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Abstract

Modern electronic devices are constructed using a large palette of materials, some of which are considered "critical," meaning that their supply-chains are tenuous to some degree and they cannot easily be substituted. The rare earth crisis of 2010–'11 brought worldwide attention to the challenge of dealing with critical materials, and resulted in several research programs being created, world wide, to find technological solutions to shortages of essential materials. Some of the approaches used to ensure the supply chains of critical materials are consistent with making electronics greener, some are neutral, and some can run counter to the greening of information devices. Some of the approaches applied to critical materials can also be applied to anacritical materials which are the opposite of critical materials in a particular sense: they are materials that need to be removed from production or eliminated from waste because they are oversupplied or have undesirable traits such as toxicity or contamination of recycle streams. We describe where critical materials strategies and greening strategies coincide, and evaluate the most significant roadblocks to success.

Keywords

Green products, Recycling, Consumer electronics, Production, Neodymium, Magnetic separation, Industries

Disciplines

Materials Science and Engineering | Natural Resources Management and Policy | Sustainability

Comments

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When Agendas Align: Critical Materials and Green Electronics

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Abstract

Modern electronic devices are constructed using a large palette of materials, some of which are considered "critical," meaning that their supply-chains are tenuous to some degree and they cannot easily be substituted. The rare earth crisis of 2010-'11 brought worldwide attention to the challenge of dealing with critical materials, and resulted in several research programs being created, world wide, to find technological solutions to shortages of essential materials. Some of the approaches used to ensure the supply chains of critical materials are consistent with making electronics greener, some are neutral, and some can run counter to the greening of information devices. Some of the approaches applied to critical materials can also be applied to anacritical materials which are the opposite of critical materials in a particular sense: they are materials that need to be removed from production or eliminated from waste because they are oversupplied or have undesirable traits such as toxicity or contamination of recycle streams. We describe where critical materials strategies and greening strategies coincide, and evaluate the most significant roadblocks to success.

1 Introduction

Concerns have existed about the environmental impacts of the manufacture, use and disposal of electronics since the introduction of the transistor, if not before.

A newer set of societal concerns revolves around the availability of the materials required for the manufacture of high-tech devices. The term “critical material” was coined in 2008 [1], to describe materials that are both essential to technology and are subject to supply-chain weaknesses. The challenges of such materials emerged as an issue of political (and geo-political) concern in 2010, when the world market for certain rare earth elements was thrown into turmoil by the perception that the available supplies would not meet the demands of the world’s high-tech industries, including electronics.

Some of the approaches used to mitigate environmental impact are also useful in addressing materials criticality, but there are other approaches to the two challenges that do not align with each other, and may even conflict.

In this paper, we identify areas of alignment and conflict between the greening and criticality agendas.

The missions of the green electronics community and the critical materials community are fundamentally different. One is concerned with minimizing environmental impacts, while the other is concerned with aligning the supply and demand for specific materials. Both can be achieved in a number of different ways, some of which overlap, and some do not.

2 Critical Materials

A material is considered critical if it is functionally essential or very difficult to substitute, making it highly important; and also if it is subject to supply risk. Materials criticality is usually assessed on a two-axis plot, as shown in Figure 1.

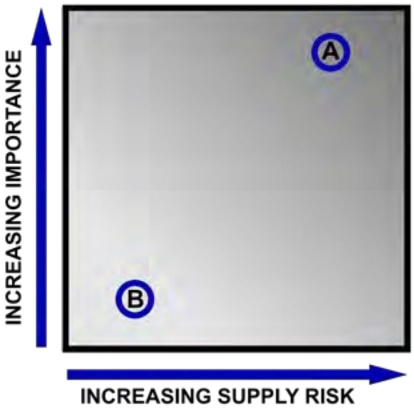

Figure 1: Classification of materials according to their supply risk and their importance to a particular application. Material A has greater supply risk, and greater consequences ensue from a supply disruption, so it is considered more critical than Material B.

The identification of materials as “critical” clearly depends on many things, and the variations among different lists of critical materials can usually be ascribed to differences among the following considerations:

- The analysis depends on the technological context. What is essential for a manufacturer of smart phones may be different from what is essential for a manufacturer of automobiles.
- The analysis depends on location. What is available in one country or region may be unavailable in other parts of the world.
- The analysis depends on time. What is a critical material today may not be critical tomorrow, as technological applications and materials availability evolve.
- The analysis depends to some extent on how essentiality and supply risk are quantified, and on how different factors are weighted.
- Small differences in the plotted locations of different materials are probably insignificant, but large differences, such as those between materials "A" and "B" in Figure 1 represent real differences in risk for the users of the materials.

In some cases, additional information is provided in plots of this kind. Of particular relevance, here, environmental risks have been added on a third, orthogonal axis in some analyses [2, 3]. In other cases, particularly in the corporate sector, financial considerations may be included, such as the company's total costs for each material [4].

Price, *per se*, is not a good guide to criticality. While a truly critical material may command a high price, price fluctuations occur for many reasons other than the emergence or disappearance of criticality.

The fact that a material is classified as critical does not automatically mean that there will be shortfalls of supply: rather, it means that there are significant risks of supply-chain interruptions, coupled with significant consequences if they happen. It is an identification of a need for appropriate concern and planning, not for panic.

2.1 Consequences of Criticality

Failure to deal with the criticality of a material can have a variety of consequences, ranging from inconvenient to extreme, and the consequences can have a short or long duration. At one end of the spectrum, a supply-chain interruption can result in a temporary suspension of manufacturing; but it can also drive changes of technology or the migration of manufacturing to locations that are not impacted by supply shortfalls.

In one specific example, sustainable wind energy has been growing rapidly worldwide, in recent years, but exact technology used for such electricity generation is impacted in at least some measure by the availability of materials: nearly all land-based utility-scale wind turbines in Europe and North America rely on gearboxes to increase the generator rotation rate. This allows for the use of smaller or lower-strength permanent magnets, or magnet-free induction generators. Larger or stronger permanent magnets enable direct drive systems that are more efficient and less prone to failure than systems that use by gearboxes. While other considerations were also in play, wind-energy growth ramped up rapidly at a time when the criticality of rare earth elements was a major consideration, pushing technology decisions away from the use of large, powerful rare earth magnets based on $Nd_2Fe_{14}B$. The world's production of neodymium is dominated by China, where direct-drive wind turbines are more widely used than in Europe or North America.

Materials criticality can have additional consequences. In September 2010, when concerns about rare earth criticality were on the rise, a Chinese fishing vessel collided with a Japanese Coast Guard patrol boat near the disputed islands in the East China Sea, known as Senkaku in Japan, and Diaoyu in China. The trawler's captain was arrested by the Japanese Coast Guard, resulting in a diplomatic incident between the two nations. At some point, the export of rare earths from China to Japan was suspended and it was widely reported that China had cut off exports to Japan to win the release of its citizens [5]. This was taken to signal the Beijing government's willingness to use its control of this particular materials supply-chain as a geopolitical bargaining chip, which raised great concerns among other national governments, worldwide.

2.2 Consequences of Failed Environmental Stewardship

Failure to deal with environmental impacts has rather different consequences that typically emerge in the form of slow degradation of the environment. While this is a very serious issue, especially for future generations, it does not always command the same level of political or industrial attention as a looming shortage of a technology material.

2.3 Alignment and Conflict between Criticality and Greening

In some cases the attention paid to materials criticality has a positive impact on greening the economy, representing a positive alignment of the criticality and green agendas.

When jet engine manufacturers were faced with a shortage of rhenium for use in high-temperature turbine blades, the problem was solved by a combination of two approaches: the development of new alloys with reduced rhenium content, and the institution of recycling of manufacturing waste and end-of-life components [4]. Increased recycling aligns both agendas in this case.

In some cases, the solutions to criticality issues can have negative consequences for the environment; and attention to environmental concerns have been also blamed for the emergence of criticality, from time to time.

While rare earth materials including neodymium, dysprosium, yttrium, europium and terbium contribute to clean energy technologies, their extraction from ore and purification into usable form involve great environmental risks, and production tends to be concentrated in places where environmental protection is weak. Increased primary production in response to criticality leads to increased threats to the environment – even while the production is intended for clean energy technologies [6].

The (first) closure of Molycorp's Mountain Pass rare earth mine in 2002 is sometimes blamed on stringent environmental regulations in California, where it is located. An acid spill at the mine required a costly clean-up that effectively bankrupted the mine; a case in which environmental challenges eventually led to increasing criticality for the rare earth metals.

3 Research and Development

3.1 Technical Approaches to Dealing with Criticality

In its 2011 *Critical Materials Strategy*, the U.S. Department of Energy identifies three pillars of a research and development approach that should be applied to materials criticality [7]:

1. *Source Diversification.* One of the primary causes of supply risk is the domination of production in by a small number of providers, so encouraging more providers to enter the market is a key strategy to moving a material to the left in Fig. 1.
2. *Materials Substitution.* The invention of new materials that can take the place of critical ones reduces the reliance upon a particular materials, and it is an important means of moving a material downward in Figure 1.
3. *Improved Stewardship of Existing Supplies.* When supplies cannot be improved through source diversification, and reliance cannot be reduced by substitution, it is necessary to live within existing resources by reducing waste during manufacturing and improving in-process and end-of-life recycling.

All three of these approaches call for extensive R&D efforts. Other approaches include market-based efforts such as anticipatory buying (stockpiling) as a hedge against shortages; the imposition of national quotas or tariffs; and technology substitution at the system level as opposed to the material level, *e.g.* using heat engines in place of electric motors, or induction motors in place of permanent magnet motors.

3.2 Technical Approaches to Dealing with Environmental Challenges

One classic approach to reducing the environmental footprint of any product is enshrined in the phrase "Reduce, Re-use, Recycle" (or a number of variants of it.) These relate most directly to the third pillar of the critical materials strategy described above, but there are some relationships to other areas, too. For example, the removal of lead from modern electronics has largely been achieved through the development of an alternative to traditional lead-tin solder [8], demonstrating that reduction can be achieved by substitution.

The second approach is the use of "sustainable chemistry" to reduce the environmental footprint of resource extraction. Particularly when applied to primary extraction (*i.e.* mining) reductions in the environmental footprint can remove barriers to the development of new mines, thereby contributing to source diversification and reducing criticality.

A third imperative of the green electronics agenda is the removal of toxins from industry products. This makes the products safer to use, and also safer to discard or recycle. Paradoxically, the existence of toxins in some products can drive recycling. In the case of cadmium telluride solar cells, for one example, toxicity results in a mandate for the manufacturer to recycle end-of-life units. Fluorescent tubes and lamps are also subject to compulsory end-of-life collection to prevent the release of mercury into the environment.

4 Critical Materials in the Palette of Electronic Devices

As noted above, the identification of critical materials takes place in the context of a particular industry, location and time. Many lists of critical materials have been developed and although they may have marked differences, there are still a few constants. In particular, the class of rare earth elements in general, subsets of the class (*e.g.* "light" or "heavy" rare earths) or specific elements within the class, appear in almost

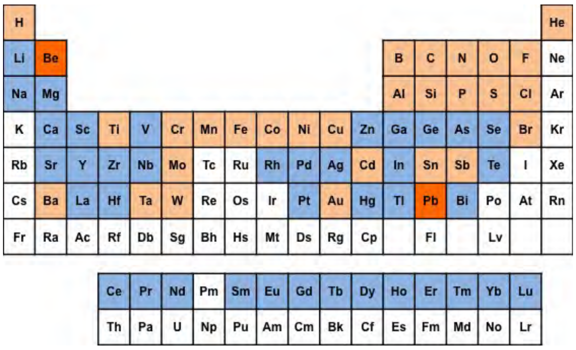

Figure 2: The elements used to make mobile phones. The elements in tan or red boxes would have been required for the world's first mobile phone, the Motorola Dyna TAC of 1984. The elements in blue boxes are additionally found in today's devices, although the red ones have been eliminated.

every list, including those that apply to the electronics industry [9, 10].

The palette of materials used to manufacture today's electronic devices is vast. While Motorola's first mobile phone required between thirty and thirty-five chemical elements, the count for today's smart-phones is somewhere between sixty-five and seventy. The growth in the number of elements has two significant consequences:

1. Today's devices are in some sense twice as vulnerable to supply-chain disruptions as their predecessors from forty years ago, because they rely on twice as many discrete materials.
2. The complexity of today's devices makes it much harder to separate their component materials for recycling at the end of life.

Since the critical materials community is, for now, overwhelmingly focused on rare earth materials, this is the primary field of intersection between the criticality and green electronics agendas. Electronics use neodymium and dysprosium in magnets; europium, terbium & yttrium in color displays; lanthanum in high-dispersion glasses for camera lenses; and yttrium & cerium in LED lamps. Ceria is also used in the manufacturing process as chemical-mechanical polishing agent for glass components and silicon wafers. Although not technically required, other rare earth elements are still frequently found in electronics because they are hard to separate from each other and (up to a point) praseodymium (At. No. 59) can substitute for neodymium (At. No. 60). Terbium and holmium (Nos. 65 and 67, respectively) can also substitute for dysprosium (No. 66) in magnets.

Magnets represent largest single use of a rare earth element in electronics. $Nd_2Fe_{14}B$ magnets (often partially substituting Dy, Tb or Ho for Nd or Pr) are used in loudspeakers, headphones, microphones, hard disk drive spindle and voice-coil motors, and also in cases, closures and fasteners. The largest individual rare earth magnets in the electronics industry are the voice-coil motors of hard disk drives.

Electronics, as a class, are the second-largest consumer of rare earth magnets today, after motors, generators and actuators.

The use of rare earth magnets in electronics is declining with the increasing use of solid-state memory in place of hard disk drives for mobile electronics, and the shrinking form factors (and increasing data densities) of hard disk drives.

The use of rare earth magnets in motors, generators and actuators is increasing, with increasing electrification of automobiles, and adoption of clean energy technologies such as wind.

Despite the shrinking share of the world's rare earth production that is going into electronics, it remains a significant fraction, with disk drives accounting for about 15% of the consumption. Electric motors, by comparison, take up more than 24%.

While there are great efforts to reduce the amount of magnet materials needed for motors, efforts to recycle motors are less strongly emphasized in the portfolios of critical materials R&D institutions. Conversely, there is great interest in recycling hard disk drives, so it is instructive to examine the considerations that justify these effort levels.

Electric motors typically use higher-grade magnets that can withstand higher operating temperatures than those used in hard disk drives. Higher grades are enabled by higher concentrations of heavy rare earths, such as dysprosium, which are more expensive than light rare earths such as neodymium, so the magnets in motors are more costly to buy and also more valuable to recycle. Driven by the cost of high-performance permanent magnets, electric motor design continues to improve, reducing the amount of magnets required for a particular power rating. At the present time, focusing on motor design appears to provide greater opportunities than other approaches for reducing demand in this application. Improved motor design [11] and materials design [12] are driving down the need for heavy rare earths, in particular.

Hard disk drives use lower-grade magnets, with lower concentrations of heavy rare earths. They are correspondingly less costly to obtain, and less valuable to recycle. Hard disk design continues to provide greater data densities, reducing the numbers of units produced annually, even while the storage capacity increases.

Motors may contain large magnets, on the order of a kilogram or more per unit, and wind turbines may contain hundreds of kilograms, while hard disk drives typically contain less than ten grams per unit. Motors and generators have lifetimes of a decade or more, and hard disk drives have lifetimes of a few years or less.

Recycling magnets from hard disk drives will not meet the needs of the motor and generator market: the grade of material is too poor in heavy rare earth elements, and the volumes are insufficient.

The most potent economic considerations in designing an effective approach, however, are (1) the cost of collecting devices for recycling; (2) the cost of materials recovery from each device, and (3) the value of all of the materials that may be recovered. Taking these into account, hard disk drives appear to be a more profitable recycling target than motors: they are available in bulk at data centers, reducing collection costs, they have common design features allowing for automated disassembly, and they contain other high-value materials such as aluminium, steel and precious metals.

Research on motors tends to focus on improved design to reduce rare earth requirements as motor use grows. Hard disk drive R&D tends for focus on technologies for recovery and recycling.

In either case, these efforts are congruent with efforts to reduce the environmental impact of the technology. However, they are also in competition with other efforts to address the shortages of critical magnet materials through source diversification and materials substitution.

Source diversification attacks supply chain vulnerabilities by seeking to start up new production for critical materials. In the wake of the rare earth crisis of 2010, as many as 400 rare earth mining projects were in various stages of development, worldwide, and a number of technologies are still being developed to extract rare earths from non-traditional sources such as ocean-floor mining, phosphate mine by-products, coal by-products and geothermal brines. Mining the moon or asteroids is also apparently under active consideration in some circles.

Materials substitution attacks the need for rare earth magnets by seeking alternative materials, recognizing that the current neodymium-based magnets were invented in response to a crisis in the availability of cobalt for the state-of-the-art Sm-Co magnets in 1978 [13]. Several groups are engaged in efforts to create new magnet materials that could replace the current generation of Nd-Fe-B magnets.

Source diversification and materials substitution represent competitors to materials criticality solutions based on reducing demand or improving recycling. Neither of these approaches is necessarily environmentally friendly: increased mining may increase environmental impacts and spread them to new locations, while the development of a new magnet material will threaten the need for new mines and for recycling, alike.

The observed alignments and conflicts between the green electronics and critical materials R&D strategies are summarized in Table 1.

Since the economic drivers for R&D on critical materials relate to meeting industrial needs, the work is likely cease once a solution is in place and synergy with sustainability efforts will cease. If the “winning” solution comes from new mines or from the development of a new material, then efforts on technologies that serve a greener economy will not necessarily be helped. Since the winning solution will be the first one to meet the needs, green solutions need to be developed with a strong sense of urgency.

		Critical Materials		
		Source Diversification	**Materials Substitution**	**Improved Stewardship**
Green Electronics	**Reduce, Reuse, Recycle**	***C***	***S***	***A***
	Sustainable Processing	***S***	***S***	***S***
	Toxin Elimination	***N***	***A***	***A***

Table 1: Alignments and conflicts between the critical materials and green electronics strategies. *A* indicates that the strategies are always aligned; *C* indicates that they always conflict; *S* indicates that they sometimes align and sometimes conflict; *N* indicates that they do not interact.

The needs of the green economy and the need to relieve materials criticality are only partly aligned. It is important to capitalize on the alignment that does exist in order to avoid the emergence of conflicting agendas and solutions.

5 Acknowledgment

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