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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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ABSTRACT

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

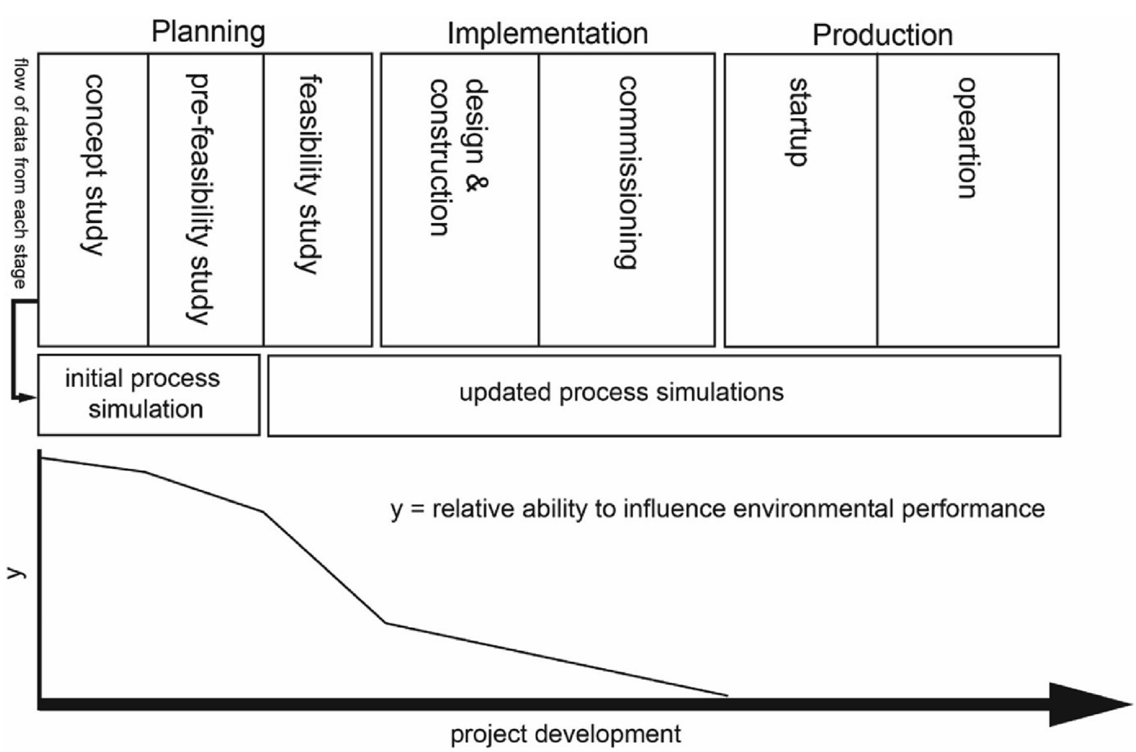

Fig. 1. Relationship between project stage, data availability for process simulations and the impact on LCA results reliability and the ability for those findings to impact project development (adapted from Schoonwinkel et al., 2019)

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

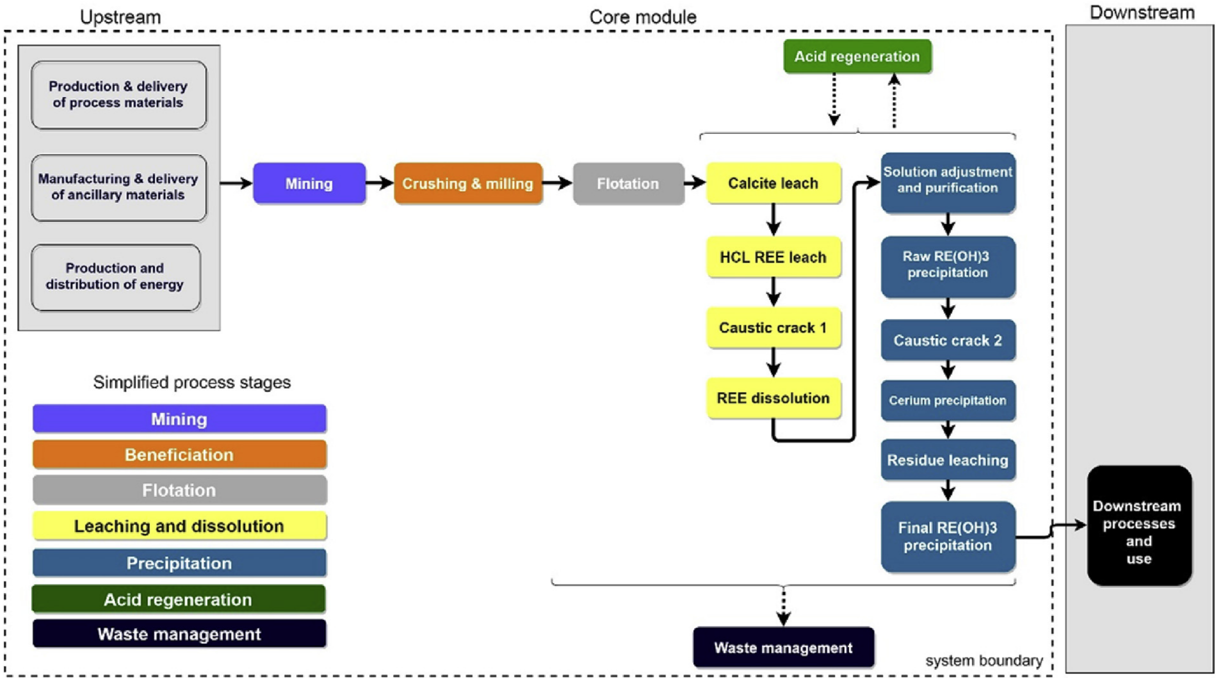

Fig. 2. Songwe Hill process flowsheet with the system boundary for life cycle assessment.

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).

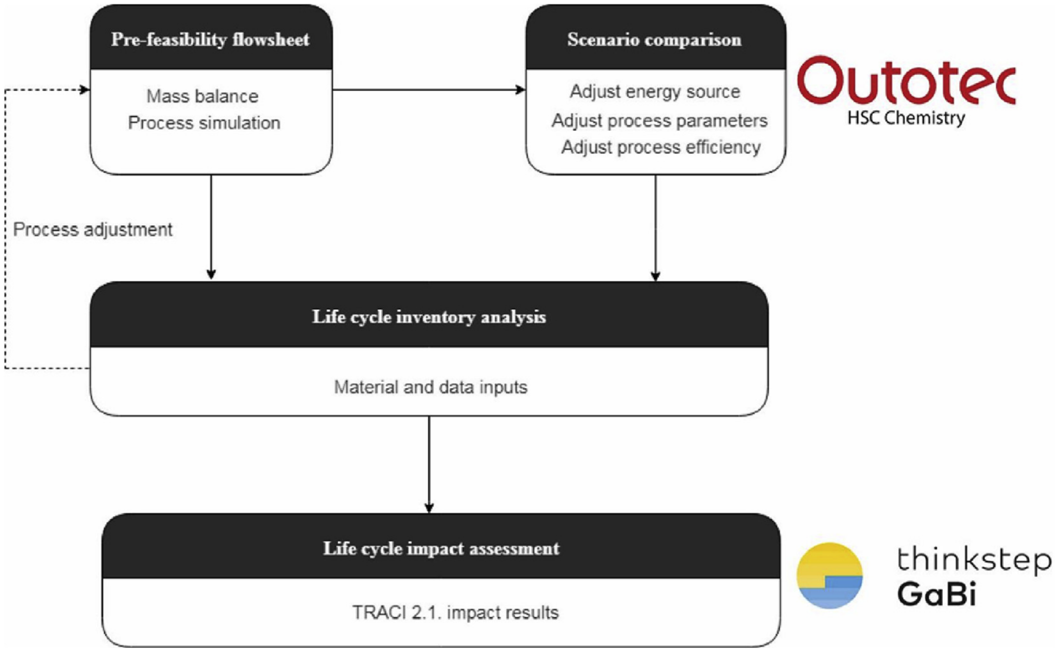

Fig. 3. Process of integration of HSC Sim simulation (www.outotec.com) with GaBi LCA software (Reuter, 1998, 2015).

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.

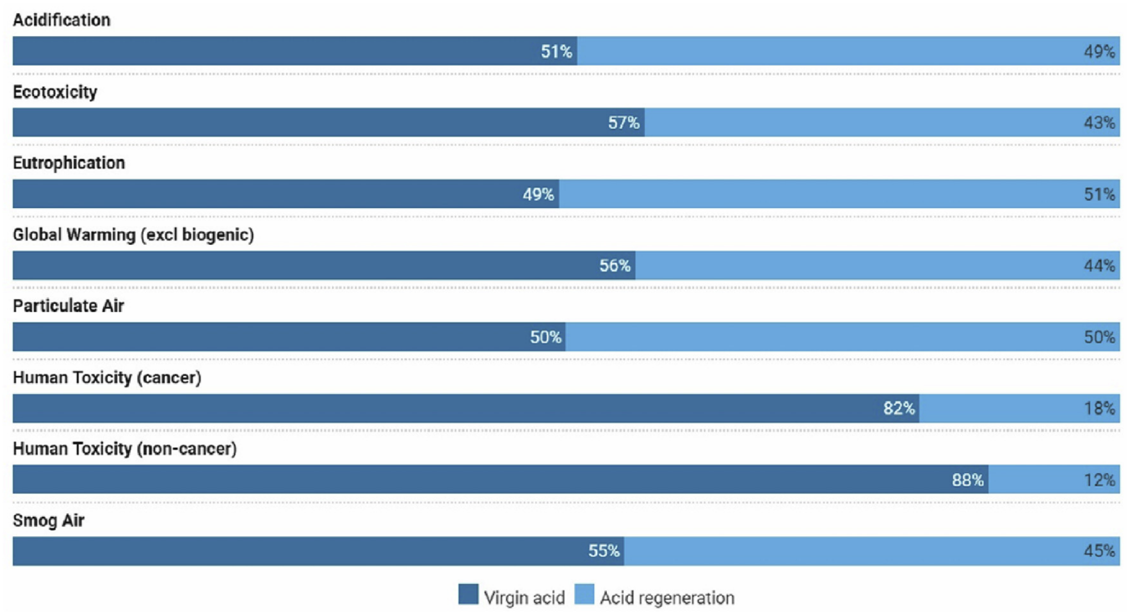

Fig. 4. Share of impact for virgin acid consumption versus on-site acid regeneration.

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.

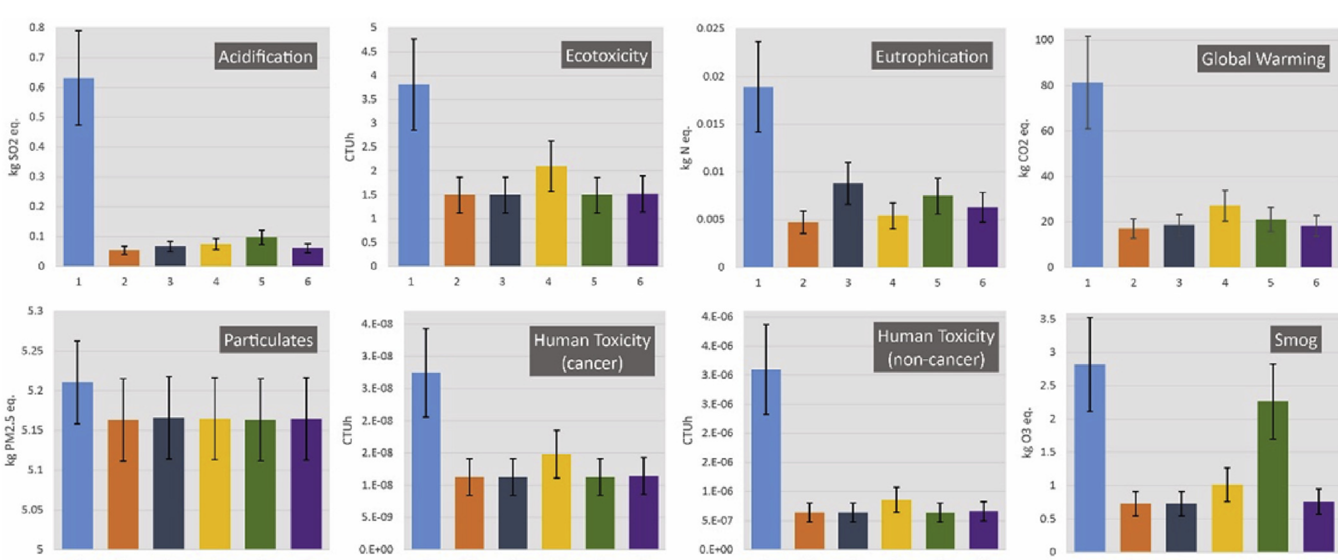

Fig. 5. Environmental impacts of 1 kg of REO produced at Songwe Hill for six energy scenarios. 1 Coal fired power station, 2 Grid power (hydroelectric), 3 Grid (off-peak) and battery storage, 4 Grid (off-peak) and heavy fuel oil, 5 Grid (off-peak) and diesel, 6 Grid (off-peak) and solar and storage.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

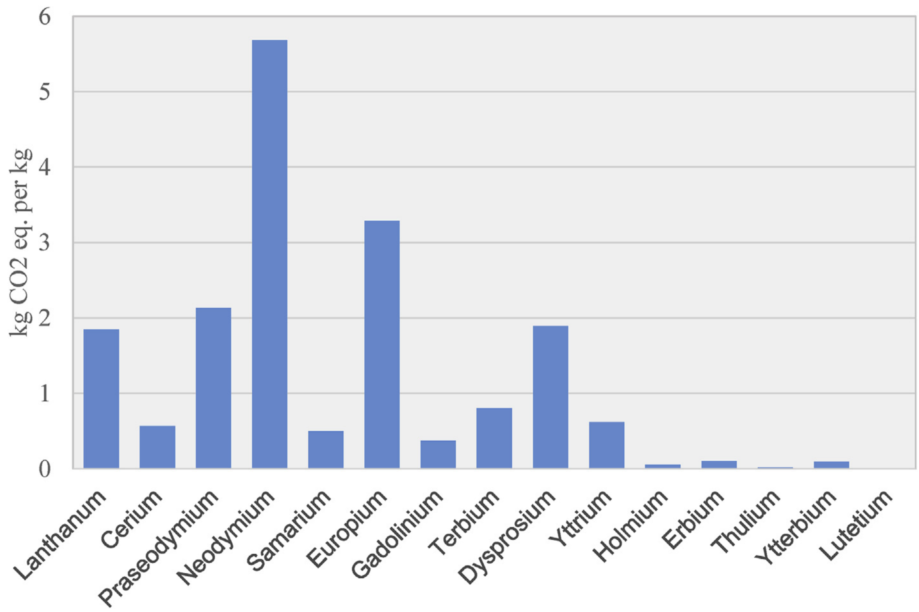

Fig. 6. Global warming potential (inc. biogenic) with allocation for the individual REE at Songwe Hill.

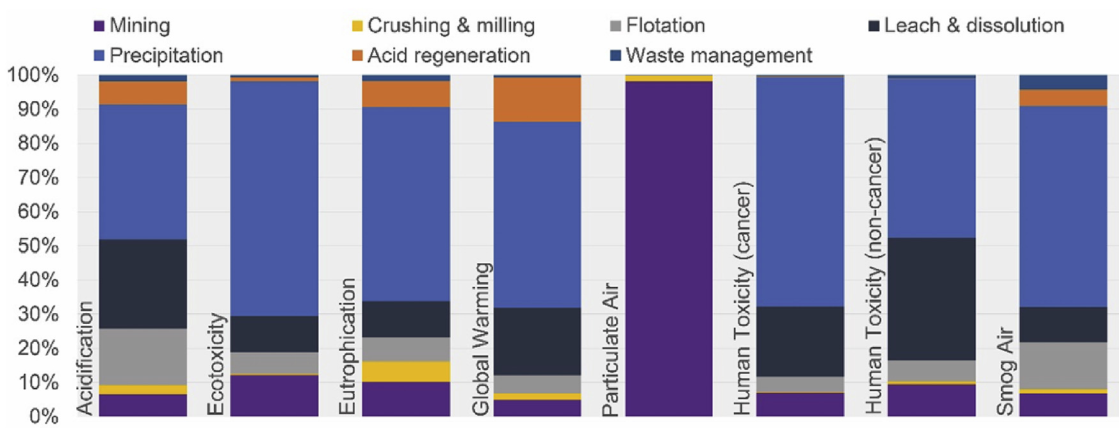

Fig. 7. Contribution analysis of eight TRACI 2.1 impact categories for rare earth oxide (REO) production assuming acid regeneration and energy supplied through a combination of hydroelectric, solar and energy storage.

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,

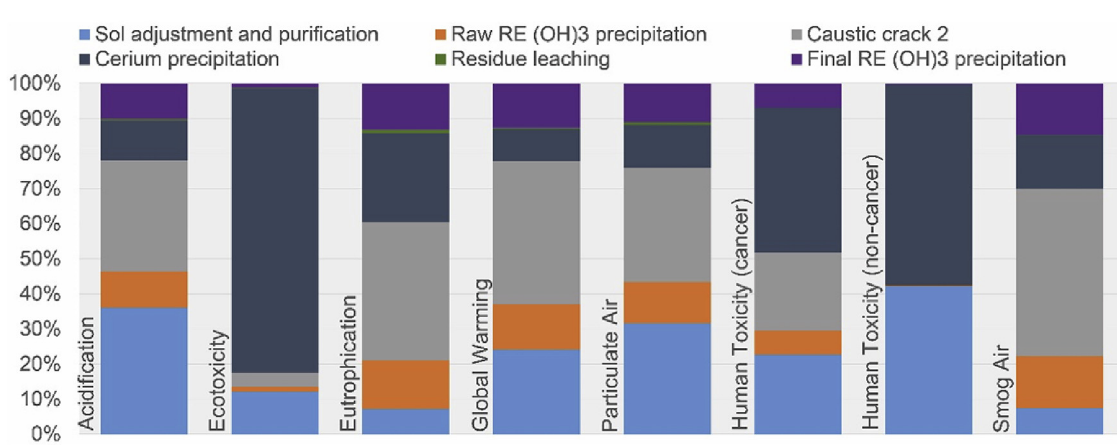

Fig. 8. Contribution of selected major inputs to precipitation stage impact categories assuming acid regeneration and energy supplied through a combination of hydroelectric, solar and energy storage.

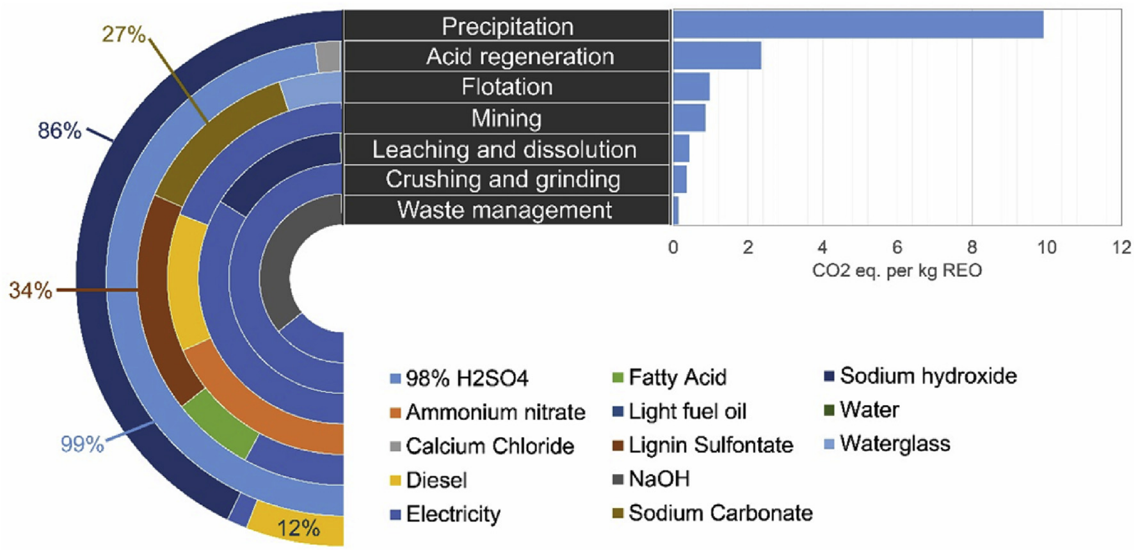

Fig. 9. Material and energy flow contribution to global warming impact in each proposed production stage at Songwe Hill.

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

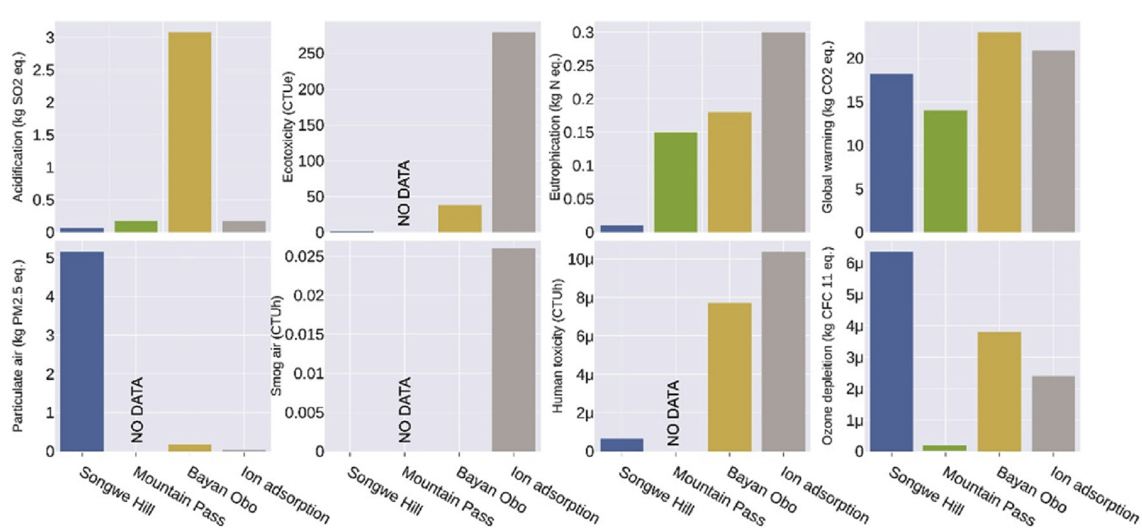

Fig. 10. LCIA results for Songwe Hill, Mountain Pass, Bayan Obo and Ion adsorption deposits.

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

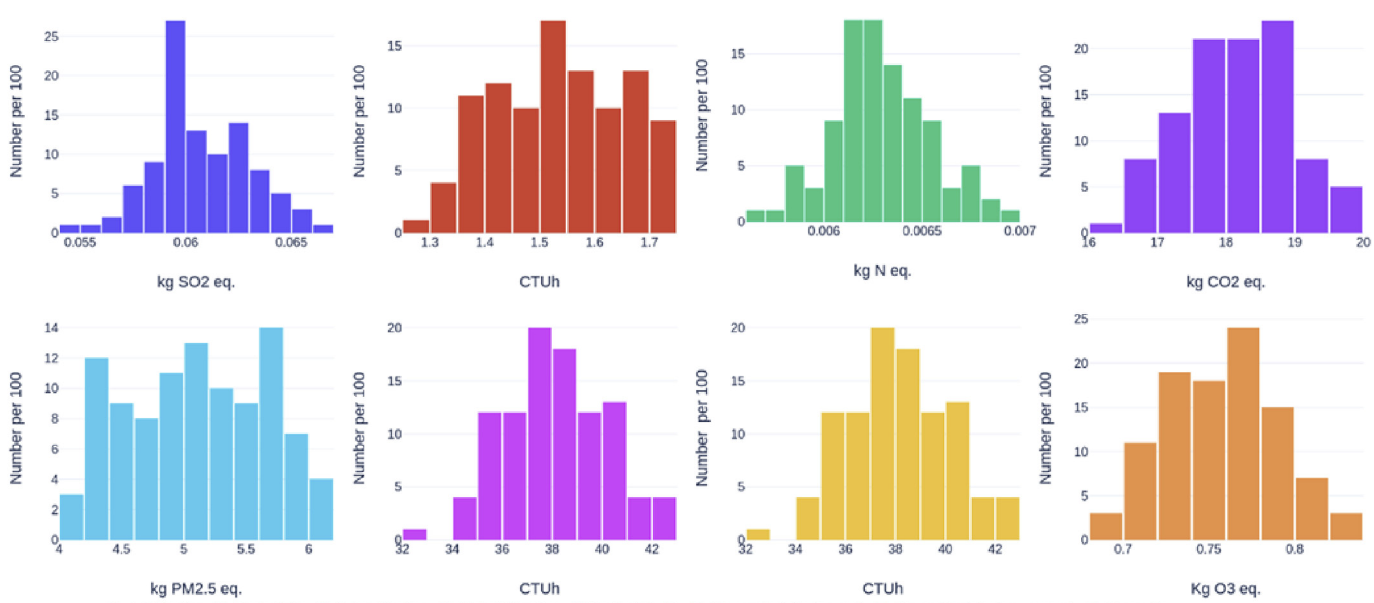

Fig. 11. Monte Carlo simulation of LCI data and impact category calculation on each impact category.

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.

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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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