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The Life Cycle of Rare Earth Elements

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INTRODUCTION

My chemistry curriculum has traditionally included a focus on environmental issues as I feel it is important to connect the classroom learning to events that affect my student's lives. Of the many environmental concerns that we have discussed, climate change and global warming are two topics that we as a classroom community consider to be of critical importance as they affect all living organisms and all of the earth's ecosystems. Given the established connection between increasing greenhouse gas emissions and rising global temperatures, our analysis of the causes (and possible solutions) to climate change has necessarily focused on the chemistry of traditional energy production processes (the combustion of fossil fuels that increase concentrations of greenhouse gases) and renewable energy technologies that produce limited (or no) greenhouse gases. It is important to note that although renewable energy technologies protect our climate by decreasing greenhouse gas emissions, one cannot assume that they do no harm to the environment. An electric vehicle may produce zero emissions, but its environmental impact must include whether the electricity was generated from the combustion of fossil fuels or through renewable energy processes (such as wind, solar or hydroelectric) as electricity generation remains a principal source of greenhouse gas emissions.[1] In fact, to fully assess the environmental impact of this vehicle, one must analyze all of the processes and resources used to produce it and properly dispose of all of it and all of its components. This complete "cradle to grave" analysis of the total environmental impact of a product is known as the Life Cycle Assessment. Life Cycle Assessment is a structured process that

> *takes a holistic approach and provides a complete view of the environmental impacts over the entire life cycle of a process or product, 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*[2]

Modern society depends on a wide range of industries and commercial processes that produce the many products and systems that we rely on. While we all benefit from these conveniences, we must acknowledge that *all* industrial processes, technologies, or consumer products produce some form of chemical emissions and / or pollutants that affect our health and our environment. In order to address these deleterious effects, we must be able to identify and mitigate all potentially harmful chemical pollutants that our society produces.

The Life Cycle Assessment by virtue of its “cradle to grave” analysis of product systems is perfectly suited for this endeavor.

Rare Earth Elements

In recent years a group of elements known as the Rare Earth Elements (REE) have become central to our information, electronics and “green energy” industries. They are used in most renewable energy systems (for example: wind turbines, electric vehicles, solar panels) and are also essential components of most of electronic devices (cell phones, computers, tablets, flat screen displays) and phosphors in high efficiency lighting systems. Each of these elements possess unique chemical properties such as (fluorescence, high refraction indexes, strong paramagnetic properties, and high hydrogen storing capacities) that make them ideal for a wide range of applications and products from military and aerospace applications,[3] to catalysts in petroleum refining, catalytic converters, fuel cells, high capacity batteries, and a host of other electronic applications [4] (a complete listing of each element’s application and products is listed in the Appendix). And although they have become indispensable components of nearly all of our modern technologies, their extraction and refining processes cause great harm to the environment, the living organisms in the ecosystems where they are mined and the workers that process them.[5]

RATIONALE

I teach chemistry in a single gender school in north Philadelphia. I have always felt that my science curriculum should provide my students the understandings necessary to become critical informed citizens of our society. This becomes especially important when considering our relationship to the environment and our responsibilities as its stewards. The study of green technologies has become an important focus of my chemistry curriculum as it has helped my students understand how scientific knowledge can be used to solve difficult societal problems.

It is however quite unfortunate and ironic that these same technologies that are meant to ameliorate climate change are themselves threatening our health and the sustainability of our ecosystems. Understanding the complete life cycle of the technologies that are meant to save our environments is critically important to my students as “green technologies” will likely become more widely used in their future. A knowledge of life cycle assessments and the way they interrogate all aspects of a product system will provide such an awareness. It is important to note that these assessments are made on all products, and product systems as all of these processes have some impact on the environment.

A second equally important goal of this unit will be to introduce my students to the engineering principles that are used to design solutions to environmental problems. My student population is largely from underrepresented groups in science and technology. Although they are highly capable, intelligent students, few consider technology or engineering as future career paths. Exploring the ways engineering is used to solve environmental problems is one way to encourage them to consider it as a possible career path.

This unit written for the 10th grade chemistry curriculum is meant to introduce students to the processes used in Life Cycle Assessments and the way their findings are used to ameliorate the environmental impacts of products and product systems in our lives.

CONTENT OBJECTIVES (aligned to science standards)

Students will be able to use the Life Cycle and Risk Assessments to critically analyze the impacts of rare earth elements on the environment and living organisms. This objective addresses the **ETS1-1 Engineering Design** standard that asks students to analyze a major global challenge and specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants. Employing the inventory analysis and impact assessment components of the LCA will provide a more complete understanding of the total ecological footprint of technologies and applications that employ rare earth metals. This addresses standard **HS-ETS1-4 Engineering Design** that asks students to create a simulation that models the impact of proposed solutions to complex real-world problem. In terms of the chemistry curriculum, the analysis of the various reaction pathways that refine REE ores will extend my student's understanding of the chemistry of minerals, chemical reactions, and catalysts. Given that many of the properties of REEs are the result of their electron configurations students will engage in various inquiry activities that will analyze the configurations, ionic properties, oxidation states of rare earth elements. These two objectives address the common core standard **CCSS.ELA-Literacy.RST.11-12.9** that asks student to synthesize information from a range of sources to create a coherent understanding of a phenomena or concept.

BACKGROUND CONTENT

Life Cycle Assessment

> The Life Cycle Assessment (LCA) "offers a method for quantitatively compiling and evaluating the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" .[6]

The LCA processes date back to the early 1960's and have continued to evolve in the ensuing decades with regular updates issued by the ISO (International Standards Organization). The following description of the current LCA standards and procedures is based on the most recent update (ISO 14040) issued in 2006.   The steps in the LCA process are depicted in Figure 1.

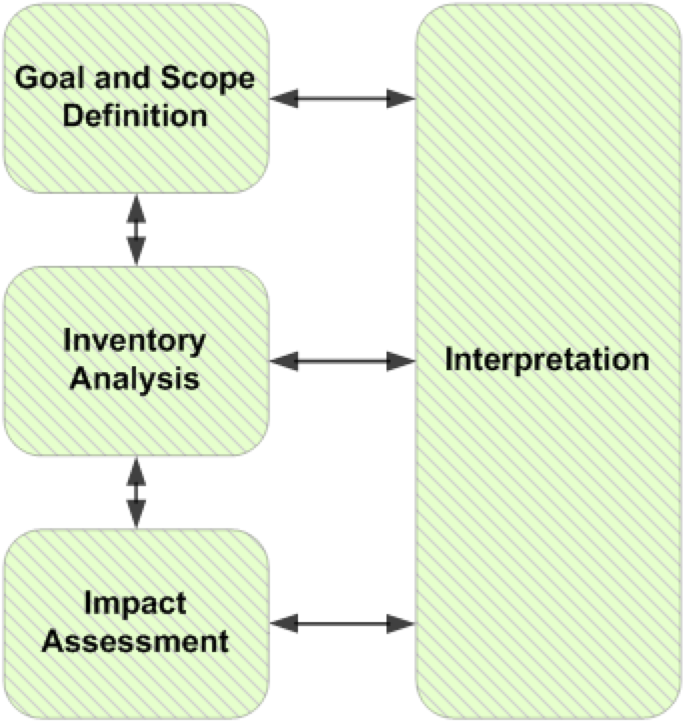

Figure 1 Life Cycle Assessment Framework:

Source:https://commons.wikimedia.org/wiki/File:PhasesOfLifeCycleAnalysis.png

Goal and Scope Definition

The LCA follows a series of steps as depicted in figure 1. The process typically begins with a definition of goals and a clear definition of the product (or product system) and the scope of the investigation. The purpose of this step is to identify all aspects of the product's life cycle, as well as the emissions and all related environmental impacts. It is important to note that although this is seen as the first step, the process (as shown by the arrows between the steps) is iterative, as evaluators often need to review and adjust their findings at any stage of the analysis.

An essential component of the scope is the definition of the function of the product (or product system) that will be the focus of the analysis. Clearly identifying the product's *function* is important given that LCA's are often used to compare the environmental impacts of various products. Such comparisons are only valid when similar specific functions are analyzed [7]

For example, to compare the sustainability of differing packing materials, an LCA compared

popcorn (PC) vs. polystyrene (PS).[8] The LCA found that the manufacture of popcorn requires less energy and produces less CO_2 emissions than the polystyrene packets (which are made from fossil fuels and are not biodegradable). However, the density of popcorn is 4.6 times that of polystyrene, meaning that it would require a smaller amount of polystyrene (given its smaller density) to fill the volume of a packing box. If packaging is the function the LCA is assessing,

then polystyrene is the more sustainable option as a smaller quantity will be needed as packaging agent .[9] Clearly identifying the function is a critical first as the focus of LCA is to relate environmental impacts to the **function** of a product over its whole life cycle. Given that LCA's are used to quantitatively compare product systems across various scenarios, the functional unit provides a numerical context that can be used to compare product function.

> A functional unit is a quantified description of the performance of the product systems, for use as a reference unit. Example: Lighting 10 square meters with 3000 lux for 50000 hours with daylight spectrum at 5600 K.[10]

Rare Earth Elements do not have a specific end use as they are primarily used as intermediate components of various products. As such they have no specific function or functional unit rather, they are assigned a reference unit. The reference unit used in their LCA is defined as 1kg of separated REEs comprising the set of elements in the lanthanide series along with yttrium and scandium.[11] The product function helps determine the system and system boundaries. The system is the set of processes that come together to perform the system's function. The processes in the refining of REEs (mining and beneficiation, chemical treatment, separation, reduction, refining, and purification of ores .[12] The inputs into the system are resources needed to complete a given process (i.e. chemicals, energy, water, land area). Outputs are the substances that exit the system into the environment: (emissions to the air, water, and, soil), chemical byproducts etc. It is imperative that *all* economic processes (i.e. energy, raw materials, product manufacturing, infrastructure production) that input the system, as well as *all* the outputs (emissions, waste processing) are identified.[13]

Inventory Analysis

LCA phase involves "the compilation and quantification of inputs and outputs for a product throughout its life cycle".[14] It is during this phase that all inputs and outputs of the various processes as well as any subprocesses in the system are linked together as a flow of interconnected unit processes. Once the size of each of the inputs is determined the scale of the inputs per unit of output can be determined.

Impact Assessment:

The Life Cycle Impact assessment is the " phase of life cycle assessment aimed at   impacts for product systems throughout the life cycle of the product.[15] This last phase of the assessment uses data from the inventory analysis to evaluate the potential environmental impacts of the product. Evaluators use established methodologies (Eco-indicator, ReCiPe, CML) to classify the impacts into categories such as, 'global warming, eutrophication, acidification, mineral depletion, etc.).[16]

Interpreting Results

The assessment ends with the creation of a summary statement that includes the conclusions of the evaluators and recommendation for the relevant stakeholders. It is important that the interpretation be consistent with the goals and scope determined in the first phase of the assessment.

Examples of LCAs

Life Cycle Assessments are used to evaluate products in a wide range of products, technologies, and industrial processes. Each follows the steps outlined in LCA framework. A list of representative LCAs is included in the Appendix. They will be used as part of student's independent research.

The Chemistry of Rare Earth Elements

Rare earth elements are a group of 15 elements (beginning with #57 (Lanthanum) and ending at # 71 Lutetium) that are known as the Lanthanide series. Although Scandium # 21 and Yttrium # 39 are not members of the lanthanides, they are included in this group because they share similar physical and chemical properties and are usually found in mineral deposits with other REEs.

The earth elements are separated into three groups based on their chemical and physical properties: (Light REEs (Lanthanum #57 to Europium # 63); Heavy REEs (Gadolinium #64 to Lutetium #71, Sc# 21, and Yttrium # 39); and the Middle REE's (Europium, Samarium, and Gadolinium).

Chemical and Physical Properties

Rare earth elements are usually together in metallic complexes as they share similar ionic radii and are mostly trivalent (3+ charge). Exceptions are Cerium (Ce^{4+} the most abundant REE) and Europium (Eu^{2+}). They also share a somewhat similar electronic configuration as each, beginning with La ([Xe] $6s^2$ $5d^1$ $4f^0$ to Lu [Xe] $4f^{14}$ $5d^1$ $6s^2$), is adding an electron to an inner *4f* orbital (Table 1). The addition of an electron to an inner electron shell shrinks the atom's atomic and ionic radius across the period. This trend (knows as the "lanthanide contraction" is responsible for the lanthanides unique magnetic and optical properties.[17] The contraction is especially important in the mining and processing of REE as it creates a fractionation effect which allows for the separation of REE complexes found in soils and rocks.

Table 1: Physical Properties of Rare Earth Elements

Element	Symbol	Atomic number	Atomic weight	Electron Configuration	Crustal abundance (ppm)
Light REEs					
Lanthanum	La	57	138.9	[Xe] $4f^0$ $5d^1$ $6s^2$	39
Cerium	Ce	58	140.12	[Xe] $4f^2$ $6s^2$	66.5
Praseodymium	Pr	59	140.91	[Xe] $4f^3$ $6s^2$	9.2
Neodymium	Nd	60	144.24	[Xe] $4f^4$ $6s^2$	41.5
Promethium	Pm	61		[Xe] $4f^5$ $6s^2$	~ 0.0
Samarium	Sm	62	150.36	[Xe] $4f^6$ $6s^2$	7.05
Europium	Eu	63	151.96	[Xe] $4f^7$ $6s^2$	2.0
Gadolinium	Gd	64	157.25	[Xe] $4f^7$ $5d^1$ $6s^2$	6.2
Heavy REEs					
Yttrium	Y	39	88.91	[Kr] $4d^1$ $5s^2$	33
Terbium	Tb	65	158.92	Xe] $4f^9$ $6s^2$	1.2
Dysprosium	Dy	66	162.50	Xe] $4f^{10}$ $6s^2$	5.2
Holmium	Ho	67	164.93	Xe] $4f^{11}$ $6s^2$	1.3
Erbium	Er	68	167.26	Xe] $4f^{12}$ $6s^2$	3.5
Thulium	Tm	69	168.93	Xe] $4f^{13}$ $6s^2$	0.52
Ytterbium	Yb	70	173.04	Xe] $4f^{14}$ $6s^2$	3.2

Lutetium	Lu	71	174.97	Xe] $4f^{14}$ $5d^{1}$ $6s^{2}$	0.8

Applications and Uses

It is difficult to describe all the ways that REEs are used in our technological society as they have become indispensable to a wide range of industrial and technological applications. They are increasingly important in "green technologies" as they are essential components in permanent magnets used in wind turbines, high capacity NiMH batteries in electric vehicles and as phosphors in compact fluorescent lamps. They are extensively used by the glass industry to color glass and polish the surfaces of flat screen displays. Lanthanum and lutetium are used to alter the refractive index of optical glass. Other REEs are used to give glass filtering and glare reducing qualities. The petroleum industry uses lanthanum-based catalysts in refining processes while cerium and trace amounts of other REEs are used in the catalytic converters in most vehicles. They are as noted earlier essential components of permanent magnets, nickel-metal hydride batteries, and in all phosphors used in flat panel displays, light emitting diodes, medical devices, and lasers. These are but some of the ways that REEs are used in our world. A complete analysis of their many applications would require a very lengthy narrative. Table 2 describes some of their many other uses.

Table 2: Applications of Rare Earth Elements

REE	Applications Products
Scandium	Aerospace materials, electronics, lasers, magnets, lighting, sporting goods
Yttrium	Ceramics, communication systems, lighting, frequency meters, fuels additive, jet engine turbines, televisions, microwave communications, satellites, vehicle oxygen sensors
Lanthanum	Catalyst in petroleum refining, television, energy storage, fuel cells, night vision instruments, rechargeable batteries
Cerium	Catalytic converters, Catalyst in petroleum refining, glass, diesel fuel additive, polishing agent, pollution-control systems
Praseodymium	Aircraft engine alloy, airport signal lenses, catalyst, ceramics, coloring pigment, electric vehicles, fiber optic cables, lighter flint, magnets, wind turbines, photographic filters, welder's glasses
Neodymium	Anti-lock brakes, air bags, anti-glare glass, cell phones, computers, electric vehicles, lasers, MRI machines, magnets, wind turbines
Promethium	Beta source for thickness gages, lasers for submarines, nuclear powered battery
Samarium	Aircraft electrical systems, electronic counter measure equipment, electric vehicles, flight control surfaces, missile and radar systems, optical glass, permanent magnets, precision guided munitions, stealth technology, wind turbines
Europium	CFL, lasers, televisions, tag complex for the medical field
Gadolinium	Computer data technology, magneto-optic recording technology, microwave applications, MRI machines, power plant radiation leaks detector
Terbium	CFL, electric vehicles, fuel cells, televisions, optic data recording, permanent magnets, wind turbines
Dysprosium	Electric vehicles, home electronics, lasers, permanent magnets, wind turbines
Holmium	Microwave equipment, color glass
Erbium	Color glass, fiber optic data transmission, lasers

Thulium	X-ray phosphors Improving
Ytterbium	Improving stainless steel properties, stress gages Catalysts,
Lutetium	Catalysts, positron emission tomography (PET) detectors

Geology of REEs

In nature REEs are most commonly found in minerals formed from carbonatites (igneous carbonate rocks), in carbonates (flurocarbonates, hydroxyl carbonates) and in silicates, oxides and phosphates. The most important REE bearing mineral is Bastnaesite (REE)(CO_3)F as it is the primary mineral in the world's largest REE mines: the Bayan Obo mine in China and the Mountain Pass Mine in California.[18] Other important REE minerals are Monazite (REE, Th)(PO_4), Xenotime (YPO_4), and Ion adsorption clays: 2(Kaolin)$^{3-}$ RE^{3+} . The processing of these elements begins with their extraction from the earth.

Production of REE Follows Three Stages

The processing of REES begins with mining of RE containing iron ores. Mining practices range from placer mining, underground to open pit mining. The type of mine depends on the site and ore type. Both Bayan Obo and the Mountain Pass mine use open pit methods to extract REE ores. Following extraction, the RE minerals are separated from gangue (waste rock components) and produce minerals that contain approximately 50% rare earth ores (REO).

Beneficiation is used to improve the quality of the ore by grinding, sifting, gravity or magnetic filtration or froth flotation. This phase of the refining process carries the first of many environmental risks. The mechanical separation processes pose minimal risks as they require little heat and use no chemicals. Froth flotation used with bastnaesite ores, employs an array of acids (organic phosphoric acids, dicarboxylic acids) as collectors (compounds that make metals more hydrophobic) thus increasing their separability. Additional compounds (sodium silicates, sodium hexafluoro-silicate, and sodium carbonate are often used as depressants (chemicals used to inhibit the flotation of gangue minerals). The chemical residues from these and other refining processes collect in tailing ponds where they mix with wastewater, heavy metals, radioactive elements (thorium is naturally associated with REEs) that pose serious environmental risks for the ecosystems and people living near the mines [19]

The concentrates formed during beneficiation are then treated with a series of acids and electrolytes that purify and increase their REO concentration to approximately 90%. Another process commonly used is high acid roasting that emits hydrogen fluoride, sulfur dioxide and trioxide and silicon tetrafluoride gases. Several scrubbers are used to capture and purify the exhaust gases.

In the final step, solvent extraction that exploits differences in basicity to separate the individual REO's. This process is necessarily slow given the slight difference in basicity between REEs. Once separated, reduction using molten salt oxide, or fused salt electrolysis can be used to separate the individual REE's from their ores.[20] Figure 2 is a representation of the system processes for the refining of REEs from bastnaesite and monazite ores.

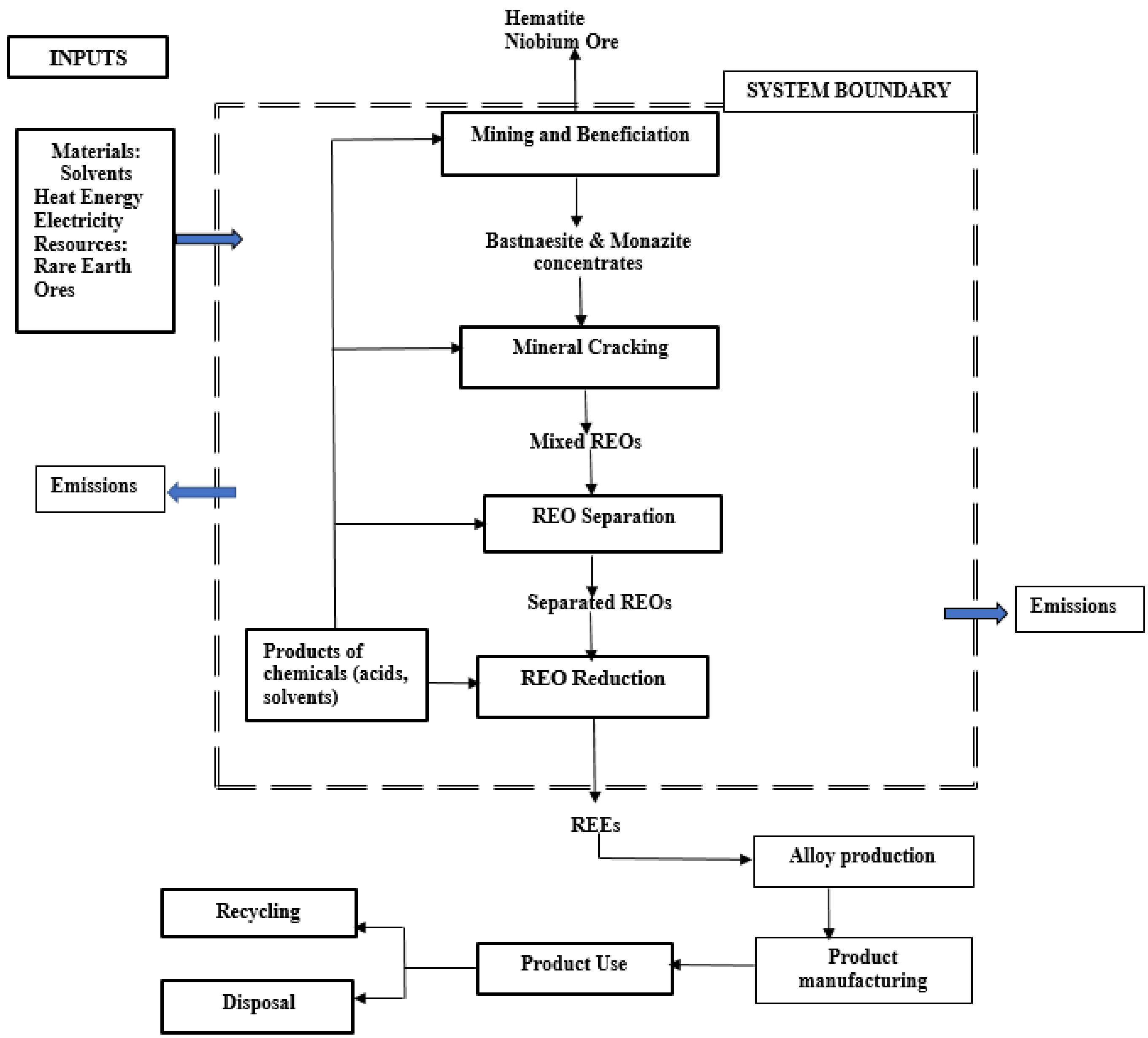

Figure 2: Rare Earth Element System Boundary with Inputs and Outputs for Production of Rare Earth Elements from Bastnaesite Ore. Source: [21]

Environmental Concerns

> Scientists say that under regulated rare earth projects can produce wastewater and tailing ponds that leak acids, heavy metals and radioactive elements into groundwater, and they point out that market pressures for cheap reliable rare earths may lead project managers to skimp on environmental protections [22]

In 2002 the only mine in the US, the Mountain Pass was closed because of continued leaks of radioactive wastewater. In China, Malaysia, Australia, and other countries citizen groups are mounting campaigns against rare earth mining given the real (and under investigated) threats these mines pose to human health and ecosystems.[23] Exposure to radioactive soils and water remain an ongoing concern for those living near REE mines because rare earth elements are often complexed with radioactive elements like thorium. The many emissions created in the processing of these ores have been implicated in the increased incidence of cancers, diabetes and other health concerns in villages surrounding the Bayan Odo mines. The toxic mix of chemicals found in the tailing ponds has contaminated the soils and groundwater for miles around the mines.[24]

Table 3: Environmental Impacts per kg of metal from the Production of Rare Earth Elements at the Bayan Obo Mine: China: Data Source [25]

REE	Energy Consumption		Water Consumption [kl]	Environmental Impact		
	Elec. [MJ]	Heat Energy [MJ]		Human Health [DALY*10]	Ecosystem Quality [PDF*m^2 yr]	Resource Depletion [MJ] surplus
Lanthanum	91.8±17.8	127.6±27.	43.5±11.0	7.38±1.32	3.48±0.88	44.3±10.6
Cerium	154.7± 29.0	199.5±41.5	75.7±19.1	12.40±2.22	5.89±1.50	74.3±18.2
Praseodymium	91.9±17.9	128.2±27.3	43.4±11.0	7.38±0.33	3.48±0.87	44.3±10.6
Neodymium	173.1±33. 3	218.9±45.2	85.5±21.4	13.85±2.47	6.59±1.69	83.0±20.4
Gadolinium	996.4±19 1.0	1166±235.0	522.3±131.7	79.80±14.19	38.12±9.89	481.6±120.2
Yttrium	331.5±636	424.4±86.8	180.7±45.9	26.82±4.77	12.81±3.31	165.7±40.8

Environmental Impact Units: Source [26]

DALY*10 - Disability Adjusted Life YearsDALY = YLL (Years of life lost) + YLD (years of life disabled) * Q (Quality of life)

Q = 0 (optimum health) : Q = 1 (Life Lost).

Damage to Ecosystem: PDF*m^2 * yr –Potentially Disappeared Fraction of species * area over which they disappear * number of years of damage.

Addressing Environmental Impacts: The need for recycling

The increasing demand (and limited supply) for rare earths, has led many has led many countries to open new mines or reopen existing sites: (the Mountain Pass mine closed in 2002 is due to reopen later this year [27]) . This is unfortunate as the LCA analysis of REE has clearly shown the environmental damage caused by the mining and processing of these elements. While much attention is given to developing new resources, research has shown that less than 1% of these elements are recycled.[28] Adding additional resources through recycling efforts would increase supply and likely lessen the need for new mines. Recycling of REE can occur during the mining, manufacturing and refining phases where resources can be recovered from waste residue and scrap or they can be found in from post-consumer “end of life” products through urban mining [29] and landfill mining.[30]

Recycling Methods

This review of recycling methods focuses on three applications that comprise approximately 80% of the rare earth market: permanent magnets (38%), nickel metal hydride batteries (13)% and lamp phosphors (32%). Table 4 lists the % use of REE in each of these applications. Recycling the end of life products in these applications yields

(See Table 2 for a detailed list rare earth element usage by %). The following protocols will serve as an introduction to recycling methods.

(Note: Students will be able to explore the recycling of REEs in other products as part of their engineering design activity. Additional information on recycling REEs used in other applications and their methods will be provided as the need arises).

Table 4: Rare Earth Usage by application in %: Source:(Curtis et al (2011) [31]

Application	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Y	Other
Magnets			23.4	69.4			2	0.2	5		
Battery Alloys	50	33.4	3.3	10	3.3						
Metallurgy	26	52	5.5	16.5							
Auto Catalyst	5	90	2	3							
FCC	90	10									
Polishing powders	31.5	65	3.5								
Glass additives	24	66	1	3						2	4
Phosphors	8.5	11				4.9	1.8	4.6		69.2	
Ceramics	17	12	6	12			1			53	
Others	19	39	4	15	2		1				

Recycling REEs in Magnets

Each of the following methods is suited for magnets of differing composition found in various devices and in different environments. They are as follows: Direct re-use, Reprocessing, Hydrometallurgical, Pyrometallurgical, and Gas-phase extraction.

Direct Re-use is the most economical method as it requires very little energy and generates no waste. It is useful for only large magnets in electric vehicles and wind turbines

Reprocessing of Alloys is especially suited for hard drives (magnets with little compositional variations), generates no waste r and requires minimal energy input. It is not suited for oxidized magnets.

Hydrometallurgical Method: Applicable to all types of magnet compositions, and oxidized alloys, but it requires many steps, generates large amounts of waste chemicals and consumes large amounts of water

Pyrometallurgical Methods: (Electrostatic refining; Liquid Metal Extraction; Glass Slag Method; Direct Melting).

These processes are applicable to all magnet compositions, generate no water waste, and require fewer processing steps than Hydrometallurgical methods. Direct melting of alloys facilitates the extraction of REE in metallic state. The processes use large amounts of energy and generate considerable solid waste. They cannot be used on oxidized magnets.

Gas Phase Extraction Methods: Applicable to all types of magnet compositions, oxidized and non-oxidized alloys and generates no wastewater. Process consumes large quantities of Chlorine gas and generates corrosive Aluminum Chloride.

Recycling REEs in Nickel Metal Hydride Batteries

Hydrometallurgical methods:

Possible to recycle and market different waste fractions (i.e. cathodes, anode materials, metal casings), requires minimal energy input, however dismantling and separating components requires many steps and consumes large quantities of chemicals.

Pyrometallurgical methods: A well-developed process that recovers energy from plastic castings and other organic components, but furnace is a major investment: REEs are extracted from slag and require additional separation.

Recycling REEs in Lamp Phosphors

Direct Re-use: This is a very simple method requiring no chemical processing. However, it is only suited to one type of fluorescent lamp since different phosphor mixtures are used in different lamps and phosphors deteriorate over the lifetime of the lamp.

Separation of phosphors in individual components: A relatively simple process that consumes limited amounts of chemicals. Pure phosphor fractions are very difficult to obtain, separation may change phosphor particle size and phosphors deteriorate over the lifetime of the lamp.

Recovery of REE content: Provides pure earth oxides that can be used in other applications, is applicable to all phosphor mixtures. Process requires many steps and consumes large amounts of chemicals and generates large quantities of water.

TEACHING STRATEGIES: (Aligned to the Content Objectives)

To gather information on the LCA process, students will engage in three guided inquiries to that analyze the benefits and environmental impacts of REEs. Additional information will be communicated through direct instruction and guided note taking. In order to learn how to use the LCA students will engage in an Independent Research Activity that analyzes representative LCAs from various industries. To understand the chemistry used to recover resources from recycled materials, students will engage in a laboratory to recover alum from waste aluminum cans. Given the focus on engineering design, students will work collaboratively (in pairs and in teams of four) to design engineering solutions that ameliorate the environmental impacts of products and product systems.

Prior Understandings

Prior to this unit, students will have studied the properties of the elements on the periodic table, their families, and trends in chemical and physical properties. They will have studied electronic configurations, the order in which the Aufbau Principle, Hund's rule, and the Pauli Exclusion Principle determine how electrons fill sub orbitals, and exceptions to these rules. Of particular importance to this unit will be the Rare Earth Elements and how their electron configurations (of *f* and *d* orbitals) affect their magnetic, optical, and electrical properties. These latter topics will serve as the foundation of the unit's exploration of the benefits and environmental consequences of our use of these elements.

UNIT ACTIVITIES

Day One: Benefits of Rare Earth Elements

Essential Question: What are benefits and environmental consequences of our use of Rare Earth Elements?

Objective: Students will analyze and evaluate the benefits and the environmental consequences of the use of rare earth elements.

Standard: **HS-ETS1-1 Engineering Design & RST.9-10.1**

Class Activities: Opening discussion questions: Students working in pairs will answer the following discussion questions. Students will be asked to name the benefits each product provides and any possible environmental impacts.

Task: Answer each of the following questions with your partner. For each product / technology describe the benefits and possible environmental impacts.

> What are the most important products that you use in your daily life?
> What are the most important technologies that you use in your daily life?
> What are the most important products (or product systems) in our society?
> What are the most important technologies in our society (in medicine, defense, scientific research) ?
> What about in green technologies (those that address climate change)?

Class Discussion on student responses. Teacher will show list of rare earth elements prominent in our technologies, products, and product systems (**List is located in Teacher Resources).** To analyze specific uses of each element, students will engage in guided analysis of Video:

Rare Earth Elements and How They are Used: (https://www.youtube.com/watch?v=e2xHfP4lAlg)

Each student will be assigned two elements to analyze. Students work independently to note the use, chemical / physical properties, benefits, and potential environmental impact for their assigned elements. Once finished class will work collaboratively to fill in a table that summarizes their findings. Table will be posted in Google Classroom as resource for homework assignment. (**Table format is located in Teacher Resources).**

Homework: Read article: Life Without Rare Earth Elements: (http://www.acschemmatters-digital.org/acschemmatters/december2016?pg=14#pg14) and answer set of analysis questions: (**Analysis Questions in Student Resources**) Once finished use table from class discussion and any of the websites listed in the classroom to answer the following (**Websites in Student Resources)**. Select a rare earth element that is of importance to your personal life, and one that is important to society(for example: a green technology, defense, or medicine). Description should include the particular properties (magnetic, optical, electrical) that make the element beneficial to you and to society. What are the possible environmental consequences of our use of this element? List the harm that might occur to living organisms, people, and the environment (land, water, soil). Work should be completed as a narrative summary.

Day Two : Environmental Impacts of Rare Earth Elements

Essential Question **:** What are the environmental impacts of human activity?

Objective: Students will evaluate their ecological footprint and the environmental consequences of the use of rare earth elements.

Standards: **HS-ETS1-1 & RST.9-10.1**

Class Activities: Students will begin by viewing video “Environmental Impacts of Rare Earth Element” (https://www.youtube.com/watch?v=f_PbVCgdut4) that describes the environmental impacts of the processing or rare earth metals. Class will note impacts on land, air, water, workers, living organisms, and on GHG emissions. Findings will be posted to table from day one.

Teacher will then explain that we measure the impact of products and product systems using the Life Cycle Assessment. Teacher will guide students in notes on the steps of the assessment. Teacher will define: Scope and Objectives, Life Cycle Inventory and Life Cycle Assessment. Particular focus will be on the (LCI) inventory of the input of resources and output of emissions, and the Impact Assessment phase of the cycle. Students will review PowerPoint “Life Cycle Assessment: What it is” (https://www.dartmouth.edu/~cushman/courses/engs37/LCA.pdf) that shows how LCAs are used to assess impacts of products. After notes are completed students will view video “A Life Cycle Assessment: A Materials Perspective" (https://www.youtube.com/watch?v=Z4LOqt7U-JE) that introduces life cycle assessments in context of engineering practices. Students will then complete a set of analysis questions that complement the LCA notes and introduce the role of materials engineering practices as a means to address environmental impacts of product cycles: (**Analysis Questions in Student Resources).**

Homework: To determine the impact that our lifestyles have on the environment,, the class will complete an Ecological Footprint analysis to determine the environmental impact of their activities in terms of carbon footprint and sustainability of their practices.

Ecological Footprint Calculator: (https://www.footprintcalculator.org)

Day Three and Day Four: Life Cycle Assessment

Essential Question: How can Life Cycle Assessments be used to determine sustainability of products and product systems?

Objective: Students will use LCAs to evaluate products / product systems. Students will use assessment to propose ways to ameliorate environmental impacts.

Standards**: HS-ETS1-3 & RST.9-10.1**

Class Activities: Class will begin with a discussion of ecological footprint calculations with a focus on ways to lower footprints and make lifestyles more sustainable. After discussion, teacher will review ways that LCAs are used to analyze and evaluate product life cycles. Teacher will review slides from materials PowerPoint "A Life Cycle Assessment: A Materials Perspective", to illustrate units used in LCA assessment. Teacher will then lead discussion on how to analyze the energy and emissions at given phases of the life cycle (Resource acquisition, Manufacturing, Use, Disposal, and End of Life Recycling), and how possible engineering changes in each of the phases might lower energy requirements and CO_2 emissions.

Once completed, students will be given a guide sheet to be used in the analysis of the LCA of various products / products systems (**Sheet is located in Student Resources)**. Students will first determine relative scale to be used to quantify the inventory of inputs / outputs for their selected product. (**Note:** scale is a relative scale determined by class given that actual quantitative data is not appropriate for this unit. Actual data will be explored later in this unit. Numbers for this day will be used to compare products). Students will work in pairs to select (one product that is personally important and one that is important to society (clean energy, industry, medicine, etc.). Students will use sets of LCA found at: Design Life Cycle: (http://www.designlife-cycle.com). Each LCA provides inputs and emission information as an Infographic and in narrative form. For each product student teams will determine a relative score to be used to compare products.

Day Four: Conclusion of LCA Assessment: Engineering Solutions

Activity: Teams will complete LCA analysis. Each team will then be responsible for determining at least two ways to improve the environmental impact of their product. Teams should suggest how to better engineer aspects of any phase of the life cycle. *Class will discuss assessments and engineering suggestions.*

Day Five and Day Six: Recovery of Alum from Aluminum Cans

Essential Question: How are essential metals recovered from waste products?

Objective: Students will conduct a laboratory to recover Alum from waste aluminum cans.

Standards: **HS-ESS3-4 & HS-PS2-6.**

Class Activities: Teacher will review the role of recycling in reducing environmental impacts of products. Teacher will introduce LCA data for aluminum cans and the importance of recycling aluminum. Students will then be given laboratory guide sheets used during laboratory: **(Laboratory is located in Student Resources)**

Day Six: Conclusion of Laboratory

Class Activities: Students will complete laboratory. Once finished pairs of students will work on completing post -lab conclusion questions.

Day Seven and Day Eight: Life Cycle Assessment and recycling of Rare Earth Elements

Essential Question: How can recycling and recovery of REE lessen the environmental consequences of their usage?

Objective: Students will evaluate LCA of rare earth metals and propose ways to modify recycling protocols and reduce GHG emissions.

Standards: **HS-ETS1-2 & HS-ETS1-4**

Class Activities: Students will analyze data from the LCA of REEs. Data will highlight importance of recycling end of life products and recovering resources. Students will analyze current methods of recycling and propose ways to engineer changes that would increase the yield of recovered resources and lessen the environmental impacts of current recovery practices.

Students will receive abbreviated protocols for current practices (Protocols are from [32]). Each team will determine which protocols can be reengineered to provide either a more efficient yield, reduce energy requirement, or reduce emissions. This activity will be completed on the following day.

Day Eight: Presentation of Engineering designs for Recycling REEs.

Activity: Each team will present their engineering design.

APPENDIX ON IMPLEMENTING DISTRICT STANDARDS

Students will use the Life Cycle Assessment to critically analyze the impacts of rare earth elements on the environment and living organisms. This objective addresses the **HS-ETS1-1** standard that asks students to analyze a major global challenge and specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants**.** Employing the inventory analysis and impact assessment components of the LCA will provide a more complete understanding of the total ecological footprint of technologies and applications that employ rare earth metals. These activities address standard **HS-ETS1-3** which asks students to evaluate a solution to a complex real**-**world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts. Standard **HS-ETS1-4** asks students to create a simulation that models the impact of proposed solutions to complex real-world problem, while standard **HS-ETS1-2** suggests that students design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering. Each of these standards is relevant to the design aspects of this unit. The aluminum recovery laboratory is informed by standard **HS-PS2-6** which asks students to communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials. The common core standard **RST.9-10.1** which states that student should use specific textual evidence to support analysis of science and technical texts, attending to the precise details of explanations or descriptions is used throughout the unit's analysis of various texts.

STUDENT RESOURCES

Student Article: Life Without Rare Earth Elements" Source: http://www.acschemmatters-digital.org/acschemmatters/december2016?pg=14#pg14

Guided Reading Questions: Adapted from Chem Matters. Source: https://www.acs.org/content/acs/en/education/resources/highschool/chemmatters/past-issues/2016-2017/december-2016.html

Anticipation Guide

Guided Reading Questions

1. List eight (8) common products that use rare-earth elements.
2. Why are rare-earth elements sometimes called "chemical vitamins"?
3. Starting in the 1970s, color televisions contained minerals with rare-earth elements. Which elements were used, and what colors did they produce?
4. Describe how the process of luminescence works.
5. What is an alloy? Why are they used?
6. Are rare-earth metals really rare? Explain.
7. Which country has the largest supply of rare-earth metals?
8. Which rare-earth element is used as a pink coloring agent and in lasers used to remove acne scars and tattoos?
9. Why are these elements called "technology metals"?
10. Why have some mines gone out of business? Where are most mines located? Why are they profitable there?

Use Table developed in class and websites listed below to complete homework assignment.

WebQuest Sources:

Rare Earth Elements: Vital to Modern Life : https://pubs.usgs.gov/fs/2014/3078/pdf/fs2014-3078.pdf

Rare Earth Elements and their Uses: https://geology.com/articles/rare-earth-elements/

Rare Earth Elements: https://www.periodni.com/rare_earth_elements.html: Closely read "The Rare Earth Dilemma"

What are Rare Earth Metals: https://www.treehugger.com/what-are-rare-earth-metals-4862190: Closely read section titled: " *Look whose toxin".*

LCA Materials Engineering Analysis Questions

1. What are the effects of your decisions as an engineer?
2. What is the source of the resources that are used to produce materials (products?) Examples?
3. Are our reserves of natural resources finite or infinite? Explain your reasoning.
4. What are some inputs and outputs to this first phase?
5. Describe each of the steps in the product's life cycle.
6. What are the inputs / outputs at the product disposal phase?
7. Why is it important to recycle products?
8. What are two other steps that can be used at the product disposal phase to limit our use of resources and extend the product's lifetime?
9. How does the video describe the Life Cycle Assessment?
10. The video says that the LCA is important to engineers because sustainability is important. What is sustainability and why is it important?

TEACHER RESOURCES

Day One

Table 2: Applications of Rare Earth Elements

REE	**Applications Products**
Scandium	Aerospace materials, electronics, lasers, magnets, lighting, sporting goods
Yttrium	Ceramics, communication systems, lighting, frequency meters, fuels additive, jet engine turbines, televisions, microwave communications, satellites, vehicle oxygen sensors
Lanthanum	Catalyst in petroleum refining, television, energy storage, fuel cells, night vision instruments, rechargeable batteries
Cerium	Catalytic converters, Catalyst in petroleum refining, glass, diesel fuel additive, polishing agent, pollution-control systems
Praseodymium	Aircraft engine alloy, airport signal lenses, catalyst, ceramics, coloring pigment, electric vehicles, fiber optic cables, lighter flint, magnets, wind turbines, photographic filters, welder's glasses
Neodymium	Anti-lock brakes, air bags, anti-glare glass, cell phones, computers, electric vehicles, lasers, MRI machines, magnets, wind turbines
Promethium	Beta source for thickness gages, lasers for submarines, nuclear powered battery
Samarium	Aircraft electrical systems, electronic counter measure equipment, electric vehicles, flight control surfaces, missile and radar systems, optical glass, permanent magnets, precision guided munitions, stealth technology, wind turbines
Europium	CFL, lasers, televisions, tag complex for the medical field
Gadolinium	Computer data technology, magneto-optic recording technology, microwave applications, MRI machines, power plant radiation leaks detector

Terbium	CFL, electric vehicles, fuel cells, televisions, optic data recording, permanent magnets, wind turbines
Dysprosium	Electric vehicles, home electronics, lasers, permanent magnets, wind turbines
Holmium	Microwave equipment, color glass
Erbium	Color glass, fiber optic data transmission, lasers
Thulium	X-ray phosphors Improving
Ytterbium	Improving stainless steel properties, stress gages Catalysts,
Lutetium	Catalysts, positron emission tomography (PET) detectors

Video: Rare Earth Elements and How They are Used: https://www.youtube.com/watch?v=e2xHfP4lAlg

Table: Benefits and Environmental Impact of Rare Earth Elements

Element & Atomic #	Use: (Product or Product System)	Benefits	Environmental Impact

Homework: Article Life Without Rare Earth Elements"
(http://www.acschemmatters-digital.org/acschemmatters/december2016?pg=14#pg14

Day Two:

Ecological Footprint Calculator: https://www.footprintcalculator.org/

Video: Environmental Impacts of Rare Earth Elements: https://www.youtube.com/watch?v=f_PbVCgdut4

Life Cycle Assessment PowerPoint: https://www.dartmouth.edu/~cushman/courses/engs37/LCA.pdf

Video:

A Life Cycle Assessment: A Materials Perspective: https://www.youtube.com/watch?v=Z4LOqt7U-JE

Day Three:

Design Life Cycle: http://www.designlife-cycle.com

BIBLIOGRAPHY

Ali, Saleem H. "Social and Environmental Impact of the Rare Earth Industries." *Resources* 3, no. 1 (2014): 123–34. https://doi.org/10.3390/resources3010123.

Binnemans, Koen, Peter Tom Jones, Bart Blanpain, Tom Van Gerven, Yongxiang Yang, Allan Walton, and Matthias Buchert. "Recycling of Rare Earths: A Critical Review," 2013. https://doi.org/10.1016/j.jclepro.2012.12.037.

Dhaliwal, Harnoor. “LIFE CYCLE IMPACT ASSESSMENT,” 2010. www.earthshiDglobal.com.

Gibson, M, and I Parkinson. “Once Ignored on the Periodic Table, Don’t Ignore Them Now.” Toronto, 2011. http://www.slideshare.net/RareEarthsRareMetals/cibc-report.

Gosen, Bradley S Van, Philip L Verplanck, Robert R Seal II, Keith R Long, and Joseph Gambogi. “Rare-Earth Elements, Chap. O of Critical Mineral Resources of the United States-Economic and Environmental Geology and Prospects for Future Supply.” *U.S. Geological Survey Professional Paper 1802*, 2017, 1–31. https://doi.org/10.3133/pp1802O.

Graedel, T. E., Julian Allwood, Jean Pierre Birat, Matthias Buchert, Christian Hagelüken, Barbara K. Reck, Scott F. Sibley, and Guido Sonnemann. “What Do We Know about Metal Recycling Rates?” *Journal of Industrial Ecology* 15, no. 3 (2011): 355–66. https://doi.org/10.1111/j.1530-9290.2011.00342.x.

Guinee, Jeroen, and Reinout Heijungs. “An Overview of the Life Cycle Assessment Method-Past, Present, and Future.” In *Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products.*, edited by MA Curran, 15–52. Beverly: Scrivener Publishing, 2012.

Hirano, Seishiro, and Kazuo T. Suzuki. “Exposure, Metabolism, and Toxicity of Rare Earths and Related Compounds.” *Environmental Health Perspectives* 104, no. SUPPL. 1 (1996): 85–95. https://doi.org/10.2307/3432699.

Ives, Mike. “Boom in Mining Rare Earths Poses Mounting Toxic Risks - Yale E360.” Yale School of Forestry & Environmental Studies, 2013. http://e360.yale.edu/features/boom_in_mining_rare_earths_poses_mounting_toxic_risks.

Jolliet, O., K. Cotting, C. Drexler, and S. Farago. “Life-Cycle Analysis of Biodegradable Packing Materials Compared with Polystyrene Chips: The Case of Popcorn.” *Agriculture, Ecosystems and Environment*. Vol. 49, 1994. https://doi.org/10.1016/0167-8809(94)90055-8.

Jones, Peter Tom, Daneel Geysen, Yves Tielemans, Steven Van Passel, Yiannis Pontikes, Bart Blanpain, Mieke Quaghebeur, and Nanne Hoekstra. “Enhanced Landfill Mining in View of Multiple Resource Recovery: A Critical Review.” *Journal of Cleaner Production* 55 (2013): 45–55. https://doi.org/10.1016/j.jclepro.2012.05.021.

Liang, Tao, Kexin Li, and Lingqing Wang. “State of Rare Earth Elements in Different Environmental Components in Mining Areas of China.” *Environmental Monitoring and Assessment* 186, no. 3 (2014): 1499–1515. https://doi.org/10.1007/s10661-013-3469-8.

Navarro, Julio, and Fu Zhao. “Life-Cycle Assessment of the Production of Rare-Earth Elements for Energy Applications: A Review.” *Frontiers in Energy Research* 2, no. NOV (2014): 1–17. https://doi.org/10.3389/fenrg.2014.00045.

Pitron, Guillame. “Dirty Metals: Digging Deeper into the Energy Transition.” Green European Journal, 2018. https://www.greeneuropeanjournal.eu/dirty-rare-metals-digging-deeper-into-the-energy-transition/.

Scheyder, Ernest. “California Rare Earths Miner Races to Refine amid U.S.-China Trade Row - Reuters.” *Business News*, 2019. https://www.reuters.com/article/us-usa-rareearths-mpmaterials/california-rare-earths-miner-races-to-refine-amid-u-s-china-trade-row-idUSKCN1VD2D3.

Shaked, S, and O. Jolliet. “Global Life Cycle Impacts of Consumer Products.” In *Encyclopedia of Environmental Health*, 331–42, 2019. https://doi.org/10.1016/B978-0-12-409548-9.11700-2.

Tharumarajah, Ambalavanar, and Paul Koltun. “Cradle to Gate Assessment of Environmental Impact of Rare Earth Metals.” *Proceedings of the 7th Australian Conference on Life Cycle Assessment, Melbourne, Australia, 9–10*, 2011, 1–5. https://doi.org/10.1021/acs.biochem.5b01073.

Vodyanitskii, Yu N. “Geochemical Fractionation of Lanthanides in Soils and Rocks: A Review of Publications.” *Eurasian Soil Science* 45, no. 1 (2012): 56–67. https://doi.org/10.1134/S1064229312010164.

Weidema, Bo. “The Product, Functional Unit and Reference Flows in LCA Introduction to the Series,” n.d.

Notes

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[1] Hirano and Suzuki, “Exposure, Metabolism, and Toxicity of Rare Earths and Related Compounds.”

[2] (Navarro & Zhao, 2014, p.3)

[3] Van Gosen et al., “Rare-Earth Elements, Chap. O of Critical Mineral Resources of the United States-Economic and Environmental Geology and Prospects for Future Supply.”

[4] Gibson and Parkinson, “Once Ignored on the Periodic Table, Don’t Ignore Them Now.”

[5] Liang, Li, and Wang, “State of Rare Earth Elements in Different Environmental Components in Mining Areas of China.”

[6] Guinee and Heijungs, “An Overview of the Life Cycle Assessment Method-Past, Present, and Future.” (p.17)

[7] Shaked and Jolliet, “Global Life Cycle Impacts of Consumer Products” (p.1004).

[8] Jolliet et al., “Life-Cycle Analysis of Biodegradable Packing Materials Compared with Polystyrene Chips: The Case of Popcorn.”

[9] Shaked and Jolliet, “Global Life Cycle Impacts of Consumer Products” (p.1004).

[10] Weidema, “The Product, Functional Unit and Reference Flows in LCA Introduction to the Series.” (p.13)

[11] Tharumarajah and Koltun, “Cradle to Gate Assessment of Environmental Impact of Rare Earth Metals.”

[12] Navarro and Zhao, “Life-Cycle Assessment of the Production of Rare-Earth Elements for Energy Applications: A Review.”

[13] Shaked and Jolliet, “Global Life Cycle Impacts of Consumer Products.”

[14] Guinee and Heijungs, “An Overview of the Life Cycle Assessment Method-Past, Present, and Future.” (p. 22)

[15] Guinee and Heijungs. (p.26)

[16] Navarro and Zhao, “Life-Cycle Assessment of the Production of Rare-Earth Elements for Energy Applications: A Review.”

[17] Vodyanitskii, “Geochemical Fractionation of Lanthanides in Soils and Rocks: A Review of Publications.”

[18] Van Gosen et al., “Rare-Earth Elements, Chap. O of Critical Mineral Resources of the United States-Economic and Environmental Geology and Prospects for Future Supply.”

[19] Ali, “Social and Environmental Impact of the Rare Earth Industries.”

[20] Van Gosen et al., “Rare-Earth Elements, Chap. O of Critical Mineral Resources of the United States-Economic and Environmental Geology and Prospects for Future Supply.”

[21] Ali, “Social and Environmental Impact of the Rare Earth Industries.”

[22] Ives, “Boom in Mining Rare Earths Poses Mounting Toxic Risks - Yale E360.”

[23] Van Gosen et al., “Rare-Earth Elements, Chap. O of Critical Mineral Resources of the United States-Economic and Environmental Geology and Prospects for Future Supply.”

[24] Pitron, “Dirty Metals: Digging Deeper into the Energy Transition.”

[25] Tharumarajah and Koltun, “Cradle to Gate Assessment of Environmental Impact of Rare Earth Metals.”

[26] Dhaliwal, “LIFE CYCLE IMPACT ASSESSMENT.”

[27] Scheyder, “California Rare Earths Miner Races to Refine amid U.S.-China Trade Row - Reuters.”

[28] Graedel et al., “What Do We Know about Metal Recycling Rates?”

[29] Binnemans et al., “Recycling of Rare Earths: A Critical Review.”

[30] Jones et al., “Enhanced Landfill Mining in View of Multiple Resource Recovery: A Critical Review.”

[31] Binnemans et al., “Recycling of Rare Earths: A Critical Review.”

[32] Binnemans et al., “Recycling of Rare Earths: A Critical Review.”
