Energy Critical Elements:

								2 **He** Helium 4.003
			5 **B** Boron 10.811	6 **C** Carbon 12.0107	7 **N** Nitrogen 14.00674	8 **O** Oxygen 15.9994	9 **F** Fluorine 18.9984032	10 **Ne** Neon 20.1797
			13 **Al** Aluminum 26.981538	14 **Si** Silicon 28.0855	15 **P** Phosphorus 30.973761	16 **S** Sulfur 32.066		
28 **Ni** Nickel 58.6934	29 **Cu** Copper 63.546	30 **Zn** Zinc 65.39	31 **Ga** Gallium 69.723	32 **Ge** Germanium 72.61	33 **As** Arsenic 74.92160	34 **Se** Selenium 78.96		
46 **Pd** Palladium 106.42	47 **Ag** Silver 107.8682	48 **Cd** Cadmium 112.411	49 **In** Indium 114.818	50 **Sn** Tin 118.710	51 **Sb** Antimony 121.760	52 **Te** Tellurium 127.60		
78 **Pt** Platinum 195.078	79 **Au** Gold 196.96655	80 **Hg** Mercury 200.59	81 **Tl** Thallium 204.3833	82 **Pb** Lead 207.2	83 **Bi** Bismuth 208.98038	84 **Po** Polonium (209)	85 **At** Astatine (210)	86 **Rn** Radon (222)
65 **Tb** Terbium 158.92534	66 **Dy** Dysprosium 162.50	67 **Ho** Holmium 164.93032	68 **Er** Erbium 167.26	69 **Tm** Thulium 168.93421	70 **Yb** Ytterbium 173.04	71 **Lu** Lutetium 174.967		

Securing Materials for Emerging Technologies

A REPORT BY THE APS PANEL ON PUBLIC AFFAIRS & THE MATERIALS RESEARCH SOCIETY

APS physics

MRS

ABOUT APS & POPA

Founded in 1899 to advance and diffuse the knowledge of physics, the American Physical Society is now the nation's leading organization of physicists with more than 48,000 members in academia, national laboratories and industry. APS has long played an active role in the federal government; its members serve in Congress and have held positions such as Science Advisor to the President of the United States, Director of the CIA, Director of the National Science Foundation and Secretary of Energy.

This report was overseen by the APS Panel on Public Affairs (POPA). POPA routinely produces reports on timely topics being debated in government so as to inform the debate with the perspectives of physicists working in the relevant issue areas.

ABOUT MRS

The Materials Research Society (MRS) is an international organization of nearly 16,000 materials researchers from academia, industry, and government, and a recognized leader in promoting the advancement of interdisciplinary materials research to improve the quality of life. MRS members are engaged and enthusiastic professionals hailing from physics, chemistry, biology, materials science, mathematics and engineering – the full spectrum of materials research.

Headquartered in Warrendale, Pennsylvania, MRS membership now spans over 80 countries, with more than 40% of its members residing outside of the United States. MRS organizes high-quality scientific meetings, attracting over 13,000 attendees annually and facilitating interactions among a wide range of experts from the cutting edge of the global materials community. MRS is also a recognized leader in education, outreach and advocacy for scientific research.

This policy report was supported by the MRS Government Affairs Committee.

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EXECUTIVE SUMMARY

A number of chemical elements that were once laboratory curiosities now figure prominently in new technologies like wind turbines, solar energy collectors, and electric cars. If widely deployed, such inventions have the capacity to transform the way we produce, transmit, store, or conserve energy. To meet our energy needs and reduce our dependence on fossil fuels, novel energy systems must be scaled from laboratory, to demonstration, to widespread deployment.

Energy-related systems are typically materials intensive. As new technologies are widely deployed, significant quantities of the elements required to manufacture them will be needed. However, many of these unfamiliar elements are not presently mined, refined, or traded in large quantities, and, as a result, their availability might be constrained by many complex factors. A shortage of these "energy-critical elements" (ECEs) could significantly inhibit the adoption of otherwise game-changing energy technologies. This, in turn, would limit the competitiveness of U.S. industries and the domestic scientific enterprise and, eventually, diminish the quality of life in the United States.

ECEs include rare earths, which received much media attention in recent months, but potentially include more than a dozen other chemical elements. The ECEs share common issues and should be considered together in developing policies to promote smooth and rapid deployment of desirable technologies.

Several factors can contribute to limiting the domestic availability of an ECE. The element might simply not be abundant in Earth's crust or might not be concentrated by geological processes. An element might only occur in a few economic deposits worldwide, or production might be dominated by and, therefore, subject to manipulation by one or more countries. The United States already relies on other countries for more than 90% of most of the ECEs we identify. Many ECEs have, up to this point, been produced in relatively small quantities as by-products of primary metals refining. Joint production complicates attempts to ramp up output by a large factor. Because they are relatively scarce, extraction of ECEs often involves processing large amounts of material, sometimes in ways that do unacceptable environmental damage. Finally, the time required for production and utilization to adapt to fluctuations in price and availability of ECEs is long, making planning and investment difficult.

This report surveys these potential constraints on the availability of ECEs and then identifies five specific areas of potential action by the United States to insure their availability: 1) federal agency coordination; 2) information collection, analysis, and dissemination; 3) research, development, and workforce enhancement; 4) efficient use of materials; and, 5) market interventions. Throughout this report, narratives on particular ECEs are provided to clarify these five action areas.

The report's specific recommendations, which can be found in their entirety in Section 4, are summarized as follows:

Coordination

- The Office of Science and Technology Policy (OSTP) should create a subcommittee within the National Science and Technology Council (NSTC) to 1) examine the production and use of energy-critical elements within the United States and, 2) coordinate the federal response.

Information

- The U.S. government should gather, analyze, and disseminate information on energy-critical elements across the life-cycle supply chain, including discovered and potential resources, production, use, trade, disposal, and recycling. The entity undertaking this task should be a "Principal Statistical Agency" with survey enforcement authority. It should regularly survey emerging energy technologies and the supply chain for elements throughout the periodic table with the aim of identifying critical applications, as well as potential shortfalls.

Research & Development

- The federal government should establish a research and development effort focused on energy-critical elements and possible substitutes that can enhance vital aspects of the supply chain, including geological deposit modeling, mineral extraction and processing, material characterization and substitution, utilization, manufacturing, recycling, and life-cycle analysis. Such an effort would address critical, but manageable, workforce needs.

Materials Efficiency

- The federal government should establish a consumer-oriented "Critical Materials" designation for ECE-related products. At the same time, steps should be taken to improve rates of post-consumer collection of industrial and consumer products containing ECEs, beginning with an examination of the numerous methods explored and implemented in various states and countries.

Market Interventions

- The Committee does not recommend that the federal government establish non-defense-related economic stockpiles of ECEs with the exception of one element: helium. Measures should be adopted that both conserve and enhance the nation's helium reserves.

These recommendations call for actions that fall within accepted roles for government: statistical information gathering, support for research and workforce development, and incentives for select activities. Taken together, these recommendations will work to enhance the domestic availability of ECEs.

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WHAT IS AN "ENERGY-CRITICAL ELEMENT"?

The twin pressures of increasing demand for energy and concern about climate change have stimulated research into new sources of energy and novel ways to store, transmit, transform, and conserve it. Scientific advances have enabled researchers to identify chemical elements with properties that meet their specific needs and to employ these elements in energy-related technologies. Elements, such as gallium, indium, lanthanum, neodymium, and tellurium, that were once laboratory curiosities, now prominently figure in discussions of novel energy systems. Many of these elements are not presently mined, refined, or traded in large quantities.

To meet energy needs, new technologies must be scaled from laboratory, to demonstration, to implementation. Many energy-related systems, such as wind turbines and solar energy collectors, are materials intensive. If new technologies like these are to be widely deployed, the elements required to manufacture them will be needed in significant quantities.

We have coined the term "energy-critical element" (ECE)[1] to describe a class of chemical elements that currently appear critical to one or more new, energy-related technologies. A shortage of these elements would significantly inhibit large-scale deployment, which could otherwise be capable of transforming the way we produce, transmit, store, or conserve energy. We reserve the term ECE for chemical elements that have not been widely extracted, traded, or utilized in the past and are, therefore, not the focus of well-established and relatively stable markets.

The general subject of the availability of minerals is huge and inextricably connected to almost every aspect of our culture and economy. We limit our attention in this report to elements that have the potential for major impact on energy systems and for which a significantly increased demand might strain supply, causing price increases or unavailability, thereby discouraging the use of some new technologies. Our focus is on energy technologies with the potential for large-scale deployment. We evaluate constraints on the availability of ECEs and make recommendations that, if put into practice, should help avoid these impediments.

This is not a report on any single ECE or group of elements like the rare earth elements (REEs) that have recently received so much media attention. Instead, it focuses on issues that are common to many ECEs and on policies that could contribute to a steady and predictable supply of ECEs or the development of satisfactory substitutions.

This report presents several examples of ECEs, but it is not our intent to generate a definitive list of ECEs. Indeed, any list of ECEs will change over time, as technology and other factors evolve.

A representative example of an ECE is neodymium, a component in high-field permanent magnets (known as neodymium-iron-boron magnets), which are key components in wind turbines, hybrid cars, and other advanced electromagnetic-to-mechanical conversion systems. Another example is tellurium, an important component in thin-film photovoltaic (TFPV) panels that may decrease the materials cost of producing solar energy significantly.

An element might be "energy-critical" for a variety of reasons. It might be intrinsically rare in Earth's crust, poorly concentrated by natural processes, or currently unavailable in the United States. Some potential ECEs, such as tellurium and rhenium, are genuinely rare in Earth's crust.[2] Rhenium, for example, is rarer than gold by approximately a factor of five. Others like indium, although not as rare, are unevenly distributed in Earth's crust, causing the United States to be highly reliant on imports. Still other ECEs, such as germanium, are seldom found in concentrations that allow for economic extraction.

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[1] See Figure 1 for a version of the periodic table of elements in which possible ECEs are highlighted. Specific elements and groups of elements that figure prominently are described further in boxes throughout the report.

[2] We take all our abundance figures from (Lide, 2005). There is considerable debate over the precise values (a variety of different sources are compared on the Wikipedia website, http://en.wikipedia.org/ wiki/Abundances_of_the_elements_(data_page)), but the exact values are not essential to our analysis.

Geopolitical issues can arise when a critical element is produced in a small number of countries or in a location subject to political instability. Technical expertise in extraction, processing, and other technologies tends to follow the resources, leaving the United States at a further disadvantage when the primary production of an element is overseas. The present concentration of REE production in China is a particularly pertinent example. Although the United States led the world in both production and expertise into the 1990s, over 95% of these important elements are now produced in China, and China is rapidly becoming the center for REE extraction and processing expertise. Even if natural resources exist in a country, a lack of expertise and extraction, refining, and processing infrastructure can significantly influence international trade of ECEs, as is now the case with REEs.

Many potential ECEs are not found in concentrations high enough to warrant extraction as a primary product, given today's prices. Instead, these ECEs are obtained primarily as by-products, during the refining process of other primary ores, especially copper, zinc, and lead. This applies to tellurium and indium, which are currently obtained as by-products of the electrolytic processing of copper and zinc ores, respectively. By-production and co-production present special economic issues. For example, it is unlikely that the mining of copper (production value approximately $80 billion in 2009) would be driven by an increased demand for tellurium (production value approximately $30 million in 2009). However, the way that copper ore is currently processed might well be modified to obtain more tellurium.

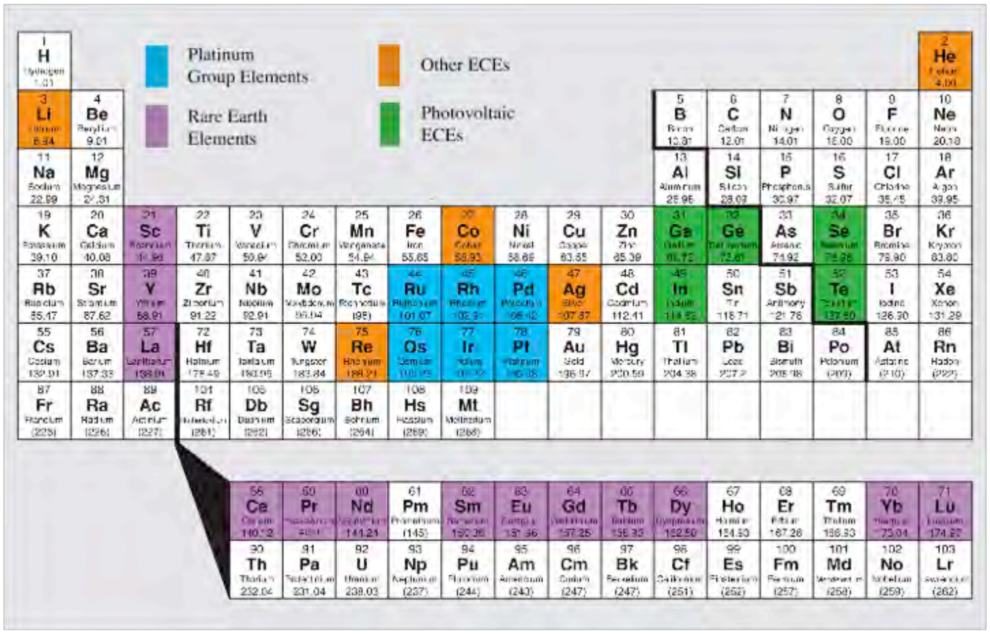

Figure 1. Possible Energy-Critical Elements (ECEs) are highlighted on the periodic table. The rare earth elements (REEs) include lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Tb), and lutetium (Lu). The closely related elements scandium (Sc) and yttrium (Y) are often included as well. The REEs are considered as a family, although Pm is unstable, and Ho, Er, and Tm have no energy-critical uses at present and are omitted from our list. Y together with the Tb—Lu form the heavy rare earth elements (HREE), and Sc plus Ce—Gd constitute the light rare earths (LREE). The platinum group elements (PGEs) include ruthenium (Ru), rhodium (Rh), palladium (Pd), osmium (Os), iridium (Ir), and platinum (Pt). Additional ECE candidates include gallium (Ga), germanium (Ge), selenium (Se), indium (In), and tellurium (Te), all semiconductors with applications in photovoltaics. Cobalt (Co), helium (He), lithium (Li), rhenium (Re) and silver (Ag) round out the list.

Joint-Production

Many of the energy-critical elements identified in this report are produced jointly with other elements. At mines and processing facilities that yield several end products, commodities are categorized based on their relative importance to the overall commercial attractiveness of a given project. These commodities can be labeled *main products, co-products,* or *by-products*. A *main product*, by itself, largely determines the commercial value of a project. *Co-products* exist when each of two or more elements significantly influences the venture's commercial viability. A *by-product* plays a relatively minor role in a project's commercial appeal. Many ECEs are, at present, only obtained as by-products of commodity metals. Since a REE mine inevitably produces some amounts of all the rare earths and since some have much higher economic value than others, it is useful to regard all of the REEs as co- or by-products of one another. Even if rare earth supply and demand were in equilibrium on average, some REEs would always be in oversupply and others would always be in undersupply. Similarly, the platinum group elements (PGEs) typically occur together and are best regarded as co-products with one another.

Among other energy-critical elements, gallium is obtained as a by-product of aluminum and zinc processing; germanium is typically derived as a by-product of zinc, lead, or copper refining; and indium is a by-product of zinc, copper, or tin processing. Selenium and tellurium are most often by-products of copper refining. In some cases, the rare-earth elements may be the by-products of iron, zirconium, tin, thorium, or uranium production. Helium is a by-product of natural gas production.

Sometimes joint-production has unexpected consequences. Cadmium, an important component in some thin-film photovoltaics, is a by-product of zinc processing. Because cadmium is toxic, it must be removed from zinc during refining. For this reason, its applications are also limited (USGS, 2010). Thus, cadmium is inexpensive compared to its crustal abundance (Price, 2010) and is unlikely to be scarce or unstable in price, for the foreseeable future. Cadmium has, therefore, been omitted from our list of ECEs.

Several additional factors complicate the availability of ECEs. Some potential ECEs are toxic; others are now obtained in ways that produce environmental damage that is unacceptable in most countries. Many ECEs are available only in low-grade ores, which necessitates the processing of tons of rock for each gram of element recovered. New mining ventures require long and complex permitting processes in the United States and other highly developed countries. The lag time between increased demand and the availability of new supplies can be extensive. Recycling and the existence of secondary markets for ECEs is quite variable. For example, recycling is highly developed for the platinum group elements (PGEs), but almost nonexistent for most other ECEs. Sometimes, one element can be substituted for another in a new technology, but more often than not, substitution requires significant research, reengineering, retooling, and recertification with attendant delays.

A definitive list of ECEs would require extensive study based on information about occurrences, reserves, extraction, processing, utilization, and recycling, much of which is not yet available. With the understanding that our list of ECEs is illustrative, rather than definitive, we can enumerate the elements we believe, at present, to be good candidates for the designation of "energy-critical:"

- Gallium, germanium, indium, selenium, silver, and tellurium, all employed in advanced photovoltaic solar cells, especially thin-film photovoltaics.

- Dysprosium, neodymium, praseodymium, samarium (all REEs), and cobalt, used in high-strength permanent magnets for many energy-related applications, such as wind turbines and hybrid automobiles.

- Most REEs, valued for their unusual magnetic and/or optical properties. Examples include gadolinium for its unusual paramagnetic qualities and europium and terbium for their role in managing the color of fluorescent lighting. Yttrium, another REE, is an important ingredient in energy-efficient solid-state lighting.

- Lithium and lanthanum, used in high performance batteries.

- Helium, required in cryogenics, energy research, advanced nuclear reactor designs, and manufacturing in the energy sector.

- Platinum, palladium, and other PGEs, used as catalysts in fuel cells that may find wide applications in transportation. Cerium, a REE, is also used as an auto-emissions catalyst.

- Rhenium, used in high performance alloys for advanced turbines.

Many of the elements on this list are presently produced in very small quantities. For example, in 2009, worldwide production of germanium was 140 metric tons (MT) (USGS, 2010). The production of tellurium[3] was estimated at only 200 MT.

Many important elements are notably absent from this list. Copper, aluminum, iron, tin, and nickel are absolutely essential for energy applications. However, because they enjoy large, mature, and vigorous markets with many suppliers, a strong demand from the energy sector would most likely be met with a market-driven increase in supply. For example, the broad distribution of copper and aluminum sources across the globe is illustrated in Figure 2. We omit these metals from our consideration, because they form a category of their own. They share more in common with one another than with the less familiar elements in the ECE family. We exclude carbon (as coal, oil, etc.) and uranium, since they have been the subject of many studies and mature regulation; moreover, increased demand does not create novel issues for these elements, beyond those already explored in the economic, technical, and political arenas. We exclude elements like phosphorus and potassium for which we can see only peripheral relevance to energy issues. Some largely manmade isotopes of elements like He-3 have important energy-related applications (e.g., neutron detection) but have more in common with

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[3] Estimated, the exact amount of tellurium production is unknown.

other artificial isotopes than with the ECEs in our study. Finally, there is considerable overlap between elements that are critical for energy applications and those that are critical for national defense. REEs, which have many defense-related applications, are an important example. We have not considered national defense matters, nor do we consider elements like beryllium that are critical for defense but do not have prominent energy-related applications.

In this section, we examine the potential constraints on ECE availability and provide the geological, mineralogical, economic, or political background regarding possible limitations. Where possible, we illustrate the issues with examples taken from our list of ECEs and provide additional information in a series of sidebars that accompany the text.

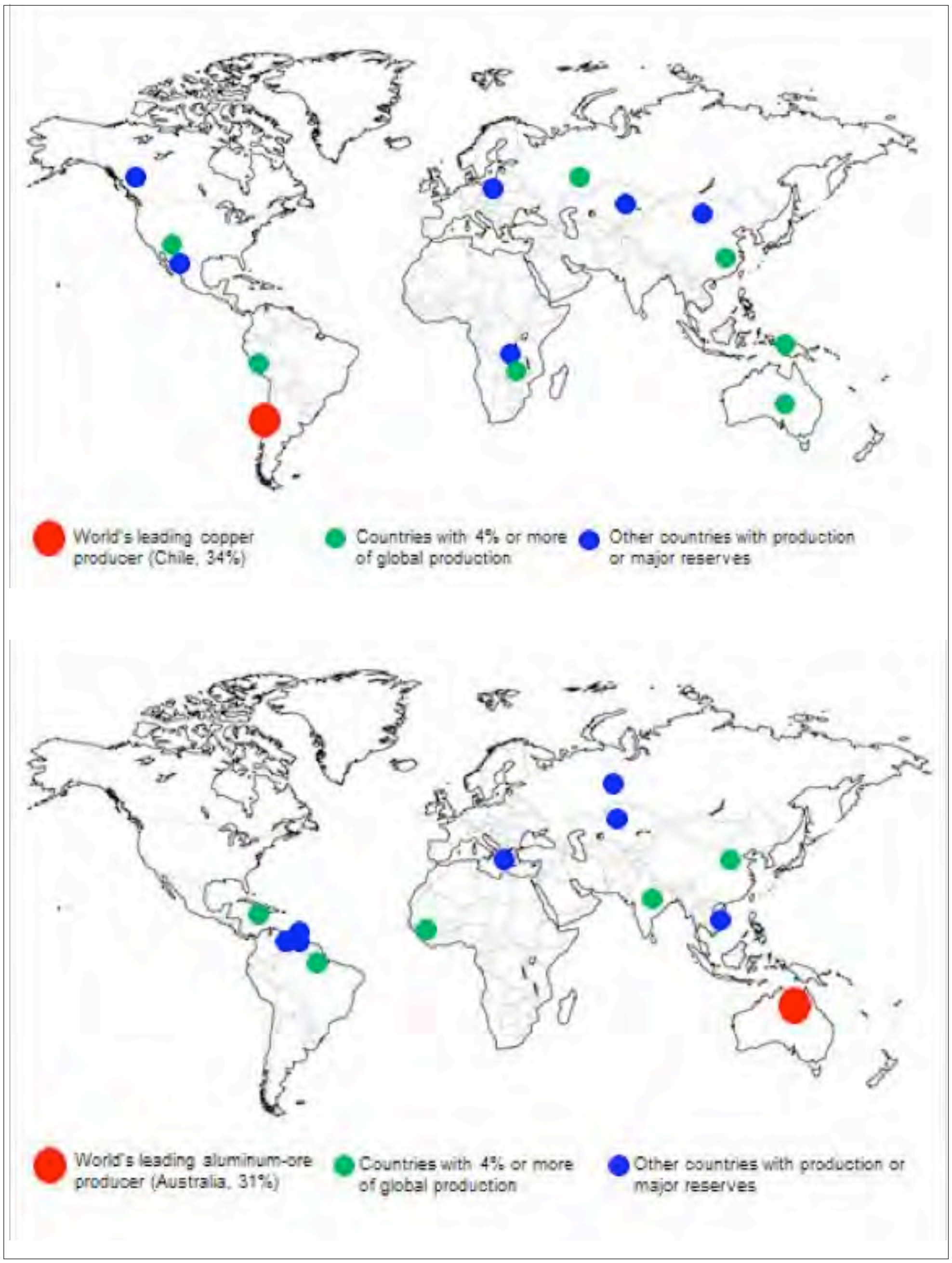

Figure 2. Leading copper producing countries in 2009 were Chile (34% of global production), Peru (8%), U.S. (8%), China (6%), Indonesia (6%), Australia (6%), Russia (5%), Zambia (4%), Canada (3%), Poland (3%), Kazakhstan (3%), and Mexico (2%); Mongolia and the Democratic Republic of Congo have major, recently discovered reserves. Leading aluminum-ore (bauxite) producing countries in 2009 were Australia (31%), China (18%), Brazil (14%), India (11%), Guinea (8%), Jamaica (4%), Kazakhstan (2%), Venezuela (2%), Suriname (2%), Russia (2%), Greece (1%), and Guyana (0.6%); Vietnam also has major reserves. Note that aluminum metal production (from bauxite) is concentrated in countries with inexpensive electricity (such as Iceland) due to the energy intensive nature of the aluminum production process. Production data are from the USGS (2010), plotted on a base map from http://english.freemap.jp/world_e/2.html.

A. Crustal abundance, concentration, and distribution

The average concentration of any chemical element in Earth's crust (the only part of solid Earth available to us for extraction of elements), expressed as percentage by weight, is called the "crustal abundance" of that element. Earth's crust is made up primarily of oxygen, silicon, and aluminum. A dozen elements in all are responsible for over 99% of the mass of Earth's crust. All other elements, including those considered as ECEs in this report, are present in much lower concentrations, below 0.1% of Earth's crust by weight.

Less abundant elements, including all of the ECEs, occur primarily as atomic substitutes in minerals composed of the common elements. When a chemical element occurs in small amounts, it does not form a separate mineral, but simply substitutes as a trace impurity in the crystalline structure of the common minerals. The low concentration of these elements in the more common minerals makes these minerals unlikely sources for economic extraction of ECEs.

Occasionally, geological processes cause a local enrichment of one or more of the scarce elements through substitution for a more common element with similar chemistry. Thus, selenium and tellurium may substitute for sulfur, which has similar chemical properties. Alternatively, a rare element may substitute in a more common mineral if its atoms have the right properties to fit into the mineral's crystal structure. The substitution of REEs in yttrium and cerium phosphates, common trace minerals in granites, is an example of this phenomenon. When this occurs and the rare elements can be economically separated from the mineral, the mineral becomes an "ore mineral" for these elements.

Germanium (Ge) — Abundance and concentration

Germanium (atomic number 32, 0.00015% of Earth's crust by weight) is an example of an element that is constrained in its availability, because it is not appreciably concentrated by geological processes. Ge is a semiconductor in the same column of the periodic table as carbon and silicon. Ge is not particularly scarce; it is twenty times more abundant than silver, for example. However, Ge substitutes for other elements in minerals and rarely forms minerals in which it is a principal component. It is produced primarily as a by-product of zinc extraction. Ge is used in fiber optics, infrared optics, and as an ECE in solar photovoltaic cells. Although statistics on mine production of Ge by country are not available, USGS (2010) reported global production in 2009 from zinc refining to be 140 MT, of which 71% came from China. For comparison, 2009 production of Zn was 11,100,000 MT, of which 25% came from China, the world's leading Zn producer.

Production of elements involves two distinct operations. The first is mining and, with the exception of a few elements (gold and some types of copper deposits), the subsequent separation of the desired ore minerals into a concentrate. The second operation is chemical processing of the concentrate to free and purify the element. It is at this stage that by-products, such as tellurium and indium, are separated from primary metals, such as copper and zinc. The special circumstances surrounding co- or by-production of ECEs are described further in the section of this report titled "The risks of joint-production."

The geological occurrence of widely used elements, such as copper, zinc, and gold, is reasonably well known, and geologists have developed sophisticated models and technologies for discovering potentially economic concentrations. Less is known about the geology and geochemistry of many ECEs, since they have not been the focus of such intensive research. Historically low demand for these elements has meant that sufficient production has been obtained from a small number of higher-grade deposits or as by-products from recovery of other metals. As demand for ECEs increases, the geochemistry and mineralogy of critical elements will have to be understood more deeply, and methods will have to be devised to locate ECE deposits that have, so far, gone unrecognized. Furthermore, additional metallurgical research is required to better understand how to extract these elements from the different minerals holding them.

Past experience and a broad familiarity with the nature and distribution of mineral deposits indicates there is no absolute limit on the availability of any chemical element, at least in the foreseeable future. Articles in the popular literature [see for example Cohen (2007)], claiming that supplies of one element or another will run out in a few years, are typically based on misunderstandings, like a misinterpretation of the terms *resources* and *reserves,* as used in the USGS Mineral Commodity Summaries (USGS, 2010). Reserve estimates are influenced by current demand—if demand diminishes, then efforts to identify reserves likewise diminish. Therefore, reserve estimates can be artificially low, appearing to only be capable of lasting a short period of time. In a free-market economy, prices rise when demand outstrips supply, and, as those prices rise, the following occur: previously low-grade, uneconomic resources become profitable ores; exploration is stimulated to discover new deposits; metallurgical research leads to new technologies for extraction; lower-priced substitutes are employed; and recycling becomes more profitable. As lower grade deposits are brought into production, the cost of extracting a chemical element rises. So, too, do the carbon emissions and energy required to produce the element from ever more dilute sources. A practical limit on availability for a particular application is reached when the material is no longer available at a competitive price. Although one can anticipate that this will come to pass for some ECEs in the long term, we believe that short-term supply disruptions pose a more immediate threat.

Although "absolute limits" are not a useful way to think about potential constraints on availability, there are a number of critical issues that can affect the price and availability of ECEs in the short term (months to years). If not anticipated, these issues can disrupt the planning and implementation of new energy technologies. It is essential to be aware of the potentially disruptive effects of these transients. The transition from reliance on primary production of a rare element from a few sources to co-production with more common elements or *vice-versa* can take many years and derail plans for large-scale deployment of the technology that relies on that rare element. The subsequent sections detail several of the most complex and disruptive potential constraints.

B. Geopolitical risks

The geopolitical dimension of mineral availability refers to the risks of a supply disruption (either in the form of physical unavailability or higher prices) due to the behavior of sellers or governments outside the United States.

The United States relies on imports for more than 90% of its supply of the majority of ECEs identified in this report. Import dependence, by itself, is not inherently or necessarily risky. In fact, relying on imported raw materials is beneficial to domestic users if foreign sources are diverse in number and location and can supply the elements at a lower cost than domestic alternatives. The present U.S. dependence on foreign production of many mineral resources has, in many cases, evolved, not because the United States has a lack of resources or reserves, but rather because foreign producers have a competitive advantage, supplying the United States (and the world) with raw materials at the lowest price.

Serious risk may develop when production is concentrated in a small number of mines, companies, or nations. When sources of rare commodities are discovered and, subsequently, developed in underdeveloped countries, the result is sometimes increased hardship and political instability, rather than improved standard of living for the majority of citizens. The history of cobalt, copper, and tantalum production in the Democratic Republic of the Congo is one of numerous examples in Africa alone. Countries dependent on ECEs produced under such circumstances might be subject to prolonged uncertainty and are at risk for acting in ways that further exacerbate the economic and human suffering in the producing country. Conversely, when established foreign governments control a major fraction of the supply of an ECE, countries dependent on that material become vulnerable to manipulative market practices. These include (a) charging higher prices than possible were there a larger number of sellers and (b) restricting exports to the advantage of domestic users in the producing nations. Even absent explicit policy on the part of a foreign government, when supply is concentrated, users are subject to unforeseen supply disruptions due to labor or civil unrest and/or technical problems at mines or processing facilities.

There are numerous examples of disruptions driven by both foreign governments and other factors. The present "rare earth crisis"—involving dramatic price escalations and possible shortages—appears to be an example of government policy. History suggests that shortages, price spikes, and abandonment of technologies can occur when the threat of a shortage arises, even if the actual shortage never materializes, as was the case for cobalt in the Congo in the 1970s (Alonso, 2007). In contrast, large, long-established markets like those enjoyed by the primary metals have evolved a diverse landscape of suppliers across the globe. The distribution of copper and aluminum production, shown in Figure 2, illustrates this point.

Among the energy-critical elements, the rare earths, platinum group elements, and lithium are perhaps most vulnerable to geopolitical risks. Nearly all current global production of rare earths occurs in China, where the government has imposed export restrictions. China's stated motives are to encourage responsible development of domestic processing and manufacturing industries that use rare earths, to stop highly polluting practices and to secure future supplies for domestic needs; opinion outside of China cites geopolitical control and maximization of price. Platinum production is concentrated in the hands of a small number of companies in South Africa, which produced 79% of the world's supply in 2009. This leaves platinum users vulnerable to opportunistic behavior,

Mineral resources and ore reserves

Mineral resources include both currently and potentially economic volumes of rock with concentrations of elements that are higher than typical rocks. Reserves are defined as economically extractable resources. The term "ore" is restricted to reserves, whereas sub-economic and as-yet-unclassified resources are said to contain "mineralized rock."[1]

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[1] For further explanation, see Appendix C, p. 189 in (USGS, 2010).

either by platinum producing companies or by the South African government. Supply could be disrupted due to technical problems at important mines or arising from an unsettled political and social environment. Lithium also has the potential for geopolitical risks, because the world's known resources of easily extractable lithium are largely concentrated in three South American countries: Chile, Bolivia, and Argentina.

Even in cases where production is, at present, concentrated in one or a few countries, the potential for developing a broader suite of producers in the future might be significant. Occurrences of REEs are known across the globe. Figure 3, compiled by A. Mariano, shows his summary of the known REE deposits that might be economically viable, given further exploration and development of new mineral processing technologies (Mariano, 2010). Clearly, China is not the only country with the potential to produce significant quantities of REEs. However, the path from recognizing a deposit to full scale production is a complex one. Many of the deposits shown in Figure 3 might never be brought to production, due to problems with metallurgical extraction, labor costs, political instability, absence of infrastructure, environmental impact, or social and political concerns. China dominates the REE market, because it has overcome the technical issues of extraction from often low-grade deposits, using techniques enabled by low environmental standards and low cost labor. Similar issues and externalities have prevented exploitation of many of the resources displayed in Figure 3 elsewhere in the world.

ECEs that are primarily extracted as by- or co-products with other, more common and widely distributed elements are less subject to geopolitical risks. However, they come with their own set of concerns.

C. The risks of joint production

The joint production of energy-critical elements has several important implications. First, producing an element as a by- or co-product is typically less expensive than producing the same element by itself. Economists call this concept an "economy of scope"—the average total cost of production decreases as a result of increasing the number of commodities produced. Jointly produced elements can have a commercial, competitive advantage over the same elements produced individually. For example, when REEs in China are produced as by-products of iron-ore mining (as at the Bayan Obo mine in Inner Mongolia), they have an inherent cost advantage over rare earths produced on their own. The rare earths and iron ore share many of the costs of mine planning, blasting, ore haulage, and other activities.

Platinum (Pt) and Palladium (Pd) — Geopolitical Considerations

Platinum (atomic number 78, 0.0000005% of Earth's crust) and palladium (atomic number 46, 0.0000015% of Earth's crust) are examples of elements whose supply could be at risk, because they occur in economic concentrations in few geological environments and in geographic locations where political stability might be a concern. Pt and Pd are used as catalysts in fuel cells that have many potential applications, including hydrogen fuel and hybrid cars. In 2009, global production of platinum (178 MT) was dominated by South Africa (79%) and Russia (11%), as was production of palladium (195 MT) with each country producing about 41%.

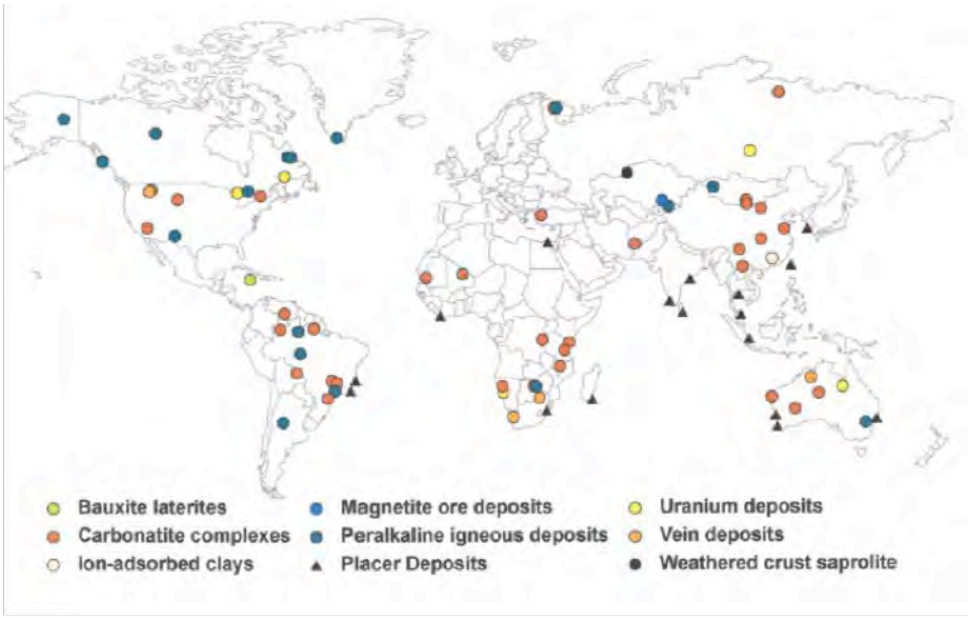

Figure 3. Distribution of documented REE deposits as presented by A. Mariano in (Mariano, 2010).

Second, the availability of an element produced as a by-product is constrained by the amount of by-product contained in the main-product ore. Consider the case of tellurium (Te; see subsequent Sidebar for the basic properties of Te). Nearly all Te is obtained as a by-product of the electrolytic refining of copper (Cu). At present, only a fraction of the Te in electrolytically processed Cu ores is recovered. It is reasonable to assume that more could be recovered cost-effectively; a small increase in price could motivate Cu refiners to retain and process the Te to meet the increased demand for it. Unfortunately, from the perspective of Te availability, acid leaching followed by solvent extraction-electrowinning (SX-EW) is replacing electrolytic refining of Cu and does not recover Te (USGS, 2010). The supply of Te available, as a by-product of Cu refining, might decrease if the amount of Cu supplied by SX-EW increases. If Te prices rise high enough, research might lead to new ways of extracting it from Cu ores that are processed by SX-EW or to more efficient ways to recover additional Te from electrolytic Cu refining.

As an example, if demand for Te grew dramatically in conjunction with widespread deployment of Cd-Te thin-film photovoltaic panels, then new sources would have to be found. The Te required for one gigawatt (GW) (average delivered) of electric power is roughly 400 MT (see the sidebar on Te), exceeding estimates of the world's Te production in 2009. Te also occurs as an impurity in sulfide ores of zinc and lead, which it could be recovered from as a by-product. When that capacity is exceeded, it is quite possible that new, primary sources of Te, which do not benefit from the cost sharing of joint-production, would have to be discovered, evaluated, and developed. Although such sources undoubtedly exist, too little is known about the geology and mineralogy of Te, its occurrences and associations, to assure a stable global supply.

The scenarios we illustrate with Te also apply to indium, gallium, and germanium, all of which have potential applications in advanced photovoltaics. The production complexities of elements primarily obtained as by-products create a difficult environment for planning and investment in these elements, as well as in the new technologies that require the unique attributes of the elements themselves. Large fluctuations in price can occur after joint-production options are saturated and before new supplies hit the market. The possibility that consumers will turn toward temporarily less expensive substitutes in response to a sudden price increase makes investments in primary production risky, and the lack of good information about the potential for primary production of these potential ECEs complicates the situation.

Tellurium (Te) — Co-production

Te (atomic number 52, 0.0000001% of Earth's crust) is one example of an ECE that is now obtained as a by-product of the mining of another element. No ores are mined primarily for their Te; essentially, all Te comes from the refining of Cu. Because Te production is so small (on the order of 200 MT in 2009) compared to that of Cu (15,800,000 MT in 2009), there is little incentive to maximize Te recovery from Cu processing, even though Te costs considerably more than Cu ($145/kg vs. $5.22/kg in 2009). Te is used in photovoltaic panels, where it is employed in films a few microns thick. Assuming a thickness of 3 microns and a photovoltaic efficiency of 10%, we arrive at a Te content of about 0.1 gram per watt of installed electric generating capacity or 100 MT of Te per gigawatt of installed capacity. Assuming a typical utilization factor of 25%, this leads to about 400 MT of Te per gigawatt of produced electric power. There are many unknowns that make predicting the capacity of supply to expand to meet a significantly increased demand for Te difficult. Data on rates of recovery of Te from Cu ores are not available. Little is known about the geological and geographic variability of Te in Cu ores or the extent of Te abundance in other sulfide ores. Less still is known about the existence, extent, and reserves of primary Te deposits.

D. Environmental and social concerns

Environmental and social considerations place strong constraints on mineral extraction and processing operations. It is not enough that a mineral resource exists and is amenable to extraction using existing technologies; it is also necessary that the whole enterprise, from extraction to utilization, takes place in ways that are consistent with local, national, and, in many cases, international standards of environmental protection and respect for society.

Environmental concerns with mining and mineral processing are increasing around the globe. The relatively stringent standards currently applied in developed countries like the United States are increasingly being adopted throughout the world. In some cases, however, these high standards have had the effect of moving mineral extraction activities off-shore to less developed countries where, in some cases, local conditions lead to greater interest in short-term economic development than in long-term environmental stewardship.

The social dimension of this issue compels mineral production to take place in ways that both (a) acknowledge and remediate potentially disruptive effects of mineral development on local communities, including strains on local infrastructure and services due to a dramatic influx of workers from outside the community and (b) appropriately share the wealth that mining may create with local communities, in part, so desirable cultural, economic, and environmental conditions can be sustained.

The social and environmental aspects of mineral development have become significantly more important in recent years. For example, an international industry association, the International Council on Mining and Metals (ICMM), has made these aspects its primary focus, and the International Finance Corporation (IFC), the commercial arm of the World Bank, has developed a set of performance standards for social and environmental sustainability that must be met by any project to which it lends money. As countries that now have lax environmental and social impact standards embrace higher standards, the price and availability of ECEs might be significantly affected.

The role played by environmental standards is well illustrated by several examples of the mining of REEs. Rare earths often occur in association with thorium and uranium, both of which pose low level, but significant, radiation hazards. The rare earths can be extracted at a profit, but the thorium and uranium are not commercially recoverable and, thus, are left in the tailings. As a result of mining and mineral processing, unacceptable levels of radiation can be released into the environment, if not properly controlled. The problem is particularly serious for the mining of monazite and xenotime REE sands, which are widely distributed over the world and have become resources largely viewed as uneconomic for this reason. Thorium and radium (by-products of uranium decay) contamination from wastewater spills resulted in closure of the chemical processing facility at Mountain Pass, California in 1998. The operation has since changed its wastewater treatment to prevent such releases. Exceptional attention to environmental and local social concerns has accompanied the efforts to restart the Mountain Pass REE mine in Southern California. In the short term, such efforts may put producers in the United States at a competitive disadvantage relative to some foreign operations.

China's dominance of REE production is based, in part, on the mining of unusual *lateritic clay* REE deposits in South China. REEs from the South China clays now account for about 30% of world REE production and are the world's major source of yttrium and heavy REEs (HREEs), which are particularly scarce. Existing mining practices result in a barren and disturbed landscape, unsuitable for agriculture or other uses and vulnerable to erosion. There is often no attempt at remediation of the mining sites to allow for future productive use, as would be the case in many other countries. Such mining practices are not possible in most countries. In fact, the Chinese government cites environmental concerns as one reason for restricting the exports of HREEs.

E. Response times in production and utilization

Delays in both production and utilization undermine the ability to plan for deployment of new energy technologies. At one end of the economic chain is the time it takes to bring a new mine or extraction process online. At the other end is the time it takes, often decades, to plan, research, develop, fund, permit, and deploy a new scheme for producing, transmitting, storing, or conserving energy. All these steps anticipate that the supply of critical elements can be secured in a timely and affordable way to make the technology cost-effective and available. For this to be done successfully, information must easily flow between the demand and supply sides on both future and current uses and availability.

Interviews with experts in exploration, mining, and mineral processing suggest that it commonly takes 5 to 15 years to render a new mine operative, that is, from the time that exploration begins until production starts. Several factors determine the timeline, including success in finding a mineral deposit that is sufficiently large and high enough in grade to be economical, the time it takes to construct the infrastructure associated with a new extraction site, the time required to obtain operating and environmental permits and the social license (the political buy-in of the local and regional community) to operate in a given geographic location, and the time it takes to arrange financing, which can reach billions of dollars.

In analyzing the impact of some of the world's largest new mines, Schodde and Hronsky (2006) documented the time between discovery and start-up of fifteen operating mines, including copper mines in Chile, diamond, nickel, and gold-silver mines in Canada, and zinc, copper, and gold mines in Australia. The average time between discovery and start-up for these mines was 8 + 3 years. These authors also studied four additional deposits that were undergoing feasibility studies in 2006 that were still not in production in 2010. Using currently estimated start-up dates for these, the average time between discovery and start-up for all nineteen mines would be 11 + 6 years, with a range from 2 to 26 years. Initial exploration leading to a discovery adds another 3 to 5 years.

The development of new technologies for the extraction and processing of elements from ores is often a protracted and uncertain process. Anyone familiar with the history of the Hall-Héroult process[4], the development of which transformed aluminum from a scientific curiosity to a mainstay of modern technology, will appreciate the time, effort, and uncertainty surrounding new extraction technologies. Utilization of several REE minerals, such as eudialyte, is currently impeded by the lack of suitable chemical technology to remove the REEs from the other elements in the ore.

Time scales on the demand side may be just as long and risky as the development of new extraction technologies. Developers and investors, whether public or private, hoping to bring a new technology to market, must plan years, if not decades, in advance. Contributing factors include time for research on selecting the best materials and approaches to manufacturing, patenting and other intellectual property issues, market research, financing, and construction and permitting of manufacturing facilities. Researchers involved in the creation of new technologies, at the earliest stage of the applications cycle, generally fail to consider the availability of raw materials at all; their focus remains on a material's suitability for the task at hand. Uncertainty about the availability of critical elements adds serious risk. The present "crisis" in the REE market is a good example of how early assumptions can be challenged at a much later time: Wind turbines designed to work with neodymium-iron-boron permanent magnets were designed over many years, under the assumption that neodymium, a fairly common element, would continue to be available in the quantities needed at reasonable prices. This situation has changed. Wind turbines could be redesigned to employ other magnets, perhaps at some cost in efficiency, but the redesign process is not trivial. It is difficult to predict whether the present steep increase in the price of neodymium (and decrease in its availability) is a short-term problem to be weathered or a long-term problem to which the industry must adapt.

Another pertinent example of the effect of long time-delays is the development of lithium (Li) resources in the United States. Li is one, but not the only, important candidate for a light, high-performance battery in hybrid and electric vehicles. Global Li production is currently dominated by Chile, which produces Li from brines in the Atacama Desert. Bolivia also appears to have the potential for large Li resources in brines. In the United States, at least one company is investigating extraction of Li from a new resource, hectorite, from which Li has not previously been commercially extracted. The company has spent several years confirming the resource potential of a deposit that was discovered in the 1980s and is now investigating how best to extract Li from the material.

Lithium — Response times in production and utilization

Li (atomic number 3, 0.002% of Earth's crust) is an example of an ECE whose future supply in the marketplace is experiencing significant uncertainty associated with time delays in production and utilization. Li, a light and highly reactive metal, is the principal component in one of the most promising forms of high energy-density batteries. As a result, many believe Li batteries are the technology of choice for all-electric vehicles. If electric vehicles are to gain a significant share of the market, battery and, therefore, Li production must grow proportionately. However, there are other materials that could be considered for use in high performance batteries. The choice of which battery technology to develop depends largely on the availability and price of the component materials. Ramping up the production of Li from existing mines and developing new ones is not a trivial matter, nor is the design of Li batteries suitable for all-electric vehicles. Lacking a clear decision on the fundamental battery design, it is not surprising that exploration for and development of new Li supplies remains in limbo.

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[4] Although aluminum was first isolated in metallic form in 1825, it proved very difficult to extract from its oxide ore, and, for decades, aluminum metal was as rare (and as valuable) as gold or platinum. In 1886, Hall and Héroult devised the modern process of aluminum refining, and aluminum quickly found its place as a major industrial metal.

A. Coordination

International relations, trade policy, environmental standards, energy independence, and long-term research and development are traditional concerns of nations, rather than individuals, companies, or local governments. The issues are complex and straddle areas that are in the portfolios of many different agencies and ministries within governments. Facilitating and coordinating these activities presents a significant organizational challenge.

In the United States, the stewardship of the multitude of issues and policies affecting ECEs does not reside entirely in any one federal department. Instead, ECEs are of concern to the Departments of Commerce, Defense, Energy, Interior, State, and Transportation. Strong involvement of the Council of Economic Advisors, the Environmental Protection Agency, and the Office of the U.S. Trade Representative is also expected. The capacity to orchestrate a productive collaboration among all these agencies and coordinate their efforts with the Office of Management and Budget lies in the Executive Office of Science and Technology Policy (OSTP). We believe that the OSTP is the natural home, at least for initial efforts, to guide the United States' response to ECE issues.

- Recommendation: The OSTP should create a subcommittee within the National Science and Technology Council (NSTC) to examine the production and use of ECEs within the United States and coordinate the federal response. The subcommittee should include high-level participation from the Departments of Commerce, Defense, Energy, Interior, State, and Transportation, as well as the National Science Foundation, the Environmental Protection Agency, the Office of Management and Budget, the Council of Economic Advisors, and the Office of the U.S. Trade Representative.

- Recommendation: The new subcommittee should immediately examine and address the recommendations listed below.

B. Information

Comprehensive, reliable, and up-to-date information on all aspects of the life cycle of ECEs would enable researchers, developers, and investors to more successfully plan for the materials needs of new technologies. The present information environment is very uneven. Relatively good information is available for elements with mature markets like platinum or silver, whereas information about newly important elements like REEs or Te is incomplete, anecdotal, and often contradictory. Information on the utilization and end-of-life of ECEs is hard to find or, for some mineral commodities, entirely absent.

Gathering, coordinating, and disseminating information about mineral resources is currently the responsibility of the Minerals Information Team (MIT) of the U.S. Geological Survey (USGS), which has recently been reorganized into the National Minerals Information Center (NMIC) within the Mineral Resources Program (MRP) of the USGS. The NMIC fulfills its task by publication of the annual "Mineral Commodity Summaries" (MCS) and other related reports, which are used in the United States by federal and state governments and by the private sector throughout the world, as a reference on mineral production, resources, and reserves. Before its dissolution in 1995, the U.S. Bureau of Mines was responsible for this task and had high visibility and support within the federal government. Since its transfer to the USGS, the MIT (now NMIC) has struggled to find funding to carry out its mission; its budget and its manpower have eroded.

Information about ECEs, and current products that make use of them, is needed beyond what is presently compiled in the annual MCS or the USGS's recent report on domestic REE deposits (Long, 2010). This includes information across the ECE life-cycle, from potential economic and sub-economic resources (both domestic and foreign) through production, scrap generation, and inventories of old scrap, and into basic applications research, product design, and manufacturing. Data are also needed on the use and disposal of products containing ECEs and the potential for recycling. Although portions of these data are collected by the Department of Commerce and life-cycle analysis is carried out for selected minerals by the USGS, there is, at present, no central agency that compiles, analyzes, and distributes information on the life cycle of minerals and materials critical for energy technologies.

Regular surveys of emerging energy technologies and their potential critical element requirements are needed. Data on the magnitudes and locations of potential resources, both foreign and domestic, and on potential constraints on availability are needed before major investments in new technologies that are reliant on these resources can be made. Nearly 40 years ago, the USGS published *Professional Paper 820* (Brobst, 1973), which documented known U.S. mineral deposits in the context of global resources, uses, and demand. An updated and extended version of this work, focusing on the broader set of issues outlined here, is urgently needed in light of the importance of ECEs.

Collecting and evaluating the data required to track the availability and uses of chemical elements that are, or may become, critical to emerging energy technologies has become a complex, multidimensional undertaking. Although some data are already collected by a number of federal agencies, the government does not have a central entity for tracking minerals and processed materials. The information gathering capacities of the Energy Information Administration (EIA), for energy sources and consumption, and the Bureau of Labor Statistics (BLS), for economic data, stand in contrast to the limited information produced primarily by the NMIC on ECEs and minerals. Both the EIA and the BLS are "Principal Statistical Agencies," a designation that enables them to require compliance with their requests for information; NMIC does not have this designation. The disparity was recognized in the recent National Research Council's study, "Minerals, Critical Minerals, and the U.S. Economy," (NRC, 2008) which recommended that the agency given the responsibility to gather mineral information also be given the "Principal Statistical Agency" designation. The federal body charged with this responsibility must have the tools necessary to respond to technological, economic, or geopolitical events that significantly impact minerals or materials demand. It will not be able to accomplish this ambitious mission unless it is empowered to enforce compliance with its requests for information that comes with the designation as a "Principal Statistical Agency."

- Recommendation: The U.S. Government should gather, analyze, and disseminate information on ECEs across the life-cycle supply chain, including discovered and potential resources, production, use, trade, disposal, and recycling. The entity undertaking this task should be a "Principal Statistical Agency" with survey enforcement authority.

- Recommendation: The federal government should regularly survey emerging energy technologies and the supply chain for elements throughout the periodic table with the aim of identifying critical applications, as well as potential shortfalls.

C. Research, development, and workforce issues

A focused federal research and development (R&D) program would enable the United States to both *expand the availability of* and *reduce its dependence on* ECEs. This federal R&D would be particularly critical to the competitiveness of small U.S. companies that are unable to engage in their own ECE basic research programs.

Several R&D areas can contribute significantly to *expanding the availability* of ECEs. These R&D areas occur throughout the supply chain, beginning with fundamental issues in geology. ECEs have not been a primary target of domestic mineral exploration in the past, so there is limited knowledge of what geological characteristics indicate the likelihood of ECE deposits. A complicating factor is that ECEs tend to exist in very low percentages, even in potentially economic ore deposits. Research on geological models of ECE mineral deposits, ore-forming systems, and the basic geochemistry of ECEs is needed. There has been little research of this kind in the United States for at least two decades.

Once a deposit is found, there might be limited experience in the United States with methods to extract the low-concentration ECE from the ore. R&D can significantly advance the metallurgy, processing, and fabrication of ECEs. Special attention should be paid to the development of more efficient methods of extraction of ECEs as by-products of primary metals.

Several R&D areas can help *reduce the dependence* on ECEs. One essential area of research is substitutional chemistry: that is, substituting elements that are more abundant and have higher projected availability for ECEs. Such substitutions cannot be made in a straightforward "drop-in" fashion, since ECEs have properties or combinations of properties that make them uniquely suitable for particular applications. Consequently, several materials may need to be substituted for the ECE, or the overall design of an energy technology might need to be altered. Given these complications, it can take years for a substitution to achieve commercial readiness. Therefore, it is imperative that research into the functional properties of a suite of potential replacements be initiated promptly, well in advance of an element becoming an ECE. As a case in point, computational methods have been developed that allow candidate materials for photovoltaic applications to be identified for further screening. With such early identification of promising alternatives and sustained support for their development, it might be possible to ease transitions from technologies reliant on scarce ECEs to new alternatives (See subsequent sidebar titled *Rhenium (Re)–R&D response to scarcity*).

Recycling is another R&D area that could enable a reduction of dependence on ECEs. Many products that use ECEs currently have extremely limited recycling capability. The result is that significant quantities of ECEs are permanently discarded every year. Conducting research on product designs that are more suited to recycling, while retaining the same functionality, could help ensure that scarce elements are more easily recovered from discarded products. In addition, R&D into environmentally benign methods to extract ECEs from the discarded product would help encourage the growth of an ECE recycling market. Taken together, research in chemical, metallurgical, and environmental science and engineering, as well as industrial design methods, can enable the creation of waste streams that result in high-value reusable ECE materials.

- Recommendation: The federal government should establish an R&D effort focused on ECEs and possible substitutes that can enhance vital aspects of the supply chain, including geological deposit modeling, mineral extraction and processing, material characterization and substitution, utilization, manufacturing, recycling, and life-cycle analysis.

All the R&D areas mentioned would benefit from a coordinated federal effort focused on elements or groups of elements. These would complement existing centers focused on particular energy sources or technologies. Success requires close interdisciplinary collaboration among scientists, engineers, and manufacturers with expertise across a range of fields, including geology, mining, extraction, processing, chemistry, material sciences, electrical and mechanical engineering, and physics. Within the United States, this breadth of expertise exists only at some national laboratories and major research universities. A consortium built around such institutions could bring the depth of knowledge and the continuity of focus that this problem requires. Such centers would form cores of activity that could engage and assist efforts by smaller groups at other universities and businesses.

- Recommendation: The federal government should create national collaborative centers, including national laboratory, university, and industry participants focused on elements or groups of elements. These would complement existing centers focused on particular energy sources or technologies. The new centers would foster the synergies needed to address the profoundly interdisciplinary aspects of ECE issues.

Currently, there are not enough scientists and engineers with ECE experience for the United States to satisfy its ECE materials and technology needs or to assume leadership in critical energy technologies. The number of graduating students required to address the domestic R&D needs at the front end of the supply chain (e.g., geology and mining) is currently small. As more mines become operational, more workers are needed. More professionals are needed in the separation and processing fields, which includes metal preparation, scrap recovery, recycling, and ceramics. Significantly more students are needed in R&D areas further along the supply chain, in specialties such as physical, inorganic, and organic chemistry, chemical and metallurgical engineering, physical metallurgy, condensed matter physics, and electrical engineering.

We estimate that approximately 70 Ph.D., Masters, and B.S. level scientists trained in ECE research areas are required per year for 4 years to fill the present void of technically trained and skilled personnel. [5] After 4 years, approximately twenty scientists trained in ECE research areas will be needed per year to sustain the anticipated level of expertise. These are conservative estimates based on current market conditions. If technologies based on ECEs "take-off" and become dominant economic drivers, then the numbers will be greater.

Rhenium (Re) — R&D response to scarcity

Re (atomic number 75, 0.00000007% of Earth's crust) is, perhaps, the rarest of all naturally occurring, stable chemical elements. In 2006, General Electric (GE) realized that demand for Re—a critical material in its turbine engines—was increasing significantly. By 2011, worldwide demand was predicted to exceed worldwide supply, potentially resulting in a Re shortage that would cripple its turbine engine market. GE made a decision to reduce the company's reliance on Re with a strategy, including both the recycling and R&D of substitute materials. Recycling enabled GE to reduce its use of Re, while buying it enough time to develop a new alloy that proved to be an adequate substitute (Fink, 2010). GE succeeded; but, many smaller U.S. companies cannot afford to engage in this level of recycling and/or substitutional research. A federal role in these areas could be critical to such smaller companies' competitiveness.

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[5] This information was compiled by committee member Karl A. Gschneidner, Jr. for this study. For the complete document consult (Gschneidner, 2010).

Government support for training the necessary workforce is required to ameliorate this situation. Training programs should be established in conjunction with the research partnerships described. Investigators at universities or laboratories outside such centers, working on ECEs and related topics, should be supported by traditional, competitive, peer-reviewed grants from the National Science Foundation (NSF), the Department of Defense (DOD), the Department of Energy (DOE), and the Department of the Interior (DOI).

- Recommendation: The federal government should support the training of undergraduate, graduate, and postdoctoral students in disciplines essential to maintaining U.S. expertise in ECEs.

D. The role of material efficiency

The term *material efficiency* refers to the variety of ways to obtain the essential services provided by a material with less material production from ores and other primary feed stocks. The aim of material efficiency is to enable the production of necessary goods, while producing as little of the material as possible. Recycling is a major, but not the sole, component of efficient material use. Other aspects include improved extraction technology, reduced concentration in applications, replacement in noncritical applications, development of substitutes in critical applications, and lifestyle adaptations. Several of these approaches fall under the previous R&D heading, "Research, development, and workforce issues." Recycling and related strategies are the focus here.

Material efficiency can serve many purposes in the economics of ECEs. It has the potential to displace some of the mining and processing of virgin ores, thereby minimizing the depletion of nonrenewable resources and reducing the expenditure of energy used in extraction, separation, and purification. Recycling generates an independent supply stream that can reduce dependence on imports and smooth out price and availability fluctuations, resulting from possible constraints on primary production. However, if use of ECEs expands as rapidly as expected, recycling and other mineral efficiency strategies will not make more than a modest contribution to meeting demand. Nonetheless, some demand will be offset, the loss of materials to landfills will be avoided, and the energy embedded in the elements during their initial processing will have been retained.

The opportunities for recycling will change as ECEs are more widely used, and a long-term commitment to stewardship of resources should include plans for recycling, during the design of manufactured products and research on technologies to recycle metals with minimal impact on the environment and human health. ECEs are well suited to functional recycling (see sidebar titled *Recycling terminology*), because they are not degraded by use. Chemical elements do not lose their properties with use, and they are often found in significantly higher concentrations in discarded products than in the original ores from which they were obtained. On the other hand, ECEs might be used in tiny quantities or low concentrations, requiring sophisticated technology to separate them for functional recycling.

Recycling of an ECE can be cost effective, particularly if it is produced from minerals from which recovery is expensive. Most gallium, for example, is obtained as a by-product of aluminum production, which is energy intensive. Because of its high energy costs, aluminum is one of the more successfully recycled metals — post consumer recycling was equivalent to approximately 35% of apparent aluminum consumption in 2009 (USGS, 2010). Because of the relatively high cost of recovering gallium from aluminum ores, the USGS noted that "substantial quantities of new scrap generated in the manufacture of GaAs-base devices were reprocessed."

Current levels of recycling for many ECEs are minimal. For example, the USGS MCS (2010) reported little or no recycling of tellurium or selenium. Similarly, the USGS noted that, for lithium, recycling is "insignificant, but increasing through the recycling of lithium batteries." Platinum Group Elements (PGEs) are routinely recycled from catalysts used in automobiles. However, the USGS estimated that only 17 MT of PGEs were recovered from scrap in 2009, compared with 195 MT of imports and 16 MT of domestic production from primary sources.

Recycling terminology

Recycling includes both preconsumer and postconsumer reuse. Preconsumer recycling is largely of *new scrap*—material produced during the manufacture of products made from the metal or other mineral commodity. Postconsumer recycling is largely of *old scrap*—discarded products. Ideally, products should be recycled such that the recovered material retains its functionality for a particular use. This is known as *functional recycling,* by which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use. This contrasts with *nonfunctional recycling,* by which the material is incorporated into a recycling stream as an impurity, and its individual characteristics are lost.

Terbium (Tb) — Failure to recycle

Tb (atomic number 65, 0.00012% of Earth's crust) is one of the heavy REEs. Tb is used (to provide the green phosphors) with europium (blue and red) in "trichromatic," or color balanced fluorescent lighting. Although minute quantities are used in each fluorescent bulb, the world's annual production of Tb is less than 0.5 MT, and Tb is in chronic undersupply. The price of Tb imported from China was nearly $800/kg in December 2010. When fluorescent lights are "recycled," the metal ends are removed and recycled, and the glass is also reused. The phosphor powder on the inside surface of the glass contains mercury, terbium, and other rare metals. Because mercury is toxic, current practice is to mix the powder into an aggregate compounded with concrete and sequester the concrete from the environment, thereby making the Tb unavailable for recycling.

Policies have been proposed or implemented in other countries to improve the level of recycling and mineral efficiency. For example, Directive 2002/96/EC of the European Parliament and the Council of the European Union calls for recycling of waste electrical and electronic equipment (WEEE). This includes encouraging "the design and production of electrical and electronic equipment which take into account and facilitate dismantling and recovery," minimizing the disposal of WEEE as unsorted municipal waste, using best available techniques for treatment, recovery, and recycling, labeling WEEE so that it is more easily sorted from other waste, and informing consumers about their obligations to recycle (WEEE, 2003). The European Union has also restricted the use of certain hazardous substances in electrical and electronic equipment. The government of South Korea, a country that is resource poor, is encouraging "urban mining," the recovery of critical elements from municipal waste (Bae, 2010).

Other proposals to improve mineral efficiency include "take-back laws" that require manufacturers or suppliers of products containing critical elements to accept their return for subsequent recycling, requiring deposits on products that should be recycled providing incentives for renting high-tech equipment that would be recycled upon return, and consumer-product labeling and ratings that encourage recycling.

- Recommendation: The federal government should establish a consumer-oriented "Critical Materials" designation for ECE-related products. The certification requirements should include the choice of materials that minimize concerns related to scarcity and toxicity, the ease of disassembly, the availability of appropriate recycling technology, and the potential for functional, as opposed to nonfunctional, recycling.

- Recommendation: Steps should be taken to improve rates of postconsumer collection of industrial and consumer products containing ECEs, beginning with an examination of the numerous methods explored and implemented in various states and countries.

E. Possible market interventions

The recommendations within the previous section call for actions that fall within accepted roles for government: statistical information gathering, support for research and workforce development, and incentives for activities, such as recycling. The Committee is hesitant to propose more direct government interventions in markets for ECEs. Rather, the Committee believes that industrial users of ECEs are best able to evaluate the supply risks they face and purchase their own "insurance" against supply disruptions (both physical unavailability and price fluctuations). This insurance may include private stockpiles of ECEs or other actions, such as long-term contracts with ECE suppliers. The Committee believes that free trade in mineral commodities works to the benefit of all parties. Existing loan-guarantee programs in various agencies can provide support for some aspects of new efforts in many ECE technologies.

Some governments maintain stockpiles of critical minerals—some for military needs, others for economic reasons on behalf of industrial ECE users. Several highly industrialized countries that are heavily dependent on imports of ECEs have recently begun high-level efforts to secure dependable supplies for the future. For example, Korea is in the process of stockpiling twenty-one elements to cover 60 days of domestic demand by its industries (Bae, 2010). Japan stockpiles seven rare elements to cover 42 days of domestic consumption, complementing private stocks of the same elements in the amount of 18 days of consumption. The United States has managed a stockpile of critical materials for national security needs since World War II. In 2008, the National Research Council released a report with major recommendations regarding the National Defense Stockpile (NRC, 2008-2).

The Committee notes that such government stockpiles can have unintended, disruptive effects on markets and can act as disincentives to innovation. Hence, with only one exception, helium, the committee does not recommend that the United States establish nondefense ECE stockpiles. (The Committee did not consider stockpiles for essential military applications, as supply risk for military needs is outside the scope of this study.)

The United States does maintain a stockpile of helium. Helium has several unique physical properties (see the sidebar titled *Helium—unique even among ECEs*), any one of which may render it critical for future technology, energy related or otherwise. More important, three facts make helium unique among the chemical elements: (1) Helium is found in economically viable quantities only in natural gas reservoirs, occuring at levels as high as 7%. In contrast, helium is only 5.2 parts per million by volume in the atmosphere, making recovery from air extremely expensive. It is unlikely that other economically viable sources of helium will ever be discovered. (2) When natural gas is extracted, unless it is recovered, the helium is vented to the atmosphere, from which it would be extremely expensive to recover. (3) Natural gas is extracted from reservoirs at a rapidly increasing rate. At the present time, much of the natural-gas-associated part of Earth's endowment of helium is being rapidly depleted. Other rare elements that occur in trace concentrations in other common ores are left behind in mine tailings to which future generations could, if necessary, return. Helium, unique in this regard, escapes. In 1995, Congress decided to sell the U.S. helium reserve. The Committee recommends that this decision be reversed and that the United States and other nations develop a long-term strategy for establishing and maintaining a significant helium reserve.

- Recommendation: With the exception of helium (see subsequent recommendation), the Committee does not propose government interventions in markets beyond those contained in the other recommendations concerning research and development, information gathering and analysis, and recycling. In particular, the Committee does not recommend nondefense-related economic stockpiles.

- Recommendation: Helium is unique, even among ECEs. The Committee concurs with and reiterates the APS Helium Statement of 1995[6] : "[M]easures [should] be adopted that will both conserve and enhance the nation's helium reserves. Failure to do so would not only be wasteful, but would also be economically and technologically shortsighted."

Helium—Unique even among ECEs

He (atomic number 2, 0.0000008 % of Earth's crust) has a set of unique properties that make it special, even among ECEs. Helium liquefies at the lowest temperature of all elements and does not solidify, even at absolute zero temperature, making it indispensible for *cryogenic* applications. A noble gas, He is also the least chemically active element. Less well known, He alone, among all elements, cannot be rendered radioactive by exposure to radiation. Finally, He has the highest specific heat capacity of any gaseous element, except hydrogen. Its excellent thermal properties, combined with its chemical and nuclear inertness, make it the fluid of choice for advanced nuclear reactor design. With such unique properties, He has already found use in unusual applications, and the breadth of its future utility is impossible to anticipate.

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[6] The full text of the APS 1995 statement on Conservation of Helium reads as follows:

"The American Physical Society is profoundly concerned about the potential loss of the nation's accumulated helium reserves. Helium is essential for achieving the extremely cold temperatures required by many current and emerging technologies as well as for advanced scientific research. The overall demand for helium has been steadily increasing, and there is every reason to believe that this trend will continue.

"Although the United States is fortunate in having a greater abundance of this critical element than any other nation, the supply has severe natural limits. Helium is obtained by extraction from natural gas. If not extracted, the helium is irretrievably lost to the atmosphere when the gas is burned. For this reason, the federal government prudently established a storage program for helium, but legislation now being considered would dispose of virtually this entire helium store within two decades.

"In view of the importance of this unique and irreplaceable natural resource to modern science and technology, The American Physical Society urges that measures be adopted that will both conserve and enhance the nation's helium reserves. Failure to do so would not only be wasteful, but would be economically and technologically shortsighted."

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APPENDIX A. REFERENCES

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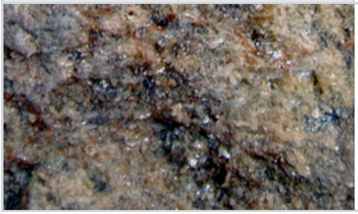
1 H Hydrogen 1.00794								
3 **Li** Lithium 6.941	4 Be Beryllium 9.012182							
11 Na Sodium 22.989770	12 Mg Magnesium 24.3050							
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 **Sc** Scandium 44.955910	♻			25 Mn Manganese 54.938049	26 Fe Iron 55.845	27 **Co** Cobalt 58.933200
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 **Y** Yttrium 88.90585				43 Tc Technetium (98)	44 **Ru** Ruthenium 101.07	45 **Rh** Rhodium 102.90550
55 Cs Cesium 132.90545	56 Ba Barium 137.327	57 **La** Lanthanum 138.9055				75 **Re** Rhenium 186.207	76 **Os** Osmium 190.23	77 **Ir** Iridium 192.217
		58 **Ce** Cerium 140.116	59 **Pr** Praseodymium 140.90765	60 **Nd** Neodymium 144.24	61 Pm Promethium (145)	62 **Sm** Samarium 150.36	63 **Eu** Europium 151.964	64 **Gd** Gadolinium 157.25

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