*Subtask 4.1 - Infrastructure Investigation: The team will access the available infrastructure for coal mining and coal byproduct processing, as well as those raw materials' transportation chains, to illustrate the current status of the feedstock supply for the basinal REE and CM industry and their potential development trend. A detailed investigation of the regional facilities of coal-to-REE and CM feedstock will be performed and reported to guide the potential basinal REE business commercialization plan and maximize the opportunity for spurring the local economy, and this will include the evaluation of a COE for San Juan College.*

REEs are an essential part of modern-day life, even though many consumers have no idea their lifestyles hinge on the availability of these metals. These elements are essential components of almost every electrical device, and mining and refining them is big business. With the rise in demand for electrical vehicles, wind turbines and other consumer electronics, REEs have never been more in demand, and that demand is only expected to increase.

China is the world's largest producer of REEs, accounting for almost 60% of global production in 2020. During the pandemic, China set limits on their rare earth exports, cornering the market and causing the dreaded chip shortage that has been making headlines. The chip shortage is estimated to impact a whopping 169 industries and could drag the U.S. GDP down by 1%.

New Mexico state, as a main mining district (Figure 1) in the southwest region of United States, possess some exiting resource for the potential REE/CM mining, supply and utilization.

***Mining Resources***

NM has some of the oldest mining areas in the United States. Native Americans mined turquoise from Cerrillos Hills district more than 500 years before the Spanish settled in the 1600s. One of the earliest gold rushes in the West was in the Ortiz Mountains (Old Placers district) in 1828, 21 years before the California Gold Rush in 1849. Value of mineral production in 2017 was $1.7 billion (does not include oil and gas), ranked 18th in the US and the employment in the mining industry is 4,685. Within the state, the main exploration efforts are focus on the garnet, gypsum, limestone, nepheline syenite, agate, specimen fluorite, gold, silver, iron, beryllium, uranium, copper, potash, rare earth elements, humate, clays.

By 2019, the acitive mines are listed as followed and most of these exploration sites have been known for over 20 years.

• ~282 active registered mines (NMMMD)

• 4 coal

• 3 potashes, 4 potash plants

• 2 copper open pits, 1 concentrator (mill), 2 solvent/electro-winning (SX-EW) plants

• 2 additional mines in permitting stage

• Several exploration

• 1 gold mine and 1 mill (on standby)

• 32 industrial minerals mines, 18 mills

• ~236 aggregate/stone

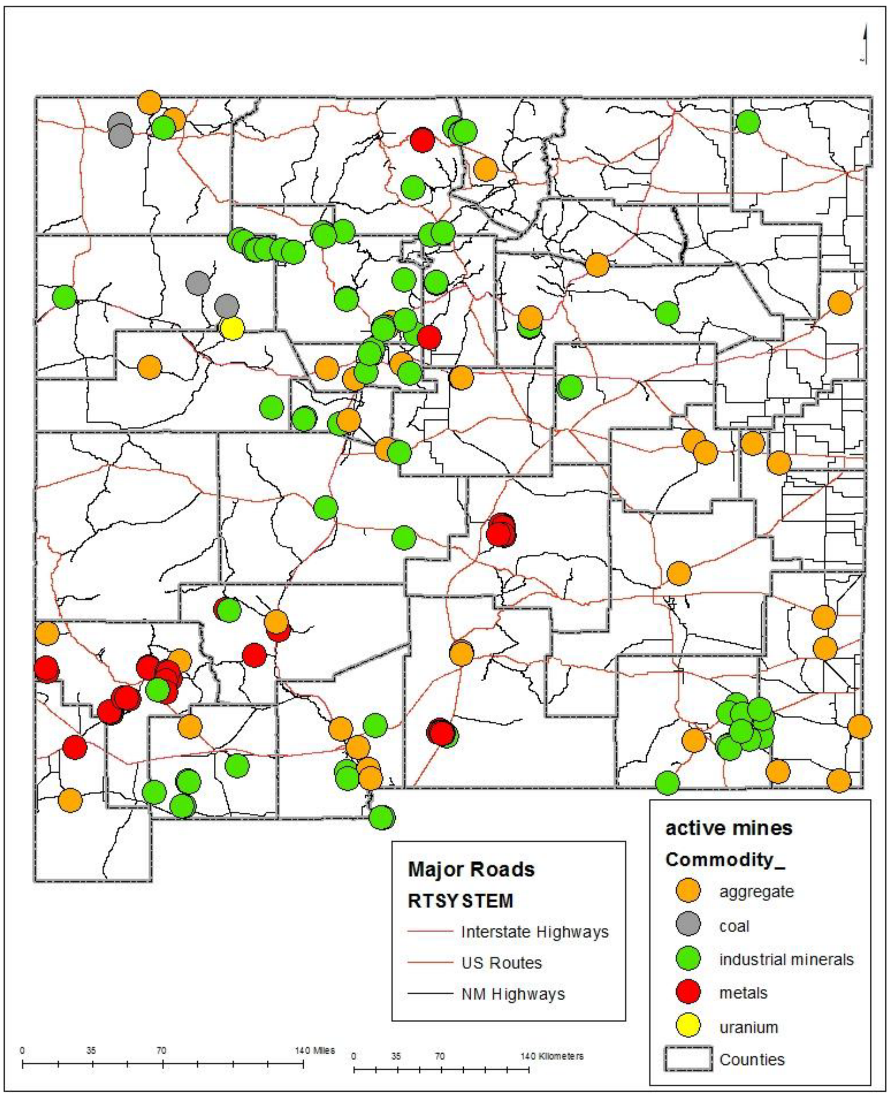


Figure 1 Active Mining Districts in NM

***Business Firms***

Surrounding the New Mexico mining district, there are several business firms are focus on the REE/CM related products.

Freeport McMoRan Inc.: Often simply called “Freeport”. This American mining company is based in Pheonix, AZ. It is the world’s largest producer of molybdenum, an essential trace mineral used in steel alloys to increase strength. They are operating the an open-pit copper mining complex (Chino mile) in Grant County, New Mexico. The Chino mine is a porphyry copper deposit with adjacent copper skarn deposits. There is leachable oxide, secondary sulfide and millable primary sulfide mineralization. The predominant oxide copper mineral is chrysocolla. Chalcocite is the most important secondary copper sulfide mineral, and chalcopyrite and molybdenite the dominant primary sulfides. The historic Chino mine was among the first low-grade, open-pit copper mines in the world. During 2011, mining and milling activities were restarted at the Chino mine. In April 2020, operations at Chino were suspended to address COVID-19 concerns. A review of options for restarting Chino operations was completed in the second half of 2020. In January 2021, FCX restarted mining activities at the Chino mine at a reduced rate of approximately 100 million pounds of copper per year.

Texas Mineral Resources is an exploration company based in Texas, which is specialize in finding REE deposits and is developing other domestic mining projects in precious and industrial metals as well as critical minerals. Recently they announced that the 3rd Phase of electro-magnetic surveying based on continued analysis of the highly encouraging Phase 2 Time Domain Electro-Magnetic (TDEM) survey of high-grade silver veins had been conducted in the Black Hawk District, Grant County, New Mexico. This 3rd Phase survey is focused on the area of the highest population of significant anomalies detected by Phase 2. Diamond drilling will be the 4th phase of the project. Owing to the abundance of near surface targets, less than 120 feet deep, a small, man-portable, diamond drill can be used. This type of drilling minimizes cost, surface preparation and logistics and allows the density of drilling necessary to define these small, high value targets.

SonoAsh LLC is a private technology company leveraging its proven and industry validated processes to create high quality, unprecedented green building materials from variable quality coal ash. SonoAsh has four (4) multi-country patents granted around its technology and processes that cover the upgrading of combustion ash and the method of producing high quality ash for cementitious applications. Its Manufactured Ash product has been 3rd party validated by Lafarge North America and SGS Mineral Services in Denver, CO.

Energy Fuels is a leading US-based uranium mining company, supplying U3O8 to major nuclear utilities. Energy Fuels also produces vanadium for certain projects, as market conditions warrant, as well as rare earth carbonate. With corporate offices are in Lakewood, Colorado, near Denver, and all of its assets and employees in the United States, Energy Fuels holds three of America's key uranium production centers: The White Mesa Mill in Utah, the Nichols Ranch ISR Project in Wyoming, and the Alta Mesa ISR Project in Texas. The Utah-based White Mesa Mill (the "Mill") in Blanding, Utah is within the San Juan Basin in the four corner region (Figure 2). The mill commences the production and shipments of an intermediate rare earth element ("REE") product, called mixed rare earth carbonate ("RE Carbonate"). Approximately 15 containers of RE Carbonate (300 tonnes of product) produced at the Mill is being shipped to Europe where it will be processed into separated rare earth oxides and other value-added RE compounds, thereby creating a new U.S. to Europe RE supply chain along with new opportunities and financial benefits for the surrounding communities. The Mill will be producing rare earths as a complement to its established uranium production business. The White Mesa Mill is the largest uranium production facility in the US and America's only operating uranium mill. Uranium is seeing increased interest recently, as it is the fuel for nuclear energy, which is the largest source of clean, carbon free energy in the U.S.


Figure 2 Location of the White Mesa Mill

*Infrastructure*

At Chino mine, the operation consists of a 36,000 metric ton-per-day concentrator that produces copper, and a 150 million pound-per-year SX/EW plant that produces copper cathode from solution generated by ROM leaching. The available mining fleet consists of twenty-five 240-metric ton haul trucks loaded by four shovels with bucket sizes ranging from 31 to 48 cubic meters, which are capable of moving an average of 180,000 metric tons of material per day.

SanoAsh also have the REE extraction facility constructed and under construction (Figure 3). The initial single sonicator SonoAsh facility will be built at the La Plata Business Park in San Juan County. The existing structure provides an opportunity for expansion to a full scale facility over time and contains much of the necessary infrastructure (e.g. industrial space, electrical service, industrial water supply and proximity to a known coal ash impoundment). The SonoAsh equipment requirements involve the addition of mineral process equipment which is already proven at industrial scale in the mining (coal and base metal) industry and deployed on a global scale. Addition conventional tankage, pumps, valves, instrumentation and control systems will be deployed.


Figure 3 SonoAsh "sonicator" reactor, magnets on both sides of the machine cause the metal bar in the center to vibrate.

Energy Fuels currently plans to ramp up to process up to at least 15,000 tons of monazite per year at its White Mesa Mill. This amount of monazite contains roughly 50% of current U.S. rare earth demand, along with significant quantities of uranium, which will be recovered for use in domestic nuclear energy production. Because monazite contains naturally occurring radioactive elements, including uranium, the White Mesa Mill is the ideal location to process this valuable material. The Mill will recover the uranium from the monazite, which will be used for the generation of clean nuclear energy. The Mill is also evaluating the recovery of thorium which has potential uses in advanced nuclear technologies along with medical isotopes needed for emerging targeted alpha cancer therapies. In addition, the monazite that is received from Georgia contains over 50% REEs, which means Energy Fuels can recover large quantities of REEs while generating relatively tiny amounts of waste.

***Supply Chain***

One less-visible supply chain is that of critical minerals, including the so-called rare earth elements (REEs). While a domestic supply for these materials is not yet established, rapid changes in the nascent national REE industry promise to give the southwest region a central role.

While the global market for tradeable REEs is thought to be about $3 billion to $5 billion [1], one estimate of the value-added market for final goods containing REEs is over $1 trillion [2]. Lanthanum, cerium, neodymium and yttrium are estimated to be the most widely used by quantity, according to a 2010 U.S. Geological Survey (USGS) analysis of imported metals and REE-containing manufactured goods [3].

As the global economy continues to become more technologically advanced and sustainable, demand for REEs will grow. Supply chains must keep up. And with substantial rare earth deposits in our state, New Mexico businesses can help ensure that high-tech goods across the world are partially made with New Mexico dirt.

With the extensive use of REEs in critical weapons, defense, renewable energy and communication systems, a comprehensive interagency effort to build a domestic, vertically integrated REE supply chain is underway, including the departments of Defense, Energy, Interior and State.

***Extraction Technology***

REEs are not truly "rare". They are found all over the world. But deposits containing economically usable concentrations are less common. Significant sources of REEs include bastnaesite and monazite, mineral ores often containing a mix of rare earths and other elements [4].

Several physical, magnetic and chemical methods can be used to separate and process the metals. First, the ore containing REEs must be milled and concentrated. Next, the concentrated ore is separated into rare earth oxides (REOs), a higher level of purity at which individual rare earth elements can be measured and traded as commodities. Finally, REOs are processed into rare earth metals and are ready to be used in the downstream manufacturing of industrial and consumer goods, either on their own or mixed in alloys with other metals [4].

U.S. Department of Defense is investing in research to extract rare earths from ore more efficiently and economically. For example, the department granted $1.8 million to a Ucore subsidiary to help it develop RapidSX, a new and more efficient solvent extraction process used to produce REO [5].

Other extraction possibilities being investigated include laser ablation, ultrasound, chromatography and electrodialysis, in addition to other, more efficient chemical processes that could make certain mineral deposits more economically viable [6]. Research also is being conducted into extracting REEs from coal ash and other coal-mining byproducts [7].

New Mexico state is supporting the REE/CM extracting technology and commercializing the new technologies. Scientists at Sandia National Laboratories (Albuquerque, New Mexico) are using limes for a lot more than spritzing up gin and tonics. The lab has applied for a patent on a new method of extracting rare-earth metals from coal ash using water, carbon dioxide, high pressure and citric acid from limes. The process, if widely developed, would serve two purposes. First, it's a new way to clean up the residue left from burning coal, which is plentiful. There is estimated to be 3 billion tons of coal ash spread across the country, and the U.S. will produce about 100 million additional tons of it a year. Secondly, the extraction of rare-earth metals, or elements, is a national security issue because the vast majority of those valuable metals used in America are imported from China.

There are nine (9) waste coal ash storage sites in New Mexico, predominately in San Juan County. There is estimated to be >100 million tons of waste coal ash in New Mexico. SonoAsh is leveraging its patented and industry validated processes to create a matrix of high value, low carbon products from variable quality waste coal ash, stored either wet or dry. By applying innovative, data-driven technology to produce its engineered products, SonoAsh redefines coal ash impoundments as above ground resource ore bodies. These ore bodies contain high value, in-demand products that are liberated by the SonoAsh process. The potential product mix includes the engineered pozzolanic material (High Performance Green Cement (HPGC)), as well as silica flour, cenospheres, rare earth elements & strategic metals and subsequent carbon offset potential for each. Under SonoAsh's no-waste business model, the company would market both fractions of ash, extracting rare earth elements and other minerals from the high-carbon concentrate while using the low-carbon ash for cement and concrete products. All of the high-carbon concentrate would eventually be used in a variety of industrial and other applications, leaving no waste product behind

*Subtask 4.2 - Competitiveness and Challenge: We will analyze existing or potential technologies to mine or access coal, coal byproducts, waste streams, or alternate source materials current (or future) facilities that refine these raw resource materials into feedstock materials, and seek to understand the basinal capital expenditures of REE-related industry and perceived obstacles to expanding REE-related business lines. The task will also identify the main challenges as the concern for the business development.*

In New Mexico, the mineral production is decreasing, especially based on the coal resource (Figure 4).

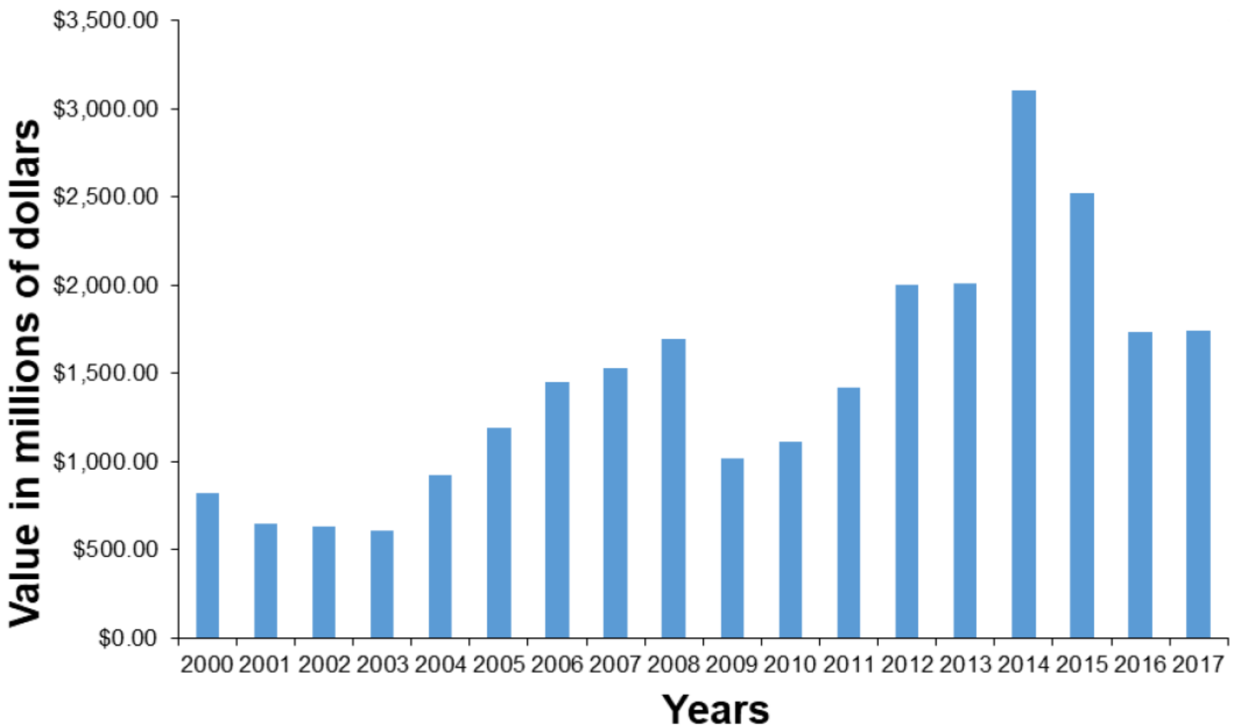


Figure 4 Value of Mineral Production in New Mexico, 2000-2017 (MMD)

Efforts to rebuild U.S. REE supply chains must contend with a number of challenges. Development of rare earth mines and processing facilities is beset by long permitting processes and complex regulations. At many sites, much of the waste can be environmentally hazardous and requires mitigation. And the high capital costs of mining, combined with the low market prices of most REOs, can make the process uneconomical.

Workforce development presents yet another obstacle, as the mining industry works to attract skilled technicians as well as workers with next-generation technology skills in AI, automation and data analytics. Some of the mineral reserves are located within the Navajo nation and the accessing of the resource, advanced training to the local citizens and obtaining the social license are challenge. Meanwhile, maintaining high levels of physical security and cybersecurity is of great importance because of the economic and national security implications of changes to the global REE status quo.

Recycling of REEs is still in its infancy. While REEs could potentially be recovered and reused from LEDs, magnets, fluorescent light bulbs and rechargeable batteries, such recycling is limited and not economical. The European Union's REE4EU is one example of an innovative program aiming to retrieve and recycle rare-earth permanent magnets to be used in hybrid vehicles and wind turbine generators. New Mexico had installed wind turbines for years and now is facing the REE magnets recycle issue. Urban Mining Co., based in San Marcos, Texas, is conducting REE recycling on a pilot, small-scale basis for Texas and New Mexico.

By applying some new technologies mentioned above, it will enable a new industry to emerge which will capitalize on the region's coal legacy. Ultimately, the opportunity to develop new, modern green jobs that build on the skillsets present in the community and create opportunities for multi-generational employment and associated economic development while transforming Farmington into a national eco-hub for waste to value businesses and utilizing local legacy skillsets to realize (effect) these solutions.

For example, the proposed SonoAsh facility at full scale, is expected to employ 90-110 full time direct jobs. The SonoAsh skill set matrix reflects many of the core skills present at Westmoreland Coal and the San Juan Generating Station workforce today including; HVAC technicians, electricians, instrument technicians, regulatory specialists, environmental health and safety (EHS) officers, millwrights, drivers, process equipment operators, logistics specialists as well as the more technically specialized skills, including mechanical and chemical engineers, geologists, chemists and chemical technicians. The opportunity to train and retrain the work force will be required and supported through San Juan College.

Another example is that the four corner community will benefit greatly from this rare earth initiative proposed by Energy Fuels, as it will offer not only a safe, environmentally sensible, and domestically-generated product, but it will also stimulate local employment and be an economic boost to the area. The White Mesa Mill is currently one of the largest private employers in this region, and it is estimated that this new rare earth effort could result in an investment of hundreds of millions of dollars into the facility, which could translate into 100+ jobs in the region—one of the largest reinvestments this region has seen in decades. In addition to the economic benefits to this region, restoring rare earth production to the United States will greatly benefit the entire U.S. economy and manufacturing sector by providing a domestic source of clean energy materials produced to the highest global standards for environmental protection, sustainability and human rights, while also allowing for source validation and tracking from mining through final end-use applications.

Extracting and refining REEs is energy- and resource-intensive and usually requires large areas of land to be excavated to extract a small amount of material. The mining process is costly and inefficient. And many US companies are forced to send their materials to China for processing. In response to this shortage, the New Mexico state and the southwest region of United States are still have a long way to go.

New Mexico will play an important role in building the domestic REE supply chain. The state gets involved in the missile development and research, for instance, uses over thousand pounds of rare earths, and the state is a major location for high-tech, clean energy and electric vehicle manufacturing — primary users of REEs. While production of rare earths in New Mexico has not yet begun, our state contains the potential domestic rare earth deposits, and work is well underway to bring those resources to market.

***Subtask 4.3 Life-Cycle Analysis:*** *Life-cycle analysis including energy and material analysis, environmental impact assessment, scalability assessment and detailed economic analysis shall be conducted to the current REE and CM supply chain and investigate the potential upgrading of the REE and CM process industry, in order to establish pathways toward net neutral carbon emission and the process engineering and design requirements to accomplish this. A cradle-to-grave concept would be adopted to set the boundary of energy and material flows for all the processes involved in the REE industry.*

## LIFE CYCLE ASSESSMENT PRELIMINARY RESULTS BASED ON GENERALIZED DATA

### 1.0 Introduction

**Life Cycle Inventory (LCI)**

To undertake the LCI the processes within the boundary of analysis requires a detailed description. This will ensure all key units, energy and material flows are well analyzed. This work looks at both the traditional/current production technique and then the recent innovation of critical metal extraction by Sandia National Lab. The proposal from this is to use supercritical CO2 (sCO2)-H2O-Chelator solvent system for in-situ and ex-situ mining.

The study area consists of coal fields, active mines, and abandoned mine sites and they include the San Juan and Raton Basins in San Juan, Rio Arriba, Sandoval, McKinley, Cibola, Catron, Socorro, and Colfax Counties.

**Traditional/current**

| Process | Brief description |
|---|---|
| Mining | Escavation, hydraulic digging, crushing etc. |
| Beneficiation | After mining, the ores are crushed and processed to increase their REE concentration. This step is normally undertaken at, or close to, the mine site. Using a range of physical and chemical processes, REE bearing minerals are separated from iron oxide and other gangue minerals. The concentrate is then subjected to six conditioning treatments with steam and different reagents (Krishnamurthy and Gupta 2005). Common reagents used in this process are either fatty acids or hydroxomates which collects the REE minerals in the slurry. Sodium silicate disperses the silicates and allows the fatty acid to attach better to the REE |

| | |
|---|---|
| | concentrate (Jordens et al. 2013) (Zhi Li 2014). The resulting final concentrate is 60% REE oxide with recovery rate of 65 to 75% (Krishnamurthy 2005). |
| Roasting/Cracking | the mineral concentrate from beneficiation is roasted with sulfuric acid. Sulfuric acid is a common reactant to dissolve carbonatite minerals, such as the bastnäsite ore. This high-temperature acid-roasting process is relatively simple but generates potentially hazardous exhaust gases (Zhang and Zhao). When bastnäsite is treated with sulfuric acid, REE precipitates as double sulfates. |
| Leaching | This relatively simple process consists of an acid-base extraction in two steps: (1) diluted HCl and an alkaline treatment are used to selectively precipitate the undesired metal concentrates and leave in a residue (2) concentrated HCl is used to transform the REE sulfates into REE chlorides. |
| Solvent Extration | During the process, leachate containing REE ions produced from the leaching operation is blended with an organic extractant and as a result, REE ions in the aqueous phase produce more soluble compounds in the organic solution (Krishnamurthy 2005) (Vahidi and Zhao 2016). In general, one of the liquid phases is an aqueous phase, whereas the other one is an organic phase (that is, kerosene, toluene, etc). The solute distribution depends on solute-solvent interactions such as metal-water interactions in the aqueous phase, or reactions of the solute with other species in the organic or aqueous phase (Hoogerstraete et al, 2013)<br><br>Subsequently, during the stripping reaction, which reverses the extraction reaction in the solvent extraction process, by using hydrochloric acid or oxalic acid, the REE ions are ultimately transported from the loaded organic extractant to a fresh aqueous medium in which the REE ions are more soluble. Eventually, the REE ions concentration in the aqueous medium after the solvent extraction process is 10–100 times of the REE ions concentration after the leaching process (Preez and S Preston 1992) (Krishnamurthy 2005) (Vander Hoogerstraete et al. 2013). |
| REO product finishing | The chlorides from the solvent extraction processes undergo oxalate or carbonate precipitation; some are sold as carbonates, and some are sent to final calcination for further treatment. The precipitation is done under low atmospheric pressure and there are no fumes. The oxalate slurry is washed with hot water to remove liquid residue. The clean slurry is pumped to a centrifuge to separate liquid from |

| | |
|---|---|
| | solid and then is transferred to a tunnel furnace for calcination. Product finishing processes such as calcination are included in the solvent extraction process. |
| Tailing, Flue gas and Waste treatment | The waste water treatment process in the HDS includes the following stages:<br>Neutralisation with hydrated lime, which in turn involves; Milk of lime production (mixing hydrated lime with water); Three stage neutralization with the hydroxide ion from milk of lime production; Thickening; Solids filtration (producing neutralization underflow). Water recovered from solids thickening and filtration then proceeds to biological treatment; Nutrition addition, Aeration and biological oxidation, Settling and Discharge. |

**Proposed Technology**

| Process | Brief description |
|---|---|
| Fracking | The solvent will be injected into an ore deposit as a fracking fluid. This operation will increase rock permeability by up to four orders of magnitude. The $sCO_2$ - chelator fluid will dissolve surrounding minerals along the flow pathway to create new transport route and more porosity. |
| Reaction | The $sCO_2$ solvent with a chelator, such as citric acid, reacts with the host minerals to extract critical metals. |
| Mineralization | $CO_2$ can be either recycled or converted into carbonate minerals. As the ore minerals react with the solvent mixture, the divalent cations ($Ca^{2+}$, $Mg^{2+}$ and $Fe^{2+}$) will release from the ore minerals, the pH value of the system increases and eventually the system reaches the solubility limit of<br>minerals, leading to the carbonate mineral formation. |
| Pump back | Pregnant solution is pumped back and with further addition of chelator group separation the solution is separated into REE and other cations. |
| REE separation | REE ore is separated into individual REEs. |

The focus extraction technology is the utilization of supercritical $CO_2$ Chelator fluids to mine these minerals (Sandia National Laboratories). In this approach, the solvent dissolves CM and extracted selectively. Also the solvent enhances solution mining by being used to fracture ores (Mark J. et al). A detail assessment of the processes involved in this technique with respect to its green or carbon neutral importance in comparison to current techniques ought to be conducted.

**2.0 Overview of Life Cycle Assessment (LCA)**

Calculating and evaluating all inputs and outputs of environmental stressors and products' potential impact on the environment, from raw material extraction and acquisition, manufacturing, transportation and distribution, use and maintenance, reuse and recycle, and all the way to disposal and waste management describes LCA. This study follows the ISO 14040 frame work (Figure 5).

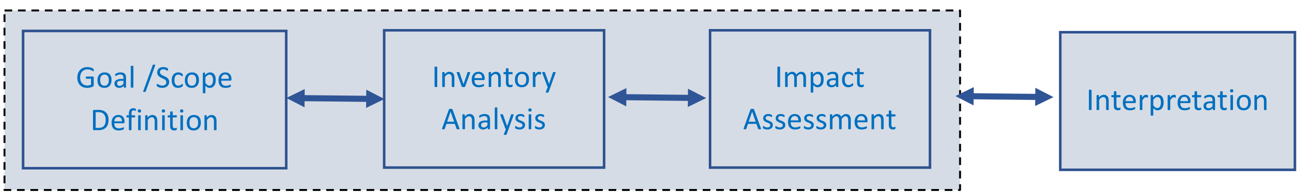


Figure 5. Life Cycle Assessment framework

**2.1 Goal and Scope**

The goal and scope of this study seeks to assess the environmental friendliness of mining critical minerals using supercritical CO2-H2O Chelator fluids (Mark J. et al). Most important is its carbon neutral or negative potential to reduce global warming. The scope thus, seeks to incorporate a cradle to gate LCA approach. In this, the central focus is on the stage of the aforementioned technique application. This begins with the general repurposing of land for top soil removal and drilling of holes for injection of fluid. CO2 is compressed to a supercritical condition of pressure and temperature. For in-situ process, the solvent is injected into the formation (ore deposit) at a pressure above the fracturing pressure of the formation, thereby fracking with the fluid. Rock permeability is increased about four times beyond tradition leaching approach. By dissolving surrounding minerals and creating more route, supercritical CO2 with citric acid as chelator undergo reactions which extract critical minraals. Divalent cations (Ca2+, Mg2+ and Fe2+) are released forming carbonates minerals. Operators could control the objectives of either maximizing mineral extraction or CO2 mineralization. Next in the process is the solvent extraction

$$CO_2 + Ca^{2+}/Mg^{2+}/Fe^{2+} \longrightarrow \text{Carbonate}$$

Figure 2, is the generalized boundary of the study. The extracted pregnant solution is pumped back to the surface to collection units. Produced CO2 is recycled and reinjected. The functional unit is the production of 1kg mixed REOs by in-situ CO2 chelator reaction and extraction. Generalized dataset was used for this study, mainly from literature and LCA database in access from OpenLCA modeling tool.

**2.2 Open LCA**

OpenLCA is an open-source software tool used for Life Cycle Assessment (LCA) and sustainability analysis. It provides a comprehensive platform for modeling and analyzing the environmental impact of products and processes throughout their entire life cycle, from raw material extraction to end-of-life disposal. OpenLCA has a user-friendly interface, making it accessible for both beginners and experienced LCA practitioners. It supports a wide range of impact assessment methods and databases, including ecoinvent, ILCD, and US LCI, among others. OpenLCA also offers features for sensitivity analysis, scenario analysis, and reporting, enabling users to make informed decisions and communicate their results effectively. Overall, OpenLCA is a valuable tool for businesses, researchers, and policymakers looking to evaluate the environmental sustainability of their products and operations.

**2.3 Life Cycle Impact assessment (LCIA)**

The LCIA step of an LCA study is used to evaluate the significance of potential environmental impacts using inventory data, and providing information for the interpretation step. TRACI 2.1 Global Warming Air, Acidification, Eutrophication, Smog Air, all Ecotoxicity categories, and all Human Health categories. Hence the relative potency of different greenhouse gases such as CO2, N2O and methane and the results in kgCO2 equivalent (Equations 1 and 2) and other environmental impacts.

$$Impact = \sum_{p \epsilon P} CF_{ip} \,.\, MassEmittedp \tag{1}$$

$$GWP[kgCO_{2eq}] = \sum_{p \epsilon P} GWP_p \left[\frac{kgCO_{2e}}{kg\ p}\right] . MassEmittedp\ [kg\ p] \tag{2}$$

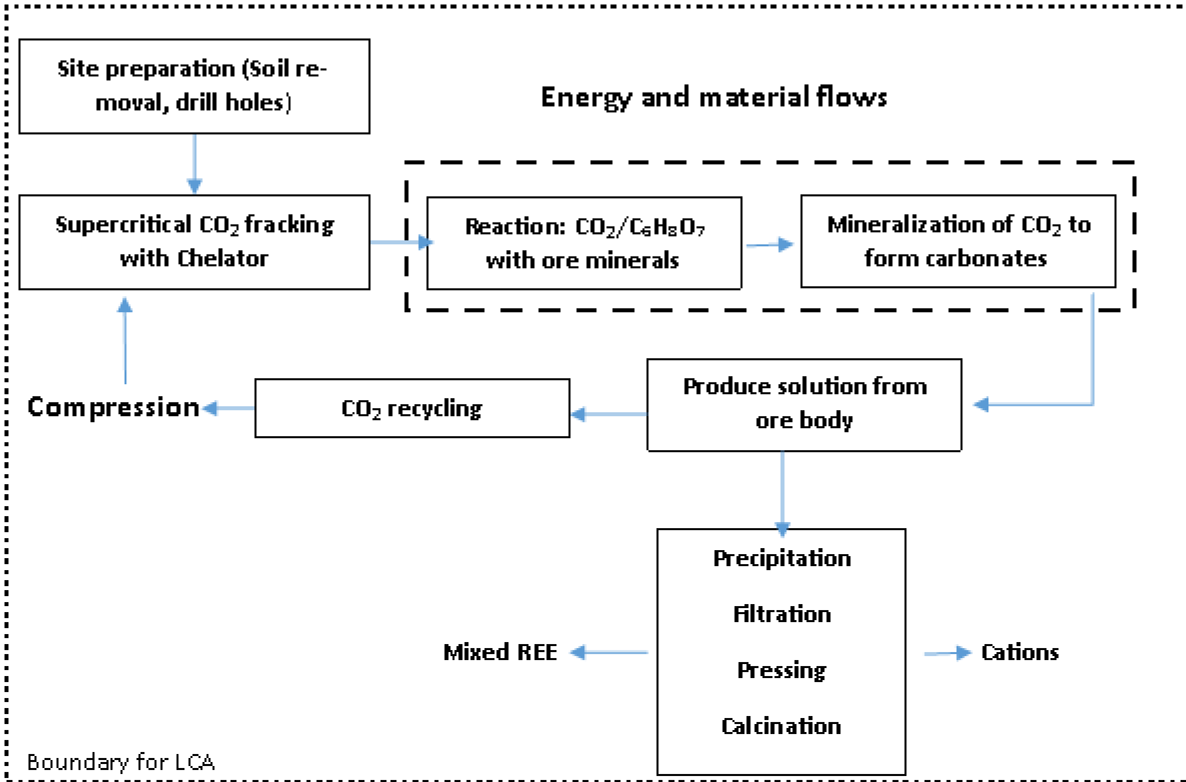


Figure 6. Summary of Key process steps involved/Boundary for LCA

**3.0 Impact Assessment**

Two life cycle impact assessment methods were used in the study and comparison made. TRACI (Tool for the reduction and Assessment of Chemical and other Environmental Impacts) by United States Environmental protection agency, US EPA together with ILDC (International reference Life Cycle Data) by the Institute for environmental and Sustainability in the European Commission Joint research center were used.

Figure 7 and 8, presents the overall impact category (TRAC) estimates for the production of 1kg of REO. With a low specified supercritical CO2 volume/mass. Ecotoxicity records excessively above all other categories, an environmental impact category that measures the potential harm that a substance or product can cause to aquatic and terrestrial ecosystems. It assesses the toxicity of a substance or product to living organisms, such as plants and animals, and their habitats. Ecotoxicity is typically quantified in terms of the potential for effects on aquatic life, such as fish and other aquatic organisms, and is often expressed as the potential for acute or chronic toxicity. Next highest impact is global warming. All other impacts are below unit or almost insignificant. This attributed by the environmental friendly technique introduce by the approach under review. ILDC, however increased the number of significant impacts. These peaks are as a results of indirect processes in the extraction procedure.

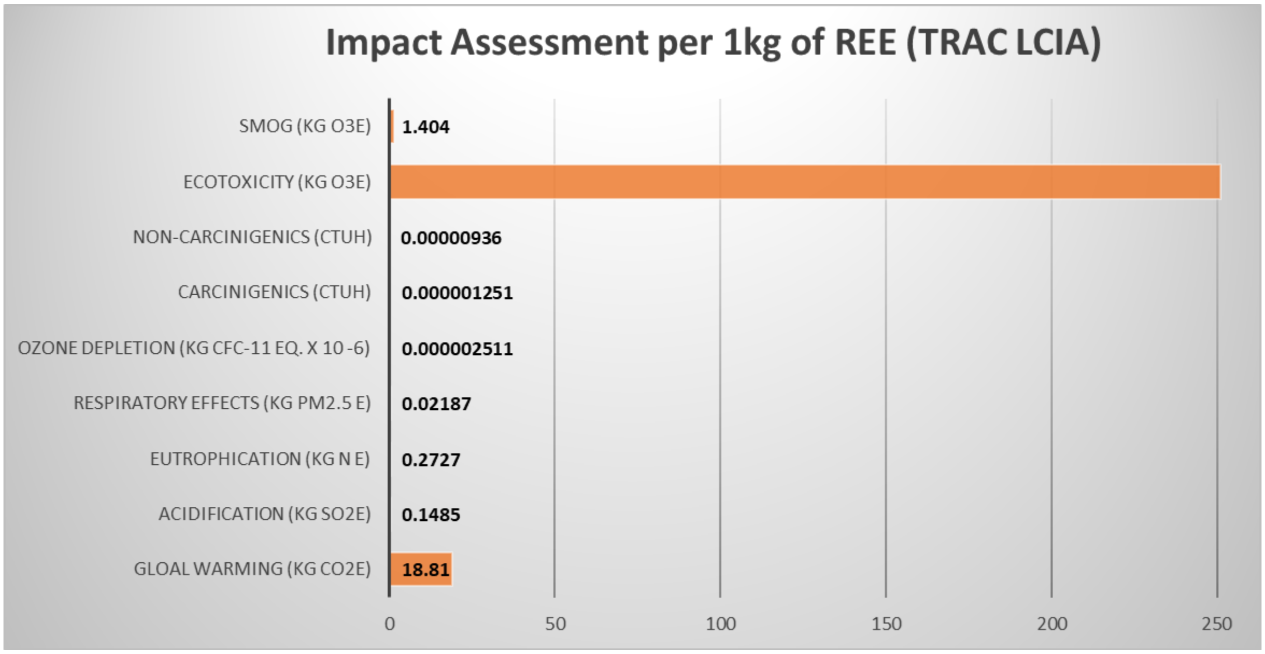


Figure 7. Overall Impact assessment per 1kg of REE produced (TRAC)

Land Use or repurposed is part of the preliminary site preparation which ought to be done and as such, this technique does not require deep excavation of soil hence the impact is minimized in this scenario. Major contributors to global warming is energy consumption. Energy is required in almost all the processes. Except during the reactions and extractions of ore by supercritical CO2 chelator (another advantage of this approach).

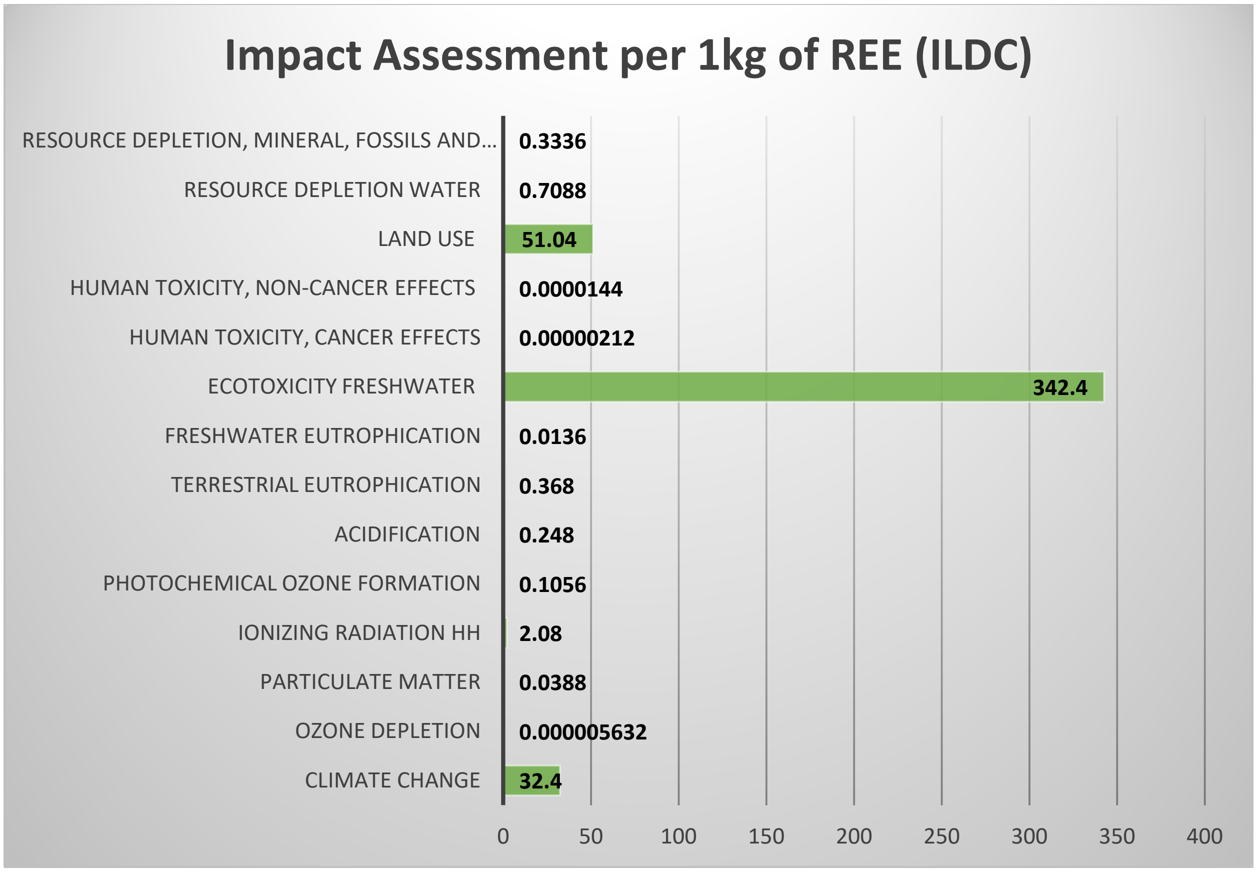


Figure 8. Overall Impact assessment per 1kg of REE produced (TRAC)

A major importance of LCA is to identify specifically unit areas or processes which contribute more or impact the environment more and possible measures taken to reduce such occurrences. Table 1 and 2, identifies unit areas or process with high impacts. Solvent extraction is the key process unit that is peaking ecotoxicity. The estimate is quite reasonable due to the number of processes and chemicals required to extract or separate pure REOs and ions. Though, this new approach employs a high percentage of less harmful solvents (citric acid etc.), there're still inorganic and others which possess a disadvantage. Red cells are high impact categories. Orange cells are the next impactful. Yellow to greenish yellow are intermediate and green being insignificantly impactful. A high percentage are in the green zone. An indication of how well irrelevant components within the rocks were not brought to surface to cause harm due to the efficient extraction by the new technique.

**Table 1. Allocation of impact levels base on unit systems within the boundary (TRAC)**

| Impact category | Site preparation | fluid compression /injection/ recycling | Insitu reactions | Pregnant solution pump | Solvent extration |
|---|---|---|---|---|---|
| Gloal Warming (Kg CO2e) | 2.2572 | 9.4050 | 0.3762 | 2.6334 | 5.6430 |
| Acidification (Kg SO2e) | 0.0178 | 0.0119 | 0.0030 | 0.0012 | 0.1054 |
| Eutrophication (Kg N e) | 0.0327 | 0.0218 | 0.0055 | 0.0023 | 0.1936 |
| Respiratory effects (Kg PM2.5 e) | 0.0026 | 0.0017 | 0.0004 | 0.0002 | 0.0155 |
| Ozone depletion (Kg CFC-11 eq. X 10 -6) | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Carcinigenics (CTUh) | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Non-carcinigenics (CTUh) | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| Ecotoxicity (Kg O3e) | 30.1320 | 20.0880 | 5.0220 | 2.1092 | 178.2810 |
| Smog (Kg O3e) | 0.1685 | 0.1123 | 0.0281 | 0.0118 | 0.9968 |

Table 2. Allocation of impact levels base on unit systems within the boundary (ILCD)

| Impact category | Unit | Site preparation | fluid compression /injection/ | Insitu reactions | Pregnant solution | Solvent extration |
|---|---|---|---|---|---|---|
| Climate change | kg CO2 eq. | 4.05 | 17.82 | 1.62 | 0.58725 | 8.35 |
| Ozone depletion | kg CFC-11 eq. | 0.000000704 | 4.5056E-07 | 1.408E-08 | 3.9424E-07 | 3.99872E-06 |
| Particulate matter | kg PM2.5 eq. | 0.00485 | 0.003104 | 0.000097 | 0.002716 | 0.027548 |
| Ionizing radiation HH | kBq U235 eq. | 0.26 | 0.1664 | 0.0052 | 0.1456 | 1.4768 |
| Photochemical ozone formation | kg NMVOC eq. | 0.0132 | 0.008448 | 0.000264 | 0.007392 | 0.074976 |
| Acidification | molc H+ eq. | 0.031 | 0.01984 | 0.00062 | 0.01736 | 0.17608 |
| Terrestrial eutrophication | molc N eq. | 0.046 | 0.02944 | 0.00092 | 0.02576 | 0.26128 |
| Freshwater eutrophication | kg P eq. | 0.0017 | 0.001088 | 0.000034 | 0.000952 | 0.009656 |
| Ecotoxicity freshwater | CTUe | 42.8 | 27.392 | 0.856 | 23.968 | 243.104 |
| Human toxicity, cancer effects | CTUh | 0.000000265 | 1.696E-07 | 5.3E-09 | 1.484E-07 | 1.5052E-06 |
| Human toxicity, non-cancer effects | CTUh | 0.0000018 | 0.000001152 | 0.000000036 | 0.000001008 | 0.000010224 |
| Land use | kg C deficit eq. | 6.38 | 4.0832 | 0.1276 | 3.5728 | 36.2384 |
| Resource depletion water | m³ eq. | 0.0886 | 0.056704 | 0.001772 | 0.049616 | 0.503248 |
| Resource depletion, mineral, fossils and renewables | kg Sb eq. | 0.0417 | 0.026688 | 0.000834 | 0.023352 | 0.236856 |

Increasing impact level from left to right (green to red)

Considering the injection of $CO_2$, this technique highly boasts of a carbon neutral or negative emission factor. A further analysis conducted by varying the percentage of $CO_2$ proved an increasing negative emission factor with an increase in $CO_2$ (Figure 9). However, the source of the $CO_2$ must be from anthropogenic source, to ensure a reduction in emission to the environment and hence reduction in global warming potential.

A comparative analysis was conducted with existing literature with varying REE recovering techniques. For all datasets of which this study analyzed (Table 3 and Figure 10), ScCO2 even with the least CO2 injection records lower impact factors as compared to four traditional processes.

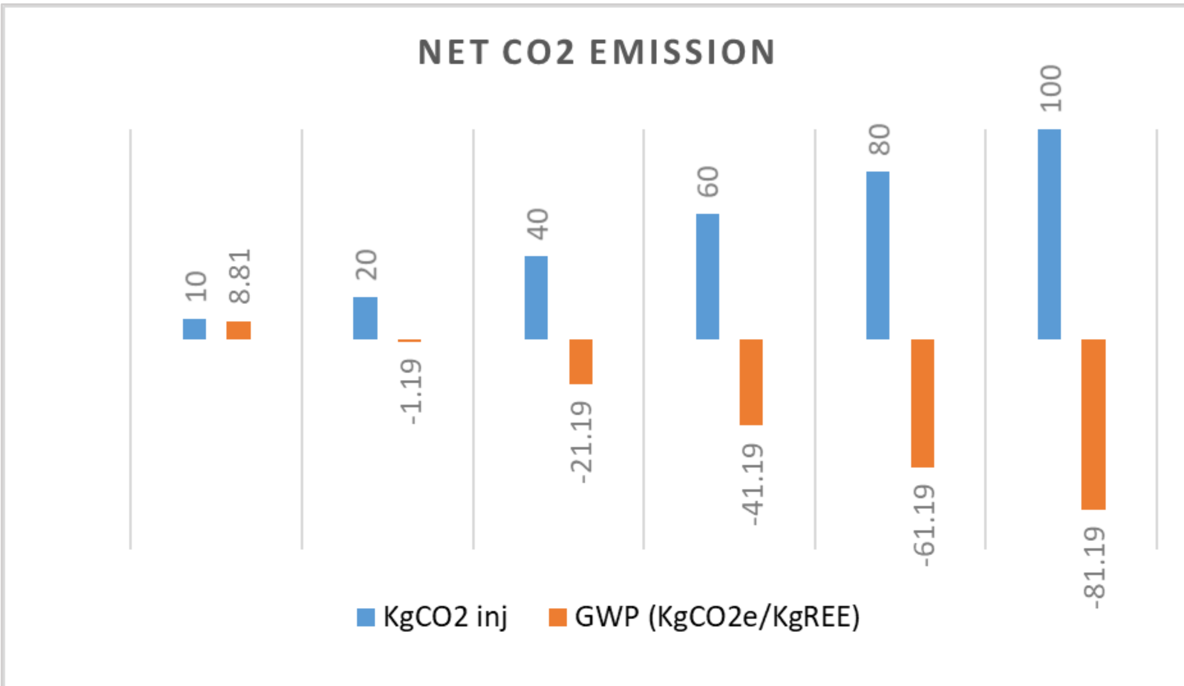


Figure 9. Global warming potential estimates based on $KgCO_2$ injected

**Table 3. Comparative Analysis with existing literature for 1kg of REE produced**

| Impact category | sCO2 | Trad1 | Trad2 | Trad3 | Trad4 |
|---|---|---|---|---|---|
| Global Warming (Kg CO2e) | 18.81 | 29.125 | 80 | 28 | 33 |
| Acidification (Kg SO2e) | 0.1485 | 97.775 | 1.31 | 0.2 | 1.13 |
| Eutrophication (Kg N e) | 0.2727 | 0.225 | 0.257 | 1.6 | 0.02 |
| Respiratory effects (Kg PM2.5 e) | 0.02187 | 0.18 | 0.837 | 0.045 | 0.907 |
| Ozone depletion (Kg CFC-11 eq. X 10 -6) | 2.51E-06 | 11.5 | | 2.8 | 9.53 |
| Carcinogenic (CTUh) | 1.25E-06 | N/A | N/A | N/A | N/A |
| Non-carcinogenic (CTUh) | 9.36E-06 | N/A | N/A | N/A | N/A |
| Eco toxicity (Kg O3e) | 251.1 | N/A | N/A | N/A | N/A |

| | | | | | |
|---|---|---|---|---|---|
| Smog (Kg O3e) | 1.404 | N/A | N/A | N/A | N/A |

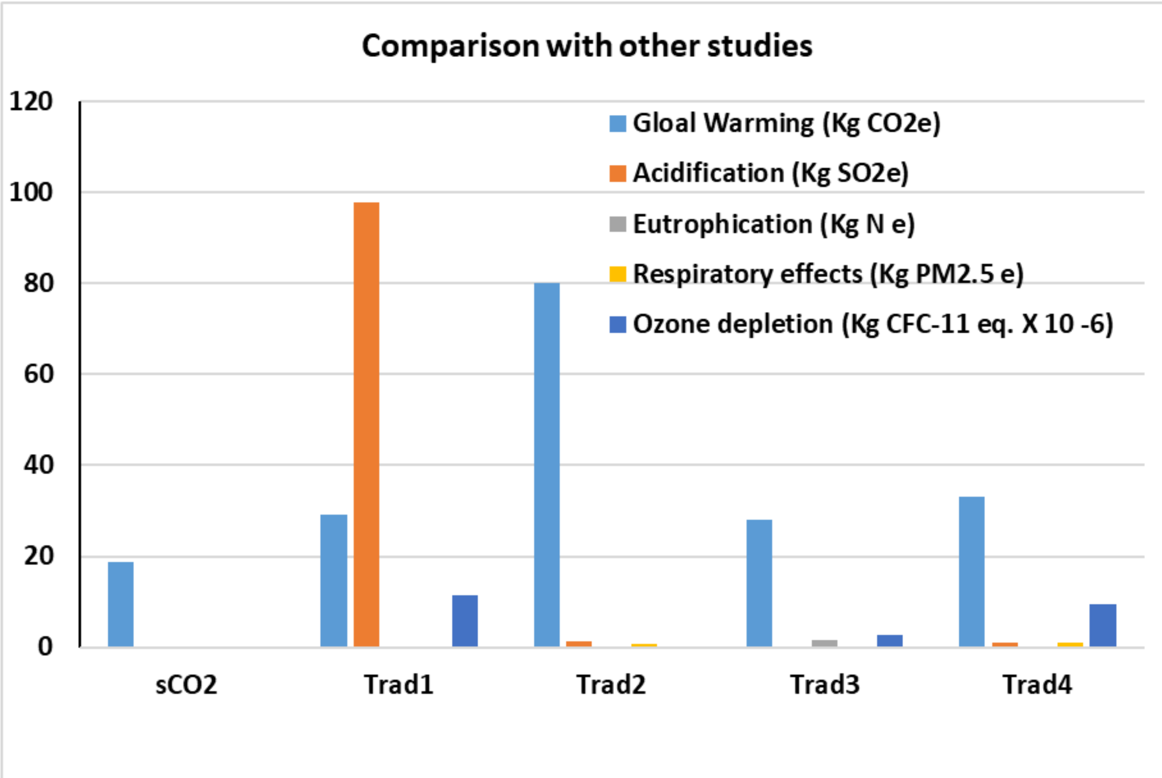


Figure 10. Comparative Analysis with existing literature for kg of REE produced

**4.0 Conclusion and recommendations**

This study sought to present an LCA of a novel REE extraction technique to verify its carbon footprint and the degree impact it can make in reducing or minimizing environmental stressors. Aside factors such as energy consumption and land repurposing which the process minimizes to the barest minimum it estimates a carbon negative emission factors as well as quite insignificant impacts factors in other impact categories.

This estimates are based on generalized and assumed values to compute this preliminary work. It is recommended that exact quantities and composition of all processing units within this technique be provided to ensure much accurate estimates.

# APPENDIX

## Input/output for Initial REE pump back pregnant solution

**Inputs**

| Flow | Category | Amount | Unit |
|---|---|---|---|
| ammonium bicarbonate | Organic chemicals/nan | 3.35000 | kg |
| carbon dioxide (biogenic) | Resources from air/Renewa... | | kg |
| cerium | Resources from ground/No... | 0.06200 | kg |
| Citric acid | Organic chemicals/nan | 8.25000 | kg |
| dysprosium | Resources from ground/No... | 0.07300 | kg |
| Electricity | Energy carriers and technol... | 10.50000 | MJ |
| erbium | Resources from ground/No... | 0.04900 | kg |
| europium | Resources from ground/No... | 0.01800 | kg |
| gadolinium | Resources from ground/No... | 0.11700 | kg |
| kaolinite | Resources from ground/No... | 0.76500 | kg |
| lanthanum | Resources from ground/No... | 0.53050 | kg |
| mineral extraction site | Land use/Land occupation | 0.09550 | m2*a |
| natural gas | Resources from ground/No... | 0.70200 | MJ |
| neodymium | Resources from ground/No... | 0.34000 | kg |
| Plastic pipe (unspecified) | Materials production/Plastics | 0.10100 | kg |
| Polyvinylchloride part (PVC) | Systems/Unspecific parts | 0.09500 | kg |
| praseodymium | Resources from ground/No... | 0.10900 | kg |
| samarium | Resources from ground/No... | 0.08850 | kg |
| terbium | Resources from ground/No... | 0.01350 | kg |
| to mineral extraction site | Land use/Land transformati... | 800.00000 | m2 |
| Water | Emissions to water/Emissio... | 1.00000 | m3 |
| ytterbium | Resources from ground/No... | 0.04650 | kg |
| yttrium | Resources from ground/No... | 0.43150 | kg |

**Outputs**

| Flow | Category | Amount | Unit |
|---|---|---|---|
| aluminium | Emissions to water/Emissio... | 1.88000 | kg |
| ammonium | Emissions to soil/Emissions... | 0.36000 | kg |
| **REE Concentrate** | | **1.00000** | **kg** |

**Sample Input output (Solvent REE extraction stage)**

**Inputs**

| Flow | Category | Amount | Unit |
|---|---|---|---|
| Citric acid | Organic chemicals/nan | 3.23000 | kg |
| Electricity | Energy carriers and technol... | 0.95400 | MJ |
| Hydrochloric acid | Organic chemicals/nan | 0.79100 | kg |
| Organophosphorus-compounds_at ... | | 0.02530 | kg |
| REE Concentrate | | 1.17000 | kg |
| Sodium hydroxide | Organic chemicals/nan | 1.05000E-5 | kg |
| spent solvent mixture [Waste] | | 1.05000E-5 | kg |
| Water deionized from tap | | 0.05650 | m3 |

**Outputs**

| Flow | Category | Amount | Unit |
|---|---|---|---|
| ammonium | Emissions to water/Emissio... | 0.00032 | kg |
| carbon dioxide (fossil) | Emissions to air/Emissions t... | 0.00102 | kg |
| chemical oxygen demand | Emissions to water/Emissio... | 0.00487 | kg |
| chlorine | Emissions to water/Emissio... | 0.01270 | kg |
| Hazardous waste (deposited) | Wastes/Other waste | 0.00268 | kg |
| Hydrocarbons, aliphatic, alkanes, cy... | Emissions to air/Emissions t... | 2.36000E-5 | kg |
| hydrogen chloride | Emissions to water/Emissio... | 0.00620 | kg |
| Low radioactive wastes | Wastes/Radioactive waste | 0.10800 | kg |
| municipal solid waste deposition | Wastes/Post consumer waste | 0.00531 | kg |
| Nitrogen oxides | Emissions to air/Emissions t... | 0.00233 | kg |
| Oils, unspecified | Emissions to water/Emissio... | 3.39000E-5 | kg |
| Sludge | End-of-life treatment | 0.00215 | kg |
| sodium | Emissions to water/Emissio... | 0.00144 | kg |
| **Solvent Extraction_Sum of REO** | | **1.00000** | **kg** |
| Sulphur dioxide | Organic chemicals/nan | 1.61000E-5 | kg |
| Suspended solids, unspecified | Emissions to water/Emissio... | 0.00081 | kg |
| Water | Materials production/Other... | 0.07500 | kg |

**Reference**

[1] U.S. Dept. of Energy, ("Rare Earths Supply Chain: A Situational White Paper," p. 9.

[2] National Energy Technology Laboratory, "Critical Minerals Sustainability Program".

[3] U.S. Geological Survey, "Preliminary Estimates of the Quantities of Rare-Earth Elements Contained in Selected Products and in Imports of Semi-manufactured Products to the United States, 2010".

[4] U.S. Dept. of Energy, "Rare Earths Supply Chain: A Situational White Paper".

[5] Congressional Research Service, "An Overview of Rare Earth Elements and Related Issues for Congress".

[6] U.S. Dept. of Energy, "Rare Earths Supply Chain: A Situational White Paper," (PDF) p. 11.

[7] National Energy Technology Laboratory, "Improved Rare Earth Element Extraction Method from Coal Ash," Nov. 16, 2020.

[8] Mark J. Rigali, Yifeng Wang, Yongliang Xiong, Green Mining of Critical Metals Using Supercritical CO2-H2O-Chelator Fluids Sandia National Laboratories (Albuquerque, NM); Guangping Xu

[9] N. A. Azzolina, J. A. Hamling, W. D. Peck, C. D. Gorecki, D. V Nakles, and L. S. Melzer, "A Life Cycle Analysis of Incremental Oil Produced via CO2 EOR," Energy Procedia, vol. 114, pp. 6588–6596, 2017.

[10] ISO 14041: Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis. 199

[11] Navarro J and Zhao F (2014) Life-cycle assessment of the production of rare-earth elements for energy applications: a review. Front. Energy Res. 2:45. doi: 10.3389/fenrg.2014.00045

[12] Carbon footprint assessment of recycling technologies for rare earth elements: A case study of recycling yttrium and europium from phosphor (Hu et al. 2017)

[13] Developing a Life Cycle Inventory for Rare Earth Oxides from Ion-Adsorption Deposits: Key Impacts and Further Research Needs (Schulze et al. 2017)

[14] Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues. EPA 600/R-12/572. (Weber and Reisman)

[15] Environmental impacts of rare earth mining and separation based on eudialyte: A new European way (Schreiber et al. 2016)

[16] An initial life cycle assessment of rare earth oxides production from ion-adsorption clays (Vahidi et al. 2016)

[17] Life Cycle Assessment of Metals: A Scientific Synthesis (Nuss and Eckelman 2014)

[18] Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets (Sprecher et al. 2014a)

[19] Life Cycle Impact of Rare Earth Elements (Koltun and Tharumarajah 2014)

[20] Environmental Life Cycle Perspective on Rare Earth Oxide Production (Zaimes et al. 2015)

[21] Comparative Life Cycle Assessment of NdFeB Magnets: Virgin Production versus Magnet-to-Magnet Recycling (Jin et al. 2016)

[22] Environmental life cycle assessment on the separation of rare earth oxides through solvent extraction (Vahidi and Zhao 2018)

[23] Evaluation of the environmental impacts of rare earth elements production (Ikhlayel 2017)

[24] Introducing a multi-criteria indicator to better evaluate impacts of rare earth materials production and consumption in life cycle assessment (Adibi et al. 2014)

[25] LCA Study of Rare Earth Metals for Magnesium Alloy Applications (Koltun and Tharumarajah 2010)

[26] Rare Earth Elements: Overview of Mining, Mineralogy, Uses, Sustainability and Environmental Impact (Haque et al. 2014)

[27] Rare Earths from Mines to Metals (Lee and Wen 2017)

[28] Life-cycle assessment of the production of rare-earth elements for energy applications: a review (Navarro and Zhao 2014b)

[29] The Life Cycle Assessment of Rare Earth Oxides Production in Bayan Obo (Zhou et al. 2016)

[30] Assessing the energy requirements and global warming potential of the production of rare earth elements (Weng et al. 2016)

[31] Environmental Effects Report for Didymium Pilot Plant (ENVIRON Australia 2013)

[32] Environmental Evaluation of Rare Earth Elements: Processing, Products, and Pathways (Navarro 2015)

[33] Life Cycle Impact of Rare Earth Elements (Koltun and Tharumarajah 2014)

[34] Life cycle assessment of rare earth production from monazite (Browning et al. 2016)