process can have a significant contribution to the REE environmental impacts on the overall life cycle.

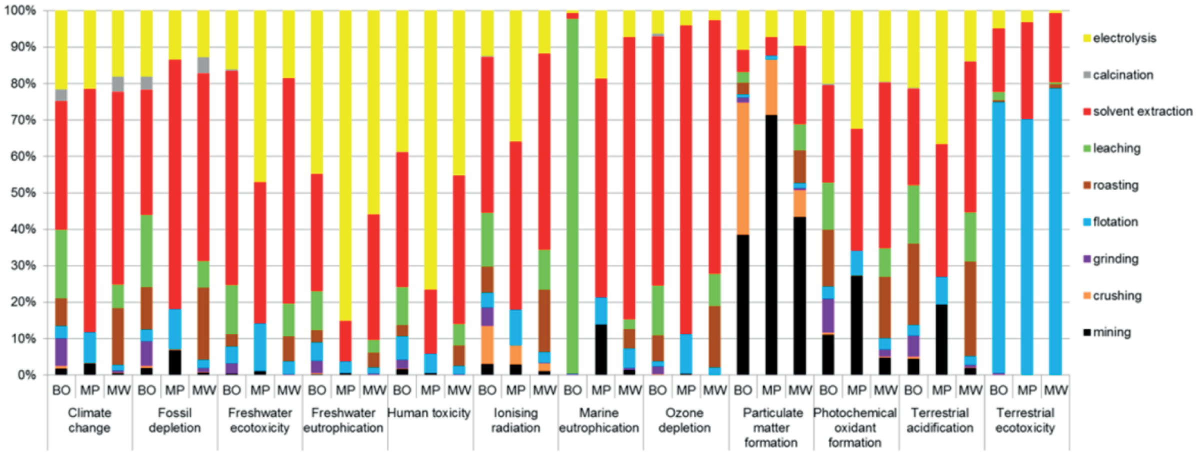

Figure 7.3: Share of single processes on total impacts of 1 kg Nd production [Marx et al., 2018].

7.8 Limitations

The application of LCA to REE production has increased substantially over the last decade, as described in the literature review. LCA is a particularly useful tool for quantifying a range of environmental impacts associated with REE production due to the high energy and material consumption. However, there are limitations that need to be considered when carrying out a study of this type.

The LCA on Bear Lodge and Songwe Hill were cradle-to-grave studies, meaning that the rest of the life cycle is ignored. Metal formation, use, and end-of-life all have significant environmental impacts but was deemed outside the scope of this research. For consideration of the total environmental impact of REE production, including these other life cycle stages, work has been completed [Arshi et al., 2018, Lee, 2016, Marx et al., 2018].

As noted earlier, the Songwe Hill and Bear Lodge case studies used the pre-feasibility study for the generation of the LCI data. The use of data from a pre-feasibility will inherently have higher uncertainty than a LCA completed on an operating project. This is because there is uncertainty associated with the geology, the processing efficiencies and techniques used and the particular material, chemical and energy use. This higher degree of uncertainty in the LCI data, and this will be expressed in the results. The results from this may over stress certain environmental results and underestimate others. However, carrying out an LCA with this data can produce environmental data to put different processess in context. During this early stage due to this higher uncertainty it would not be as important to into a high level of detail for each process and may be more suitable to have a higher cutoff criteria. Future work could explore the relationship between uncertainty and development stage and provide a framework for suitable LCA methodology during these different project stages.

The allocation procedure applied within the LCA studies includes subjectivity and has limitations. REE production is a simplified phrase used for the co-generation of a selection of the individual or mixed REE. The range and number of end products makes it challenging to allocate the impacts. The most scientifically robust form of allocation is by mass allocation [ISO, 2006]. However, when applying this to REE production it will generate results that that over represent the environmental impacts of low-value, high-volume elements, such as La and Ce. However, these are not the elements that make a deposit economic [Wall, 2014]. Alternatives to mass allocation are presented in [Weng, 2016] who applies economic allocation. The economic allocation may also provide a distorted impact on the elements that are produced in lower quantities and the results are easily impacted by changing REE prices and may over represent the impact of the high value elements. One solution to the fluctuating prices of REE is to use a 5 year price average.

Another challenge of using the LCA approach for REE production is obtaining LCI data for flows such as reagents that are used during processing. If it was possible to find suitable data, it was difficult to obtain it for the site where it was used and was commonly a global average data. This is a common challenge in many LCA studies. Site specific production of materials and energy can have a significant impact, and so with more resources, a more detailed study of the individual flows and spatially explicit LCA could be applied. The studies completed employed uncertainty analysis to minimise the distortion of results.

Within LCA, only a select number of LCIA methods are available, and not all are reflect the impacts generated from REE production. Certain LCIA have different levels of certainty and agreement on the calculation methodology. Some important impact categories are not suitable for REE production. For example although there have been an increase of radioactivity LCIA categories. Limited data is available for specific exposure pathways that exist in the REE industry. This may ignore some of the most important environmental criteria that can dictate whether a project is feasible or not. One example of this is the fact that current LCIA doesn't take into account the range of radioactive element impacts and the daughter elements. Despite advances in the development of impact categories for ionising radiation, the focus on artificial radionuclides produced in the nuclear fuel cycle means that the potential impacts resulting from increased exposure to naturally occurring radioactive materials (NORM) are still only covered to a limited degree in life cycle assessment (LCA) [Joyce, 2016].

The LCA approach may provide quantitative data for the environmental performance in certain impact categories, however it does not provide reasonable detail in the risks associated with these different process choices. Understand the relationship between risk and LCA with the context of REE produciton. A framework could be developed to highlight how both these approached can be used in a complimentary manner for REE production.

The fourth chapter explored the ESP approach. One of the limitations of this approach and many criticality studies is the subjective nature of valuing the impact categories. The availability of data is inconsistent for the calculations of the ESP impact categories. A specific challenge with REE data is the different estimates of illegal mining and a difficulty in obtaining good data for the material flow of REE from cradle-to-grave.

7.9 Recommendations for further work

Based on the foregoing chapters of this thesis a number of topics for further research have been identified.

7.9.1 Harmonising the LCA methodology for REE production

A review of the LCA studies examining REE production highlighted the lack of harmonisation in the LCA methods employed. For example there was a range of system boundaries and allocation methods have been used for LCA studies as described in the literature review. In order to develop this into a process that is easy to adopt for mining companies, and to allow for comparison across projects, a harmonisation of methodologies needs to be made. In other sectors, such as with product manufacturing it is through the development of product category rules (PCR), which refers to the calculation rules for the underlying LCA of a product or process, as well as provides information and the format for presentation in an environmental product declaration (EPD). There is currently a lack of PCR for specific commodities such as REE as well as a number of other commodities. The development of a REE specific PCR would provide clarity for future LCA and pave the way for LCA integration within project development frameworks.

7.9.2 Integrating LCA into project development frameworks

LCA has been identified as a useful tool to reduce the environmental impact of REE projects if it is applied early on during the development stage of a project. However, no project development framework such as the Australasian Code for Reporting of Exploration Results, Mineral Resources and Ore Reserves (JORC) or National Instrument 43-101 (NI 43-101) have an LCA element to them.

Within these standards, it is indicated that detailed assessment of the environmental and socio-economic impacts should be well advanced, and a simple LCA would fit early on in project development.

In order for this to be possible, harmonisation of the methods would need to be employed and it a framework for REE specific LCA should be made.

In support of developing techniques that are useful to projects in development. For example the methods presented in [Rönnlund et al., 2016a, Rönnlund et al., 2016b] offer solutions for projects in development to understand and reduce environmental impacts

7.9.3 Mineralogy and environmental impact

In this thesis, there was a brief exploration into the relationships between REE mineralogy and the associated environmental impacts. An in-depth understanding of the mineralogy is essential for process design and all of the deposit types have mineralogical advantages and challenges. The geochemistry and mineralogy of REE deposits is diverse and these differences will require unique process flowsheets, and require different chemicals and energy in different quantities.

For example, the deposits with the best established processing routes are monazite-bearing mineral sands but monazite radioactivity renders most unusable. Ion adsorption clays are easily leachable but deposits are low grade and shallow so new environmentally-friendly leaching techniques are needed.

The diverse mineralogy of alkaline rocks has required development of processing routes for rare minerals such as steenstrupine and eudialyte. Carbonatites tend to have high proportions of the least valuable, lightest REE in REE fluorcarbonates or monazite. A deposit with two ore minerals, REE fluorcarbonate and apatite, that combine to give a REE profile close to that required by industry has an advantage if the ore minerals can be recovered efficiently.

7.10 Overall advantages and disadvantages of the LCA approach

LCA is a useful tool to assess impacts of an entire system, allowing for a comparison of scenarios and quantifying impacts without shifting environmental burdens. In particular it can quantify environmental releases to air, water, and in relation to each stage of a project or process. It allows for a comparison of environmental trade-offs associated with particular processes. It can also be useful to communicate impacts.

LCA is becoming more efficient and this needs to continue if widespread adoption of LCA is to penetrate into industry.

There are limitations to the approach, including the lack of scientifically robust characterisation factors for certain impacts. It is also important to note that LCA will not determine which product or process is the best for performance or has the highest risks. Therefore LCA should be integrated into a broader more comprehensive decision process assessing the trade-offs with lower life cycle impact, performance and risk analysis.

Chapter 8

Conclusions

The purpose of this Thesis was to assess and reduce the environmental impacts associated with REE production. More specifically, this involved developing techniques to assess the environmental impact of different project choices by using a life cycle assessment approach. The outcome of this research shows that by incorporating LCA within the development stage of REE projects, different environmental impacts can be quantified and contributions to these impacts can be analysed. The impacts can be explored both spatially and temporally to highlight relationships between physical and chemical properties determined by geology and different mining and mineral processing scenarios can be compared in terms of environmental impact. This process can be integrated with design phase by directly exporting mineral processing simulation data to the LCI to complete a full LCA. Project choices can be adjusted at low cost during the pre-fesaibility and feasibility phase of development, and changes made during this phase can have a significant impact on the environmental profile of the project through its lifetime. The approaches developed throughout this thesis and applied to REE can be applied to other raw material production.

It is possible to complete an early stage LCA during the pre-feasiblitty stage of a REE project. This is presented in Chapter 3 and highlights how it is possible to update the LCA as certainty of the geology and processing efficiencies increases. The method could be generated as a standard approach for LCI generation for PEF and better inform decision makers during the development of projects. This approach has practical application for the REE industry as a number of projects are in development stage and could implement this approach resulting in reduced environmental impacts.

The temporal nature of LCA impacts in relation to REE production is explored in Chapter 4. The results showed that it was possible to identify environmental hotspots, making it possible to understand the relationships between the properties of the deposit, the mining and mineral processing methods used, and the environmental impacts. The results indicate that there is a positive relationship between decreasing grade and global warming impact, but there are also patterns that exist between the ore composition and the global warming potential.

A method to include environmental considerations in long-term mine scheduling simulations is presented in Chapter 5. The results indicate that it was possible to reduce GWP impacts by introducing GWP constraints to the mine scheduling simulation, causing non-optimal economic performance. From this it is possible to determine the economic cost required to reduce CO2 emissions during the planning stage of a project.

The ESP approach for the REE, highlighting the economic and supply risk challenges with individual REE is explored in Chapter 6. Results from this study indicated that REE should be considered as distinct elements and not as a single group in criticality studies. The conclusion of this work was that economic and supply risk indicators that fit alongside or within LCA should be further explored and methods such as the ESP approach can be considered complementary to other resource depletion methods.

This work highlights the utility of LCA for assessing the environmental performance of different project designs for REE production. LCA allows the inclusion of a range of impacts that are not considered in a traditional environmental impact statement, and environmental-economic trade-offs can be explored. The current environmental assessment methods employed during REE project development are useful in identifying environmental risks that are spatially specific, but fail to consider the environmental impacts in a life cycle context. This is particularly important for REE projects as they can require the consumption of energy and chemicals to produce REO or separated REE. The novel approaches developed during this thesis can be applied for future REE projects to improve the environmental footprint of REE.

Appendix A

Supplementary Information

A.1 Additional publications

A.1.1 Response to ‘Assessing the energy requirements and global warming potential of rare earth production

Journal of Cleaner Production 162 (2017) 791–794

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Letter to the editor

Response to 'Assessing the energy requirements and global warming potential of the production of rare earth elements'

A B S T R A C T

In this letter, we respond to the article in this journal by Weng et al. (2016) which performs a cradle to gate scale life cycle impact assessment for 26 operating and potential rare earth element (REE) mining projects. The work focuses on gross energy requirement and the global warming impacts of the primary REE production stage. The results suggest that the declining ore grades of REE significantly increase the environmental impact of REE production. We agree that a life cycle impact approach can be useful in comparing proposed REE production routes in the various different deposits currently under exploration, and were pleased to see a range of deposit types included in this work. However, we would like to make five points to clarify some of the results, which if taken at 'face value' from the graphs presented by Weng et al. (2016) may be misleading.

The paper by Weng et al. (2016) is a positive attempt to compare the energy requirements and global warming impacts of a number of rare earth element (REE) projects with a range of mineralogy, processing technology and material outputs. The work is moving the subject area forward, encouraging broader comparative life cycle assessments (LCA) of a number of complex REE production routes. However, there are areas that need clarification or reconsideration to allow for a fair and representative evaluation of these production routes. Life cycle inventory data that is used by Weng et al. (2016) to calculate global warming potential (GWP) and gross energy requirements (GER) is not available in the paper or supplementary information and therefore cannot be used. Instead a comparison between the environmental impacts included in the supplementary information was used.

The first point is that these results should not refer to increasing 'environmental impacts' because rather than a comprehensive environmental impact they represent a subset of the full data set in that they consider only gross energy requirements and global warming impacts. These are the only criteria discussed in the comparison. Additional environmental impact data were made available in the supplementary information but not included in the results presented in the main manuscript.

The second point, and one that we would like to emphasize particularly, is that the LCA 'gate' for the various different projects is at varying stages in the production process so the graphs of LCIA results such as Figs. 2, 3, 4, 7 in Weng et al. (2016) are not comparing like with like. It was noted in the study that there are challenges associated with comparing different end product(s) and a method was used to divide the refining stages into two categories, although three categories were then used in the results as follows:

- fully refined: where the defined end products are individual or mixed REO (rare earth oxide),
- semi-refined: where the end products are other REE products, such as mixed REO concentrates, REE carbonates and REE hydroxides
- not refined: where the end products are flotation or other concentrates containing REO

This 'not refined' division, labelled as mining and beneficiation (M + B) on Fig. 3, is an important difference in that these projects, at Thor Lake, Strange Lake and Tanbreez, propose to produce and ship mineral concentrates and therefore do not dissolve the REE-bearing minerals. In contrast, the other projects all carry out this chemical-intensive dissolution stage onsite and the embodied energy and GWP in these chemicals, as well as the direct energy requirements, makes a large difference to the outcomes. A plot of refining stage versus 'environmental impact' (*not* the term as used by Weng et al., 2016 but a new figure calculated from the supplementary data to include all of the impacts not just global warming potential and gross energy requirement) identifies the relationship between the environmental performance and the level of refining for each project, highlighting that those with a

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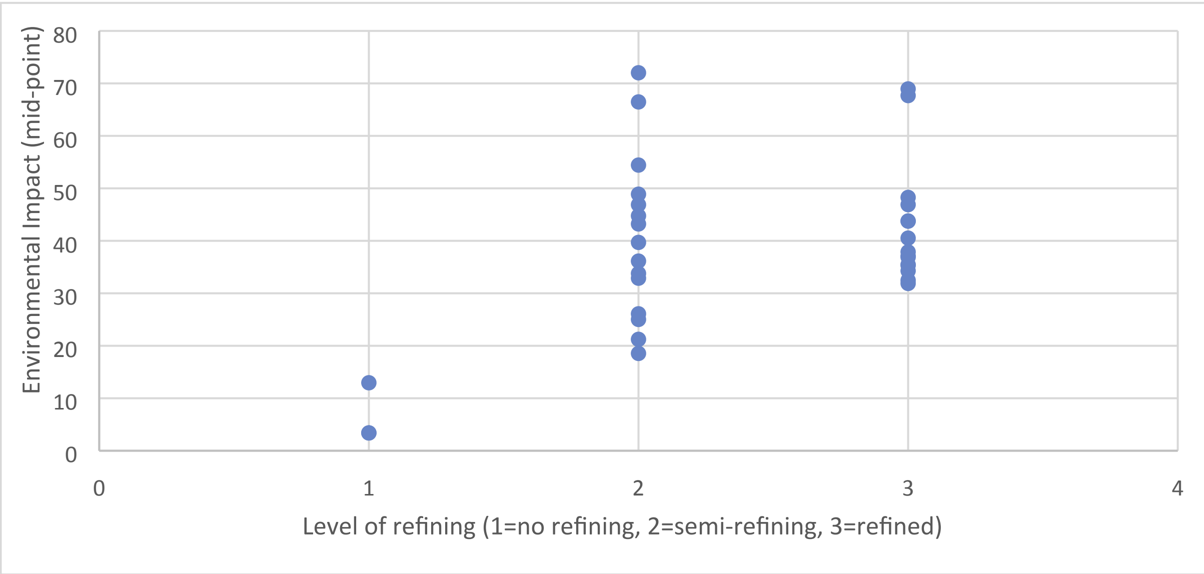
http://dx.doi.org/10.1016/j.jclepro.2017.06.059

greater level of refining are more like to have a higher environmental impact, and those projects with less refining have lower environmental impacts (Fig. 1). Those projects that complete less processing on-site will require less energy and will have the lowest global warming impacts, but this only represents a small part of the production life cycle for REE and does not imply that these *deposits* are more environmentally-friendly than other projects or deposit types. The conclusion of Weng et al. (2016) that grade is the key factor in controlling environmental performance is not supported by a robust enough methodology or sufficient data. Using different gate stages does not permit this conclusion.

Fig. 1. There is a correlation between the gate, i.e. the end point of production used in the life cycle analysis and the measure of environmental impact given; recalculated here using the supplementary data for all environmental impacts given in Weng et al. (2016) rather than just global warming potential and gross energy requirement. 1 = end product(s) from beneficiation only, mineral concentrate with no further refining), 2 = end product(s) is from semi-refining, such as production of intermediate mixed REE products and 3 = end product(s) is from refining to produce separated REE products. The three Level 1 projects are Thor Lake, Strange Lake and Tanbreez (Thor Lake and Strange Lake have the same environmental impact and so placed one on top of another).



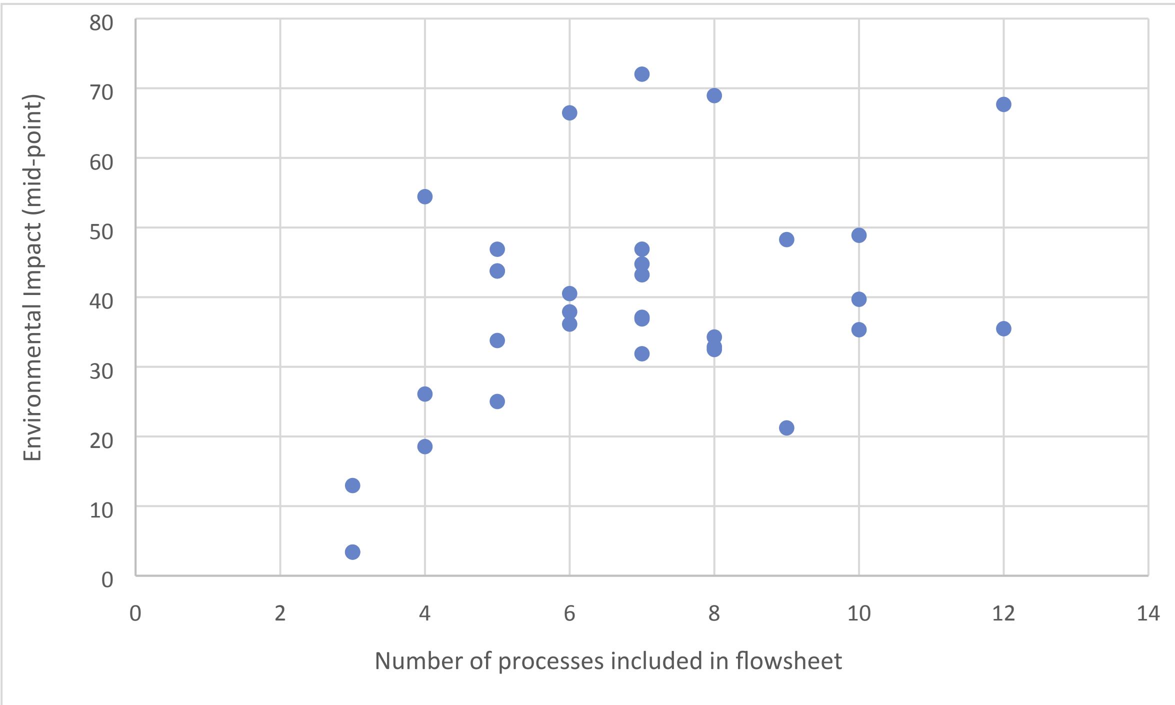


Fig. 2. There is a broad positive correlation, especially at lower number of processes, between the number of processes included in the life cycle assessment for a project (= unit black boxes in the flowsheet used in LCA) and the environmental impact.

The third point is that Weng et al. (2016) note that a large number of assumptions had to be used for many of the processing methods and highlighted that this is a limitation to the study. Flowsheets for individual projects have been included in the additional information but there is no information on the inventory analysis to clarify which chemical inputs and which outputs are included in the study. We agree that consistent data from each of the REE projects for the inventory analysis is a major challenge. Each project requires a bespoke processing flowsheet depending on a number of factors (Bongaerts et al., 2015). Weng et al. (2016) also noted this problem. It is critical that all assumptions are justified, especially when these choices are informed by data/information coming from diverse flowsheets. Assuming that two (or more) mines have the same mineral compositions and topology is geologically incorrect. For example, Bayan Obo, the World's largest REE mine, in Inner Mongolia, China, was used as the basis for calculations for synchysite and apatite production at Songwe Hill (text wrongly attributes bastnäsite as the ore mineral at Songwe Hill) (Croll et al., 2015) (Table 1, Fig. 3 in Weng et al., 2016). Results are presented for 36 scenarios at 26 locations and project specific flowsheets were used for 24 of these scenarios. The other eight are much more speculative and based on REE processing data from other operations. These eight projects rely on assumed REE processing project configurations of other deposits (Table 1) and owing to the bespoke nature of REE production routes, these assumptions are unlikely to be accurate. Deciding how much it is possible to predict the performance of any particular project using assumptions from other projects is an interesting topic and would benefit from some additional research and analysis.

The results obtained from certain deposit types don't necessarily provide an environmental standard for future projects with the same geology. Eco Ridge is the only alluvial placer used in the study, and is atypical of the minerals sands that one would normally associate with placer deposits of REE. The conglomerate/quartzite deposit is not sufficient to draw conclusions for all placer deposits. REE are only semi-refined at Eco Ridge, which fails to represent the energy intensive and environmentally demanding refining phase.

Alkaline rocks look superficially more environmentally friendly than other deposit types but three projects: Thor Lake (Nechalacho), Strange Lake and Tanbreez, have no refining on site thus have low GWP and GER in this study. Kvanefjeld nepheline syenite (mineral is streenstrupine, lujavrite given in Weng et al., 2016 is a rock name) performs around average in the LCIA, there are two inputs on the flow chart for this project and no stage for dissolution of the minerals, as well as no detail on the refining to remove U or process and separate REE. Norra Kärr is also probably in the mid-range (as best we can interpret Figs. 2, 3 and 7). This project has a more detailed processing flowsheet, but only sulphuric acid and magnesia as chemical inputs and no account of use of chemicals in solvent extraction etc.

Table 1
Projects using REE processing configuration based on other operations

Project	Assumed REE processing project configuration
Bokan-Dotson	Bear Lodge
Browns Range	Araxá
Tantalus	Southern Chinese Ion Adsorption
Foxtrot	Roundtop (which is based on Southern Chinese Ion Adsorption)
Kipawa Lake	Dubbo Zirconia
Round Top	Southern Chinese Ion Adsorption
Songwe Hill	Bayan Obo
Zandkopsdrift	Bayan Obo

A fourth and important factor in comparing REE projects is that of the functional unit used for the LCA. Weng et al. (2016) used a functional unit for their life cycle assessment of "1t of run of mine (ROM) materials from the mining site of selected REE projects, in conjunction with the project's annual production capacity and recovery rate of REO, as well as the principal by/co-products". In general, in LCA, the functional unit must be consistent and should define what quantity of the product's function is achieved to cause the environmental impact identified (ISO, 2006). The functional unit described above suggests that each project has a unique functional unit depending on the scale, recovery rate and co/products of the project. If this method has been used rather than the use of a static 1t of ROM material for each project, then the results would not be suitable for comparison.

A fifth, and final important point is that Weng et al. (2016) used an economic allocation for the life cycle assessment as indicated by equation (1). This method of economic allocation used a unit price for separated individual REE, which does not reflect the different end product(s) at each project. For example the flotation concentrates produced at Thor Lake, which include REE, do not actually have the same market value as the separated individual REO used as the unit price. Weng et al. (2016) highlights the prices of individual REO with no reference to REE concentrate prices. Mineral concentrates are cheaper than mixed REE compounds, which can be orders of magnitude cheaper than separated individual REE and REO (Roskill, 2016). Table 2 in the paper also provides U and Th (which are not REE) with a unit price but does not explain whether these have been used in the economic allocation.

$$Xi = \frac{Ei*Ri*Ci*P}{\sum_i (Ei*Ri*Ci*P)} \quad (1)$$

Xi: Environmental footprint contribution of Commodity *i* (%)
Ci: Ore grade of commodity *i* (%)
Ei: Unit values of commodity *i* ($USD/t)
Ri: Recovery rate of commodity *i* (%)
P: Annual production capacity of the project (t ROM/y)

Our conclusion is that the research is heading in the right direction, but the inconsistencies in the comparison of projects means that the LCIA are not formed with a rigorous enough methodology to draw truly meaningful conclusions. The level of refining and the number of processes in the flowsheet show a greater positive correlation than grade, mineralogy or deposit type. This highlights the importance of ensuring consistent detail in the inventory analysis, as well as a robust method of allocation.

Acknowledgements

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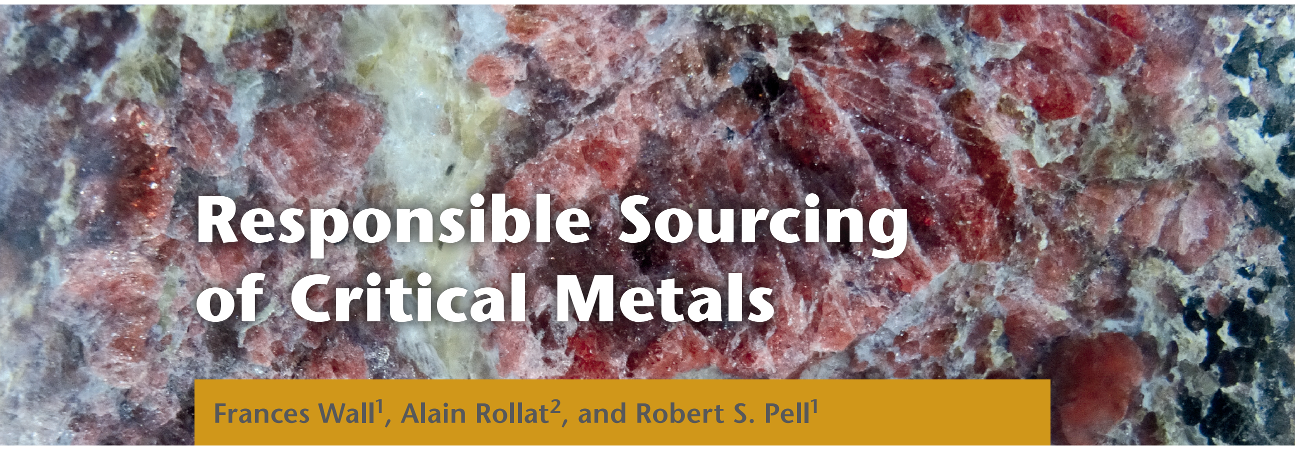
A.1.2 Responsible sourcing of critical metals



Responsible Sourcing of Critical Metals

Frances Wall[1], Alain Rollat[2], and Robert S. Pell[1]

1811-5209/17/0013-0313$2.50 DOI: 10.2138/gselements.13.5.313

Most critical raw materials, such as the rare-earth elements (REEs), are starting products in long manufacturing supply chains. Unlike most consumers, geoscientists can become involved in responsible sourcing, including best environmental and social practices, because geology is related to environmental impact factors such as energy requirements, resource efficiency, radioactivity and the amount of rock mined. The energy and material inputs and the emissions and waste from mining and processing can be quantified, and studies for REEs show little difference between 'hard rocks', such as carbonatites, and easily leachable ion-adsorption clays. The reason is the similarity in the embodied energy in the chemicals used for leaching, dissolution and separation.

Keywords: responsible sourcing, critical metals, rare earths, life cycle assessment

INTRODUCTION

Current technologies use a wider range of elements in their fabrication than ever before. The manufacture of a computer chip demands 44 different elements (Graedel et al. 2015). Touch screens need a thin film of indium tin oxide; capacitors used in electronics need tantalum; permanent magnets of all types, ranging from the tiny speakers in smartphones to huge tonne-weight magnets in large wind turbines, are made of NdFeB. Lithium ion batteries, which also contain cobalt and graphite, are now widespread and are rapidly increasing in use. The total amounts needed of many of the aforementioned elements, despite their many uses, are often only in the tens to thousands of tonnes per year, orders of magnitude less than those of mainstream commodities such as copper. This means that just a few mines can be sufficient for supply and, thus, the choice of source mines at any one time is limited. For commodities such as indium, there are no mines: smelter by-products are the only source. Recycling rates are often low. The potential supply risk is high, and such elements are called 'critical'. The concept of 'criticality' is usually calculated from a combination of the economic importance of the raw materials, the difficulty of substituting another raw material, and the supply risk (European Commission 2014; British Geological Survey 2015; Graedel et al. 2015).

Because many of these critical metals are used in technologies that improve our care of the Earth's environment, it seems appropriate to try to ensure that their production does not itself harm the environment, nor the local communities and people that produce them. Responsible mining is about minimising the negative effects of mining and maximising the positive outcomes (e.g. Goodland 2012). Responsible mining takes into account environmental protection, community interaction, workforce health and safety, transparency in economic contributions (such as taxes), and also energy use, carbon footprint, water use, resource efficiency, and resource and reserve reporting. Responsible sourcing is about all of these issues and how we, as final consumers, can be assured that the supply chains, including the ultimate sources, for our goods meet acceptable standards. Responsible sourcing was noted as a key stakeholder requirement of the mining industry in the seminal *Breaking New Ground: Mining, Minerals and Sustainable Development* report (IIED 2002) and again more recently by multinational mining companies (ICMM 2015).

In this article, we consider the issues involved in critical raw materials, using the example of rare-earth elements (REEs), and draw attention to the challenges relevant to geoscientists.

RESPONSIBLE MINING AND SOURCING SCHEMES

Most mining companies seek to demonstrate their commitment to responsible mining practices. In order to be able to distinguish 'window dressing' from effective and comprehensive action, however, some kind of assurance is required. Examples include the Global Reporting Initiative used by multinational companies who are members of the International Council on Mining and Metals (ICMM) (www.icmm.com), and the Responsible Jewellery Council scheme (www.responsiblejewellery.com). Some schemes for gold and gemstones, such as Fairmined (www.fairmined.org), are similar to the well-known fair-trade schemes for tea and coffee. To date, only a few raw materials, such as the conflict mineral 'coltan' (columbite–tantalite; the main ore of Ta) are covered under legally binding social regulations. Some manufacturers, such as Fairphone (a manufacturer of smartphones free of conflict minerals) have attempted to understand their supply chain and to connect consumers with the raw materials used. For most complex products, though, it is hard for the consumer to make a connection to the mines that have produced the raw materials. The main drivers for responsible mining of most critical metals are not responsible sourcing initiatives from consumers but the need for mining companies to (1) satisfy investment banks in order to raise capital, (2) gain informal approval (social licence to operate) from

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SOLVENT EXTRACTION OF RARE-EARTH ELEMENTS

Perhaps the most complex chemical challenge for producing REEs is that applications need individual high REE purity. The separation of the natural mixtures into an individually pure REE is particularly difficult, chemically intensive and has always been a challenge in terms of science, technology and economics (Lucas et al. 2015). A breakthrough in developing a separation process that could use more environmentally friendly chemicals and/or can be applied at the same time as first-stage processing, or during in-situ leaching, would be a major advance in responsible sourcing of REEs. Historically, REE separation was done first by selective crystallization, then came ion exchange methods, and now it is mostly done by solvent extraction. A number of new techniques have been proposed but none are being used commercially.

Solvent extraction is currently the only industrial scale REE separation process. The separation is done step by step, with a mixer–settler technology and each step performed in equipment called a solvent extraction battery. Each solvent extraction battery can separate one group of REEs into two sub-groups, or a mixture of two REEs into two pure individual REEs. So, the separation of mixture of n REEs into n individual REEs will need n-1 solvent exchange batteries. Industrially, REE separation processes are all done in a battery of mixer–settlers with counter-current flows: the purification of each REE can reach as high as 6N (i.e. 99.9999% pure).

The choice of solvent depends on the following: selectivity (for the REE^{3+} valency), loading capacity, and how the extracting molecule affects the energy and chemical reagent consumption. The classical extractants used are 2-Ethylhexyl phosphonic acid, mono-2-ethylhexyl ester (HEHEHP or H(EH)EHP), tributyl phosphate (TBP) and Aliquat 336 (*N*-Methyl-*N,N,N*-trioctylammonium chloride). It is the extractant HEHEHP that gives the highest total difference of partition coefficients between REEs: $P(Lu^{2+})/P(La^{3+}) > 10^6$ (Fig. 1 Box). It is the most selective extractant along the lanthanoid series and can be used for all REE separations. Nevertheless, tributyl phosphate in a nitrate medium can be used for La/Ce/Pr/Nd separation, and Aliquat 336 in a nitrate medium can be used for some light and heavy REE separations (Fig. 1 Box). The loading capacity of a solvent, defined as the maximum quantity of REE that this solvent can load, can be improved by lower molecular weight and lower viscosity of the solvent.

The chemical and energy consumptions depend on the extraction mechanisms. All the solvents can be classified into three different types of extracting molecules: solvating agents or neutral extractants (e.g. TBP), which consume steam and water; anion exchangers (e.g. Salts of trilauryl methyl ammonium and of tricapryl methyl ammonium), which also consume steam and water; and cation exchangers (e.g. HEHEHP), which consume basic chemicals (NaOH or NH_4OH) in the extraction section and acids (HCl or HNO_3) in the stripping section.

The usual way to classify solvent extraction processes is to distinguish between the chloride process and the nitrate process. The chloride process is the most widely used, and is used in all Chinese plants. The advantages of the chloride process are that the same solvent can be used for all the REE separations because HEHEHP is selective throughout the lanthanoid series (Fig. 1 Box) and because the liquid wastes contain NaCl which can usually be released into the environment with no constraints. The main disadvantage is the large consumption of HCl and NaOH. The nitrate process has lower operating costs than the chloride process. Solvating and basic extracting molecules can both be used, and the solvents based on these molecules consume almost no chemicals. Cerium and europium are easy to convert to their 4+ and 2+ oxidation states, respectively, and this can be used to facilitate their separation.

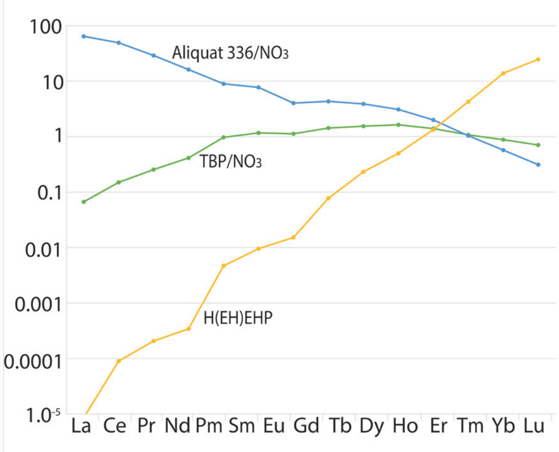

Figure 1 Box Relative partition coefficients (P) of REE^{3+}, i.e. [$P(REE^{3+})$] for the three extractants: (1) 2-Ethylhexyl phosphonic acid, mono-2-ethylhexyl ester (H(EH)EHP). (2) Tributyl phosphate in a nitrate medium (TBP/NO_3). (3) Aliquat 336 in a nitrate medium (Aliquat^{336}/NO_3). The scale is normalized to a partition of one for Y. The larger the difference of $P(REE^{3+})$ between two adjacent REEs, the more selective the extractant. Modified from Lucas et al. (2015).

their host communities, and (3) comply with the laws of the countries in which they operate. These drivers and controls all apply to critical-metal mines, as well as to the production of mainstream commodities. There are so many different management and reporting systems that it is still difficult to identify any clear 'responsibly mined' mark that could penetrate and influence the long supply chains in which critical metals are normally involved.

RARE-EARTH SUPPLY

An introduction to the REEs has been given by Chakhmouradian and Wall (2012) in a previous issue of *Elements*. Other reviews of REEs as critical metals are given in Wall (2014) and Verplanck and Hitzman (2016). As mentioned above, the REEs (the term is used here to include 15 elements: Y, plus La through to Lu, but without Pm which has no long-lived isotope) are essential in many technologies owing to their magnetic, redox and luminescent properties. They are classed as critical because supply is dominated by just one country, China. Prices for REEs rose dramatically in 2010 and 2011 when China threatened to cut supply quotas, but, more recently, the supply situation has eased and prices have now dropped back to 2010 levels. A complication of REE deposits is the propensity of the REEs to follow one another geochemically, such that there are no ore deposits of individual members of the REE series. Although some geological processes fractionate the light REEs from the heavy REEs (Chakhmouradian and Wall 2012) all members of the series occur together.

The production of REEs usually follows conventional mining techniques. Production starts with open pit mines; this is followed by comminution (crushing and grinding) of the ore; then comes separation of the ore from waste by physical methods, such as gravity and magnetic separation, or by froth flotation, or a combination of the two (Fig. 1). The REE minerals then need to be dissolved ('cracked') to release the REEs. An intermediate mixed REE carbonate or oxalate produced at this stage can now be shipped. The next step, required in all cases, is further processing to separate the REEs from each other, which is the most important step in adding value and leads to the high purity REE metals and oxides that are sold to the manufacturing industry (Fig. 1).

By far the largest REE mine is in altered and metamorphosed carbonatite at Bayan Obo, Inner Mongolia (China), with smaller carbonate/alkaline rock and carbonatite mines at Weishan County in Shandong Province (China)

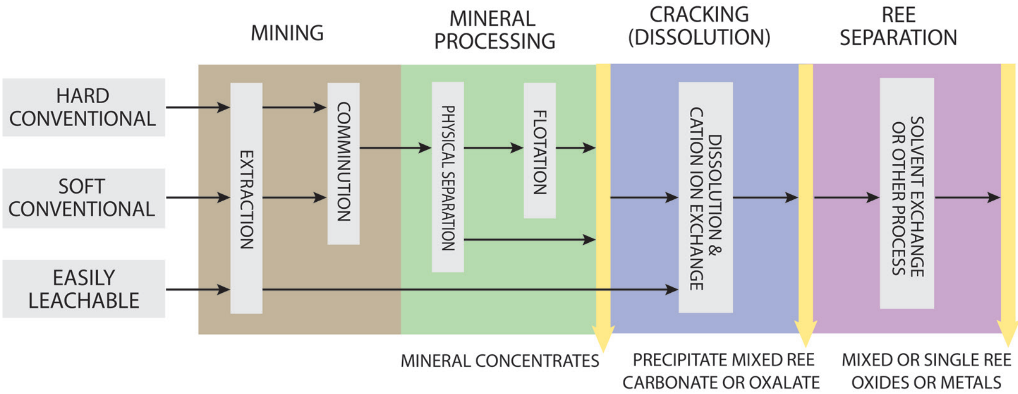

FIGURE 1 Summary of mining and processing routes for rare-earth element (REE) deposits. Ores are divided into three types: hard conventional, such as igneous carbonatite and alkaline igneous rocks; soft conventional, such as mineral sands; and easily leachable, which includes ion-adsorption clays.

and the Maoniuping/Dalucao area in Sichuan Province (China), both important sources for the 'light' REEs (La–Sm) (LREEs). All are open cast quarries. The higher atomic number 'heavy' REEs (Eu–Lu) (HREEs) come mainly from about 200 small mines working 'ion-adsorption clays' in weathered granite across southern China, especially in Jiangxi Province. The mining methods used for these HREE deposits are either removal of the ore material to leaching tanks or in situ leaching with ammonium sulphate (FIG. 2). These leaching methods use very simple technology but cut out the comminution and physical upgrading stages and go straight to dissolution (FIG. 2).

FIGURE 2 In situ leaching pond for ion-adsorption clay REE deposit, China. A low technology technique is used whereby drainage holes at the rear of the collection pond bring the leach solution down the hillside through the weathered granite. In theory, this could be a low environmental impact method to produce REEs, but it depends on the chemicals used and how well they are controlled. PHOTO COURTESY OF ALAIN ROLLAT.

The pollution damage from Bayan Obo and associated processing plants in nearby Baotou is significant, frequently featured in newspaper articles (Ali 2014). The extensive land degradation and pollution associated with mining the ion-adsorption clays is also a serious problem, as is illegal mining. The Chinese government is taking action to consolidate the REE industry throughout China and improve its environmental performance. Nevertheless, it is a sobering thought that we are all implicated in this environmental damage through everyday pieces of equipment that almost certainly contain Chinese REEs.

There are, however, few alternative supplies. Outside of China, there are only three substantial active mines. The loparite mine in nepheline syenite at Lovozero, Kola Peninsula (Russia) produces REEs as a co-product with Nb. Ore treatment is done in Solikamsk (Russia). Mineral sands at Orissa (India) are mined by Indian Rare Earths Ltd. This ore is treated on site and the REE separation is also done in India, through a joint venture between Indian Rare Earths Ltd. and Toyota Tsusho. There is little public information on the environmental performance of either of these operations. The third mine is in weathered carbonatite at Mount Weld (Western Australia) operated by Lynas Corporation Ltd, with ore treatment and REE separation in Kuantan (Malaysia). The mining operation itself has not been controversial but the Lynas Advanced Materials Plant ('LAMP') in Malaysia, which was needed to separate the REEs, was subject to considerable protest on environmental grounds during its development because of fear of pollution from Th and U in the monazite ore (Ali 2014). The company now publishes details on their website (www.lynascorp.com) of environmental monitoring around the plant and uses international auditable management systems (e.g. ISO 14001, OHSAS 18001). The company is also developing their own chain of assurance with magnet manufacturers. The Mountain Pass (California, USA) carbonatite mine re-opened in 2012. It also made an issue of being a more environmentally friendly source of REEs than the Chinese producers (Loye 2015) but did not survive the recent low REE prices and closed again in August 2015. So, since the crisis of 2010/11, the choice of major supplier has only widened by one mine (Mount Weld). Processing and separation of REEs is becoming progressively more concentrated in China. For example, Solvay, a chemical company based in Belgium and one of the few processors outside of China, has moved to downstream applications rather than processing REE raw materials. Its two Chinese plants have stopped their REE separation lines, and its separation lines at La Rochelle (France) are only partly used. The plant at NPM Silmet AS in Sillamae (Estonia) only produces separated LREE products.

CONNECTING GEOLOGY AND GEOCHEMISTRY TO RESPONSIBLE SOURCING

Despite the difficulties in current REE supplies, a wide range of REE deposits are being, or have recently been, explored, providing a particular opportunity to consider how the geology and geochemistry of a deposit can affect responsible mining and sourcing. Deposits include carbonatites (both hydrothermally altered and weathered varieties), alkaline igneous rock (including nepheline syenite and granite), other types of hydrothermal deposits, high-temperature igneous monazite veins, mineral sands, and REEs as by-products of other ores. Even deep-sea muds are being explored (Chakhmouradian and Wall 2012; Wall 2014)

A qualitative comparison of the intrinsic properties of the main varieties of REE ore deposits shows wide variation (TABLE 1). Five factors have been chosen to characterise the different types of REE deposits: (1) the presence of radioactive minerals, because this is the main reason for restrictions on shipping and processing of REE ores and concentrates, as well as the main public fear; (2) the amount of environmental disturbance likely, considering the size of the likely mine (assumed to be open cast, few REE mines are proposed as underground operations) and the amount of rock that needs to be processed to obtain the REE; (3) the energy needed for crushing and grinding, which is the main energy use in mining, according to whether the deposit is a hard rock that requires considerable energy for comminution or is a friable placer or weathered deposit; (4) the resource efficiency, based on how easy it usually is to recover a high proportion of the REEs from the type of deposit in question; (5) the measure of whether the REEs are a by- or a co-product of another commodity.

Light REE-enriched carbonatites are generally low in Th and U, even if the ore mineral is monazite (see above). As these are some of the highest-grade ores, the amount of land disturbed is likely to be low compared to other REE deposits. The energy required for comminution is variable. Carbonatites, for example, are not particularly tough rocks, but even weathered deposits require comminution to a fine grain size (~50 μm) if flotation is used to recover the REE minerals.

The nepheline syenite alkaline rock deposits are large, low grade, hard rock deposits, requiring large amounts of energy for comminution. The mineralogy is complex, and attaining good separation and thus resource efficiency is difficult. There are possibilities for multiple products, and an intermediate rating has been given for this situation (Table 1). The radioactivity of eudialyte as the REE ore mineral in nepheline syenite is low and is a particular advantage of these deposits. Other minerals, such as steenstrupine, may, however, contain higher amounts of Th and U. In alkaline granites, the amount of Th and U can be much higher, hence the 'variable' label in Table 1.

Mineral sands, being unconsolidated, easy to process, and shallow deposits score well in all categories except radioactivity. With monazite and xenotime derived from granitic rocks, they are at the higher end of the range of Th contents, making derived concentrates significantly radioactive.

Ion-adsorption deposits (i.e. REEs adsorbed onto clays, which are usually the products of granite weathering) are the ones that tend to hold the HREEs and are easy to mine. They occur close to the surface in weathering profiles and are typically 15–35 m thick. They require disturbance of a large amount of land, owing to their low grade (typically about 800 ppm, but usually <4,000 ppm). On the plus side, the amounts of HREEs are small and near the surface, making high-quality remediation shortly after mining possible. Also, little energy is required for mining or processing. The recovery of exchangeable REE

Figure 3 Waste tips associated with the apatite mines in the Khibiny nepheline syenite complex, Kola Peninsula (Russia).

cations is likely to be good, but insoluble REE minerals will remain in the waste. Values of Th and U are low, although the presence of Th- and U-bearing minerals in insoluble residual minerals such as monazite, xenotime, thorite or uraninite is likely to vary according to the protolith composition.

Production of REEs as by-products of ores such as apatite and bauxite is possible (Table 1) and the environmental impact of this depends on whether the production of the REEs is considered a bonus or whether, as is more usual, the overall environmental impacts (which may be large, see Fig. 3) are apportioned to both the major products and the by-products.

Overall, the conclusions from this comparison are that mineral sands score well, apart from the radioactivity of the ore minerals. Most mineral sand operations ship concentrates from their mine to separate processing factories, but their monazite and xenotime concentrates are likely to be too radioactive for transportation, or even for storage. However, this is a challenge that could be overcome if a processing method was installed on site so that Th and U (and Ac) were removed from the ore concentrates. Then, an intermediate product could be shipped, and the Th and U stabilized and returned to source. Ion-adsorption clay deposits can also score well as environmentally favourable deposits, so long as good methods are designed to strip mine and remediate rapidly or to carry out safe in-situ leaching. Carbonatites generally appear more environmentally favourable than alkaline rock deposits because of their higher grade. Alkaline rock deposits have the advantage of higher proportions of HREEs.

Table 1 EXAMPLES OF RARE-EARTH ELEMENT (REE) DEPOSITS AND QUALITATIVE ANALYSIS OF THEIR MINING AND PROCESSING CHARACTERISTICS. Characteristics shaded green and in bold are generally advantageous to responsible sourcing, grey are less so and unshaded cells are less favourable.

Ore type	Energy for crushing and grinding	Grain size/ Difficulty of beneficiation	Chemicals (acid, flotation reagent)	Radioactivity: ore mineral and host rock	Amount of rock to be moved*	By-products
Carbonatite	Medium – High	Variable – 10 μm	Flotation – medium	Medium	**Low**	Not usually
Weathered carbonatite	Medium	10 μm and finer	Flotation – medium	**Low–Medium**	**Low**	Not usually
Alkaline rock	High	Variable 1 μm and larger	Variable	Variable	High	Co-products common
Ion adsorption clay (in-situ leaching)	**None**	**Beneficiation not needed**	Leaching, so can be high	**Low**	**Low**	None
Mineral sand (placer)	**None–Low**	**10 – 100 μm**	**Low**	High	High	**from TiO_2, zircon etc production**
By-product of igneous apatite	High	100 μm–mm	Medium	**Low**	High	**from fertiliser manufacture**
Red mud	Bauxite processing	**n/a REE from red mud**	Medium?	**Low**	High	**from Al production**

* i.e. low grade = large amount of rock

QUANTIFYING THE COMPARISON OF DEPOSIT TYPES USING A 'LIFE CYCLE ASSESSMENT' (LCA) APPROACH

It is possible to compare the environmental performance of the production of critical raw materials by using the "life cycle assessment" (LCA) approach. An LCA is performed by calculating all the energy and material inputs, and the associated emissions and waste outputs, over an entire life cycle, from raw material acquisition to ultimate disposal [International Organization for Standardization (ISO) 14040 2006a]. This method has the advantage of incorporating a wide range of environmental issues into an integrated assessment framework, including climate change, ecotoxicity and resource depletion. Calculations are done with proprietary software that incorporate databases of previous LCAs for inputs such as chemical reagents and power generation. The assessments can stop part-way through a life cycle, and most studies of mined materials go 'mine to gate', encompassing mining and some parts of the processing to give an intermediate product used in the next stage of the value chain. To date, there have only been a handful of LCAs for REE production, primarily focusing on Bayan Obo (Sprecher et al. 2014; Koltun and Tharumarajah 2014; Zaimes et al. 2015). Sprecher et al. (2014) extended their LCA to the production of NdFeB magnets. These studies yielded different results (Table 2). For example, global warming impacts range from 12 to 35.27 kg CO_2 equivalent (eq) at Bayan Obo, and acidification has a range from 6.4 to 99.28 kg SO_2 eq. The variation of the REE results can be explained by the fact that different software packages, datasets and methods have been used and that different assumptions about the processing routes were made for each LCA. For example, Koltun and Tharumarajah (2014) used a two-step allocation procedure to deal with the co-production of iron ore at Bayan Obo. Comparison of two LCAs done at different times can also be difficult because the inventories in the software are updated periodically as new data become available for specific processes, and because of the need to reflect the changing mix of energy generation in the countries in the database.

An important point that comes from these analyses is the high contribution made by chemical reagents, especially when they are manufactured in countries with high fossil fuel use. Although crushing and grinding prior to mineral separation is energy intensive, it has a smaller contribution to greenhouse gas emissions than dissolving the REE minerals and separating the individual REEs from each other (Fig. 4). Various new processes have been proposed to separate REEs but none are in commercial production yet. Learning from nature in order to find novel ways to carry out these processing stages is certainly a challenge to which geochemists could contribute.

Recent work by Vahidi et al. (2016) has examined the environmental performance of ion-adsorption clays. The LCA results indicated that production of REEs from ion-adsorption clays has a similar global warming impact as production from Bayan Obo, a lower acidification rate than from Bayan Obo, and a higher cumulative energy demand. It should be noted that the difference in REE composition (i.e. higher HREE content in the ion-adsorption clays) and the use of an economic allocation in the comparison means that the potentially better environmental performance of the ion-adsorption clays is offset by its higher relative economic value. Comparisons could be improved by comparing LCA results for individual REEs, e.g. Nd, Dy, or Eu, rather than grouping the whole set together.

Other challenges specific to using LCAs in evaluating REE production are that there are often limited data available for specific processing steps. Therefore, surrogate information is required. This is especially true when comparing deposits that are still in the exploration and development phase. There is also the issue about what factor to measure environmental performance against. Should it be measured against an individual REE or against an economic value? Previous studies have tended to incorporate some economic criteria because this is more realistic when considering the high-value variation of the individual elements. Cerium

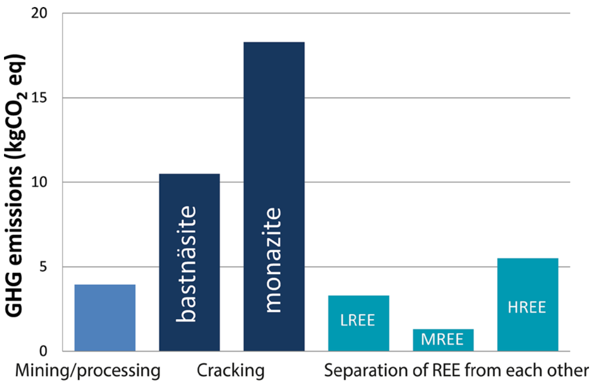

Figure 4 Greenhouse gas (GHG) emissions equivalent per kg of rare-earth oxide produced calculated from a life cycle assessment of a) mining, concentrating Bayan Obo REE ore; b) dissolving (cracking) the two ore minerals bastnäsite and monazite to release their REEs; c) separating the light (L), medium (M) and heavy (H) REEs from each other. After Koltun and Tharumarajah (2014).

Table 2 SUMMARY OF FOUR LIFE-CYCLE ASSESSMENTS (LCAs) with a functional unit of 1 kg of rare-earth oxides (REOs), three from Bayan Obo (Inner Mongolia, China), highlighting different results obtained from the same deposit, plus one for a Chinese ion-adsorption deposit.

Factor	Unit	Bayan Obo 1	Bayan Obo 2	Bayan Obo 3	Ion adsorption clay
Global warming	kg CO_2 eq	12–16	32.29–32.49	22.98–35.27	20.9–35.5
Acidification	kg SO_2 eq	6.4–8.8	N/A	96.27–99.28	0.165–0.288
Eutrophication	kg N eq	0.04–0.06	N/A	0.18–0.27	0.303–2.87
Respiratory effects	kg PM2.5 eq	N/A	N/A	0.16–0.18	0.026-0.045
Ozone depletion	kg CFC-11 eq x 10^{-6}	2.0–3.5	N/A	3.8–20	2.4–3.2
Cumulative energy demand	MJ	174–232	169.2–179.5	315–578.8	255–388

Data from Sprecher et al. (2014), Koltun and Tharumarajah (2014), Zaimes et al. (2015), Vahidi et al. (2016)

All results are presented as a range from low to high

The eq units simplify all of the chemicals causing each factor into one equivalent unit, e.g. kg CO_2 eq includes other gases responsible for global warming such as methane. PM2.5 = atmospheric particulates smaller than 2.5 µm diameter. CFC-11 = ozone-depleting chemicals equivalent to trichlorofluoromethane.

N/A = no result available for this factor oxide sells for a few dollars a kg whereas the scarcer HREEs that have specific uses, such as Dy and Eu, sell for thousands of dollars per kg. Trying to work on the whole set of REEs adds a complicating factor but, of course, this is how the REEs occur in ore deposits.

Production of REEs as whole (using data for Bayan Obo) performs slightly worse than average when compared against LCA results for other metals. For example, Graedel et al. (2015) used an LCA metric for environmental impact, based on the earlier studies of Bayan Obo contained in LCA inventories. Graedel et al. (2015) graded the LREEs (La, Ce, Pr, and Nd) as having low environmental impact, and three of the HREEs (Eu, Dy, Tb) as medium, when compared with other metals. All the REEs had a lower environmental impact (in terms of production) than gold, whereas the LREEs themselves were similar to copper and higher than iron.

A limitation of the LCA approach is that although the software packages have been developed to incorporate many factors, such as those discussed in the quantitative comparison above, the results tend to be presented in term of energy use, global warming impact, and greenhouse gas emissions. Thus, the results either miss or apparently downplay all the other factors of responsible sourcing. The LCA approach also misses the behavioural element of whether a mining company is abiding by the regulations and following good practice guidelines. Despite the challenges that exist in LCAs, it can be a powerful tool in calculating the environmental performance of REE production and of offering insight into hotspots of production that need further research, as well as calculating values that can feed into full life cycle analyses of manufactured goods. At the moment, the only deposit information available in commercial inventories is for Bayan Obo (China), and this is a major limitation when considering future supplies. Further work will be needed to formalise a consistent process for LCA use in the context of REE production.

CONCLUSIONS

Most critical raw materials contribute to the long supply chains used for the manufacture of complex devices such as smartphones, computers and cars. It is much more difficult for consumers to engage with the original mining operations in these cases than for mining operations for gemstone products used in jewellery where the raw materials are more obvious. Only high-profile humanitarian issues, such as conflict minerals, have really penetrated these long supply chains to produce the action needed to help ensure responsible sourcing. As yet, there are no responsible mining schemes generally applicable to mid-size critical metal suppliers, although there are international management systems and other relevant information that companies can use and make directly available.

Considering the beginning of the supply chain, and using the REEs as an example, it can be demonstrated that geology and geochemistry have a strong influence on mining and processing techniques. This, in turn, feeds into environmental performance and responsible sourcing. There are plenty of challenges for the geoscience community to find more environmentally friendly ore types, processing methods (including mitigating the ore dissolution stage), and remediation techniques.

Life cycle assessment and qualitative approaches have different uses in responsible sourcing. An LCA is particularly good for refining a technical application in processing design and supply chain analysis. More studies of critical raw materials are needed to show the manufacturers a better choice of raw materials supply routes. However, an LCA is less useful for communicating directly to the public because of the way it condenses information. A single issue, such as radioactivity or landscape degradation, can outweigh all other factors in pubic consideration and will have to be addressed as highest priority. These issues of responsible sourcing are the same for critical as for non-critical raw materials.

For REEs, it is important to consider that most users still purchase from China and much of the REE supply chain sits in China. Several mining projects under development outside China have agreements to sell to Chinese processors. A particular challenge for Chinese REE producers is that they have to demonstrate both an improvement in their environmental and social performance and show that there is enough diversity in the world market to guarantee a secure supply.

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A.1.3 Mineral processing simulation based environmental life cycle assessment for rare earth project development: a case study on the Songwe Hill project

Supporting Information for: Mineral processing simulation based environmental life cycle assessment for rare earth project development: a case study on the Songwe Hill project

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Allocation

	Acidification	Ecotoxicity	Eutrophication	Global Warming (excl biogenic)	Global Warming (incl biogenic)	Particulate Air	Human Toxicity (cancer)	Human Toxicity (non-cancer)	Ozone Depletion	Resources	Smog Air
La2O3	0.00621	0.156061	0.000647	1.869024	1.846644	0.53039	1.18E-09	6.77E-08	6.55E-07	3.897387	0.078051
CeO2	0.0019	0.047754	0.000198	0.57192	0.565072	0.162299	3.6E-10	2.07E-08	2E-07	1.192597	0.023883
Pr6O11	0.007167	0.180116	0.000746	2.157112	2.131282	0.612143	1.36E-09	7.82E-08	7.56E-07	4.498123	0.090081
Nd2O3	0.019123	0.480555	0.001991	5.755251	5.686336	1.63322	3.62E-09	2.09E-07	2.02E-06	12.00115	0.24034
Sm2O3	0.001679	0.042183	0.000175	0.50519	0.49914	0.143362	3.18E-10	1.83E-08	1.77E-07	1.053448	0.021097
Eu2O3	0.01106	0.277929	0.001152	3.328551	3.288694	0.944573	2.09E-09	1.21E-07	1.17E-06	6.940869	0.139001
Gd2O3	0.00124	0.031172	0.000129	0.373324	0.368854	0.105942	2.35E-10	1.35E-08	1.31E-07	0.778475	0.01559
Tb4O7	0.002695	0.067734	0.000281	0.811197	0.801483	0.230201	5.1E-10	2.94E-08	2.84E-07	1.69155	0.033876
Dy2O3	0.006373	0.160156	0.000664	1.918069	1.895102	0.544308	1.21E-09	6.95E-08	6.72E-07	3.999659	0.080099
Y2O3	0.002081	0.052301	0.000217	0.626371	0.61887	0.177751	3.94E-10	2.27E-08	2.2E-07	1.306141	0.026157
Ho2O3	0.000187	0.004698	1.95E-05	0.056259	0.055585	0.015965	3.54E-11	2.04E-09	1.97E-08	0.117313	0.002349
Er2O3	0.000345	0.008682	3.6E-05	0.103976	0.102731	0.029506	6.54E-11	3.77E-09	3.64E-08	0.216817	0.004342
Tm2O3	6.23E-05	0.001566	6.49E-06	0.018753	0.018528	0.005322	1.18E-11	6.8E-10	6.57E-09	0.039104	0.000783
Yb2O3	0.000312	0.007829	3.24E-05	0.093764	0.092642	0.026608	5.9E-11	3.4E-09	3.29E-08	0.195522	0.003916
Lu2O3	3.12E-05	0.000783	3.24E-06	0.009376	0.009264	0.002661	5.9E-12	3.4E-10	3.29E-09	0.019552	0.000392

	Mining	Crushing and milling	Flotation	Calcite leach	HCL REE leach	Caustic crack	REE dissolution	Sol adjustment and purification	Raw RE (OH)3 precipitation	Caustic crack 2	Cerium precipitation	Residue leaching	Final RE (OH)3 precipitation	HCL regeneration 1	HCL regeneration 2	HCL regeneration 3	Waste neutralisation
Acidification	0.003983964	0.001617866	0.009951246	0.000689451	0.000173345	0.000289937	0.001235323	0.013429639	0.003892193	0.011805838	0.00423598	0.00015932	0.003756435	0.001365543	0.001288941	0.001462631	0.001129004
Ecotoxicity	0.185730344	0.006353881	0.095217404	0.002707698	0.00068078	0.001154088	0.0096676	0.144614831	0.016261229	0.048848733	0.965223137	0.000625701	0.015728062	0.007051126	0.005054735	0.005735478	0.00886309
Eutrophication	0.000639852	0.00037335	0.000450252	0.000159102	4.00022E-05	5.94367E-05	0.000124872	0.000276805	0.000537255	0.001520482	0.000978849	3.67657E-05	0.000505926	0.000158147	0.000152897	0.000173255	0.000109289
Global Warming (excl biogenic)	0.871569803	0.362786198	0.975450212	0.154600859	0.038870354	0.081721834	0.154484556	3.158994304	1.681011983	5.33953225	1.202254971	0.035725504	1.650569828	0.805533963	0.724891566	0.823310805	0.136827535
Global Warming (incl biogenic)	0.831246383	0.362853493	0.974903443	0.154629537	0.038877565	0.081898634	0.154190691	3.159147824	1.689386413	5.366569975	0.981539608	0.035732131	1.658938612	0.805686152	0.724895372	0.82331461	0.136417236
Particulate Air	5.073939572	0.085961849	0.00079752	0.000110329	2.77395E-05	4.05914E-05	0.000141301	0.000917396	0.000341696	0.000953666	0.000350673	2.54952E-05	0.000319972	6.54973E-05	6.03329E-05	6.82166E-05	0.000127796
Human Toxicity (cancer)	7.96526E-10	4.54993E-11	4.92632E-10	1.93895E-11	4.87497E-12	1.9874E-11	5.19999E-11	2.25614E-09	6.81671E-10	2.22062E-09	4.10175E-09	4.48056E-12	6.77853E-10	1.79689E-11	2.60522E-12	2.88896E-12	4.49104E-11
Human Toxicity (non-cancer)	6.17296E-08	6.16253E-09	4.0029E-08	2.62615E-09	6.60278E-10	8.20611E-10	7.33534E-09	2.25383E-07	1.15212E-09	-7.59008E-10	3.04877E-07	6.06858E-10	6.35007E-10	8.36523E-10	2.81128E-10	3.11101E-10	6.76666E-09
Ozone Depletion	1.33575E-06	1.51085E-06	6.43851E-07	6.43848E-07	1.61879E-07	2.03265E-07	2.03266E-07	4.59968E-07	3.66722E-07	1.48802E-07	1.05353E-07	1.48782E-07	2.39943E-07	1.48766E-08	1.48705E-08	1.48705E-08	1.60963E-07
Resources	3.598253897	0.23791699	2.819406835	0.101388011	0.025491371	0.058011607	0.22028767	4.144224563	1.317302771	4.213623288	14.69232124	0.023428963	1.297338655	1.7429378	1.52345322	1.731003521	0.201318953
Smog Air	0.051968446	0.008497146	0.104938886	0.003621048	0.000910418	0.002565394	0.035096574	0.036376407	0.070909084	0.230016177	0.074557665	0.00083676	0.07019607	0.012481329	0.011283157	0.012811085	0.032890736

Global warming value including

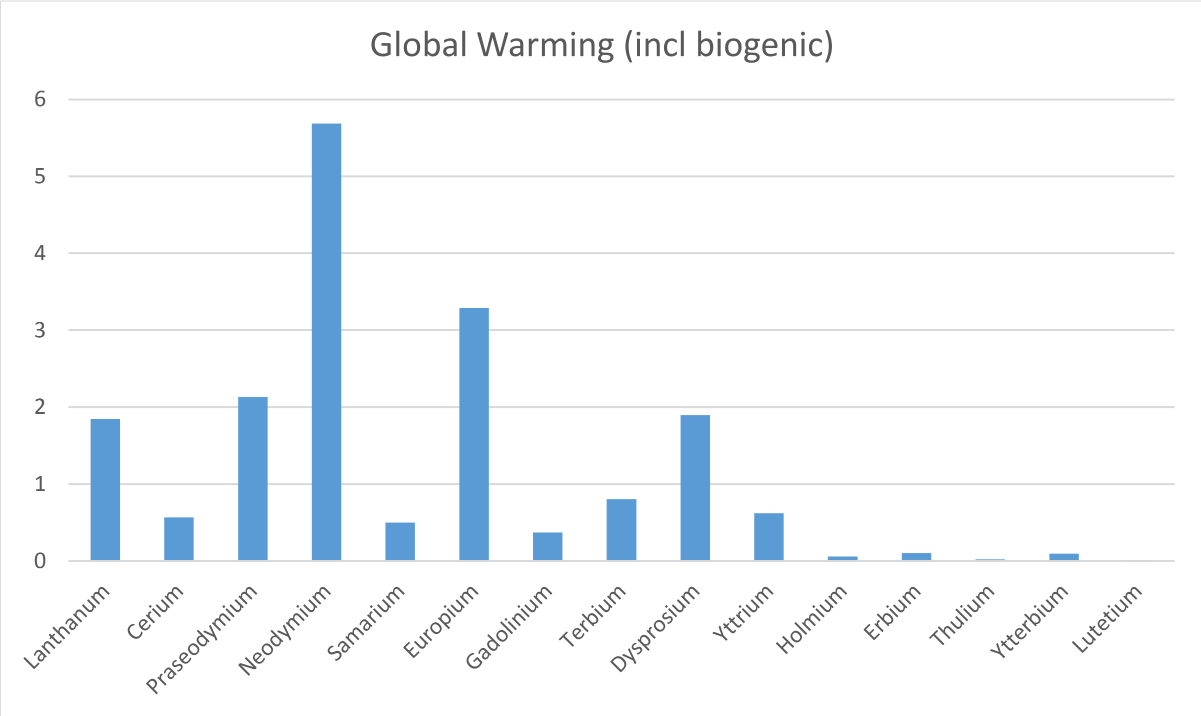
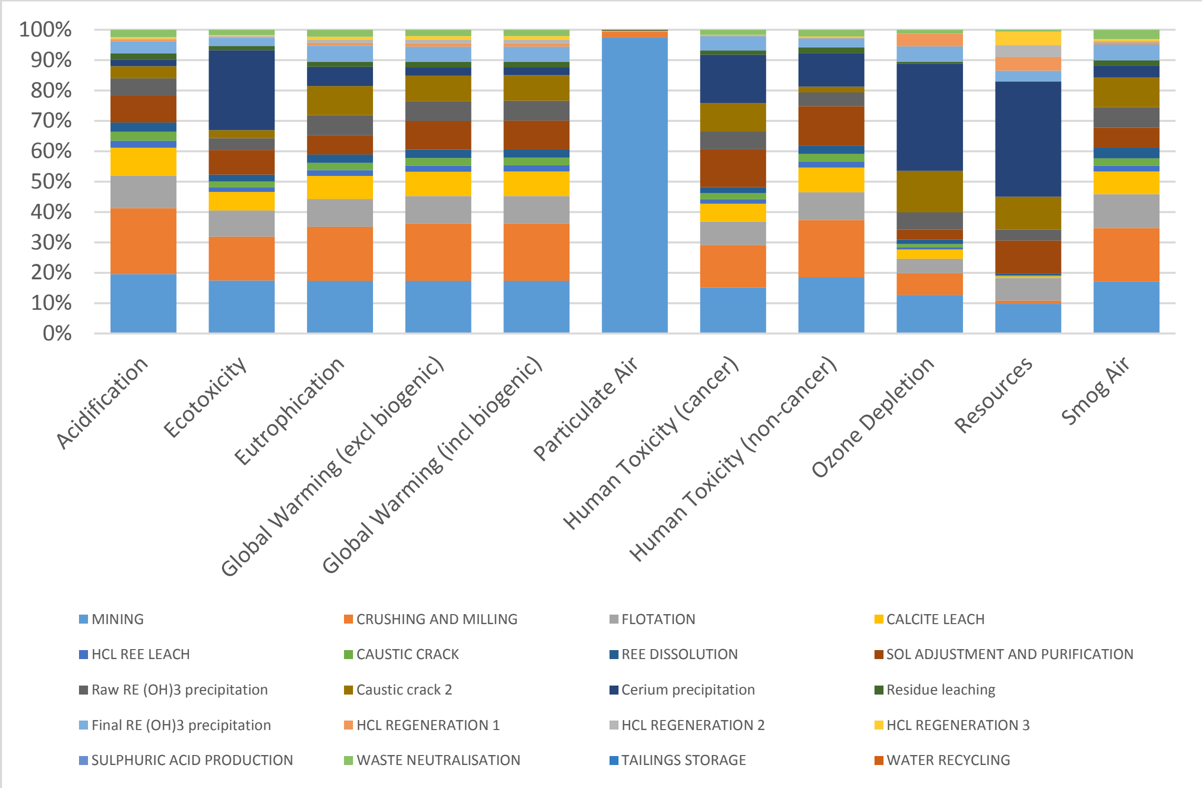


Table 2.

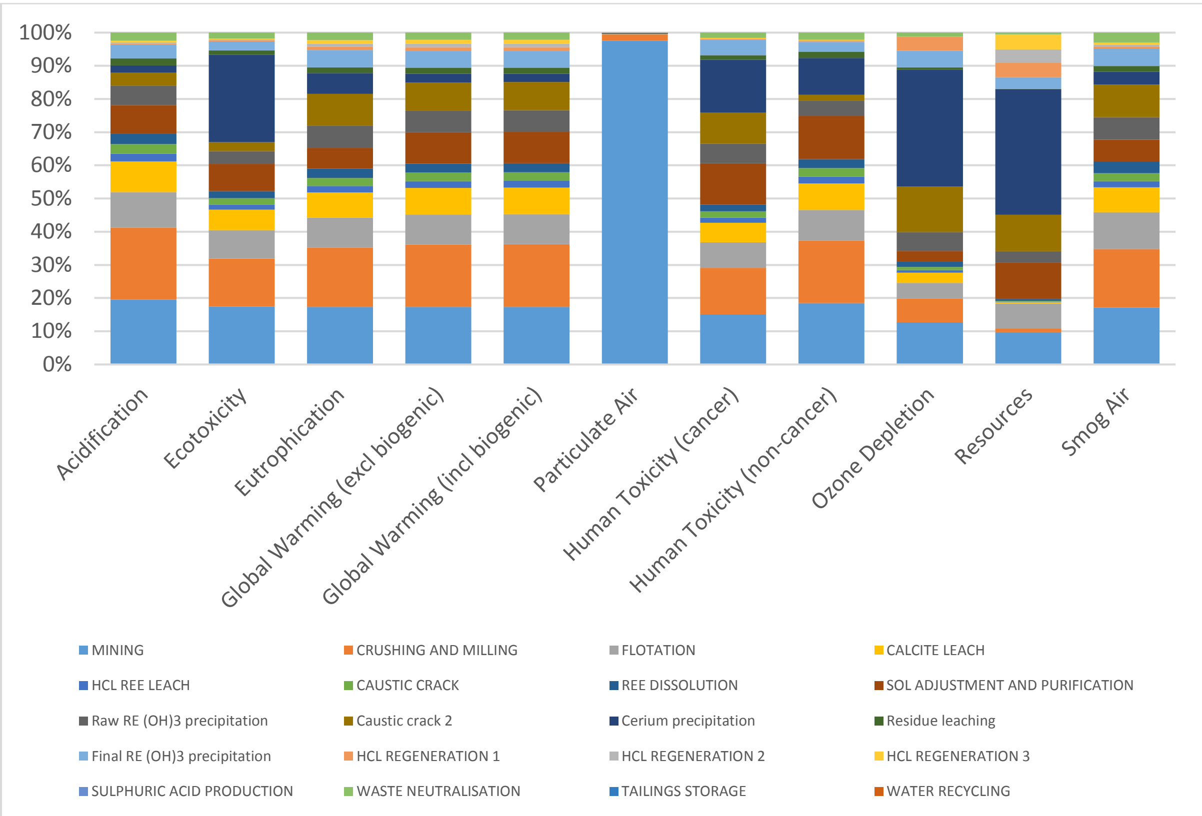
Environmental impacts per kg of REO produced at Songwe Hill under different scenarios as indicated in the goal and scope

Environmental impact indicator	Unit	A-H	A-US	A-L	V-H	V-US	V-L
Acidification	kg SO_2 eq.	0.054	0.071	0.632	0.063	0.080	0.637
Ecotoxicity	CTUe	1.496	1.662	3.814	2.016	2.181	4.318
Eutrophication	kg N eq.	0.005	0.006	0.019	0.006	0.007	0.020
Global warming	kg CO_2 eq.	17.027	24.404	81.347	23.396	30.721	87.265
Human health	kg PM2.5 eq.	5.163	5.164	5.210	5.164	5.165	5.211
Carcinogenic	CTUh	1.1E-08	1.2E-08	2.7E-08	5.1E-08	5.3E-08	6.7E-08
Non-carcinogenic	CTUh	6.3E-07	7.1E-07	3.0E-06	4.8E-06	4.9E-06	7.3E-06
Ozone depletion	kg CFC 11 eq.	1.0E-10	3.3E-09	1.5E-10	1.1E-10	3.3E-09	1.6E-10

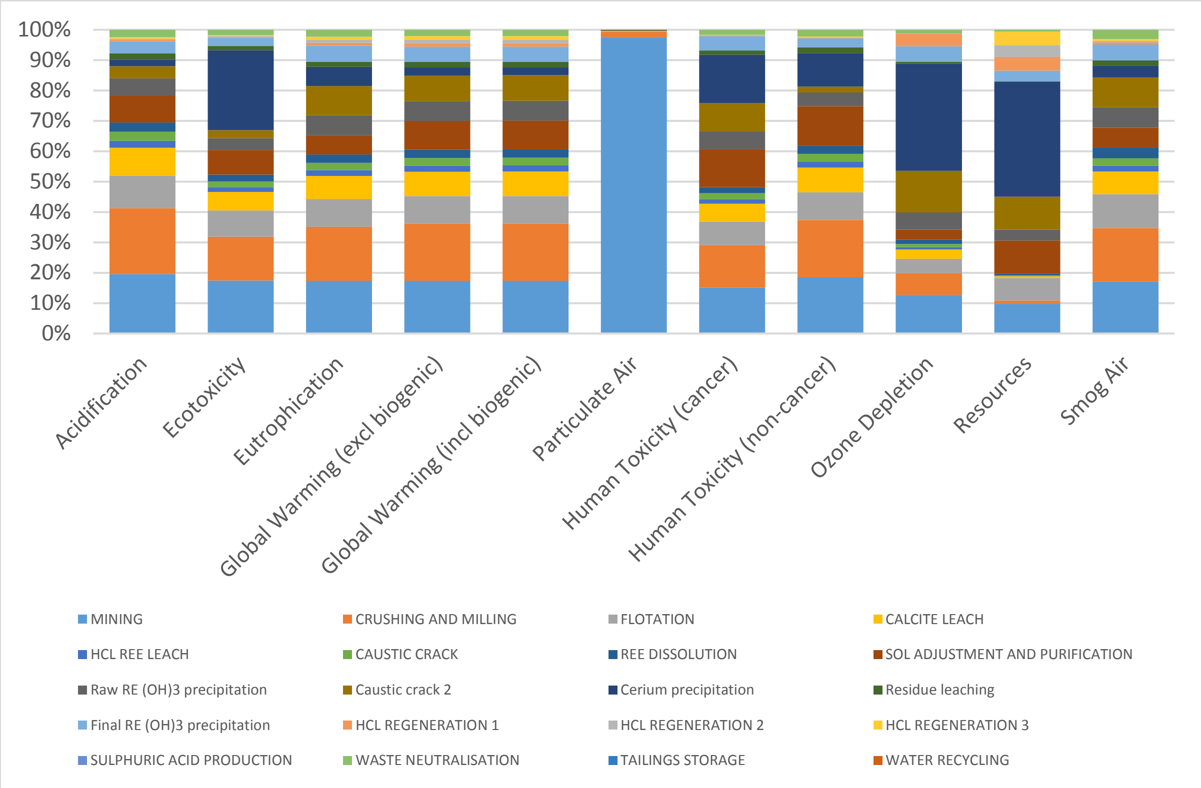
Hydroelectric power and acid regeneration (no cutoff)



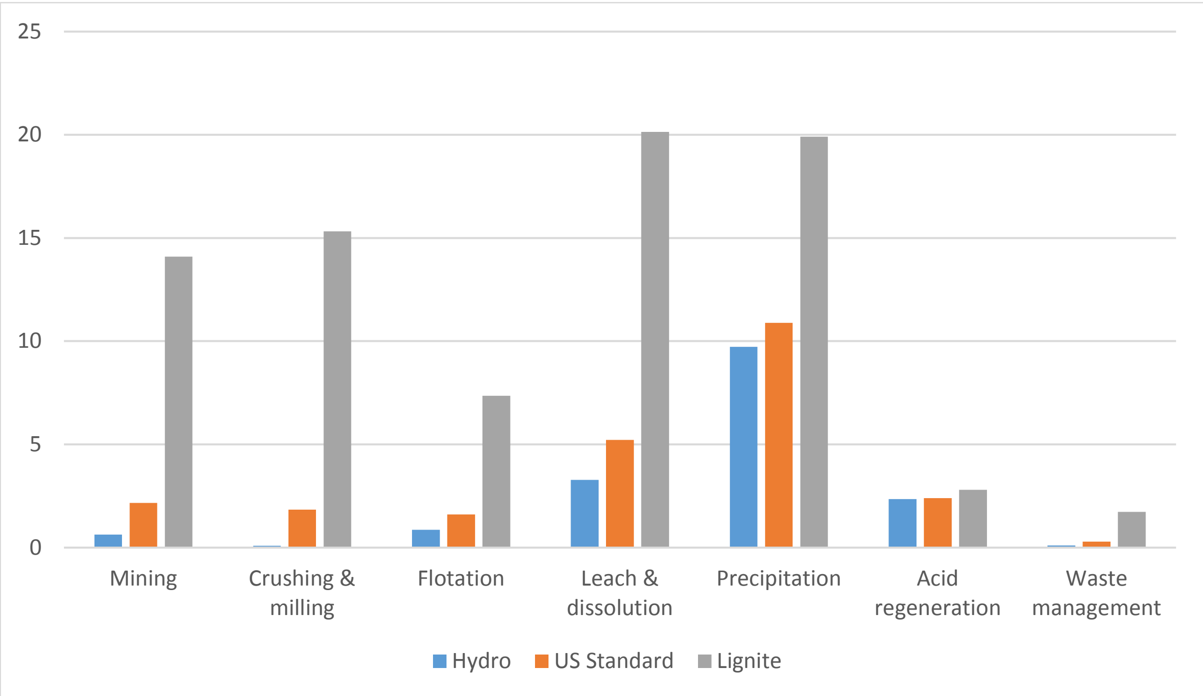
US Standard and acid regeneration (no cutoff)



Lignite and acid regeneration

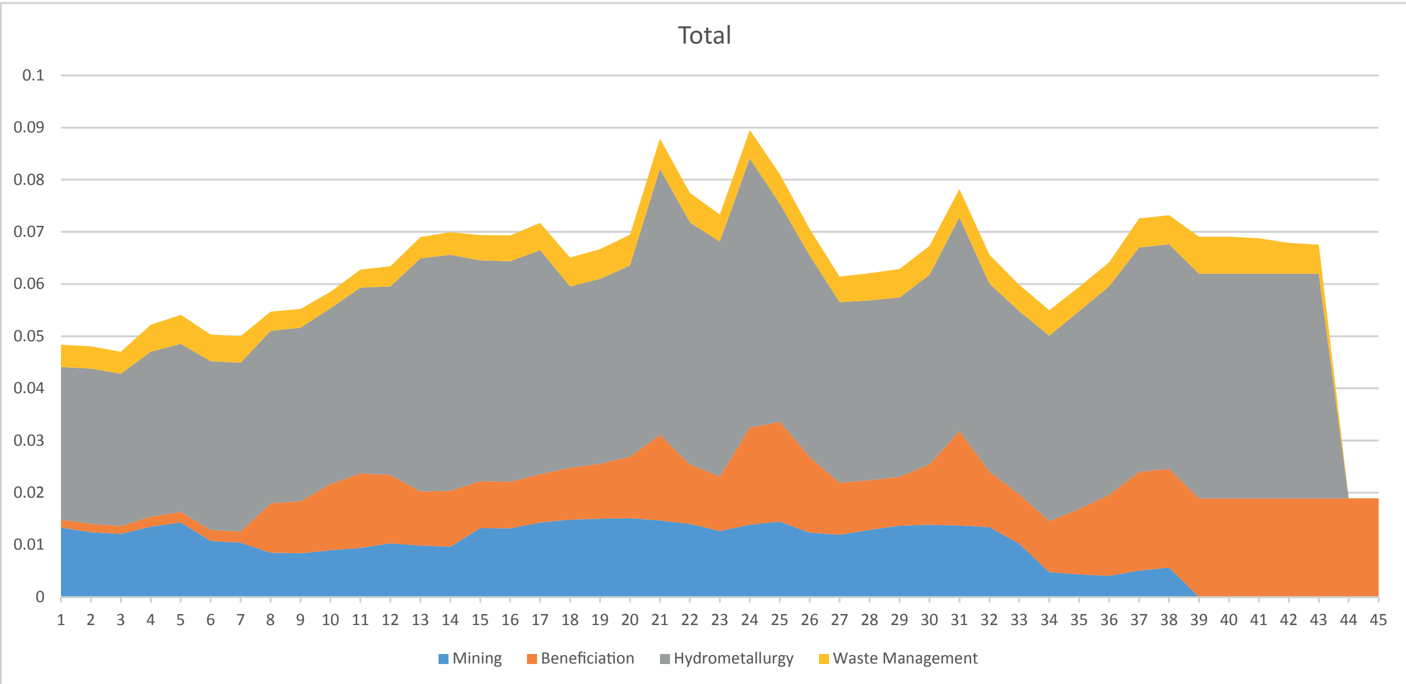


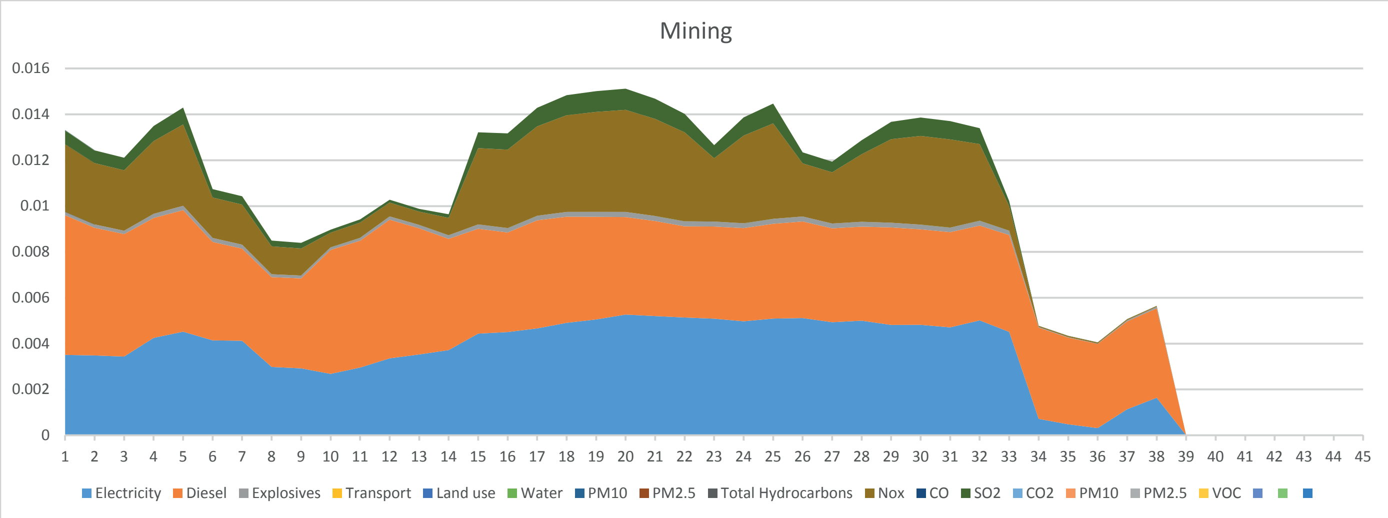
Overall acid regeneration

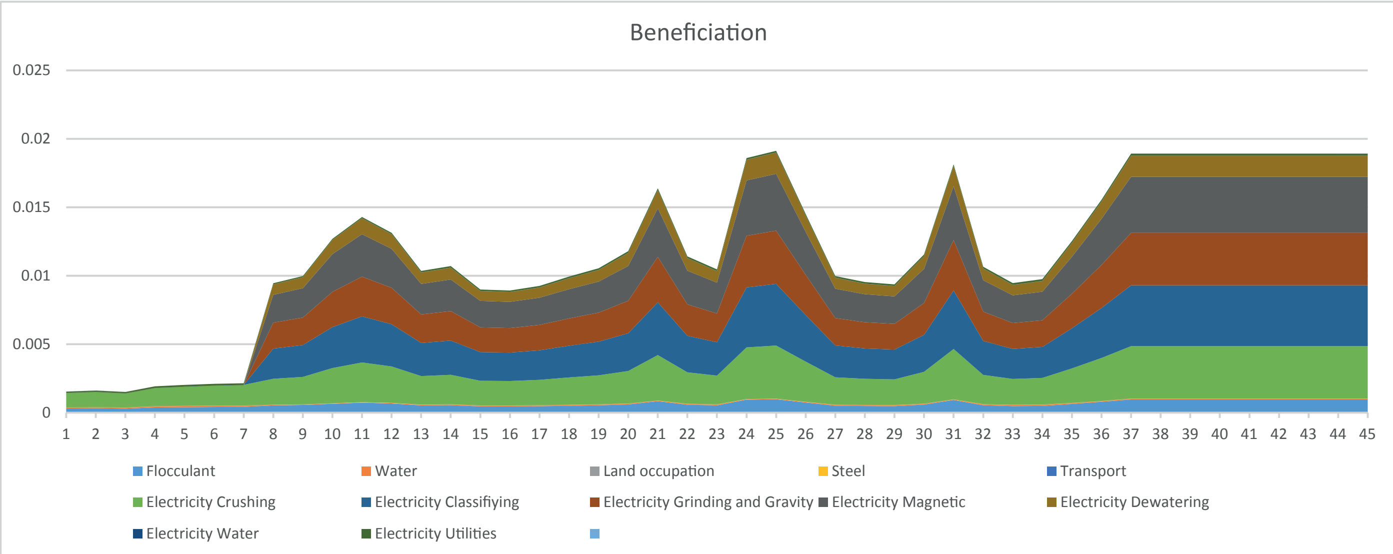


A.1.4 Temporally explicit life cycle assessment as an environmental performance decision making tool in rare earth project development - Supplementary information

TRACI 2.1, Acidification kg SO2 eq.




Mining
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Electricity Diesel Explosives Transport Land use Water PM10 PM2.5 Total Hydrocarbons Nox CO SO2 CO2 PM10 PM2.5 VOC


Beneficiation
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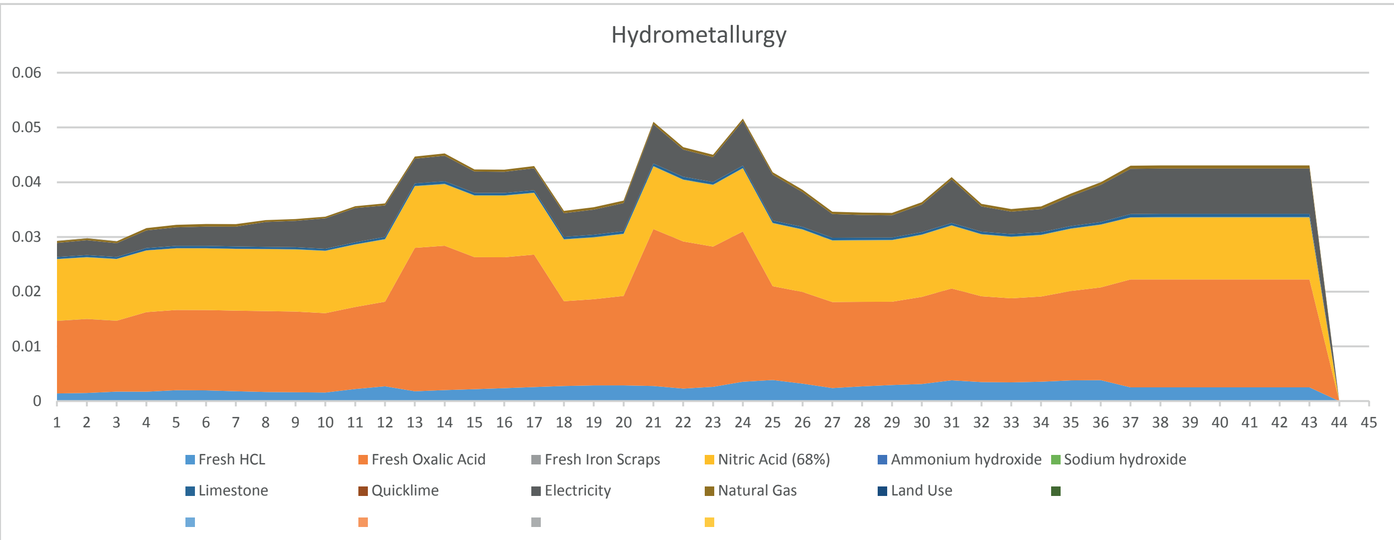
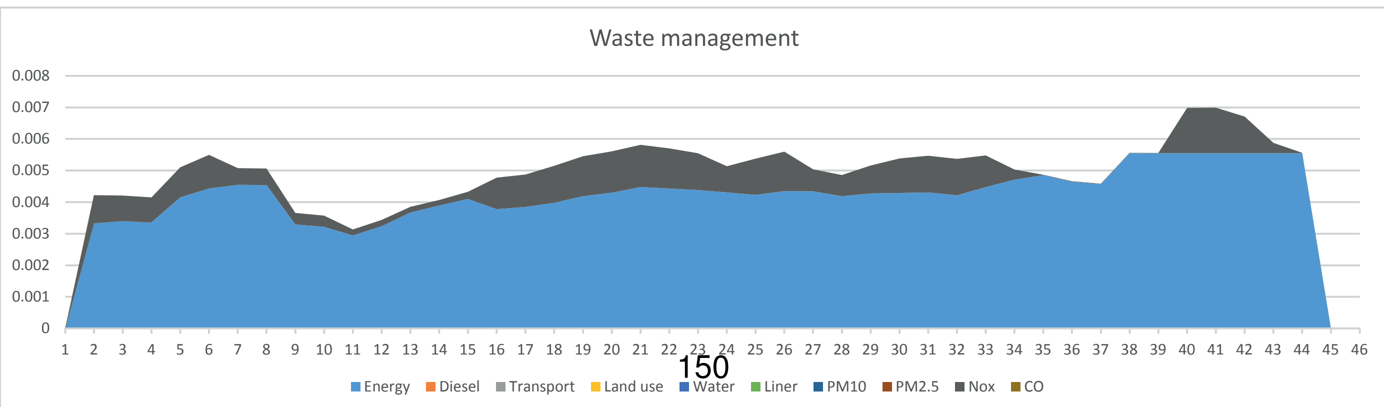
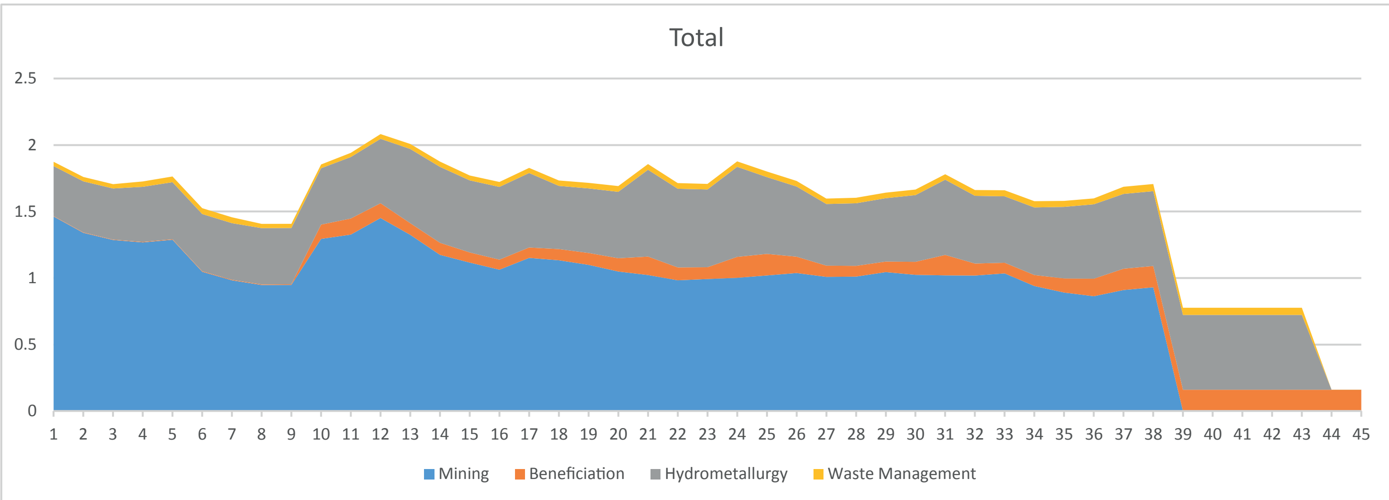
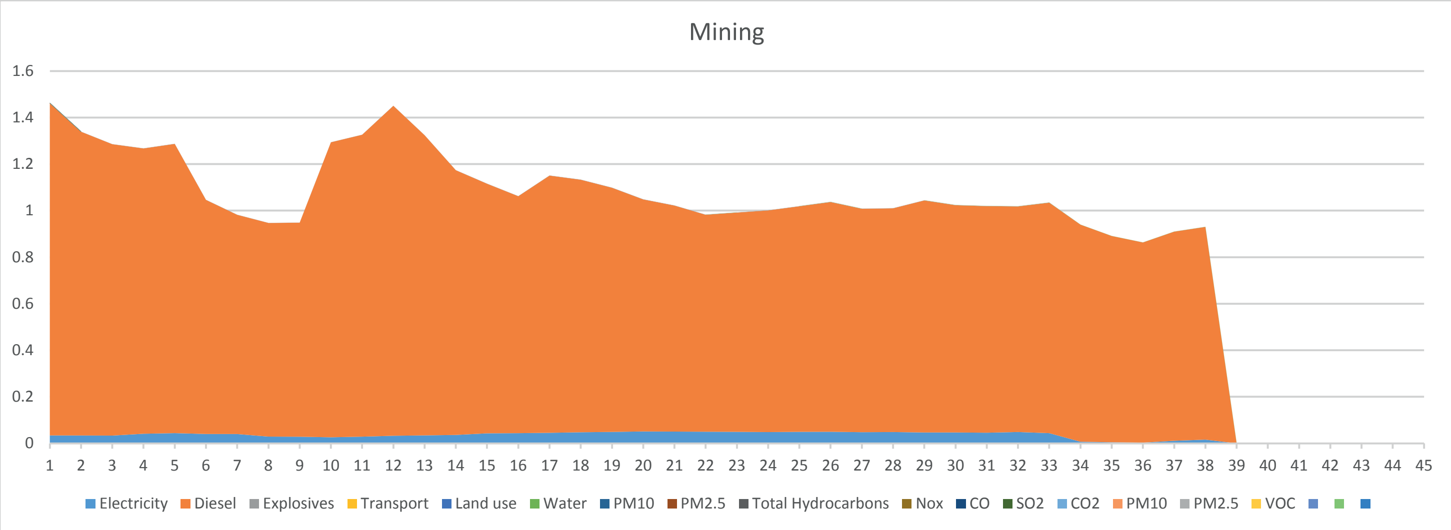
0.02
0.015
0.01
0.005
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Flocculant Water Land occupation Steel Transport
Electricity Crushing Electricity Classifiying Electricity Grinding and Gravity Electricity Magnetic Electricity Dewatering
Electricity Water Electricity Utilities

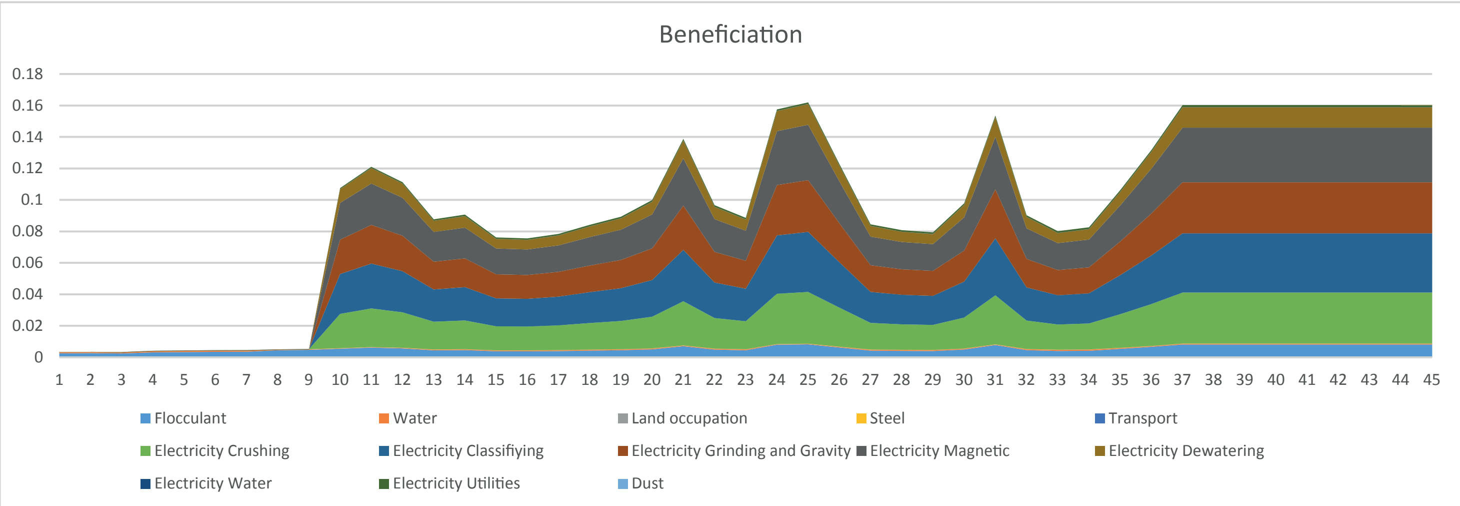

Hydrometallurgy
0.06
0.05
0.04
0.03
0.02
0.01
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Fresh HCL Fresh Oxalic Acid Fresh Iron Scraps Nitric Acid (68%) Ammonium hydroxide Sodium hydroxide
Limestone Quicklime Electricity Natural Gas Land Use

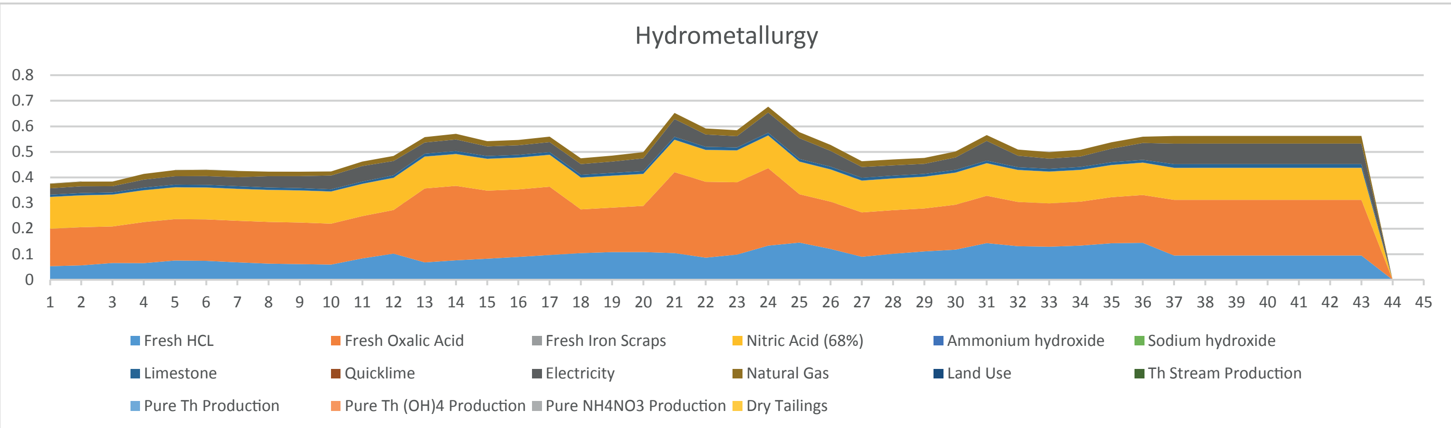

Waste management
0.008
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46
Energy Diesel Transport Land use Water Liner PM10 PM2.5 Nox CO

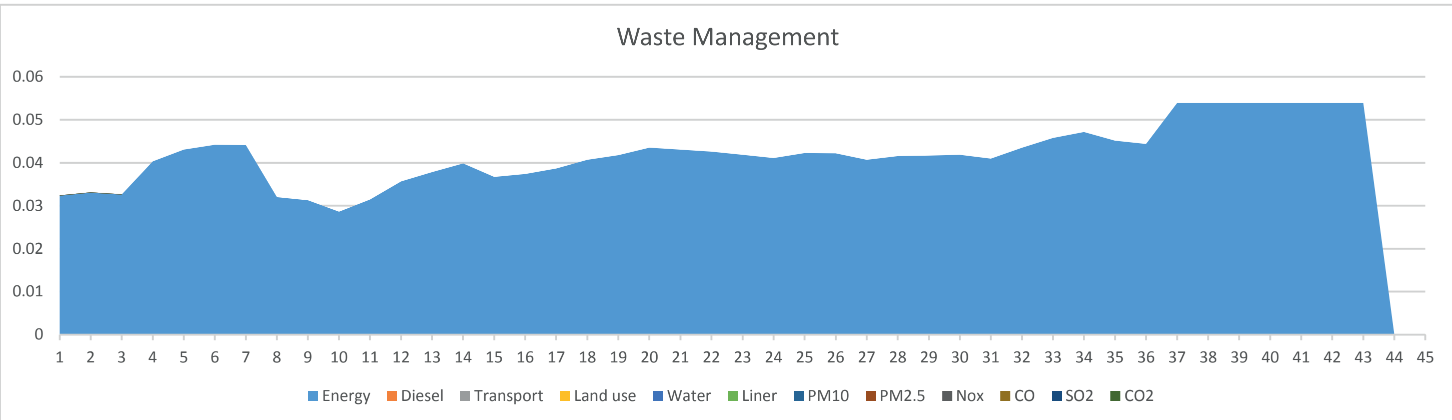
TRACI 2.1, Ecotoxicity (recommended) CTUe



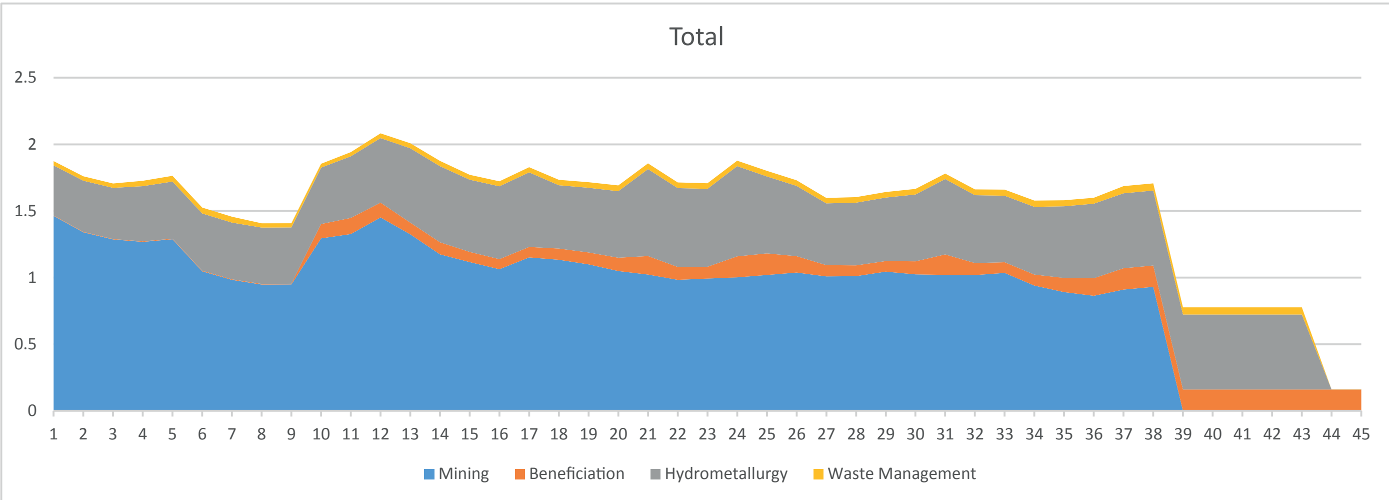

Mining
Electricity Diesel Explosives Transport Land use Water PM10 PM2.5 Total Hydrocarbons Nox CO SO2 CO2 PM10 PM2.5 VOC

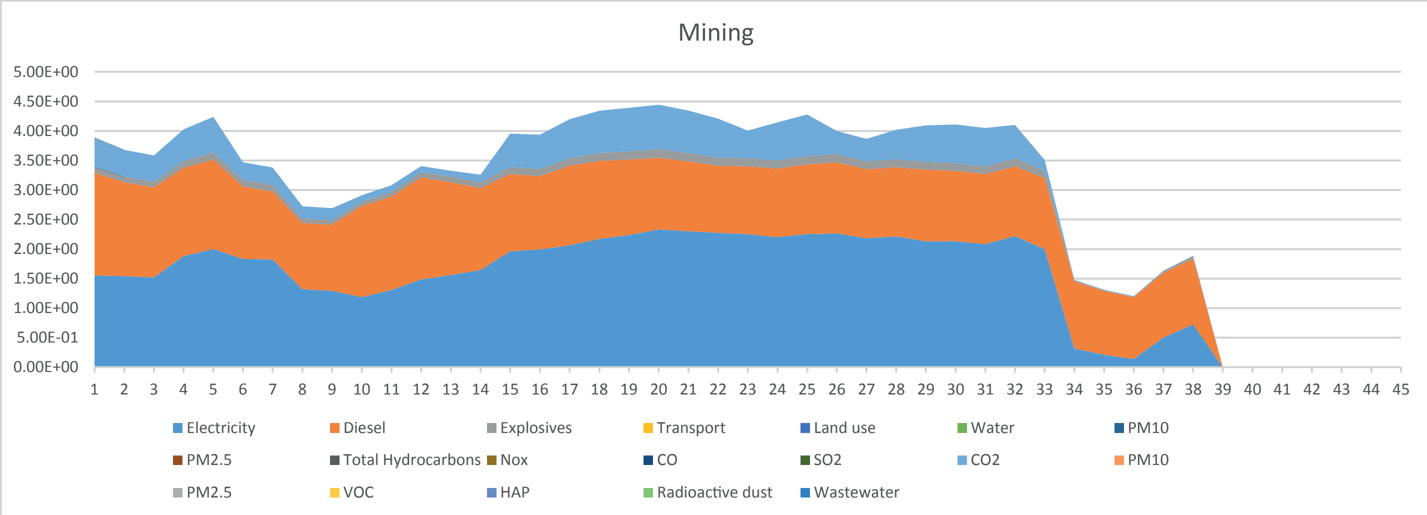

Beneficiation
Flocculant
Water
Land occupation
Steel
Transport
Electricity Crushing
Electricity Classifiying
Electricity Grinding and Gravity
Electricity Magnetic
Electricity Dewatering
Electricity Water
Electricity Utilities
Dust


Hydrometallurgy
Fresh HCL
Fresh Oxalic Acid
Fresh Iron Scraps
Nitric Acid (68%)
Ammonium hydroxide
Sodium hydroxide
Limestone
Quicklime
Electricity
Natural Gas
Land Use
Th Stream Production
Pure Th Production
Pure Th (OH)4 Production
Pure NH4NO3 Production
Dry Tailings

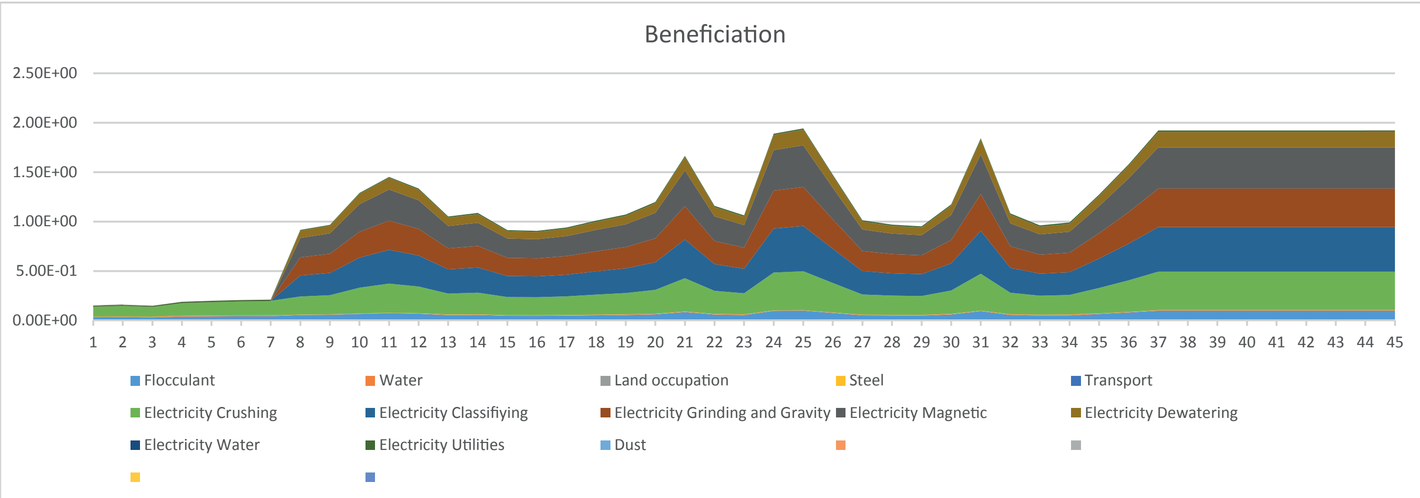

Waste Management
Energy Diesel Transport Land use Water Liner PM10 PM2.5 Nox CO SO2 CO2

TRACI 2.1, Global Warming Air,
excl. biogenic carbon kg CO2 eq.

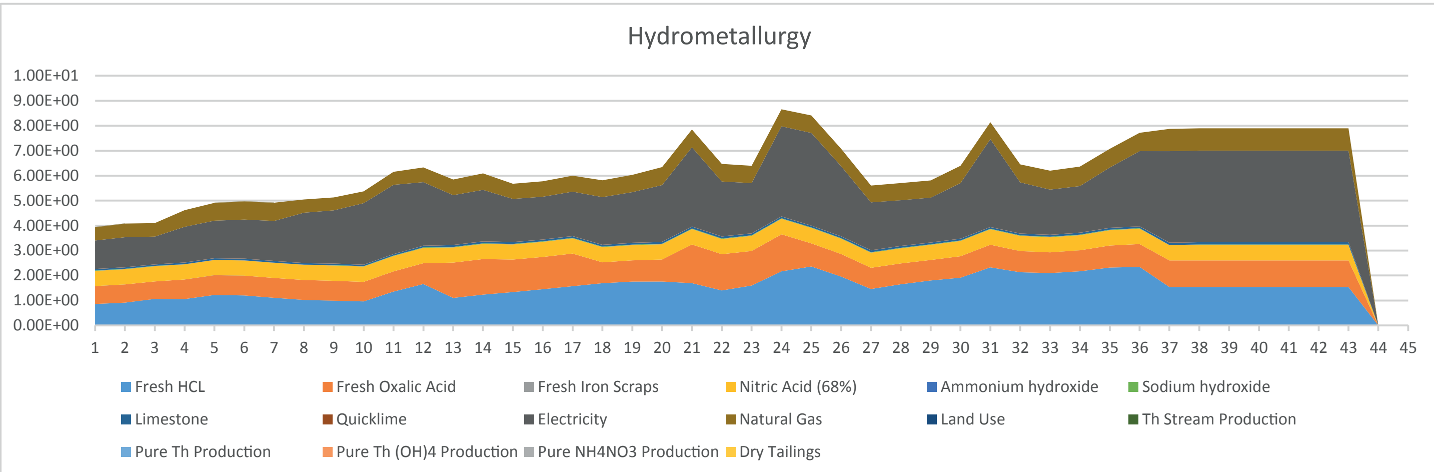




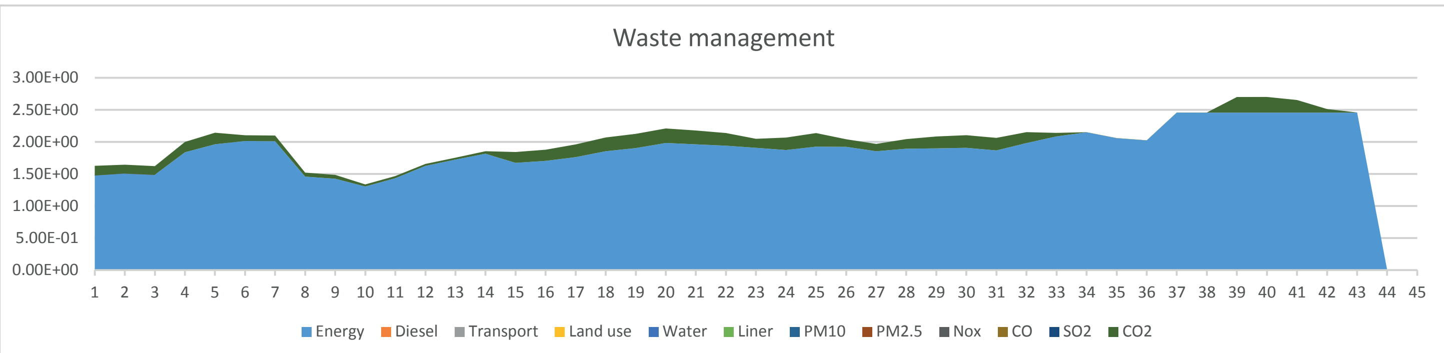
Mining
5.00E+00
4.50E+00
4.00E+00
3.50E+00
3.00E+00
2.50E+00
2.00E+00
1.50E+00
1.00E+00
5.00E-01
0.00E+00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Electricity
Diesel
Explosives
Transport
Land use
Water
PM10
PM2.5
Total Hydrocarbons
Nox
CO
SO2
CO2
PM10
PM2.5
VOC
HAP
Radioactive dust
Wastewater



Beneficiation
2.50E+00
2.00E+00
1.50E+00
1.00E+00
5.00E-01
0.00E+00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Flocculant
Water
Land occupation
Steel
Transport
Electricity Crushing
Electricity Classifiying
Electricity Grinding and Gravity
Electricity Magnetic
Electricity Dewatering
Electricity Water
Electricity Utilities
Dust



Hydrometallurgy
1.00E+01
9.00E+00
8.00E+00
7.00E+00
6.00E+00
5.00E+00
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Fresh HCL
Fresh Oxalic Acid
Fresh Iron Scraps
Nitric Acid (68%)
Ammonium hydroxide
Sodium hydroxide
Limestone
Quicklime
Electricity
Natural Gas
Land Use
Th Stream Production
Pure Th Production
Pure Th (OH)4 Production
Pure NH4NO3 Production
Dry Tailings



Waste management
3.00E+00
2.50E+00
2.00E+00
1.50E+00
1.00E+00
5.00E-01
0.00E+00
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45
Energy
Diesel
Transport
Land use
Water
Liner
PM10
PM2.5
Nox
CO
SO2
CO2

A.1.5 Environmental optimisation of mine scheduling through life cycle assessment integration - supplementary information

Supplementary information

2.1. Raw Data

Start with a data set that has element percentage for Al, Fe, Mn, P, and SiO2 for the whole block model. The model also has x, y, z coordinates for each of these readings.

Table 1. Element to mineral conversion

	Hematite ([stoichiometric])	Kutnohorite ([stoichiometric])	Gibbsite ([stoichiometric])	Quartz ([stoichiometric])	Apatite ([stoichiometric])
Si %				46.74349	
Al %			34.59016		
Fe %	69.94255				
Mn%		25.54854			
Ca %		18.638			39.89357
P %					18.49876
O %	30.05745	44.64247	61.53347	53.25651	41.40702
C %		11.17099			
H %			3.876369		0.200652
SG	5.26	3.11	2.35	2.65	3.1

2.2. Mineral and Economic Data

Each block is assigned an economic value and a waste value, based on the elemental grades and tonnage of the block. The waste value is calculated by multiplying the tonnage of the block, which is found by multiplying specific gravity with the dimensions of the block, with the mining cost per tonnage. The mining cost per tonne is defined at \$8/t. This can be seen in Equation 1 where WV is defined as Waste Value, T as tonnage and $C_m$as mining cost.

Equation 1.

$$WV = T \cdot C_m$$

The economic value is calculated by considering the economic value of the iron in the block and by subtracting the mining costs, processing costs and penalties for phosphorus content. The economic value of the iron is calculated by multiplying the Fe grade with the block tonnage at an iron ore price of 108 \$/t under an 85% recovery. The mining costs and processing costs are set at \$8/t and \$6/t respectively and the phosphor penalty is \$4/t. This is shown in Equation 2 where EV is defined as Economic Value, $\%_{Fe}$ as the iron content in the block, P_{Fe}as the price per ton of iron ore, R_{Fe} as the recovery for iron ore, $C_p$as as processing costs, $\%_P$the phosphor grade and $P_P$as the penalty per ton of phosphorus.

Equation 2.

$$EV = T \cdot \%_{Fe} \cdot P_{Fe} \cdot R_{Fe} - T \cdot (C_m + C_p) - -T \cdot \%_P \cdot P_P$$

The SimSched software resolves during the calculation process if a block is waste or ore by evaluating what maximizes the NPV at that point in time: mining and processing that block or mining and sending it to the waste dump (SimSched, 2017).

2.3. **Life Cycle Assessment**

TRACI utilize the amount of the chemical emission or resource used and the estimated potency of the stressor. The impacts associated with the consumption of diesel, electricity and ANFO are shown in table 2.

Table 2. TRACI 2.1. impacts based on consumption of diesel, electricity and ANFO

INPUTS		**1 kg Diesel US**	**1 MJ Electricity grid**	**1 kg ANFO**
TRACI 2.1, Acidification	kg SO2 eq.	0.00195	0.000367	0.004329
TRACI 2.1, Ecotoxicity (recommended)	CTUe	0.457016	0.003564	0.017861
TRACI 2.1, Eutrophication	kg N eq.	0.000451	2.03E-05	0.001397
TRACI 2.1, Global Warming Air, excl. biogenic carbon	**kg CO2 eq.**	**0.556196**	**0.162547**	**2.767791**
TRACI 2.1, Global Warming Air, incl. biogenic carbon	kg CO2 eq.	0.451491	0.162477	2.77358
TRACI 2.1, Human Health Particulate Air	kg PM2.5 eq.	0.000157	2.81E-05	6.78E-05
TRACI 2.1, Human toxicity, cancer (recommended)	CTUh	1.94E-09	2.54E-11	2.32E-10
TRACI 2.1, Human toxicity, non-canc. (recommended)	CTUh	1.44E-07	1.62E-09	1.21E-09
TRACI 2.1, Ozone Depletion Air	kg CFC 11 eq.	2.53E-11	6.80E-11	2.43E-12
TRACI 2.1, Resources, Fossil fuels	MJ surplus energy	6.952115	6.80E-11	5.030187
TRACI 2.1, Smog Air	kg O3 eq.	0.034976	0.00393	0.02198

2.3.1. Energy calculations example

Drilling					
Input	**Unit**	**Reference**	**Data Quality**	**Calculation**	**Remarks**
Electricity	MJ				
Diesel	kg	1		0.03kg/t	
Equipment					
Output	Unit	Reference	Data Quality	Calculation	Remarks
Dust	kg	1			
Blasting					
Input	**Unit**	**Reference**	**Data Quality**	**Calculation**	**Remarks**
ANFO	kg	1		0.5kg/t	
Output	Unit	Reference	Data Quality	Calculation	Remarks
Dust	kg/t handled	1	3	459.0597	*Blasting Dust emissions*
CO	kg/t used	1	3	34	*ANFO emission factors*
Nox	kg/t used	1	3	8	*ANFO emission factors*
SO2	kg/t used	1	3	0.06	*ANFO emission factors*

CH4	kg/t used	1	3	0.01	*ANFO emission factors*
CO2	kg/t used	1	3	167	*ANFO emission factors*

Excavating

Input	Unit	Reference	Data Quality	Calculation	Remarks
Diesel	g				
Output	**Unit**	**Reference**	**Data Quality**	**Calculation**	**Remarks**
Particle emissions	kg/t handled		3	0.019824	*Particle emissions of dumping overburden, loading stocpiles and truck overburden loading with excavator process*
Traffic emissions	kg/t handled		3	79.16967	*Dust emissions from truck traffic on unpaved roads*
Exhaust emissions	g/hp-hour			2E-07	*Off road vehicle emissions*

Loading & Hauling

Input	Unit	Reference	Data Quality	Calculation	Remarks
Diesel				2.2kg/t	
Output	**Unit**	**Reference**	**Data Quality**	**Calculation**	**Remarks**
Particle emissions	kg/t handled	1	3	0.019824	*Particle emissions of dumping overburden, loading stocpiles and truck overburden loading with excavator process*
Traffic emissions	kg/t handled		3	79.16967	*Dust emissions from truck traffic on unpaved roads*

Ore Dump

Input	Unit	Reference	Data Quality	Calculation	Remarks
Output	**Unit**	**Reference**	**Data Quality**	**Calculation**	**Remarks**
Particle emissions	kg/t handled	1	3	0.019824	*Particle emissions of dumping overburden, loading stocpiles and truck overburden loading with excavator process*
Traffic emissions	kg/t handled		3	79.16967	*Dust emissions from truck traffic on unpaved roads*
Dust emissions from stockpiles	kg/t handled		3	0.308186	*Dust emissions caused due to wind erosion on exposed areas and stockpiles*

Table 2.3. Parameters that are used in the calculations for global warming impact

Distance to crushing (blocks)	Tonnage per block	Specific Gravity	Hardness of Block
Location of block in model in relation to the crushing plant in 3D. This impacts the diesel consumption.	The total tonnage in a block	The specific gravity of the material in the block	The hardness of the block calculated from

Results

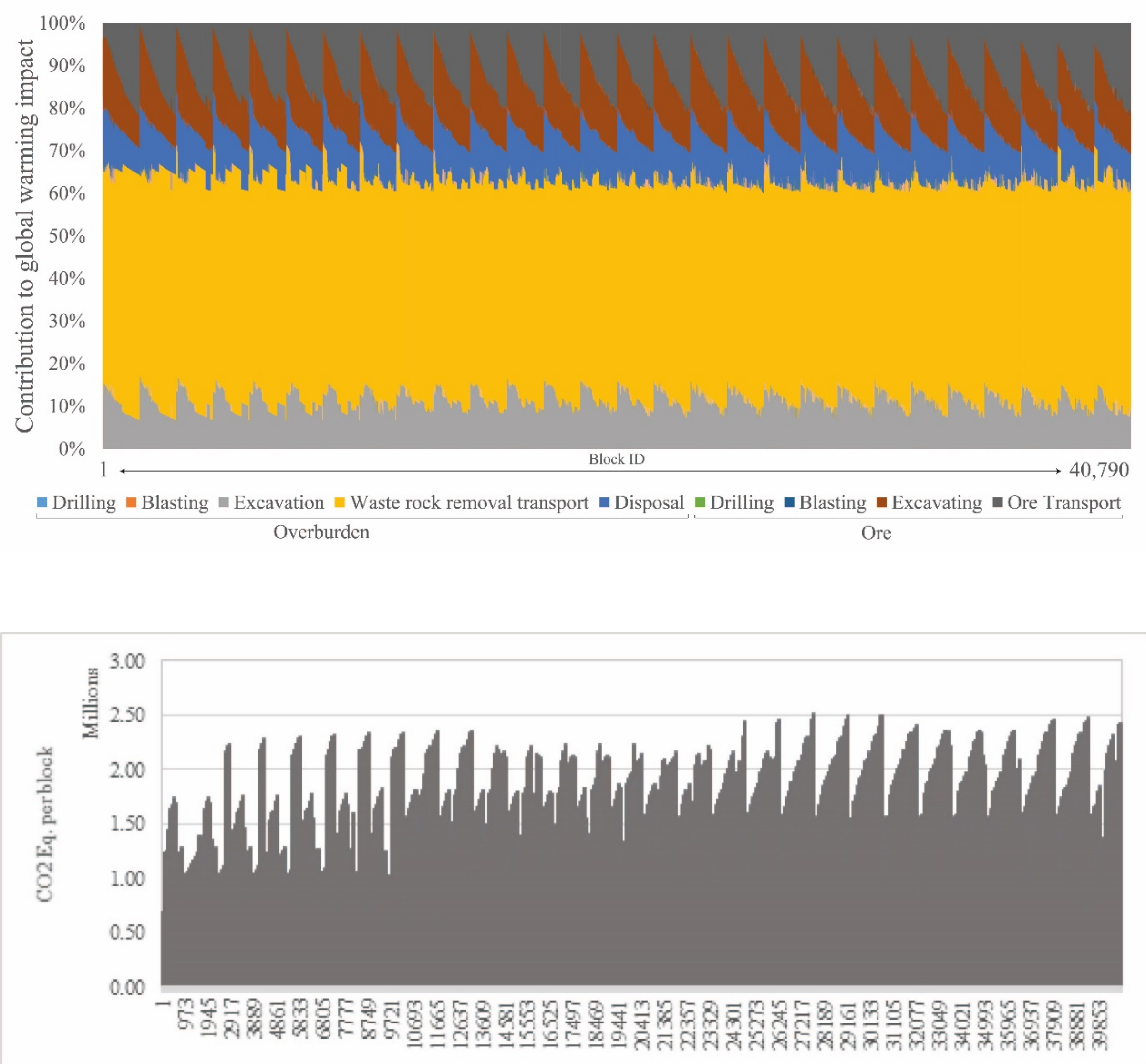


Figure 2.3.2. Global warming potential per block in the block model

2.8. **Multi-Criteria Decision Analysis**

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision analysis method developed by Hwang and Yoon (1981). The method is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution.

The results in table 2.8. shows the final year economic and environmental scores for each of the 9 scenarios.

Table 2.8. Economic and environmental data used for the TOPSIS analysis

Scenario	Economic	Environmental
1	64989.9	60535377870
2	64634	60359261820
3	62382.5	55607937939
4	65990.6	60298369118
5	62781.1	55562771824

6	67256.9	60320419448
7	64613.8	55551229300
8	68314	60223850890
9	67106.4	58909058000

Table 2. Economic and environmental data

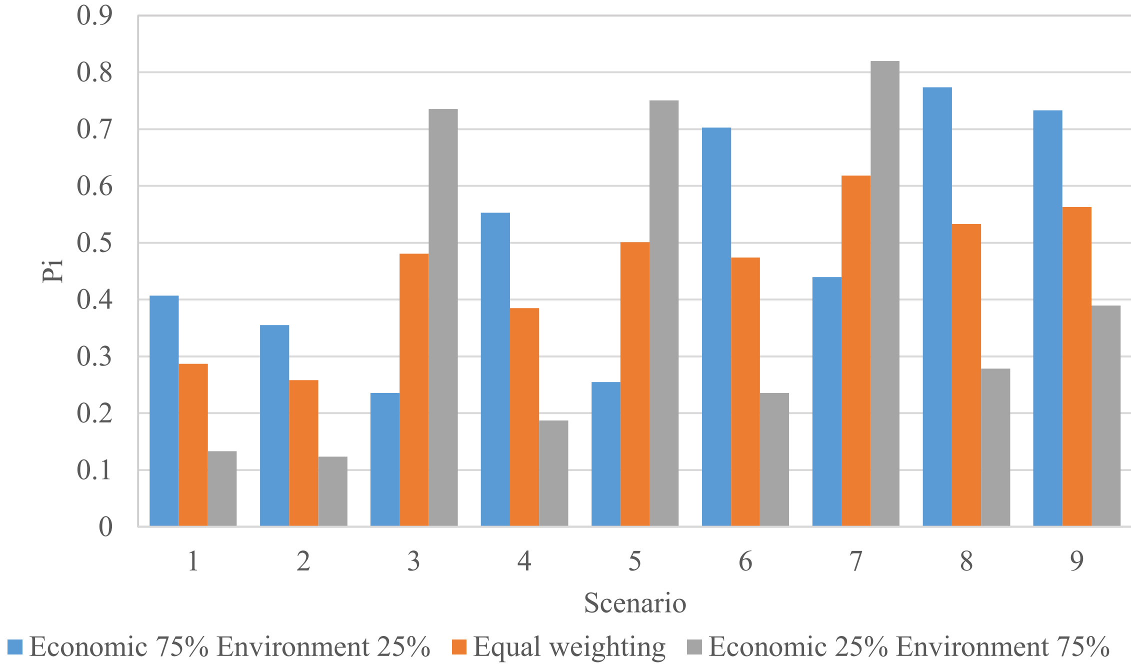
Scenario	Economic	Environmental
1	0.331402	0.344124296
2	0.329587	0.343123133
3	0.318106	0.316113374
4	0.336505	0.342776977
5	0.320139	0.315856619
6	0.342962	0.342902326
7	0.329484	0.315791003
8	0.348352	0.342353365
9	0.342195	0.334879187

Table 3. Distance from best case scenario (Si+) and worst case scenario (Si-)

Scenario	Economic	Environmental	Si+	Si-	Pi
1	0.165701	0.172062148	0.016508301	0.006647937	0.287091
2	0.164794	0.171561566	0.016576974	0.005762303	0.257945
3	0.159053	0.158056687	0.015124061	0.014005461	0.4808
4	0.168252	0.171388489	0.014736097	0.009223996	0.384973
5	0.160069	0.157928309	0.014106952	0.01417033	0.501121
6	0.171481	0.171451163	0.013821006	0.012442985	0.473766
7	0.164742	0.157895502	0.009434185	0.015266263	0.618056
8	0.174176	0.171176682	0.013281181	0.015149101	0.532851
9	0.171097	0.167439594	0.01002844	0.012900855	0.562636

Table 4. Weighting scenarios for the TOPSIS multi-criteria decision analysis

Economic 75% Environment 25%	Equal weighting	Economic 25% Environment 75%
0.406602	0.287091	0.132999
0.355095	0.257945	0.12364
0.23588	0.4808	0.735229
0.553014	0.384973	0.187144
0.25465	0.501121	0.750407
0.702598	0.473766	0.23561
0.439366	0.618056	0.81966
0.773588	0.532851	0.278174
0.732808	0.562636	0.389436



0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Pi
1
2
3
4
5
6
7
8
9
Scenario
Economic 75% Environment 25%
Equal weighting
Economic 25% Environment 75%

A.1.6 Applying and advancing the economic resource scarcity potential (ESP) method for rare earth elements - Supplementary information

Supplementary information

Contents

1. Glossary of terms and impact categories

1.1. Terms

Characterization factors: Life-cycle impact assessment provides characterization factors (CF) that express "impacts" per "amount" of inventory. The impact score (or damage score) on a target (humans, ecosystems, climate, etc.) can be estimated as the product of an emission (E) and a characterization factor (Rosenbaum et al. 2007):

Herfindahl-Hirschmann Index: The indicator system also takes into account each element's HHI or Herfindahl-Hirschmann Index (HHI), which is calculated from the percentage of worldwide production (by mass) that takes place in each of its producing countries. The HHI is calculated by squaring the market share of each company or country with regard to the production/reserves and the summation of results (Graedel et al, 2012).

1.2. Impact categories

Reserve availability refers to the amount of time it would take to deplete reserves under current production rates. The USGS definition of reserves was used which included economic considerations referring to reserves as "…a working inventory of mining companies' supply of an economically extractable mineral commodity." Using this definition underestimates the stocks as it only depicts the profitable extraction under current economic conditions. Reserve availability was calculated by obtaining data from the annual element reports USGS (2016). A reserve-to-annual-production ratio was then calculated under the assumption that current production technologies are used. High levels of recycling can reduce the reliance on a raw material supply (Binnemans et al., 2013).

Recycling rates are calculated by the annual tonnage of material scrap consumed divided by the tonnage of material produced. Lack of data availability meant that 1% of production was assumed (EU, 2014).

Country concentration of reserves - The Herfindahl-Hirschman Index (HHI) was used to calculate the market concentration for the country concentration of reserves.

Country concentration of mine production: The Herfindahl-Hirschman Index (HHI) was used to calculate the market concentration for the country concentration of mine production.

Company concentration of mine production: The Herfindahl-Hirschman Index (HHI) was used to calculate the market concentration for the company concentration of mine production.

Governance stability - Governance stability data aim to quantify the stability of the governance in the mineral producing countries. For this WGI data were used from The World Bank Group (2012), which calculated voice and accountability, political stability and absence of violence and government effectiveness creating one factor. These three factors were given equal weighting and multiplied by the production rates of the individual elements in each country

Socioeconomic stability - A similar approach was used to calculate socioeconomic stability. Human Development Index (HDI) data were used from the UNDP (2011) to calculate human development in the mine producing countries. Life expectancy, educational attainment and income were equally aggregated before being multiplied by the relative production in each producing country.

Trade barriers to mine production - The risk associated with material supply also includes trade barriers and restrictions. This is calculated by using data from BDI (2010) then calculating the percentage share of the elements under trade barriers.

Companion metal fraction -Raw material that is mined as a companion metal within host metal ore bodies is at a greater risk of supply disruption due to the fact that if a host metal deposit becomes uneconomic, then so does the companion metal. This is the case for REE, with a large amount of current production being obtained as a by-product from Bayan Obo iron ore mine. Data for the companion metal fraction was replicated from Nassar et al (2015).

Economic importance - Economic importance. The method was adjusted from the approach of Schneider et al (2014). A simple percentage growth in demand did not reflect the importance of growth because some individual REE which may have had a large forecasted demand growth in percentage per annum could appear anomalously important if they are produced in small quantities. The variation in price of individual REE also needed to be taken into account to reflect the economic importance of REE production. In response to this a calculation was made of total predicted production over 10 years, using data from Roskill Information Services (2017), and multiplying this by the current price of the individual REE.

2.1.1. Overall impact scores - raw data

	Companion metal	Policy potential	Demand growth	Socioeconomic stability	Governance stability	Company concentrati	Country concentrati	Country concentrati	Recycling	Reserve availability
La	93.1	55	3075.535	0.788542	0.045846	3922.223	7291.869	2916.413	14.88665	1488.665
Ce	88.1	55	2711.883	0.847695	0.082812	9856.264	6208.354	2844.913	20.99382	2099.382
Pr	98.4	55	11730.6	0.783372	0.041704	9831.641	7423.457	3272.404	13.67734	1367.734
Nd	94.9	55	66736.54	0.792318	0.045518	9818.796	7340.245	3073.738	13.55472	1355.472
Sm	90.8	54.9	18.93991	0.799467	0.0439	9416.427	7646.843	2495.973	11.3569	1135.69
Eu	96.2	54.9	858.307	0.837892	0.064185	9597.236	7510.005	2557.774	10.98798	1098.798
Gd	95.7	54.9	1288.245	0.730071	0.007235	9412.272	8880.936	2827.828	8.67814	867.814
Tb	95.8	54.8	4275.342	0.715179	-0.00252	9464.422	9407.891	2977.735	9.291468	929.1468
Dy	94.2	54.9	14895.65	0.696716	-0.00917	7689.828	9517.926	3067.402	9.13735	913.735
Ho	94.3	55.2	17.75238	0.664843	-0.01178	2422.85	8931.727	3351.271	8.840075	884.0075
Er	96.4	55	1391.534	0.680789	-0.01354	2795.743	9509.818	3684.092	10.30319	1030.319
Tm	92.5	55	5.477501	0.683137	-0.01264	2742.286	9496.86	3504.471	10.40735	1040.735
Yb	92.5	54.9	15.70765	0.687076	-0.01454	2914.861	9765.934	3635.959	13.13579	1313.579
Lu	91.4	55.1	1556.629	0.664945	-0.01665	2795.553	9368.251	3721.356	12.26733	1226.733
Y	84.3	54.9	1496.986	0.691659	-0.0139	3035.769	9819.29	3289.774	8.020798	802.0798

2.1.2. Overall impact scores - normalised scores

	Economic importance	Companion metal fraction	Policy potential index	Socioeconomic stability	Governance stability	Company concentration of mine production	Country concentration of mine production	Country concentration of reserves	Recycling	Reserve availability
La	0.046006	0.624113	0.5	0.323504	0.371664	0.201707	0.300065	0.656891	0.52924	0.52924
Ce	0.040557	0.269504	0.5	0	0	1	0	0.71524	1	1
Pr	0.175707	1	0.5	0.351774	0.413316	0.996688	0.336506	0.366377	0.436024	0.436024
Nd	1	0.751773	0.5	0.302849	0.374968	0.99496	0.313462	0.528502	0.426572	0.426572
Sm	0.000202	0.460993	0.75	0.263752	0.391235	0.94083	0.39837	1	0.257157	0.257157
Eu	0.01278	0.843972	0.75	0.053613	0.187281	0.965154	0.360475	0.949566	0.22872	0.22872
Gd	0.019223	0.808511	0.75	0.643274	0.759871	0.940271	0.740136	0.729182	0.05067	0.05067
Tb	0.063986	0.815603	1	0.724719	0.857907	0.947286	0.886069	0.606847	0.097947	0.097947
Dy	0.223137	0.702128	0.75	0.825691	0.924846	0.708554	0.916541	0.533673	0.086067	0.086067
Ho	0.000184	0.70922	0	1	0.951012	0	0.754201	0.302016	0.063152	0.063152
Er	0.020771	0.858156	0.5	0.912791	0.968779	0.050164	0.914296	0.03041	0.175934	0.175934
Tm	0	0.58156	0.5	0.89995	0.959721	0.042973	0.910707	0.176994	0.183962	0.183962
Yb	0.000153	0.58156	0.75	0.878413	0.978767	0.066189	0.985224	0.06969	0.394279	0.394279
Lu	0.023245	0.503546	0.25	0.999441	1	0.050139	0.875091	0	0.327336	0.327336
Y	0.022351	0	0.75	0.853344	0.972343	0.082455	1	0.352201	0	0

2.1.3. Overall impact scores – weighted scores

	Demand growth	Companion metal	Policy potential	Socioeconomic	Governance	Company concentra	Country concentra	Country concentra	Recycling	Reserve availabilit
La	0.132906	9.737941	4	7.267706	2.210148	1.808256	4.001729	19.17801	1.120382	0.017506
Ce	0.184456	1.815804	4	1E-08	1E-08	1E-08	0	22.73635	4	1E-08
Pr	1.416507	1E-08	4	8.593408	2.733278	44.1505	5.032731	5.965869	1E-08	0.011882
Nd	44.44444	14.12907	4	6.369258	2.249619	43.99754	4.367039	12.41397	0.727854	0.011373
Sm	1.52E-05	5.312862	9	4.830895	2.449036	39.34048	7.053275	44.44444	0.264519	0.004133
Eu	0.03123	17.8072	9	0.199608	0.561186	41.40095	5.775196	40.07446	0.20925	0.00327
Gd	0.011249	16.34224	9	28.73619	9.238454	39.29375	24.3467	23.63141	0.01027	0.00016
Tb	0.145014	16.6302	16	36.4734	11.77608	39.88229	34.89412	16.36728	0.038375	0.0006
Dy	2.157087	12.32458	9	47.34484	13.68544	22.3133	37.33546	12.65807	0.02963	0.000463
Ho	1.34E-06	12.57482	1E-08	69.44444	14.47078	0	25.28088	4.053927	0.015953	0.000249
Er	0.012308	18.41079	4	57.86029	15.01653	0.111843	37.15277	0.041102	0.123811	0.001935
Tm	0	8.455309	4	56.24381	14.73703	0.082075	36.86169	1.392299	0.135368	0.002115
Yb	9.05E-07	8.455309	9	53.58393	15.32777	0.194711	43.14071	0.215852	0.621823	0.009716
Lu	0.005428	6.338967	1	69.36679	16	0.111729	34.03485	1E-08	0.428595	0.006697
Y	0.050379	0	9	50.56917	15.12721	0.302167	1E-08	5.513144	0	0

2.2. Calculations for impact categories

2.2.1. Reserve to production ratio – data obtained from USGS (https://minerals.usgs.gov/minerals/pubs/mcs/2017/mcs2017.pdf)

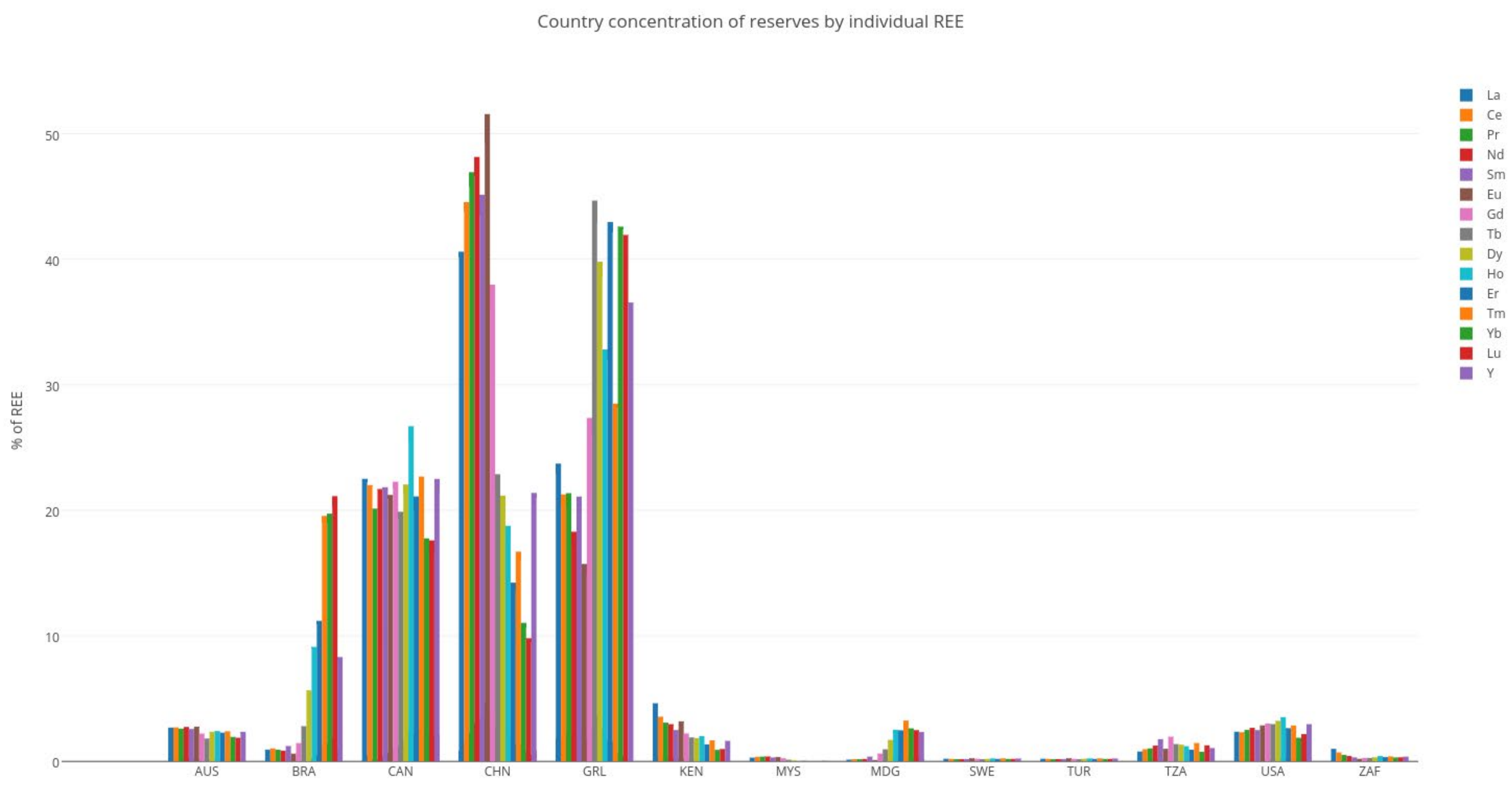
2.2.2. Recycling rates – data obtained from - data obtained from United Nations Environment Programme 2011 (https://www.unep.org/greeneconomy/sites/unep.org.greeneconomy/files/field/image/green_economy report_final_dec2011.pdf)

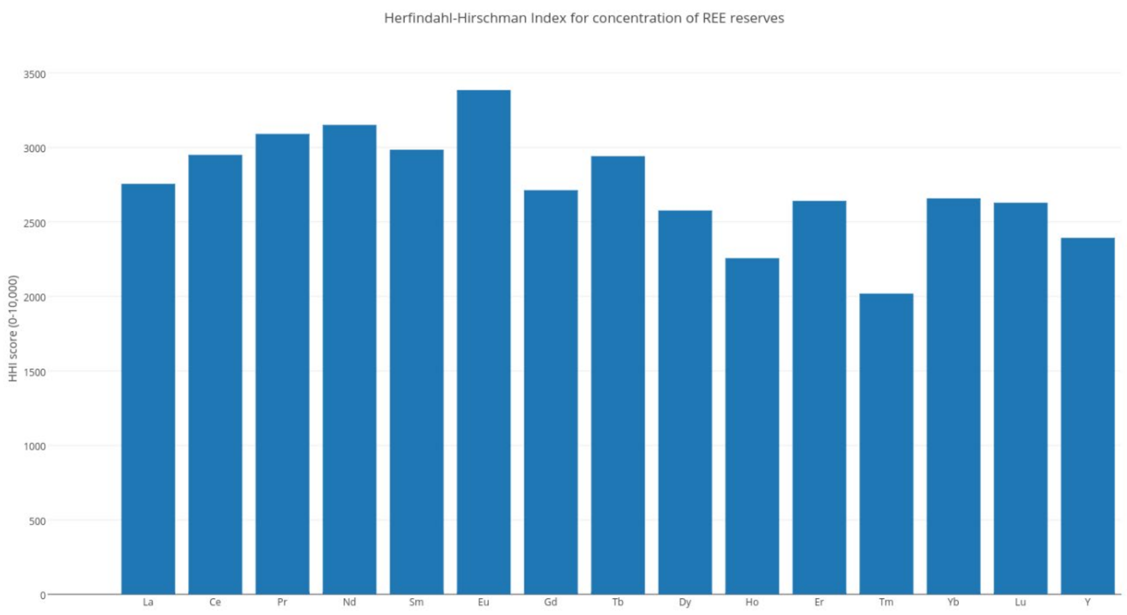
2.2.3. HHI calculation for country concentration of reserves

	AUS	BRA	CAN	CHI	GRE	KEN	MAL	MDG	SWE	TUR	TZA	USA	ZAF	HHI
La	2.694	0.941	22.509	40.600	23.722	4.632	0.299	0.142	0.211	0.211	0.788	2.363	1.001	**2754.761**
Ce	2.710	1.031	22.007	44.549	21.261	3.561	0.365	0.180	0.197	0.197	0.971	2.322	0.715	**2949.120**
Pr	2.609	0.933	20.134	46.934	21.367	3.090	0.379	0.173	0.175	0.175	1.034	2.509	0.523	**3089.789**
Nd	2.747	0.855	21.700	48.149	18.294	2.965	0.391	0.194	0.177	0.177	1.257	2.679	0.435	**3150.177**
Sm	2.582	1.223	21.841	45.138	21.094	2.497	0.313	0.380	0.187	0.187	1.773	2.498	0.319	**2983.638**
Eu	2.769	0.617	21.225	51.559	15.728	3.190	0.351	0.110	0.245	0.245	1.003	2.868	0.207	**3383.938**
Gd	2.217	1.458	22.275	37.974	27.360	2.227	0.252	0.628	0.204	0.204	1.965	3.021	0.277	**2712.376**
Tb	1.820	2.806	19.884	22.874	44.672	1.911	0.135	0.964	0.176	0.176	1.380	2.970	0.275	**2940.807**
Dy	2.361	5.658	22.060	21.176	39.805	1.858	0.086	1.714	0.204	0.204	1.334	3.232	0.329	**2575.923**
Ho	2.421	9.123	26.702	18.766	32.815	2.015	0.000	2.523	0.235	0.235	1.208	3.525	0.428	**2255.666**
Er	2.291	11.196	21.107	14.239	42.963	1.356	0.033	2.478	0.199	0.199	0.935	2.647	0.343	**2640.742**
Tm	2.403	19.555	22.690	16.713	28.495	1.680	0.000	3.252	0.241	0.241	1.463	2.861	0.397	**2018.252**
Yb	1.953	19.735	17.766	11.036	42.596	0.922	0.007	2.631	0.196	0.196	0.766	1.885	0.314	**2657.155**
Lu	1.883	21.129	17.606	9.809	41.930	0.987	0.000	2.492	0.198	0.198	1.277	2.176	0.327	**2628.047**
Y	2.355	8.311	22.504	21.384	36.549	1.635	0.040	2.337	0.227	0.227	1.064	2.964	0.378	**2392.476**

Table 1. HHI calculation for country concentration of reserves.

Reserve data from USGS was divided by the relative proportion of individual REE in the deposits

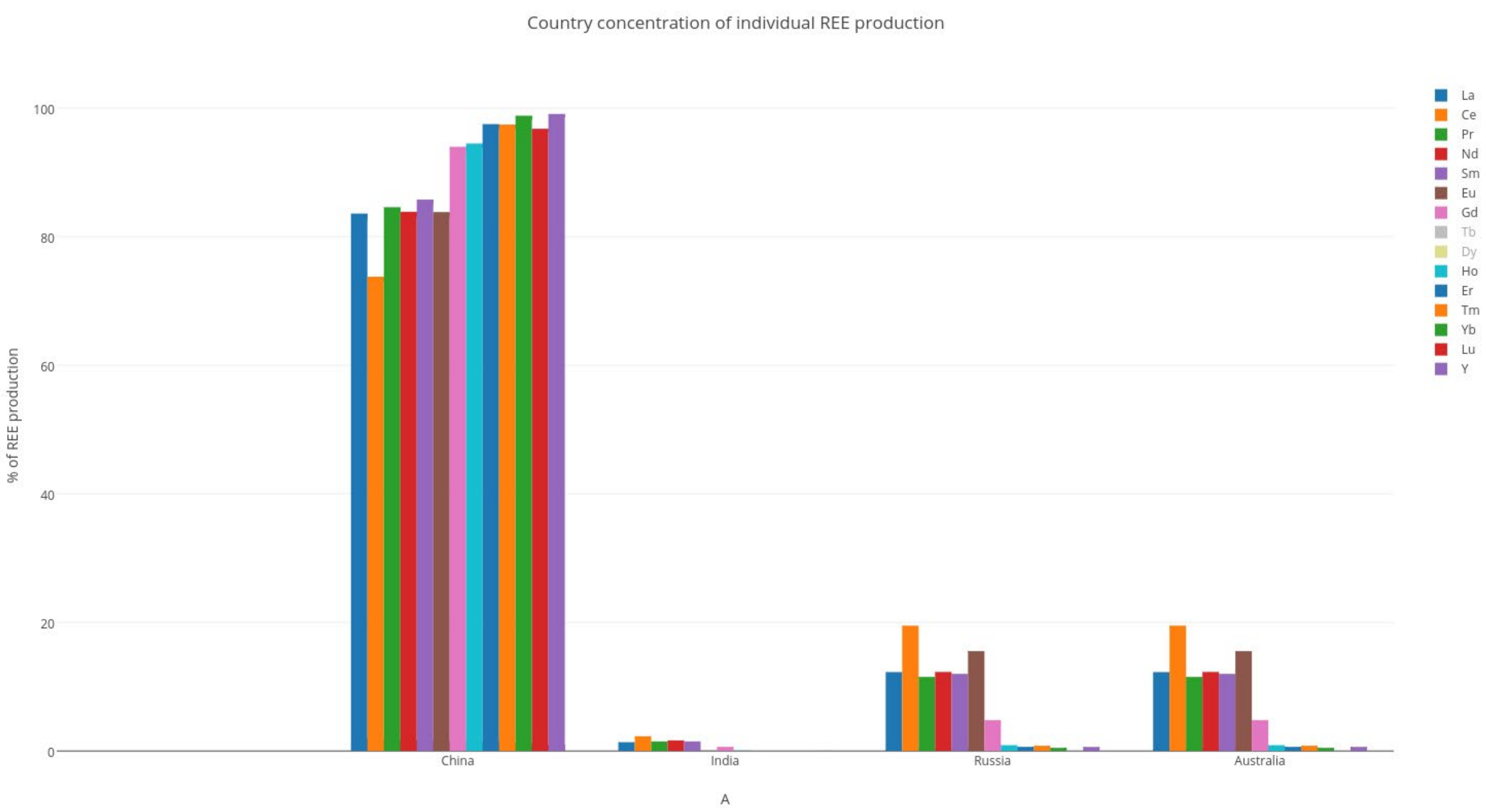

Country concentration of reserves by individual REE
% of REE
0
10
20
30
40
50
AUS
BRA
CAN
CHN
GRL
KEN
MYS
MDG
SWE
TUR
TZA
USA
ZAF
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Y



Herfindahl-Hirschman Index for concentration of REE reserves
HHI score (0-10,000)
0
500
1000
1500
2000
2500
3000
3500
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Y

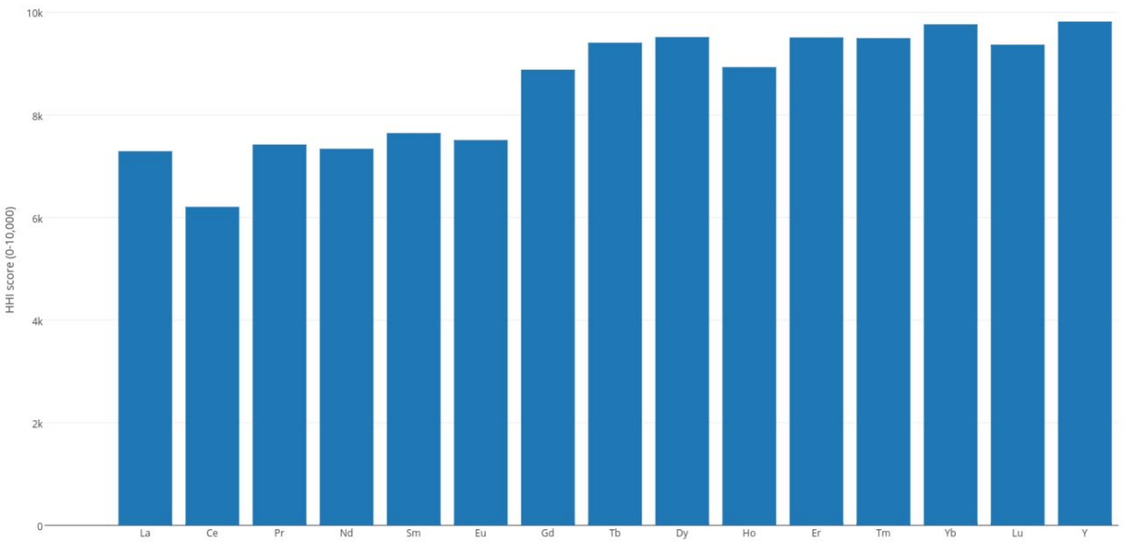
2.2.4. HHI calculation for country concentration of mine production

	Australia	Russia	India	China	HHI Index
La	12.27504517	12.27504517	1.373195409	83.59802532	6208.354239
Ce	19.49691401	19.49691401	2.290308962	73.77566951	6208.354239
Pr	11.52461904	11.52461904	1.491627741	84.59076754	6208.354239
Nd	12.2971291	12.2971291	1.647239735	83.87546092	6208.354239
Sm	11.99846858	11.99846858	1.492783708	85.77113694	6208.354239
Eu	15.53406189	15.53406189	0.071180337	83.82950216	6208.354239
Gd	4.800357353	4.800357353	0.64172536	93.99168903	6208.354239
Tb	2.858860767	2.858860767	0.231431586	96.90970765	6208.354239
Dy	1.538667821	1.538667821	0.13452353	97.53549377	6208.354239
Ho	0.904607034	0.904607034	0.073230093	94.4991277	6208.354239
Er	0.641133279	0.641133279	0.012975316	97.51408203	6208.354239
Tm	0.812937317	0.812937317	0	97.44505415	6208.354239
Yb	0.485737251	0.485737251	0	98.82035239	6208.354239
Lu	0	0	0	96.78972713	6208.354239
Y	0.633836063	0.633836063	0.04557186	99.08826495	6208.354239



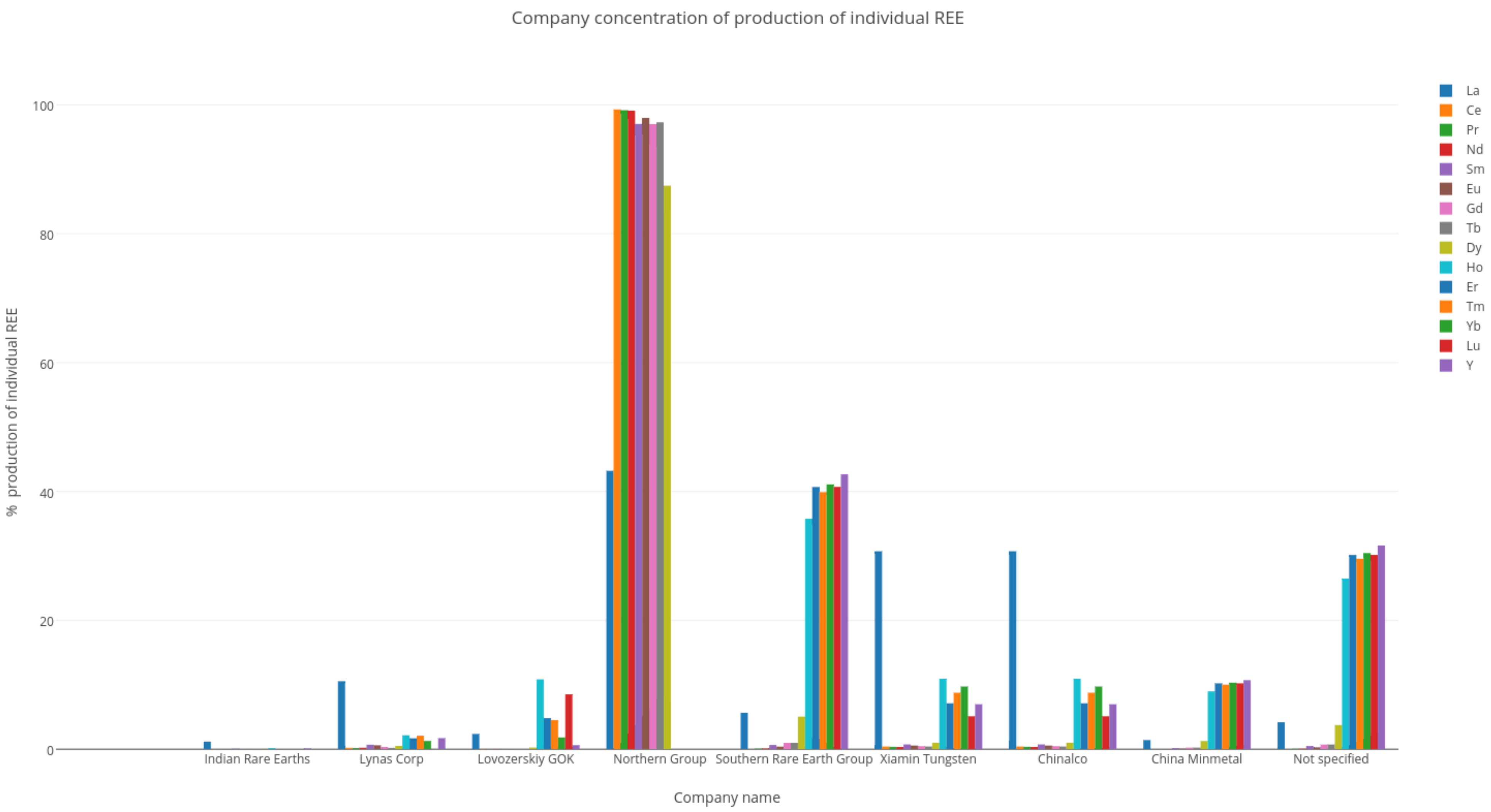
Country concentration of individual REE production
% of REE production
0
20
40
60
80
100
China
India
Russia
Australia
A
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Y

Herfindahl-Hirschman Index for country concentration of mine production



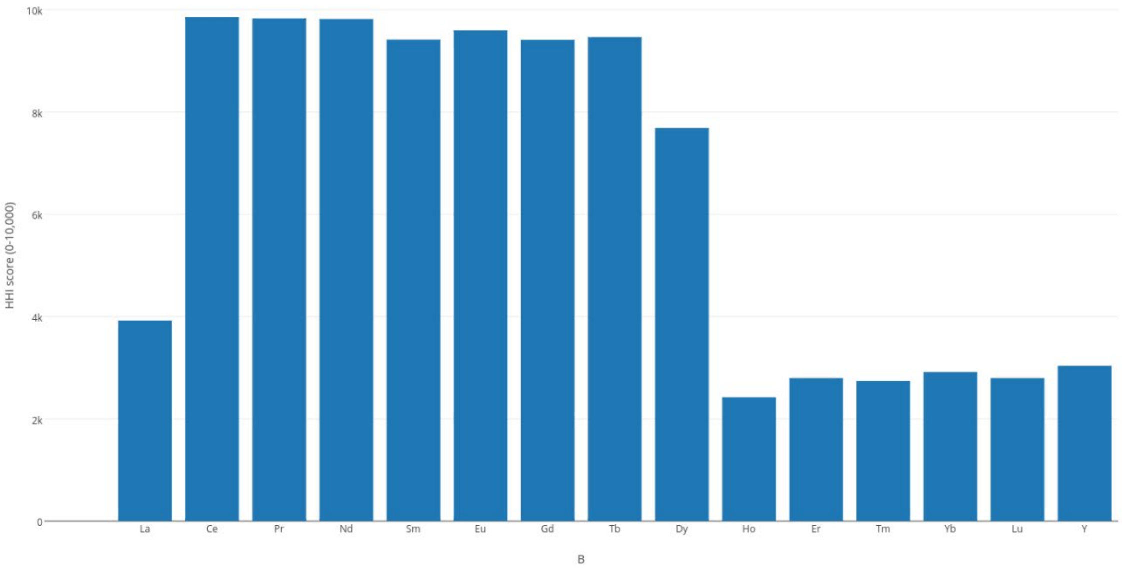
2.2.5. Company concentration of mine production

	Not specified	China Minmetal	Chinalco	Xiamin Tungsten	Southern Rare Earth Group	Northern Group	Lovozerskiy GOK	Lynas Corp	Indian Rare Earths	HHI
La	4.186	1.419	30.713	30.713	5.652	43.195	2.367	10.552	1.180	**3922.223**
Ce	0.005	0.002	0.410	0.410	0.007	99.277	0.051	0.222	0.026	**9856.264**
Pr	0.075	0.025	0.374	0.374	0.101	99.153	0.040	0.194	0.025	**9831.641**
Nd	0.091	0.031	0.353	0.353	0.122	99.088	0.041	0.228	0.031	**9818.796**
Sm	0.489	0.166	0.747	0.747	0.660	97.026	0.043	0.696	0.087	**9416.427**
Eu	0.293	0.099	0.566	0.566	0.396	97.959	0.022	0.611	0.003	**9597.236**
Gd	0.726	0.246	0.468	0.468	0.981	97.006	0.042	0.355	0.048	**9412.272**
Tb	0.730	0.247	0.411	0.411	0.985	97.275	0.000	0.206	0.017	**9464.422**
Dy	3.746	1.270	1.004	1.004	5.057	87.443	0.265	0.514	0.045	**7689.828**
Ho	26.490	8.980	10.941	10.941	35.762	0.000	10.838	2.168	0.175	**2422.850**
Er	30.139	10.217	7.119	7.119	40.688	0.000	4.827	1.689	0.034	**2795.743**
Tm	29.544	10.015	8.763	8.763	39.885	0.000	4.507	2.103	0.000	**2742.286**
Yb	30.435	10.317	9.719	9.719	41.088	0.000	1.824	1.277	0.000	**2914.861**
Lu	30.153	10.221	5.111	5.111	40.707	0.000	8.518	0.000	0.000	**2795.553**
Y	31.610	10.715	6.977	6.977	42.673	0.000	0.632	1.723	0.124	**3035.769**



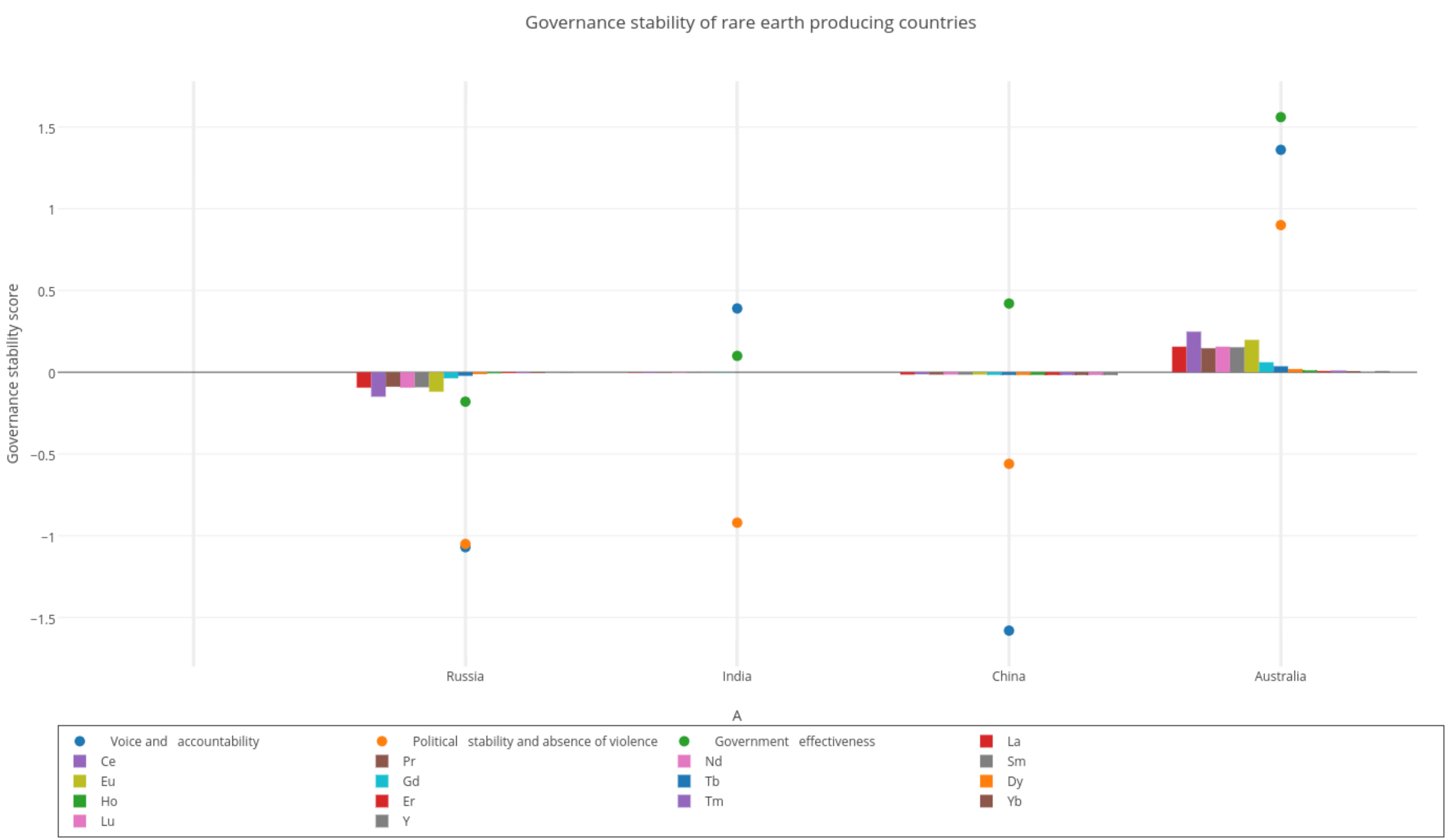
Company concentration of production of individual REE
% production of individual REE
0
20
40
60
80
100
Indian Rare Earths
Lynas Corp
Lovozerskiy GOK
Northern Group
Southern Rare Earth Group
Xiamin Tungsten
Chinalco
China Minmetal
Not specified
Company name
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Y

Herfindahl-Hirschman Index for company concentration of REE production



2.2.6. Governance stability

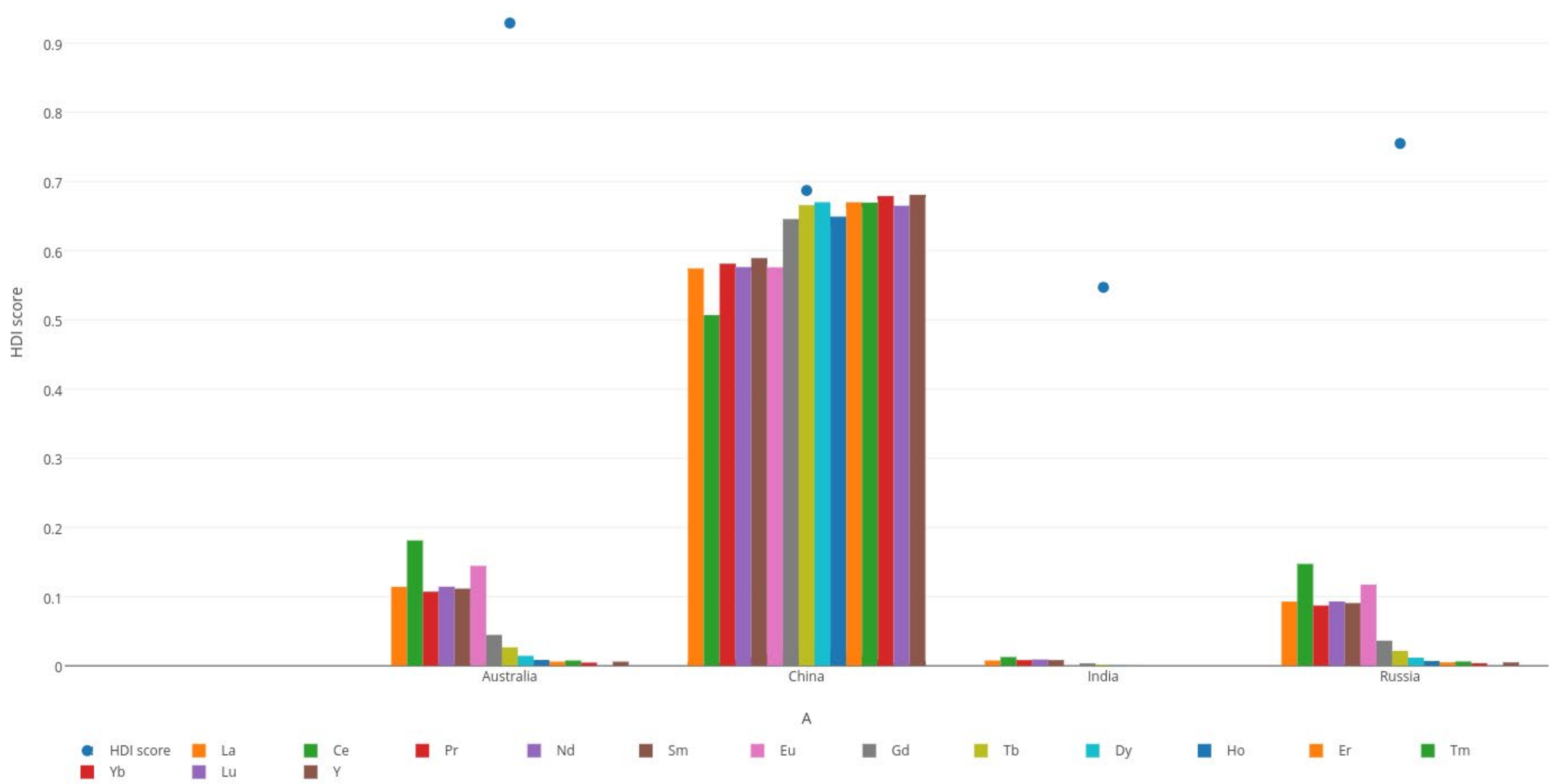
Country	Australia	China	India	Russia
Voice and accountability	1.36	-1.58	0.39	-1.07
Political stability and absence of violence	0.9	-0.56	-0.92	-1.05
Government effectiveness	1.56	0.42	0.1	-0.18
La	0.156302	-0.01438	-0.00197	-0.09411
Ce	0.248261	-0.01269	-0.00328	-0.14948
Pr	0.146747	-0.01455	-0.00214	-0.08836
Nd	0.156583	-0.01443	-0.00236	-0.09428
Sm	0.15278	-0.01475	-0.00214	-0.09199
Eu	0.1978	-0.01442	-0.0001	-0.11909
Gd	0.061125	-0.01617	-0.00092	-0.0368
Tb	0.036403	-0.01667	-0.00033	-0.02192
Dy	0.019592	-0.01678	-0.00019	-0.0118
Ho	0.011519	-0.01625	-0.0001	-0.00694
Er	0.008164	-0.01677	-1.9E-05	-0.00492
Tm	0.010351	-0.01676	0	-0.00623
Yb	0.006185	-0.017	0	-0.00372
Lu	0	-0.01665	0	0
Y	0.008071	-0.01704	-6.5E-05	-0.00486


Governance stability of rare earth producing countries
Governance stability score
1.5
1
0.5
0
−0.5
−1
−1.5
Russia
India
China
Australia
A
Voice and accountability
Political stability and absence of violence
Government effectiveness
La
Ce
Pr
Nd
Sm
Eu
Gd
Tb
Dy
Ho
Er
Tm
Yb
Lu
Y

2.2.7. Socioeconomic stability of rare earth producing countries

Country	Australia	China	India	Russia
HDI	0.929	0.687	0.547	0.755
La	0.114035	0.574318	0.007511	0.092677
Ce	0.181126	0.506839	0.012528	0.147202
Pr	0.107064	0.581139	0.008159	0.087011
Nd	0.11424	0.576224	0.00901	0.092843
Sm	0.111466	0.589248	0.008166	0.090588
Eu	0.144311	0.575909	0.000389	0.117282
Gd	0.044595	0.645723	0.00351	0.036243
Tb	0.026559	0.66577	0.001266	0.021584
Dy	0.014294	0.670069	0.000736	0.011617
Ho	0.008404	0.649209	0.000401	0.00683
Er	0.005956	0.669922	7.1E-05	0.004841
Tm	0.007552	0.669448	0	0.006138
Yb	0.004512	0.678896	0	0.003667
Lu	0	0.664945	0	0
Y	0.005888	0.680736	0.000249	0.004785

Socioeconomic stability of rare earth producing countries



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