Manage Raw Material Supply Risks

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Some materials are more vulnerable to supply disruptions than others. Identify these materials and implement strategies to address challenges related to them.

Modern society depends on a wide and increasing array of raw materials — from simple steels to esoteric compounds derived from the far corners of the periodic table — to produce the products that enrich our lives and sustain our standard of living. Some of these materials are particularly vulnerable to supply disruptions due to natural disasters, geopolitics, or step changes in demand brought about by technological breakthroughs. Materials criticality is concerned with understanding these dynamics and finding ways to ensure adequate near- and long-term supply of these materials.

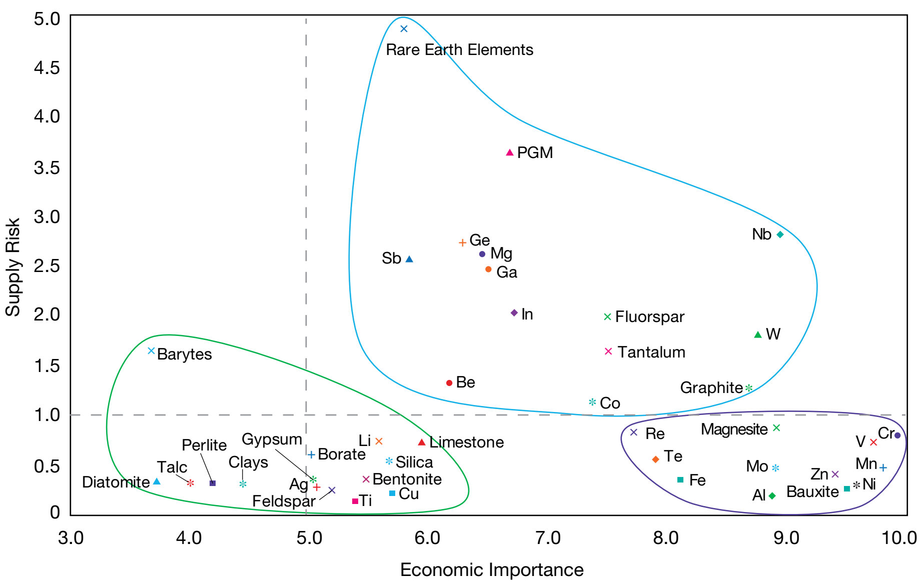
This article introduces methods to identify at-risk, critical materials, and outlines general strategies to address challenges related to these materials. It then highlights some of the technical aspects associated with the production, processing, and recycling of such materials.

What are critical materials?

Over the past decade, both public and private sectors have begun to identify critical materials using metrics such as the risk of supply disruption and the impact of disruption *(1–5)*. While specific definitions of critical materials vary according to the user and time frame of interest, criticality assessments have proven to be a valuable tool in directing attention and resources toward materials with the greatest risks and economic impacts. To highlight the similarities and differences in how organizations define criticality, Figures 1–3 compare the results of assessments by the European Union (EU), the U.S. Dept. of Energy (DOE), and the General Electric Co. (GE), respectively. The critical materials appear in the upper right sections of the plots.

European Union. The EU study evaluated the supply risks and importance of 41 raw materials not produced in Europe yet essential to its economic vitality over the 2010–2020 time period *(4)*. Three indicators were calculated for each material — supply risk, environmental policy risk, and economic importance. Supply risks were calculated based on the political and economic stability of countries producing the raw materials, the extent that production occurs at a small number of sources, and the potential for recycling or substitution. The environmental policy risk accounts for the possibility that measures or policies may be implemented by a producing country to protect the environment, and in so doing, endanger the supply of raw materials to the EU. The EU team calculated an economic importance score based on the value that the raw material added to different sectors of the EU economy. For a material to be considered critical, it must face high supply risks or high environmental country risks and be of high economic importance.

This study designated 14 materials as critical (Figure 1, upper-right section). These critical materials include: rare earth elements used in catalysis, lighting, and permanent-magnet motors; magnesium used in lightweight alloys; niobium, which is added to steel to improve its strength and corrosion resistance; and platinum group metals (PGM) used in catalysis and electronics. Twelve additional materials (Figure 1, lower-right section) were identified as economically important but at lower risk; the study team noted that some of these materials are vulnerable to changes in the supply situation that could escalate them into the critical category.

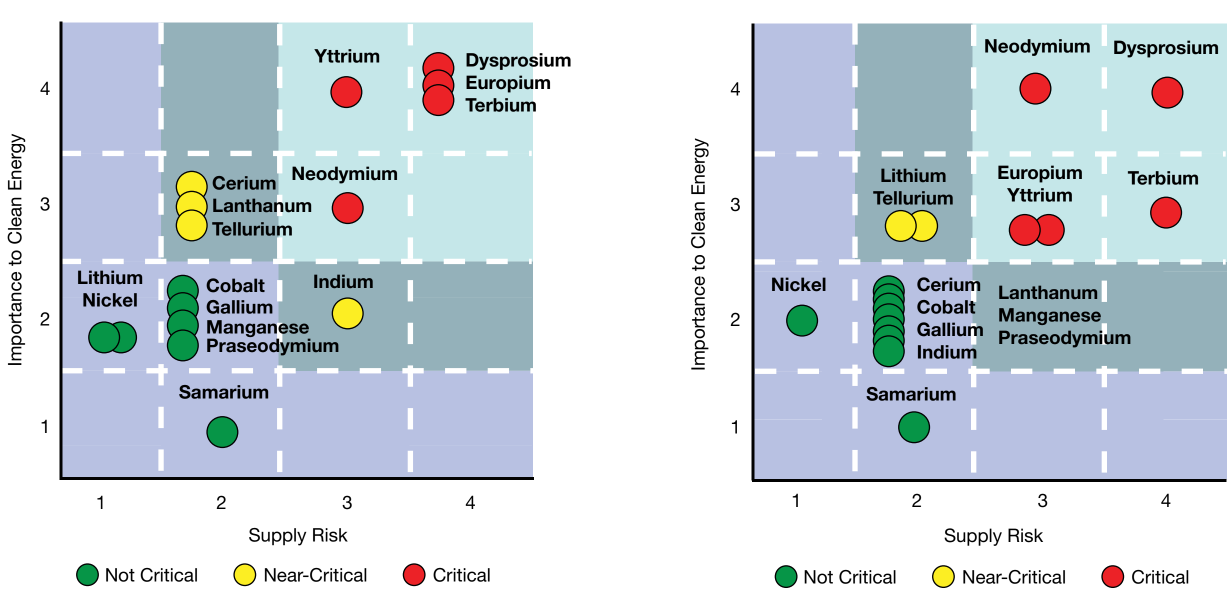


▲ **Figure 1.** The EU critical materials analysis for the 2010–2020 time period identified 14 critical materials (circled in the upper-right section). Source: *(4)*.

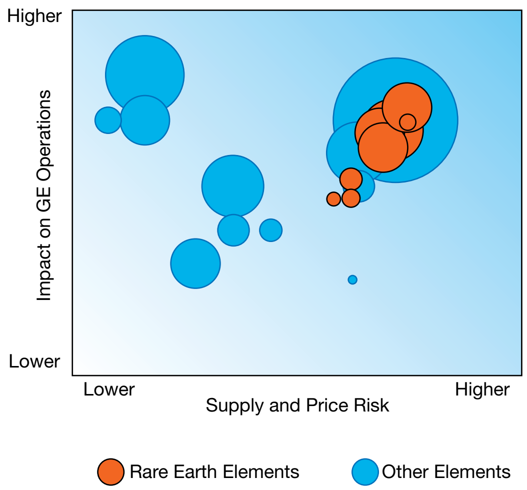
Earlier this summer, the EU released results of an updated analysis that includes more raw materials and updated data. It is available at: http://ec.europa.eu/enterprise/policies/raw-materials/critical/index_en.htm.

U.S. Dept. of Energy. The DOE performed an assessment of critical materials used in four clean-energy technologies — wind turbines, electric vehicles, solar cells, and energy-efficient lighting — over the near term (2011–2015) and medium term (2015–2020) *(3)*. DOE used a modified version of the conceptual method developed by the National Academy of Sciences to assess these clean-energy materials based on two criticality metrics: importance to clean energy and supply risk. Scores for each of the two metrics ranged from least critical or important (1) to most critical or important (4). The importance-to-clean-energy metric accounts for two attributes of each material: clean-energy demand and material substitution limitations, which were weighted 75% and 25%, respectively. Supply risk is based on five risk categories: basic availability (weighted 40%); competing technology demand (10%); political, regulatory, and social factors (20%); co-dependency on other markets (10%); and producer diversity (20%).

The results are shown in Figure 2 as a plot of each material's importance to clean-energy technologies vs. its supply risk. The critical materials appear in the upper-right corners and include all the rare earth elements, including europium (Eu), terbium (Tb), and yttrium (Y) for lighting, and neodymium (Nd) and dysprosium (Dy) used for permanent magnets in electric vehicles and some wind-turbine drives. A few other elements, including lithium for batteries and



▲ **Figure 2.** The DOE identified critical materials related to clean-energy technologies for the short term (left) and the medium term (right). Source: *(3)*.



▲ **Figure 3.** General Electric assessed critical materials used in its manufacturing and commercial operations. Elements are assigned scores in two areas — supply and price risk, and impact on GE operations. Each circle on the plot represents a different element, and the size of the circle represents the annual amount spent on the element in 2008. The orange circles represent individual rare earth elements. Source: *(5)*.

tellurium for thin-film solar cells, were rated near-critical.

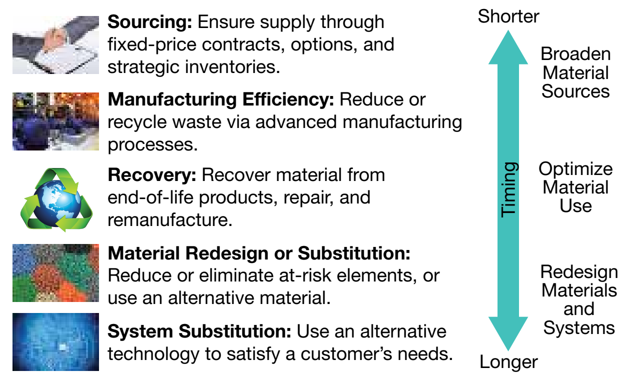
The DOE results also illustrate the dynamic nature of criticality. Market trends related to the adoption rates of different clean-energy technologies are expected to reduce the criticality of rare earth elements used in lighting, while increasing the criticality of materials used in magnets and energy-storage devices.

General Electric. Criticality assessments performed at the level of an individual company can also take into account market competition and price volatility. GE was the first company to publish the results of a corporate criticality assessment *(5)*. Figure 3 plots the supply risk against the potential impact to GE commercial operations. Several elements were identified as high risk, including five rare earth elements and rhenium, an additive to high-performance superalloys used in aircraft engines.

Looking at the EU, DOE, and GE assessments together, it is clear that different entities can and will rate different materials as critical, and that some materials (*e.g.*, rare earth elements) tend to be rated highly across a wide range of interests.

Minimizing the risks of critical materials

The challenges related to critical materials can be addressed in a variety of ways, depending on the specific material. In some cases, additional supply may be available through new mining projects or recycling efforts. Conversely, demand for materials can be reduced through the development of new processes to recover manufacturing scrap and to allow for the use of substitutes.



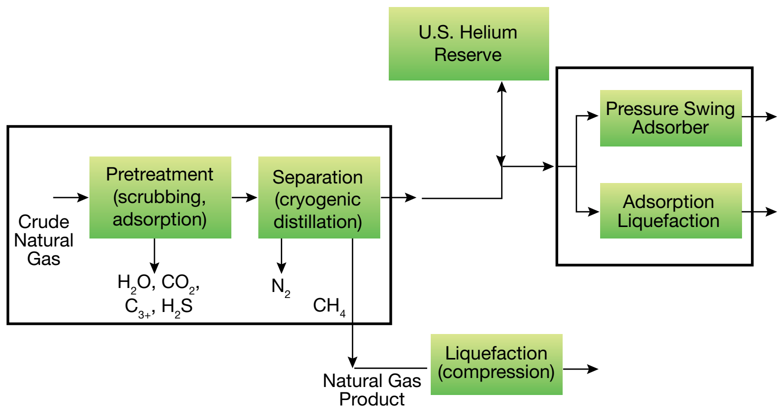
▲ **Figure 4.** Various strategies can be employed to address issues related to critical materials. One corporation relied on sourcing, manufacturing efficiency, recycling, material substitution, and system substitution. Source: *(6)*.

Figure 4 summarizes the approaches used by one corporation *(6)*. Sourcing arrangements and strategic inventories offer a buffer against short-term volatility in materials supply and pricing. Sourcing activities are often combined with efforts to optimize existing usage through improved manufacturing yields, recovery of manufacturing scrap, and recycling of end-of-life products. Advanced manufacturing processes, such as 3D printing, have the potential to increase yields and enable mass-production of new, less-materials-intensive designs. Investments in research and development can also yield new technology options — either alternative materials that are made using less of a critical element, or alternative system designs that avoid the use of a particular material entirely. These approaches are complementary, and the details vary depending on the specific elements and applications. Moreover, different entities and organizations will pursue these approaches with differing degrees of intensity.

When considering these approaches, several technical themes familiar to chemical engineers and chemists emerge. The material inputs into industrial processes must meet a range of specifications on purity, consistency, and cost. Separation processes play important roles, especially early in the supply chain, in producing materials of suitable quality at competitive prices. Process control and optimization needs, particularly those related to equipment utilization and economics, abound. Decisions around recycling can be informed by the thermodynamics of the constituent materials.

The role of economics in separation

Helium plays a role in a wide range of industrial processes. In liquid form, it is employed for cryogenic applications, such as the cooling of superconducting magnets for medical imaging and scientific research. In gaseous form, helium is used to control atmospheres for arc welding and titanium processing, transport



▲ **Figure 5.** Helium production involves a multistep process to recover crude helium from natural gas and then refine it into high-purity helium. Source: *(8)*.

reactive gases in the fabrication of microelectronics, and fill balloons for commercial uses. Helium is currently produced directly as a byproduct of natural gas liquefaction, or refined from low-purity (crude) helium (which typically contains CO_2, water, and nitrogen) inventory sourced from the U.S. helium reserve *(7)*.

The U.S. helium reserve was established in 1925 as a strategic supply of helium for airships and later as a coolant. The reserve is the largest helium source, supplying nearly one-third of the world's helium. In 1996, the U.S. Congress passed legislation to phase out and sell off the reserve's helium, a process that is ongoing. Because the U.S. reserve is the largest helium source, any disruptions in this supply have significant short- and medium-term implications. The resulting supply shocks, particularly in the last few years, have increased the perceived supply risk, leading some organizations and governments to classify helium as a critical or near-critical material.

Helium production is a simple and relevant example of some of the techno-economic trade-offs found in industrial gas-separation processes. The concentration of helium varies widely by natural gas field, as do the purity levels required for different applications. In practice, a natural gas field must have a helium concentration greater than 0.1%, and preferably greater than 0.5%, to warrant consideration for helium production. Over the longer term, the growth of shale gas production has the potential to impact helium supply because almost all shale gas fields fall below this threshold. If producers shift their production from the traditional natural gas fields with high helium content to shale gas fields with lower helium content, the amount of available helium will be reduced, leading to supply constraints and cost increases.

The production of helium is a multistep process, illustrated in Figure 5 *(8)*. The first step involves a combination of adsorption, extraction, and cryogenic distillation to remove condensables such as methane, natural gas liquids, CO_2, hydrogen sulfide, and water. The resulting crude helium is about 50–70% helium, with the balance mainly nitrogen. Pressure swing adsorption (PSA) produces refined helium to a purity of 99.99%. Catalytic- or cryogenic-adsorption processes can produce higher grades, up to 99.9999% purity.

Bulk helium production plants have been optimized over several decades of commercial operation. Each individual separation process is now well suited for the removal of specific components and is economical at the specific concentration ranges and production scales for which it is used. Worldwide, several plants are expected to come online in the next decade. The additional supply is expected to help mitigate some of the supply risk associated with the limited number of helium sources.

Additional opportunities to further improve the robustness of the helium supply chain include recovery and recycling. Systems that capture boil-off from cryogenic helium applications are of particular interest, as the helium concentration of the boil-off is much higher than that in crude helium. In general, the economics of separation are more favorable at higher starting concentrations, so the separation costs are lower for the boil-off than they are for crude helium.

As the cost of raw helium increases, so will the economic incentives for conservation and recovery from less-concentrated, raw, and recycled streams *(8)*. Similar market dynamics exist across many other critical materials. A general lesson is that advances in separation technologies are always welcome, and will contribute to efforts to alleviate supply bottlenecks through increased production or through recovery opportunities elsewhere in the supply chain.

The challenge of co-production

Just as helium is a byproduct of natural gas production, many minor metals are byproducts of base-metal production. This is because the natural concentrations of these metals in ores are too low to justify their recovery alone.

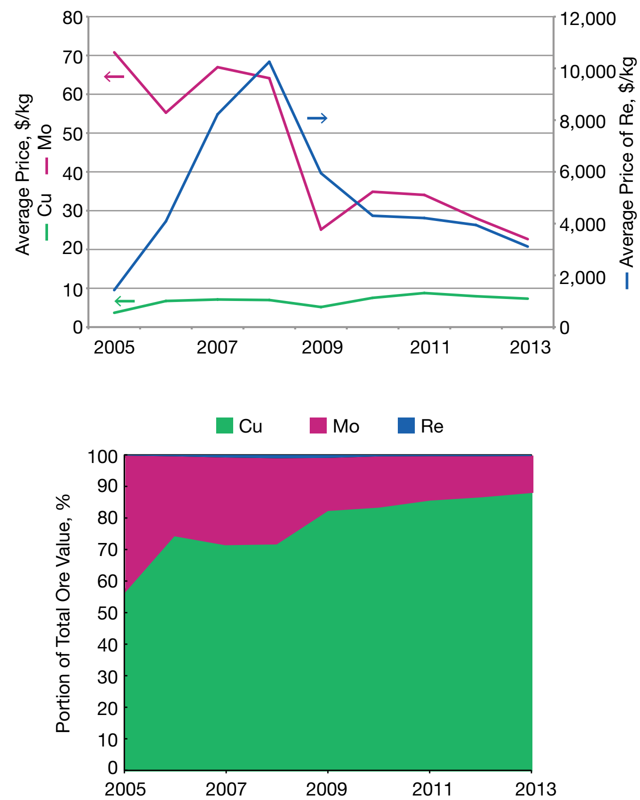
Rhenium is one such material. It is added to nickel superalloys used in high-pressure turbine blades in jet engines, and also as a catalyst in petrochemical manufacturing. Its crustal abundance of about 2 ppb makes it one of the rarest metals.

Much of the world's rhenium supply is derived as a byproduct from molybdenite sludges, which themselves are a byproduct of mining porphyry copper deposits. The

Table 1. Companion risk refers to risks associated with elements that are co-produced with a host element (darker-shaded boxes). The co-produced elements (lighter-shaded boxes) are vulnerable to any changes that impact the production of the host material.

Cu	**Pt**	**Zn**	**Pb**	**REE**
Ag	Ag	Ge	Ag	Sc‡
Au	Au	In	Bi	Y†
As	Ir	Se	In	La*
Bi	Pd	Te	Se	Ce*
Co	Rh		Te	Pr*
Mo–Re	Ru			Nd*
PGM				Pm*
Se	**Ni**	**Sn**	**Natural Gas**	Sm*
Te	Au	In	He	Eu*
	Co	Nb	Ethane	Gd*
Al	Cu	Ta	Propane	Tb†
Ga	PGM			Dy†
				Ho†
				Er†
				Tm†
				Yb†
				Lu†

* Light rare earth element (LREE).
† Heavy rare earth element (HREE).
‡ Neither LREE or HREE.



▲ **Figure 6.** A plot of the average annual prices of copper, molybdenum, and rhenium (top) shows that rhenium has a significantly higher value than its host material (copper). However, because the ore from which it is mined contains a relatively small amount of rhenium, its relative value (bottom) is much lower than that of either copper or molybdenum. Source: *(9)*.

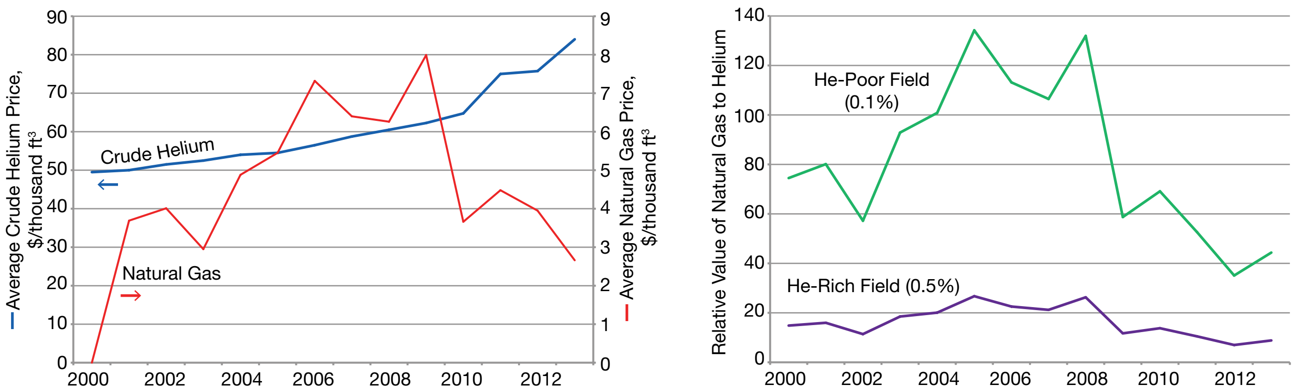
cost of rhenium production is subsidized by the host metals (copper and molybdenum in this case). Thus, the supply of rhenium depends on factors beyond the cost of its extraction and separation. Scenarios that impact global copper production, or even the distribution of copper production among different deposits, can significantly affect the supply of rhenium entering the world market. Given its status as a major user of rhenium, GE recently implemented several measures to reduce the risks associated with this supply chain *(9–10)*.

This type of supply risk is referred to as companion risk, which is illustrated in Table 1. Only a few common metals, shown in the darker-shaded boxes, are mined as primary products. Many other elements, including several that appear on different critical-materials lists, are only recovered as secondary products (lighter-shaded boxes). The rare earth elements are co-mined, with relative abundance generally declining with increasing atomic number. This phenomenon is not limited to metal ores; natural gas and some of its companion materials are also included.

Figures 6–8 illustrate three examples of significant companion risk.

• *Rhenium*. The plots of the average annual prices of copper, molybdenum, and rhenium in Figure 6 illustrate the significantly higher per-mass value of rhenium relative to that of its copper host *(11)*. The relative value of rhenium in the ore must be weighted by its concentration. The relative concentrations of copper, molybdenum, and rhenium vary widely across porphyry deposits, so a representative composition of 0.5 wt.% Cu, 0.02 wt.% Mo, and 50 ppb Re was selected for illustration purposes *(12)*. Even with the significant run-up in rhenium prices around 2008, rhenium accounts for less than about 1% of the total value of the ore.

• *Helium*. Figure 7 shows the average annual market prices for natural gas and helium from 2000 to 2013. The relative value of the helium in a natural gas field can be estimated from the relative price and concentrations. Two cases are plotted: a helium-rich field (0.5%), and a helium-poor field (0.1%). In helium-rich fields, the value of the natural gas ranges from about 10 to 20 times the value of the helium over the past 10 years. Conversely, in helium-poor fields, the value of the helium amounts to only a few percent of the total value of the natural gas. This ratio was



▲ **Figure 7.** A plot of the average annual prices of natural gas and helium (left) shows the value of helium relative to natural gas. A second plot (right) shows the relative value of helium to natural gas for two cases: a helium-rich field (right, purple) and a helium-poor field (right, green). In helium-rich fields, the value of natural gas is about 10–20 times the value of helium, whereas in helium-poor fields, the value of helium amounts to only a few percent of the value of the natural gas. Source: *(9)*.

higher in the mid-2000s, when natural gas prices were high, and has dropped since 2009 in the U.S. as helium prices have increased and natural gas prices have dropped *(11)*. As discussed previously, the companion risk for helium could be further impacted by developments in the shale gas market.

• *Rare earth elements*. Rare earth elements are mined together and then separated into individual elements. Although the relative abundance in a particular deposit can vary widely, the light rare earth elements (LREEs) are more abundant than the heavy rare earth elements (HREEs) (Table 1).

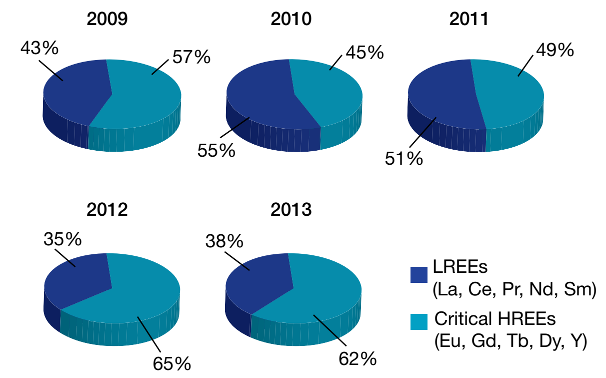
In spite of their lower abundances, HREEs can account for a significant fraction of the value of a deposit and their prices can significantly impact the economics of a mining project. Figure 8 compares the relative value of some key rare earth elements found in the earth's crust. The value of each element was calculated from its average crustal abundance and average annual price *(9, 12)*. Each pie chart compares the cumulative value of the LREEs with that of five critical HREEs. Despite accounting for less than 10% of the total mass of rare earths, these critical HREEs account for at least half of the total value.

Companion risk is most pronounced in cases where the value of the co-produced material is negligible relative to the value of the host material. In these situations, users of a particular element face a risk that supply dynamics are driven by the dynamics of the host metal. Physical shortages can arise due to the economics of producing new material. For instance, if the economics of mining the primary material are poor (*e.g.*, copper prices are low), then the companion material will not be produced unless its price is outrageously high. Under these conditions, alternative paths, such as recycling and substitution, become attractive.

Making the decision to recycle

The supply of a raw material can be augmented by recovering and reusing manufacturing scrap and recycling products at the end of their life. In general, decisions to recover and recycle materials take into account many technical, economic, and strategic considerations. The logistics of collection and sorting are common barriers *(13)*. Consequently, some materials that are in short supply do not get recycled while other, relatively abundant, materials do — material scarcity or abundance is not the only factor that determines whether or not a particular material is recycled. The case of magnesium highlights some of the considerations related to recycling.

Magnesium alloys have attracted interest as lightweight structural materials for transportation applications *(14)*. Although magnesium is abundant in the earth's crust and



▲ **Figure 8.** The abundance of rare earth elements varies depending on the field from which they are mined. The value of an individual rare earth element depends on its average crustal abundance and its average annual price. These pie charts compare the cumulative value of the LREEs with that of five critical HREEs from 2009 to 2013. Source: *(9, 12)*.

can also be recovered from seawater, about 80% of the current world production comes from China. This has led some, including the EU, to consider magnesium a critical material. Historically, up to 33% of the magnesium used in the U.S. was recycled, mostly in the form of alloys from beverage cans *(15)*. The anticipated increased use of magnesium for transportation applications has triggered renewed interest in recycling this element.

The appeal of magnesium recycling stems from potential energy savings. Due to the low specific heat and melting point of magnesium, very little energy (~1 kWh/kg) is required to melt it — about 3% of the energy required to produce new magnesium (30–35 kWh/kg) *(16)*. Magnesium oxidizes readily, and much of the energy used to process raw ores goes toward reducing it to a metal.

An important consideration for recycling is the removal of impurities, which can adversely impact the properties of the reconstituted material. This is particularly true for some of the new magnesium alloys, which can contain a wide range of additives, such as base metals added to modify the alloy's properties, including aluminum (Al), calcium (Ca), manganese (Mn), silicon (Si), tin (Sn), zinc (Zn), and several of the rare earth elements. In pyrometallurgical processing, which is one of the two approaches used to process alloys, the alloys are melted and purified by distillation.

Thermodynamic calculations *(17)* can be used to predict which elements tend to partition into the pure metal, slag, and gas phases. This information provides guidance for designing processes to recover material of the right purity and quality. A radar chart can be constructed from these calculations. Figure 9 is a radar chart for six host metals (inner ring) and the partitioning of additive elements into the pure metal, slag, and gas phases (middle and outer rings) upon melting. For example, when a magnesium alloy is melted, any Ca, gadolinium (Gd), Li, Y, and ytterbium (Yb) present

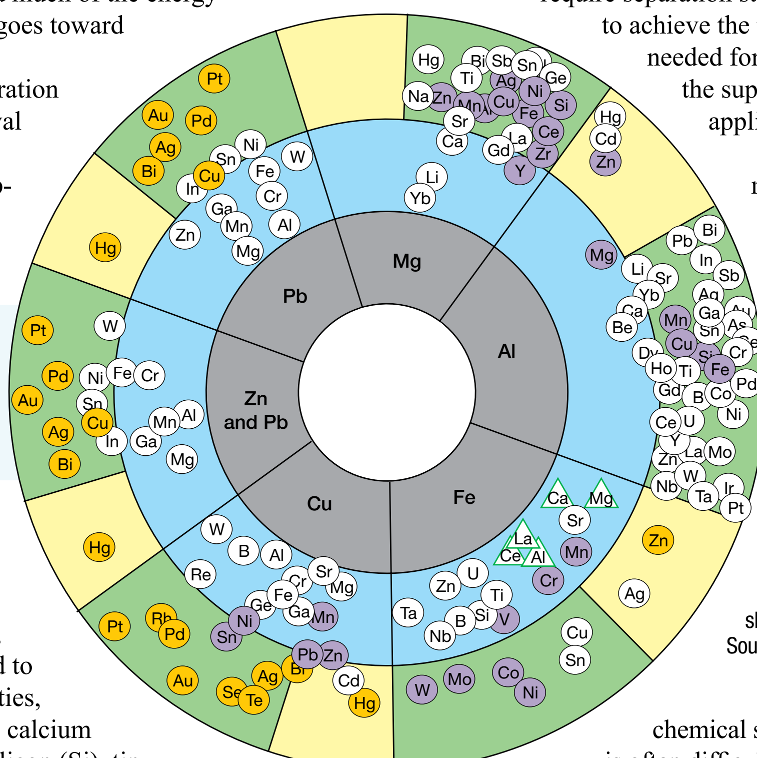


Figure 9. This radar chart shows six host metals (center) and the partitioning of additive elements into pure metal (green), slag (blue), and gas (yellow). Source: *(17)*.

will oxidize and partition to the slag phase as oxides, while the other remaining alloying elements will be retained in the molten magnesium.

The idea of using thermodynamics to understand the partitioning of recycled materials can be extended beyond alloy recycling. In modern electronics, a wide range of elements is dispersed throughout a device, carefully placed for function and performance rather than ease of recovery. In these cases, it is not the abundance of a material that is important, but instead the proximity of a critical material to other elements that are difficult to separate, that becomes of paramount importance. Consequently, recycling of electronic waste for critical and other valuable metals may require separation steps not initially anticipated to achieve the target levels of purity needed for that material to re-enter the supply chain for certain applications.

Recovering critical materials from end-of-life products can pose other challenges in addition to chemical separation. For example, it is often difficult to physically isolate the desired materials. Thus, mechanical processes can play a role in materials recovery schemes. An example is the recovery of high-value materials such as lanthanum (La), cerium (Ce), neodymium (Nd), and praseodymium (Pr) from nickel-metal-hydride batteries *(18)*. In this application, the use of a mechanical crusher with a magnetic separator prior to chemical processing greatly improves the separation process performance. Design-for-recycling principles have begun to permeate into the industrial consciousness and can also play a role in reducing the severity of these challenges *(19)*.

A useful tool for quantifying the material flows and environmental trade-offs associated with decisions to recycle is lifecycle analysis (LCA). LCA provides a framework for modeling the energy, water, and emissions footprint of a product or process. Activities are ongoing to extend the necessary databases to predict the environmental impact of recycling versus mining for the production of critical materials such as rare earth elements *(20)*. Some of the methodological issues that must be overcome include limited data on the environmental impacts from mining, mine-specific differences due to process design variations and ore deposits, and allocation of the environmental impact to different co-produced elements. This is an active area of research, and progress in this area will further solidify the economic and technical foundations for recovery and recycling options in addressing materials criticality.

Closing thoughts

The challenges posed by critical materials are diverse and persistent. Finding solutions to these challenges will require cooperation among industries and participants throughout the supply chain.

With our deep understanding of, and expertise in, relevant topics such as separations technologies, process modeling, and process optimization, chemical engineers have ample opportunities to contribute to addressing these challenges. CEP

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