# Criticality of Seven Specialty Metals

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This is the accepted version of the following article: Panousi, S., E.M. Harper, P. Nuss, M.J. Eckelman, A. Hakimian, and T.E. Graedel. 2016. Criticality of Seven Specialty Metals. Journal of Industrial Ecology 20(4): 837–853., which has been published in final form at http://onlinelibrary.wiley.com/doi/10.1111/jiec.12295/abstract

Please cite as:
Panousi, S., E.M. Harper, P. Nuss, M.J. Eckelman, A. Hakimian, and T.E. Graedel. 2016. Criticality of Seven Specialty Metals. Journal of Industrial Ecology 20(4): 837–853.

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## <heading level 1> Summary

Evaluating metal criticality is a topic that addresses future metals supply and that has inspired research in corporations, academic institutions, and governments. In this article, we apply a comprehensive criticality methodology to seven specialty metals – scandium (Sc), strontium (Sr), antimony (Sb), barium (Ba), mercury (Hg), thallium (Tl), and bismuth (Bi) – at the national and global levels for 2008. The results are presented along with uncertainty

estimates in a three-dimensional "criticality space" comprised of supply risk (SR), vulnerability to supply restriction (VSR), and environmental implications (EI) axes. The SR score is the highest for antimony over the medium term (i.e., five to ten years), followed very closely by bismuth and thallium; for the long term (i.e., a few decades), the highest SR is for thallium, followed very closely by antimony. Strontium and barium, followed very closely by mercury, have the lowest SR over the medium term, and mercury has the lowest SR over the long term. Mercury has the highest EI score. For VSR, thallium is the most vulnerable at both the national level (for the United States) and global level, followed by strontium at both levels. In general, specialty metals are found to possess a unique mix of sparse data, toxicity concerns (in some cases), and inadequate or nonexistent substitutes for a number of specialized uses, a situation that would seem to demand increased effort in acquiring the information needed to characterize specialty metal criticality with more rigor and transparency than is now possible.

# <heading level 1> Introduction

The criticality of metals – the quality, state, or degree of being of the highest importance – is a subject in rapid evolution. A number of studies in recent years have purported to evaluate metal criticality (e.g., (NRC 2008; Morley and Eatherley 2008; EC 2010, 2014; BGS 2012; USDOE 2010). The methodologies differ radically in these studies, and (Morley and Eatherley 2008) and (BGS 2012) list metals in order on the basis of their analyses but do not distinguish between "critical" and "not critical". As has been shown in (Erdmann and Graedel 2011), results differ among the studies.

The criticality work at Yale University began with developing a comprehensive methodology to evaluate criticality on corporate, national, and global levels, described in detail in (Graedel and colleagues 2012). Most of the metals of the periodic table can be grouped naturally, either by geological similarities (as with the rare earth elements) or by functional similarities (the superalloy metals), and our methodology was subsequently applied to all metals in groupings. Studies have been completed that evaluate the results for the geological copper family (Nassar and colleagues 2012); the zinc, tin, lead geological grouping (Harper and colleagues 2014b); iron and its alloying elements (Nuss and colleagues 2014); the rare earth elements (Nassar and colleagues 2014); and nuclear energy metals (Harper and colleagues 2014a). Other studies are in the works for the platinum group metals, the light metals, and the superalloy metals.

Here, we address the seven metals not included in our other studies that are essentially individualistic and cannot be grouped in our traditional way by geological or functional similarities: scandium (Sc), strontium (Sr), antimony (Sb), barium (Ba), mercury (Hg), thallium (Tl), and bismuth (Bi). These metals are listed here and discussed throughout the paper in order of increasing atomic number. Many of these metals tend to be used in relatively small quantities (e.g., thallium) in quite specialized applications (see table 1). We discuss them briefly below.

*Scandium*. Scandium is primarily used in aerospace and military vehicles as an alloying element to provide strength and weldability (Ahmad 2003; Hunn 2006). Other scandium uses include the high-intensity metal halide lamps and sports equipment (e.g., baseball and softball bats, and bicycle frames) (USGS 2009; Simpson 2003; Easton Technology Report 2013). In 2008, scandium was produced in China, Kazakhstan, Russia and Ukraine (USGS 2009). Scandium is not recycled at end-of-life (Graedel and colleagues 2011).

*Strontium*. Strontium is mined as celestite ($SrSO_4$), with China and Spain as the major source countries. Its uses are varied, and the major uses are in cathode ray tube televisions, pyrotechnics, and ceramic magnets. It is thought not to be recycled at end-of-life (Graedel and colleagues 2011).

*Antimony*. Stibnite is the principal source of mined antimony and the antimony bearing deposits contain significant concentrations of metals like copper, lead, silver, bismuth, selenium, arsenic, and mercury (Schwarz-Schampera 2014). Its major uses are as an accumulator (grid) in lead-acid batteries and as a flame retardant in plastics, with smaller employment in ceramics and glass and chemicals (Roskill 2012). The use of antimony in flame retardants is expected to remain its principal market in the future (Schwarz-Schampera 2014). Lead-acid batteries are efficiently recycled, and antimony's end-of-life recycling rate across uses is estimated at 10 to 25% (Graedel and colleagues 2011).

*Barium*. Barium is mined as the mineral barite (barium sulfate). Nearly all of the barium employed in modern technology is used in the form of barium sulfate in drilling muds, an application in which barium sees no recycling (Graedel and colleagues 2011).

*Mercury*. Mercury occurs as the mineral cinnabar (mercuric sulfide) and is mined for itself. The only metal that is a liquid at room temperature, it was once widely employed, but because of its toxicity many of its uses are being phased out (UNEP 2002) (e.g., in paints and coatings and thermostats). The most significant uses at present are as an intermediate in chlor-alkali plants, as a catalyst in vinyl chloride manufacture, and to form amalgams in gold mining. Mercury is also used in lighting applications and in dental amalgams. Many of its uses see at least some degree of recycling (Maxson 2006); much of this recovery is mandated and, in some cases, tightly controlled and regulated.

*Thallium*. Thallium is a trace constituent of lead/zinc ores. It sees specialized use in a variety of electronics applications involving radiation detection, medical imaging, and communications. It is not currently recycled at end-of-life (Graedel and colleagues 2011).

*Bismuth*. Bismuth is a trace constituent of lead ores, with many uses. Roughly equal amounts go into free-machining alloys, pharmaceuticals, and safety fuses and solders. Rates of end-of-life recycling are negligible (Graedel and colleagues 2011).

No previous criticality studies that divided elements into "critical" or "not critical" have evaluated any of these seven elements except for (EC 2014), which rated scandium "not critical" and did not evaluate any of the other six elements in the present study. In the present work, we apply a previously developed methodology of our own to study the criticality of the seven specialty metals. The methodology is briefly described below, particularly the sources of the data that we used. Results are then presented in both tabular and graphical form, and we discuss the degree of criticality of each specialty metal and what indicators contribute to our evaluations. It is important to note that publicly available data were sparse for some of the metals in this group (e.g., scandium and thallium and, to a slightly lesser degree, antimony and bismuth). As such, we relied in a number of cases upon informed estimates garnered from industry experts, which we note as such wherever relevant. Determining the criticality evaluations for this diverse group of metals was an important exercise in developing assessments for less well characterized metals that have important and diverse uses.

**<heading level 1>Methodology**

Criticality is not simply dependent on the balance between the supply and demand of a metal. Rather, it depends on a number of different factors, some quantitative, some more subjective, and its evaluation is important in many ways, including product design, resource planning, and material selection/composition. They involve geology, regulation, geopolitics, material science, international trade, and many more. Our approach to this challenge is to evaluate metals in three-dimensional "criticality space", one axis of which is termed Supply Risk (SR), the second Environmental Implications (EI), and the third Vulnerability to Supply Restriction (VSR). Each of these components is in turn comprised of several indicators, as shown in Figure 1. The indicators and their quantification are discussed in detail in previous publications (Graedel and colleagues 2012), with modifications of the methodology addressed in (Harper and colleagues 2014b). All indicators are transformed to a 0 to 100 scale, and weighted equally. A list of acronyms and abbreviations for the components and indicators is provided as an appendix to this manuscript.

Important considerations in criticality analysis include the major uses of each of the metals, the distribution of total metal use among those major uses, the degree to which substitutes exist in the event of supply restriction, and historical and current recycling rates. To investigate substitution in more detail, we examine each major use from the perspective of the best-performing (or primary) substitute, how well that substitute performs, and whether substitution would result in a change in environmental impacts or import dependence. Through quantitative consideration of these factors, we define the “substitutability” for each element, that is, the evaluation of the degree to which material substitution in a metal’s major uses is likely to be relatively successful. Table 1 lists the complete table of potential substitutes for the major uses of the seven specialty metals. Details of the analysis are discussed in (Graedel and colleagues 2013).

Throughout this work the selection of data year is 2008 (and nearby years if no 2008 data were available). Data availability at the start of the project dictated this selection, but neither the supply nor demand of the seven specialty metals have changed dramatically over the past several years, nor have there been significant end use revisions. We are now gathering information to update the data set to 2012; the preliminary result is that little change to the data set is indicated.

A strength of the methodology is that it can be implemented at varying organizational levels (e.g., national and global) to assess criticality from different perspectives. We present our methodology in a transparent manner in order to give each end user the option to change the weightings assigned to the indicators and/or components. We quantify the uncertainty in the results, and we utilize “uncertainty clouds” to provide visual representation of the uncertainties in our analyses.

## <heading level 2> Supply Risk for the Specialty Metals

SR is evaluated by considering three components, described in (Graedel and colleagues 2012): a geological, technological, and economic considerations component, a social and regulatory issues component, and a geopolitical considerations component. Each is comprised of indicators, many of which are weighted by each metal's production in different countries. The production quantities used for weighting are either the metal's mine or refining production (whichever yields the higher score), except for one of the indicators (i.e., Policy Potential Index (McMahon and Cervantes 2011)), which is a mining consideration and so is only weighted by mine production). For companion (or byproduct) metals, it is often the case that no mine production data are available, and the mine production of the host metal was used as a proxy for production location in those cases. If production values were reported in gross weight rather than elemental concentration (e.g., strontium content), conversion factors were obtained from experts or derived using atomic weight ratios. Each metric in the set of indicators is weighted equally to derive component scores, and components are weighted equally to derive overall SR scores. Each result is transformed to a 0 to 100 SR scale.

Additional details for the specialty metals are described in the supporting information, but a few comments are included here. Our primary data sources for mine and refinery production were the United States Geological Survey (USGS) (USGS 2010) and World Mining Data (WMD) (Weber and colleagues 2011). In cases where data were available from both sources, those from the USGS were utilized. In these cases, it was not uncommon for data to be listed for some countries in WMD statistics, but not in USGS statistics, and these differences are noted in the supporting information.

According to an industry expert, strontium is the only metal of the seven that is a "bachelor metal" (i.e., it is not a companion or host of other metals). In the case of strontium, mine production data were utilized (USGS 2010), with the conversion factor to convert from gross weight to strontium content obtained from an industry expert.

Scandium, antimony, barium, mercury, thallium, and bismuth all have at least some degree of byproduct production, ranging from a few percent to one hundred percent. Scandium is present in small amounts, for example, in ores of aluminum, iron, cobalt, nickel, molybdenum, phosphate, tantalum, tin, titanium, tungsten, uranium, zinc, and zirconium (USGS 2009). Scandium can also be found in low concentrations with rare earth elements (McGill 2000). Because of its low concentration, scandium is obtained exclusively as a byproduct during the processing of various ores, or is recovered from process tailings or residues (USGS 2009; Wang and colleagues 2011), with the exact production shares not reported. In 2008, global production of scandium took place in China, Kazakhstan, Russia, and Ukraine (USGS 2009). Global mine production data in 2003 were estimated at about 2 metric tons per year in the form of scandium oxide (Wang and colleagues 2011), using data from (Deschamps 2003). This estimate is commensurate with data reported elsewhere (Merchant Research & Consulting ltd 2013; Munnoch and Worstall 2006).

Antimony is mined as a principal product or as a byproduct of the smelting of base-metal ores (USGS 2010). In our analysis and based upon information from an industry expert, we assumed 80% of antimony primary production is as a byproduct, with a breakdown of 50% from lead, 20% from silver, 15% from tungsten, 10% from tin, and 5% from gold. Mine production data were used in the analysis (USGS 2010), and refinery production data were not available.

The primary source of mined barium is barite, which sometimes occurs in conjunction with metals like copper, gold, lead, silver, and zinc and with minerals such as fluorite. Barite is rarely recovered as a commercial byproduct (companion) when these metals or minerals are mined. Data regarding the percentage of global production of barite that results from byproduct recovery of barite were unavailable, and an approximate estimate would be one to two percent of the world total (Miller 2013). In our analysis, we used a value of two percent to be conservative. Mine production data were available from the (USGS 2010). The conversion factor to convert to barium content was based upon information provided by an industry expert.

Globally in 2003, 5% of mercury was mined as a companion of gold–silver and sulfide deposits (Rytuba 2003); this value was confirmed as likely being similar for 2008 global production (Rytuba 2003). Mine production statistics for mercury were available and used in our analysis (USGS 2010).

Thallium occurs in sulfidic ores and is usually associated with cadmium, mercury, indium, and germanium (Micke and Wolf 2000). According to an industry expert, all global 2008 production of thallium may be attributed to the processing of lead/zinc ores. Mine and refinery production data were not available. In the case of bismuth, an industry expert indicated that 90% of bismuth primary production is as a byproduct, with an approximate breakdown of 60% from lead, 15% from tungsten, 10% from copper, 10% from tin, and 5% from molybdenum. Both mine and refinery production data were used in the analysis (USGS 2010).

## <heading level 2> Environmental Implications for the Specialty Metals

The EI axis of criticality space illustrates the cradle-to-gate environmental burdens estimated to occur per kilogram of material, as described in (Graedel and colleagues 2012). The indicator consists of impacts to human health and ecosystem damage, as calculated using SimaPro8.0.3 LCA software and the ReCiPe impact assessment method (v1.10 Endpoint H/H global) (Goedkoop and colleagues 2009). Life cycle inventory data for antimony, barite, and mercury were available from the ecoinvent 2.2 database (ecoinvent 2010). The environmental burdens of thallium production were based on the ProBas database (UBA 2010), and bismuth production was estimated from an inventory reported in (Andrae and colleagues 2008); in both cases, the life cycle inventory was entered into SimaPro8.0.3 LCA software and linked to existing unit processes from the ecoinvent 2.2. database (ecoinvent 2010, 2). For scandium and strontium, inventory data were obtained from various sources described in detail in the supporting information, which also provides details regarding how environmental impacts of each substitute were estimated. A comprehensive overview of metals environmental impacts, including the metals discussed in this publication, is also available from (Nuss and Eckelman 2014).

## <heading level 2> Vulnerability to Supply Restriction for the Specialty Metals

VSR is comprised of components that vary according to the organizational level evaluated and that are comprised of indicators described in detail in (Graedel and colleagues 2012). Similar to SR, the evaluation approach for each indicator is independent, with each result transformed to a 0 to 100 scale. Each indicator is weighted equally to yield the component scores, and each component is weighted equally to yield the overall VSR scores. As mentioned earlier in Methodology, determining the major uses of each metal, the primary substitute for each use, and the primary substitute's performance is an important evaluation for determining VSR. Substitute availability is determined by calculating SR for each primary substitute. In cases in which the substitute is a compound whose composition is not easily determined, the element within the compound that has the highest SR score was selected for SA, with the justification that that element would most strongly influence the compound's criticality.

# <heading level 1>Results

In this article we present the criticality assessments for the seven specialty metals for the national and global levels for the year 2008. The results are shown in figure 2 on a 0 to 100 scale.

Figure 2 shows details at the component and indicator level for all three criticality axes: SR, EI, and VSR. The median values for each score are listed in the columns labeled “D”. The columns labeled “U” show the uncertainty range by providing the fifth percentile, the median, and the 95th percentile. These scores are used to calculate the overall supply risk score for the medium time scale of five to ten years ($SR_M$) (which applies to the national level) and the long term ($SR_L$) (which applies to the global level and may generally be thought of as a several decade perspective).

In figure 2a, the $SR_M$ scores are 78 for antimony, 77 for bismuth, and 77 for thallium, and the $SR_L$ scores are 87 for thallium, 86 for antimony, and 70 for bismuth. The $SR_M$ scores are high partly due to the fact that the global supply concentration indicator for all three of these metals is high, indicating concentration of production in only a few countries. The high scores are also due to the fact that the depletion time indicators and companion fraction indicators for these metals are high. In the long-term, the SR score is reduced to two indicators, the depletion time and the companion fraction. As noted when discussing the $SR_M$ scores, in the cases of antimony, thallium, and bismuth the companion fraction is high due to the fact that most or all production for these metals occurs as a companion (or byproduct). Additionally, for all three metals the depletion time score for the long term is high, reflecting modest reserve base values compared to the amounts entering use. Little or no end-of-life recycling exists that would offset primary demand for these metals.

The lowest $SR_M$ scores are 62 for strontium and barium, and 64 for mercury. Both barium and mercury have very low companion fraction scores, as they are mainly mined in operations in which they are the primary products. Strontium is not mined as a companion at all, so has a companion fraction score of zero. The depletion time score for the medium term for all three of these metals is high, but is offset by the low companion fraction scores. The social and regulatory component is moderate for all three metals. Mercury and barium have the lowest $SR_L$ scores at 5 and 17, respectively. Again, in the long-term the SR score is reduced to two indicators, the depletion time and the companion fraction. The depletion time for both mercury and barium is low, indicating an adequate reserve base when compared to production for these metals.

The EI scores are displayed in figure 2b. That for mercury is the highest at 62, and is largely governed by potential mercury emissions to air during the roasting of cinnabar and subsequent condensation of the liquid mercury. The emissions are estimated at 0.161 kg per kilogram of metal, as reported in (Althaus and colleagues 2007). However, mercury emissions factors reported by (IPPC 2001) indicate that mercury emissions to air during primary production from cinnabar may be in the range of 0.005 to 0.02 kilogram mercury per kilogram metal. Taking an average emission factor of 0.01 kilogram mercury per kilogram metal reduces the EI score in our criticality axis from 62 to 39, indicating the large sensitivity of the model in regard to mercury emission factors used, which is represented by the large uncertainty range for EI in our analysis. Scandium's environmental burdens are approximated using an estimate of energy consumption during the mining and refining processes (see the supporting information), yielding a score of 49. Strontium with a score of 1 and barium with a score of 0 are found at the low end of the EI axis, mostly due to the fact that both are used in their mineral form and, as such, do not require energy intensive processing into a metallic form. Given the sparse life cycle inventory data situation on many of these metals, the results should be seen as a first indication of the potential cradle-to-gate environmental impacts associated with their production (see (Nuss and Eckelman 2014) for more details).

VSR is assessed at both the national (i.e., United States) and global levels, and scores are presented at the national level in figure 2c and at the global level in figure 2d. At the national level (figure 2c), the scores range from a high of 69 for thallium to 36 for scandium. In the case of thallium, there are no viable substitutes for its uses – this, along with a high score for material assets and a high reliance on imports, yield the relatively high VSR score. Strontium has a relatively similar VSR score of 60, due to the fact that several of its uses (e.g., pyrotechnics and signals) do not have viable substitutes and those that do have substitutes do not have high substitute performance ratings. Like thallium, strontium at the national level also has a high material assets score and a high reliance on imports. The other metals in the specialty metals grouping –antimony, barium, mercury, and bismuth – have VSR scores of 49, 45, 37, and 44, respectively. It is of note that scandium has very low material assets and national economic importance scores, modest substitute scores, and a high import reliance score. Antimony, barium, and bismuth all have high material assets and import reliance scores, and low national economic importance scores. The highest indicator score for mercury is that of net import reliance ratio, indicating that substitutes for mercury's uses have higher import reliance scores than does mercury.

Figure 2d displays the global level, in which the specialty metal VSR scores range from 19 for scandium to 76 for thallium. Similar to the national level, the high score for thallium is attributed to the fact that there are no viable substitutes for its uses. Scandium's low score is due to the fact that its material assets at the global level are very low, and its substitutes overall have good availability.

As shown in table 2, assessment of specialty metals criticality has been quite diverse and the results lack consistency across the different methodologies. Scandium has been regarded as critical by the European Commission and the South Korea studies (EC 2010; Bae 2010). Antimony is considered to be critical by the majority of the studies presented. However, (Bae 2010) assesses the metal as non-critical. The Oakdene Hollins and the British Geological Survey studies consider strontium, barium, and mercury to be at high risk (Morley and Eatherley 2008; BGS 2012). However, barium in the form of barite was assessed as non-critical by the European Commission (Bae 2010) and mercury as having no shortfalls by the Institute for Defense Analyses study (Thomason and colleagues 2010). Bismuth is considered critical by three of the aforementioned studies. More specifically, the British Geological Survey study considers the metal to be at very high risk while the South Korea Study regards the metal as non-critical (BGS 2012; Bae 2010). Thallium was not addressed in any of the studies.

# <heading level 1>Discussion

Figure 3 displays the results of the national and the global level assessments in criticality space, with the cloud around each metal's median score indicating the uncertainty obtained from a Monte Carlo analysis using the @RISK® software package. The figures were produced using R (R Core Team 2003), a language for statistical computing and graphics, and with Scatterplot3d, an R package for Visualizing Multivariate Data (Ligges and Mächler 2003).

At the global level, the criticality clouds for most of these metals are large, reflecting the relatively high uncertainty in a number of our estimates. In the United States case (Figure 3(a)), all the specialty metals are seen to have SR in the 60 to 80 range, indicating rather strong supply risk across this entire group of metals. EI scores show a substantial range, with mercury and scandium being the highest (i.e., of most concern) and barium and strontium being the lowest (i.e., of less concern) (all comparisons are on a per kilogram basis). The United States is fairly vulnerable to supply restrictions for all of these metals, especially thallium. However, scandium and mercury are of less concern.

The global level criticality space diagram (Figure 3(b)) is quite different from that for the United States. The metals on the global diagram are widely dispersed in regard to SR, with antimony and thallium by far the highest and mercury the lowest. EI ratings show a range, with mercury and scandium the highest and barium and strontium the lowest. Except for thallium, vulnerability is moderate to low throughout. Especially, scandium presents the least concern in terms of its vulnerability to supply restriction.

This group of seven specialty metals presents a unique set of challenges to users and to policy makers. Unlike more widely used metals, information is generally sparse as regards to source countries (for some of the metals), annual production, fractional uses of production, recycling rates, and other parameters of interest. As a result, we have been forced to rely on expert judgment rather than published data in a number of cases. As indicated by the moderate extent of the uncertainty clouds in figure 3, however, we nevertheless regard our results as sufficiently precise to be quite useful.

Four of the seven metals have high to relatively high toxicity concerns in some of their chemical forms: mercury (Zahir and colleagues 2005), antimony (Okkenhaug and colleagues 2013), barium (USEPA 1998), and thallium (Peter and Viraraghavan 2005). Product designers generally avoid the use of such materials in their most toxic chemical forms where possible, but some uses of mercury (e.g., specialty lighting) and thallium (i.e., specialized electronics) have no suitable substitutes. No suitable substitutes are available either for scandium in high-intensity lighting or for strontium in pyrotechnics and in phosphorescent pigments. Other seemingly important uses of the specialty metals have substitutes that rank no higher than adequate or poor: scandium in aerospace and defense, strontium in master alloys, antimony in flame retardants, barium as a drilling chemical, and bismuth as a metallurgical additive, among others.

# <heading level 1>Conclusions

Many studies of metal supply, demand, and implications focus on the metals most widely used – copper, zinc, and the like. With modern technology employing almost all the elements, however (e.g., (Greenfield and Graedel 2013), the list of metals addressed in such studies needs to be increasingly comprehensive. We have addressed in the present work several of the most challenging metals in this regard – those used in specialized applications, exchanged largely in private transactions, and with spectra of uses that are challenging to determine. While we cannot claim the highest precision for our results, we believe that they provide a heretofore missing overview of the cycles of the seven specialty metals treated herein.

The information presented in the above paragraphs constitutes something of a quandary for corporations using the specialty metals (or planning to), as well as for resource considerations in general. This group of metals has generally low rates of use, but often in important and sometimes unsubstitutable uses; toxicity is a concern for several of them; and the database for analysis is sparse. As a consequence, corporations and countries cannot have a high degree of confidence in the routine availability of these metals. The situation would seem to call for increased efforts by all interested parties to enhance the publicly available database – particularly in the case of uses of the metals – for the benefit of all concerned.

Unlike the challenges that the specialty metals present to using corporations or countries, the information in this paper may instead provide an incentive for those who mine, process, and recycle those metals. For those that are companion metals (Sc, Sb, Tl, Bi), there is incentive to recover them more extensively from their parent ore bodies. For all seven specialty metals, having shorter-term supply risks in the 60-80 range, enhanced recycling can mitigate the need to pursue virgin resources to at least some degree.

Notwithstanding the obvious supply and vulnerability issues for some of these metals, it is well established that a universal list of “critical” metals cannot be developed. Doing so requires arbitrarily establishing a boundary in criticality space, and supply and demand variability among users is so diverse that the most appropriate action is to recognize that criticality is a matter of degree, not of state (Lloyd and colleagues 2012; Poulton and colleagues 2013). Our view is that the information provided herein enables users of various kinds to decide the appropriate level of concern for themselves. Such actions will constitute the most beneficial and informed use of criticality information.

# <heading level 1>Acknowledgements

We thank A-1 Specialized Services & Supplies, General Electric Company, Renault Group, Volkswagen Group, Grundfos, and Shell Global Solutions for support and input, and the National Science Foundation for support. We are appreciative of extensive efforts in figure preparation by N.T. Nassar, as well as helpful discussions.

## TABLES

Table 1. Specialty metals applications for the planet and for the United States, together with primary substitutes and substitute performance

| Metal | Application | Application Details | Percentage into Application | Primary Substitute | Substitute Performance | Analysis Details | Material Considered for Supply Availability |
|---|---|---|---|---|---|---|---|
| Sc | Aerospace and defense | Primarily used in aerospace and military vehicles (Ahmad 2003; Hunn 2006) as an alloying element with aluminum to provide strength and weldability (Ahmad 2003; Royset 2007) | 50% (informed estimate) (global)<br>4% (United States) (DOD 2013) | aluminum itself, without addition of scandium | adequate | | aluminum |
| | Lighting | Used in high-intensity metal halide lamps (Simpson 2003) | 20% (informed estimate) (global)<br>20% (DOD 2013) (United States) | none | not applicable | | not applicable |
| | Sports equipment | Used primarily in bicycles, baseball bats, golf clubs, and lacrosse sticks (Easton Technology Report 2013) | 20% (informed estimate) (global)<br>70% (DOD 2013) (United States) | titanium itself, without addition of scandium | good | | titanium |
| | Other | Includes metallurgical research, analytical standards, capacitors, and transistors | 10% (informed estimate) (global)<br>6% (DOD 2013) (United States) | not applicable | not applicable | | not applicable |
| Sr | Televisions | Used in faceplate glass for color television cathode-ray tubes (USGS 2007) | 55% (global) | barium (USGS 2009) | adequate | Global values based on estimates for the United States (USGS 2007). Data for | barium |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | uses in the United States were available for 2008, but were not thought to be representative for the globe based upon the fact that 2007 saw the cessation of operations of television faceplate plants in the United States (USGS 2007). Television technology continues to shift to replacing cathode ray tube systems with flat panel display systems. | |
| | Pyrotechnics and signals | Used mainly fireworks and flares | 22% (global)<br>30% (USGS 2009) (United States) | none (USGS 2009; Halford 2008) | not applicable | Global values based on estimates for the United States (USGS 2007). Data for uses in the United States were available for 2008, but were not thought to be representative for the globe based upon the fact that 2007 saw the | not applicable |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | cessation of operations of television faceplate plants in the United States (USGS 2007). Television technology continues to shift to replacing cathode ray tube systems with flat panel display systems. | |
| | Ferrite ceramic magnets | Used mainly in toys, electronics, and windshield wipers | 13% (global)<br>30% (USGS 2009) (United States) | barium (USGS 2009) | adequate | Global values based on estimates for the United States (USGS 2007). Data for uses in the United States were available for 2008, but were not thought to be representative for the globe based upon the fact that 2007 saw the cessation of operations of television faceplate plants in the United States (USGS 2007). Television technology continues to shift to replacing cathode | barium |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | ray tube systems with flat panel display systems. | |
| | Master alloys | Used mainly as an additive to aluminum-silicon alloys | 10% (USGS 2009) (United States) | sodium (Lidman 2013) | adequate | Global values based on estimates for the United States | sodium |
| | Pigments and fillers | Used as an anticorrosive primer for zinc, magnesium, aluminum and in phosphorescent pigments | 10% (USGS 2009) (United States) | none | not applicable | Global values based on estimates for the United States<br>Although barium can substitute for some of the filler applications, the category is too diverse to assign a single substitute | not applicable |
| | Electrolytic production of zinc | Used to produce high purity zinc | 10% (USGS 2009) (United States) | barium (Chow and colleagues 1982) | adequate | Global values based on estimates for the United States | barium |
| | Other | Includes use in toothpaste (West 2007) and fluorescent lamps | 10% (global)<br>10% (USGS 2009) (United States) | not applicable | not applicable | Global values based on estimates for the United States (USGS 2007). Data for uses in the United States were available for 2008, but were not thought to be representative for the globe based upon the fact that 2007 saw the cessation of | not applicable |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | | | operations of television faceplate plants in the United States (USGS 2007). Television technology continues to shift to replacing cathode ray tube systems with flat panel display systems. | |
| Sb | Flame retardants | Includes use in plastics, textiles, rubber, adhesives and plastic covers for aircrafts and automobiles | 51% (Roskill 2012) (global)<br>40% (USGS 2009) (United States) | hydrated aluminum oxide (USGS 2009) | adequate | | alumina |
| | Lead-acid batteries | Used mainly in vehicle batteries | 26% (Roskill 2012) (global)<br>22% (USGS 2009) (United States) | calcium alloy (Drivers Technology 2013) | good | United States statistics lists this category as “transportation, including batteries” | calcium |
| | Ceramics and glass | Used as an additive to glass to remove microscopic bubbles | 4% (Roskill 2012) (global)<br>11% (USGS 2009) (United States) | tin oxide[a] (Renewable Energy Sources 2009) | adequate | | tin |
| | Chemicals | Used mainly as a heat stabilizer and as a catalyst for the production of polyester | 7% (Roskill 2012) (global)<br>14% (USGS 2009) (United States) | titanium (Thiele 2001) | poor | | titanium |
| | Other | Includes ammunition, cable coverings, fireworks, metal castings, paper, pigments, and rubber products | 12% (Roskill 2012) (global)<br>13% (USGS 2009) (United States) | not applicable | not applicable | | not applicable |
| Ba | Oil industry | Used mainly as a weighting agent | 84% (The Barytes | hematite | adequate | Global values are | iron oxide |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | in gas and oil-well drilling fluids | Association 2013) (global)<br>95% (USGS 2009) (United States) | | | for 2008/2009 and, based upon input from an industry expert, we assume that barite represents one hundred percent of barium use | |
| | Other | Includes use as a filler in plastics, paint, and rubber, as well as use in automobile brakes and clutch pads, electronics, ceramics, and medical applications | 16% (The Barytes Association 2013) (global)<br>5% (USGS 2009) (United States) | not applicable | not applicable | Global values are for 2008/2009 and, based upon input from an industry expert, we assume that barite represents one hundred percent of barium use | not applicable |
| Hg | Artisanal and small-scale gold mining | Used for gold extraction | 21% (AMAP/UNEP 2008) (global) | borax (Barber 2012) | adequate | Global values are for 2005, and United States values are for 2002 | boron |
| | Vinyl chloride monomer production | Used as the catalyst in the production of vinyl chloride monomer | 20% (AMAP/UNEP 2008) (global) | precious metal salts[a] (FECO/MEP 2011) | adequate | Global values are for 2005, and United States values are for 2002 | gold |
| | Chlorine-caustic soda manufacturing | Used in the mercury cell process for the production of chlorine and sodium hydroxide | 13% (AMAP/UNEP 2008) (global)<br>63% (United States) (USGS 2013) | membrane cells (USGS 2009) | good | Global values are for 2005, and United States values are for 2002 | 1/3 natural gas, 1/3 crude oil, and 1/3 fluorspar |
| | Dental equipment and supplies | Used mainly in dental amalgams | 10% (AMAP/UNEP 2008) (global)<br>16% (USGS 2013) (United States) | ceramic composites (USGS 2009) | exemplary | Global values are for 2005, and United States values are for 2002 | 75% silicon and 25% fossil fuel (which, in turn, is 2/3 natural gas and 1/3 crude oil (Graedel and colleagues 2012) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Batteries | Used in batteries | 10% (AMAP/UNEP 2008) (global)<br>8% (United States) | lithium ion batteries | exemplary | Global values are for 2005, and United States values are for 2002<br>United States value is an aggregate category of “electrical and electronic instruments” (USGS 2013) and was disaggregated based upon global values (AMAP/UNEP 2008) | lithium |
| | Electrical and electronic devices | Used in wiring devices and switches | 5% (AMAP/UNEP 2008) (global)<br>4% (United States) | gallium indium alloy (Galligan and colleagues 2003) | adequate | Global values are for 2005, and United States values are for 2002<br>United States value is an aggregate category of “electrical and electronic instruments” (USGS 2013) and was disaggregated based upon global values (AMAP/UNEP 2008)<br>Substitute of gallium indium alloy functions as a direct replacement for mercury within switches | 75.5% gallium and 24.5% indium (Cheng and Wu 2012) |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Lighting | Includes usage in fluorescent lamps | 4% (AMAP/UNEP 2008) (global)<br>4% (United States) | none (Matson 2008) | not applicable | Global values are for 2005, and United States values are for 2002<br>United States value is an aggregate category of “electrical and electronic instruments” (USGS 2013) and was disaggregated based upon global values (AMAP/UNEP 2008) | not applicable |
| | Measuring and control devices | Used mainly in thermometers and thermostats | 9% (AMAP/UNEP 2008) (global)<br>5% (USGS 2013) (United States) | galinstan (an alloy of gallium, indium, and tin) (USGS 2009) | exemplary | Global values are for 2005, and United States values are for 2002 | 68.5% gallium, 21.5% indium, and 10% tin (Cheng and Wu 2012) |
| | Other | Includes use in fungicides, chemicals, pigments, and pesticides | 8% (AMAP/UNEP 2008) (global) | not applicable | not applicable | Global values are for 2005, and United States values are for 2002 | not applicable |
| Tl | Electronics | Used in gamma radiation detection equipment, communications equipment, cardiovascular imaging, and in thallium-impregnated glass used as coverings on electronic devices (e.g., semiconductors and capacitors) | 90% (informed estimate) (global and United States) | none | not applicable | Detailed, quantitative end-uses of thallium are not available, making it intractable to select a single primary substitute | not applicable |
| | Other | Includes chemical uses (e.g., synthesis of organic compounds) and in alloys to improve corrosion | 10% (informed estimate) (global | not applicable | not applicable | Detailed, quantitative end-uses of thallium are | not applicable |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | resistance (e.g., in switches) | and United States) | | | not available, making it intractable to select a single primary substitute | |
| Bi | Fusible alloys, solders, and ammunition cartridges | Includes use in solders, wires, safety fuses, and molded products | 35% (Mining Journal Online 2008) (global)<br>24% (USGS 2009) (United States) | lead[a] | good | Global values are for 2006 | lead |
| | Metallurgical additives | Used in automobiles, planes, grip tubes, tools, and punches | 35% (Mining Journal Online 2008) (global)<br>43% (USGS 2009) (United States) | lead[a] (DOD 2013) | adequate | Global values are for 2006 | lead |
| | Pharmaceuticals and chemicals | Includes use in antacids | 28% (Mining Journal Online 2008) (global)<br>31% (USGS 2009) (United States) | magnesium compounds (DOD 2013) | good | Global values are for 2006 | magnesium |
| | Other | For example, used in pigments, dentistry, glass, enameled ceramics, and plastic lenses | 2% (Mining Journal Online 2008) (global)<br>2% (USGS 2009) (United States) | not applicable | not applicable | Global values are for 2006 | not applicable |

[a] In these cases, at least a portion of the metal of focus is mined with the primary substitute; in these instances and in the case of a supply risk, we note that there may be challenges with using the substitute due to the fact that they are at least partially from the same ore body.

Table 2. Criticality designations in selected studies where “-“ designates “not being considered”. This table was modified and adapted from (Erdmann and Graedel 2011).

| Metal | European Commission (EC 2010) | Institute for Defense Analyses Study (Thomason and colleagues 2010) | National Research Council Study (NRC 2008) | Oakdene Hollins Study (Morley and Eatherley 2008) | South Korea Study (Bae 2010) | British Geological Survey (BGS 2012) |
|---|---|---|---|---|---|---|
| Sc | critical | - | - | - | critical | - |
| Sr | - | - | - | insecure | - | high risk |
| Sb | critical | shortfalls | - | insecure | not critical | very high risk |
| Ba | not critical[a] | - | - | insecure[a] | - | high risk |
| Hg | - | no shortfalls | - | insecure | - | high risk |
| Tl | - | - | - | - | - | - |
| Bi | - | shortfalls | - | insecure | not critical | very high risk |

[a] Focused on barite, which is the form of barium most commonly used

## FIGURES

Figure 1. Components comprising each axis and indicators comprising each component, all illustrated in criticality space at the global level from (Graedel and colleagues 2013).

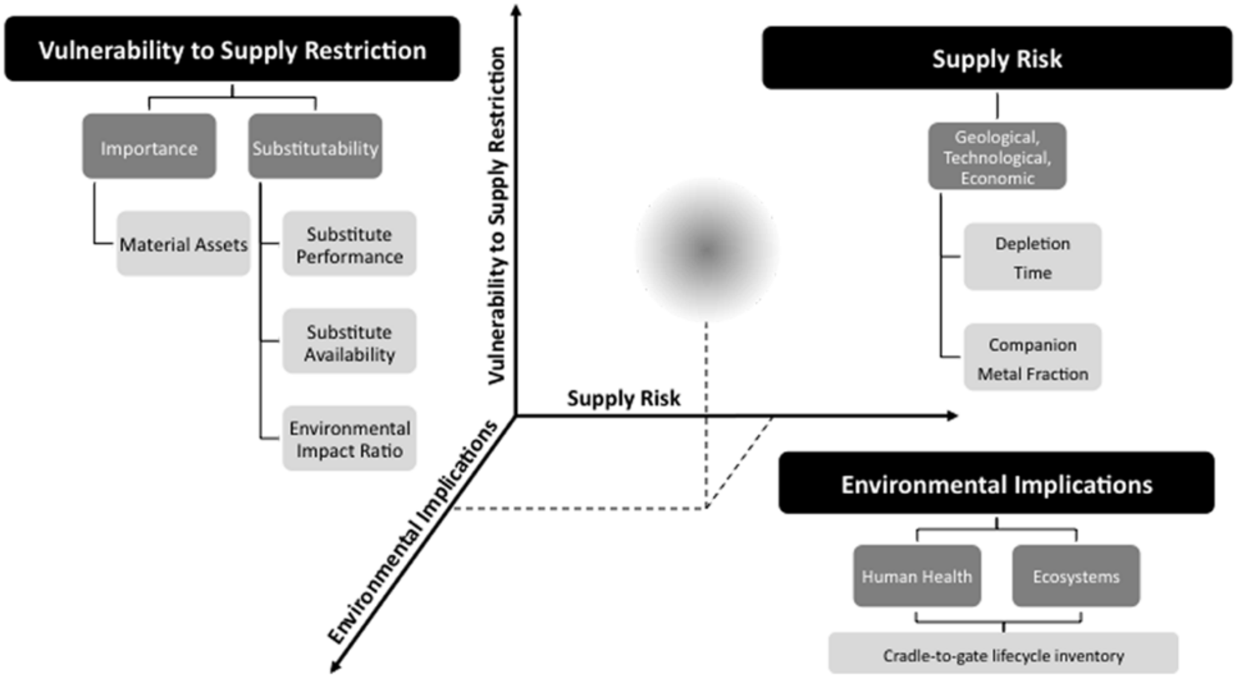


Figure 2. Resulting criticality assessment values for indicators, components, and parameters of the specialty metals, with acronyms and abbreviations defined in the appendix. For each indicator, component, and axis score, four values are provided per metal. Under the column labeled "D", the default value is provided; this value is obtained when all of the stated assumptions are utilized. Under the column labeled "U", three values from the uncertainty analysis are provided: the fifth percentile, the mean, and the 95th percentile in that order, from top to bottom. Note that values reported for all indicators are based on the appropriately weighted and scaled "transformed" scores (see (Graedel and colleagues 2012) for details). More information regarding the assumptions and uncertainty analysis is provided in the supporting information. Note that the $DT_M$ was used to calculate GTE. Values are reported to the nearest whole number and colored according to the following color ramp:

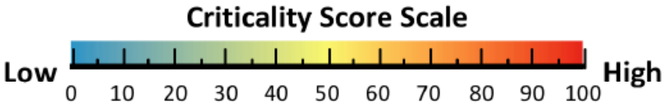
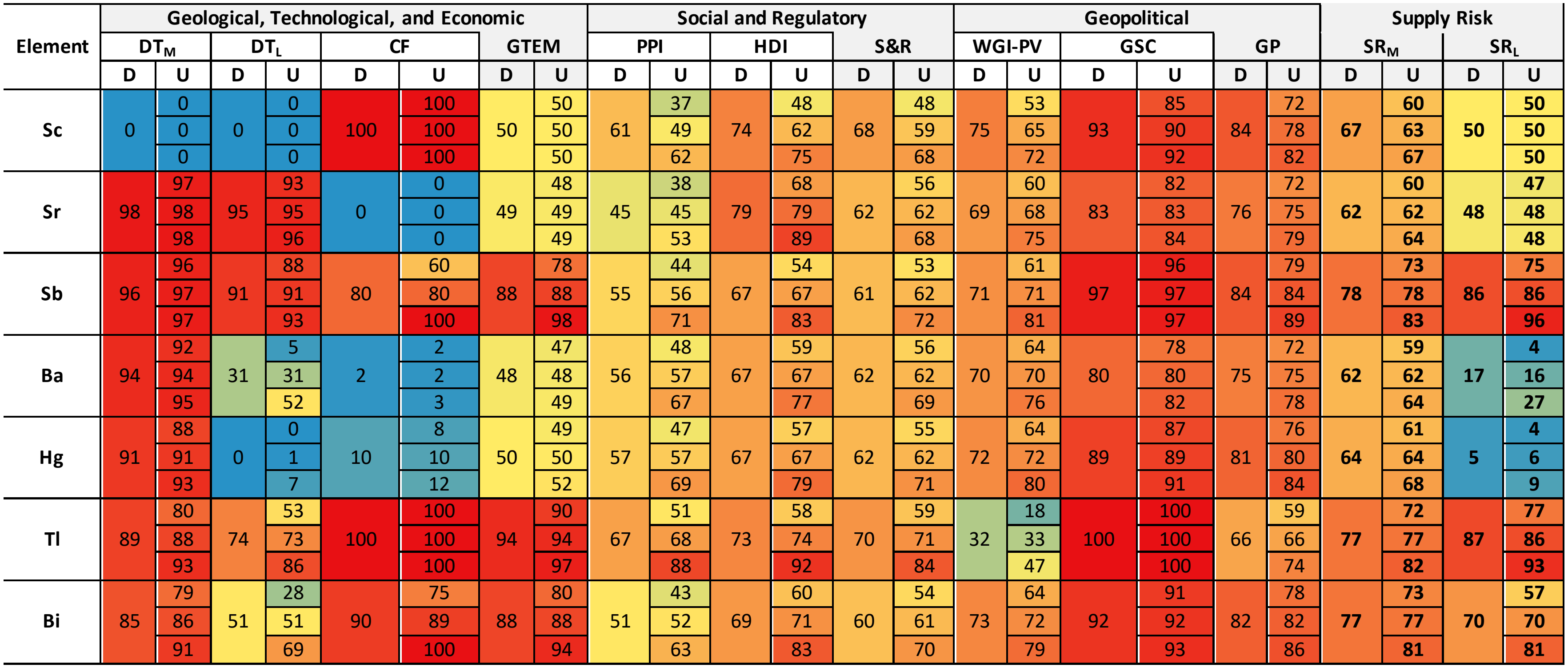


Figure 2a. Supply Risk Scores

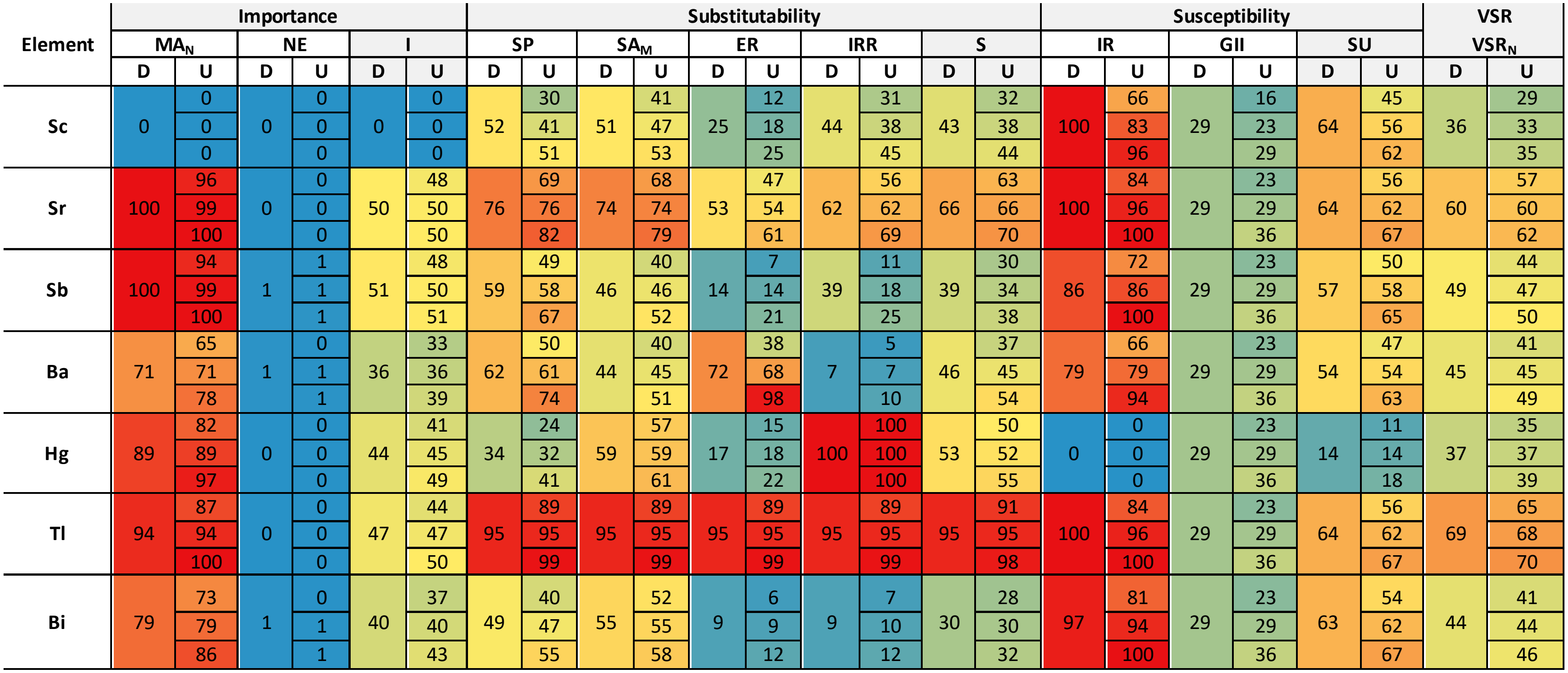


| Element | Geological, Technological, and Economic | | | | | | | | Social and Regulatory | | | | | | Geopolitical | | | | | | Supply Risk | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $DT_M$ | | $DT_L$ | | CF | | GTEM | | PPI | | HDI | | S&R | | WGI-PV | | GSC | | GP | | $SR_M$ | | $SR_L$ | |
| | D | U | D | U | D | U | D | U | D | U | D | U | D | U | D | U | D | U | D | U | D | U | D | U |
| **Sc** | 0 | 0 | 0 | 0 | 100 | 100 | 50 | 50 | 61 | 37 | 74 | 48 | 68 | 48 | 75 | 53 | 93 | 85 | 84 | 72 | **67** | **60** | **50** | **50** |
| | | 0 | | 0 | | 100 | | 50 | | 49 | | 62 | | 59 | | 65 | | 90 | | 78 | | **63** | | **50** |
| | | 0 | | 0 | | 100 | | 50 | | 62 | | 75 | | 68 | | 72 | | 92 | | 82 | | **67** | | **50** |
| **Sr** | 98 | 97 | 95 | 93 | 0 | 0 | 49 | 48 | 45 | 38 | 79 | 68 | 62 | 56 | 69 | 60 | 83 | 82 | 76 | 72 | **62** | **60** | **48** | **47** |
| | | 98 | | 95 | | 0 | | 49 | | 45 | | 79 | | 62 | | 68 | | 83 | | 75 | | **62** | | **48** |
| | | 98 | | 96 | | 0 | | 49 | | 53 | | 89 | | 68 | | 75 | | 84 | | 79 | | **64** | | **48** |
| **Sb** | 96 | 96 | 91 | 88 | 80 | 60 | 88 | 78 | 55 | 44 | 67 | 54 | 61 | 53 | 71 | 61 | 97 | 96 | 84 | 79 | **78** | **73** | **86** | **75** |
| | | 97 | | 91 | | 80 | | 88 | | 56 | | 67 | | 62 | | 71 | | 97 | | 84 | | **78** | | **86** |
| | | 97 | | 93 | | 100 | | 98 | | 71 | | 83 | | 72 | | 81 | | 97 | | 89 | | **83** | | **96** |
| **Ba** | 94 | 92 | 31 | 5 | 2 | 2 | 48 | 47 | 56 | 48 | 67 | 59 | 62 | 56 | 70 | 64 | 80 | 78 | 75 | 72 | **62** | **59** | **17** | **4** |
| | | 94 | | 31 | | 2 | | 48 | | 57 | | 67 | | 62 | | 70 | | 80 | | 75 | | **62** | | **16** |
| | | 95 | | 52 | | 3 | | 49 | | 67 | | 77 | | 69 | | 76 | | 82 | | 78 | | **64** | | **27** |
| **Hg** | 91 | 88 | 0 | 0 | 10 | 8 | 50 | 49 | 57 | 47 | 67 | 57 | 62 | 55 | 72 | 64 | 89 | 87 | 81 | 76 | **64** | **61** | **5** | **4** |
| | | 91 | | 1 | | 10 | | 50 | | 57 | | 67 | | 62 | | 72 | | 89 | | 80 | | **64** | | **6** |
| | | 93 | | 7 | | 12 | | 52 | | 69 | | 79 | | 71 | | 80 | | 91 | | 84 | | **68** | | **9** |
| **Tl** | 89 | 80 | 74 | 53 | 100 | 100 | 94 | 90 | 67 | 51 | 73 | 58 | 70 | 59 | 32 | 18 | 100 | 100 | 66 | 59 | **77** | **72** | **87** | **77** |
| | | 88 | | 73 | | 100 | | 94 | | 68 | | 74 | | 71 | | 33 | | 100 | | 66 | | **77** | | **86** |
| | | 93 | | 86 | | 100 | | 97 | | 88 | | 92 | | 84 | | 47 | | 100 | | 74 | | **82** | | **93** |
| **Bi** | 85 | 79 | 51 | 28 | 90 | 75 | 88 | 80 | 51 | 43 | 69 | 60 | 60 | 54 | 73 | 64 | 92 | 91 | 82 | 78 | **77** | **73** | **70** | **57** |
| | | 86 | | 51 | | 89 | | 88 | | 52 | | 71 | | 61 | | 72 | | 92 | | 82 | | **77** | | **70** |
| | | 91 | | 69 | | 100 | | 94 | | 63 | | 83 | | 70 | | 79 | | 93 | | 86 | | **81** | | **81** |

Figure 2b. Environmental Implications Scores

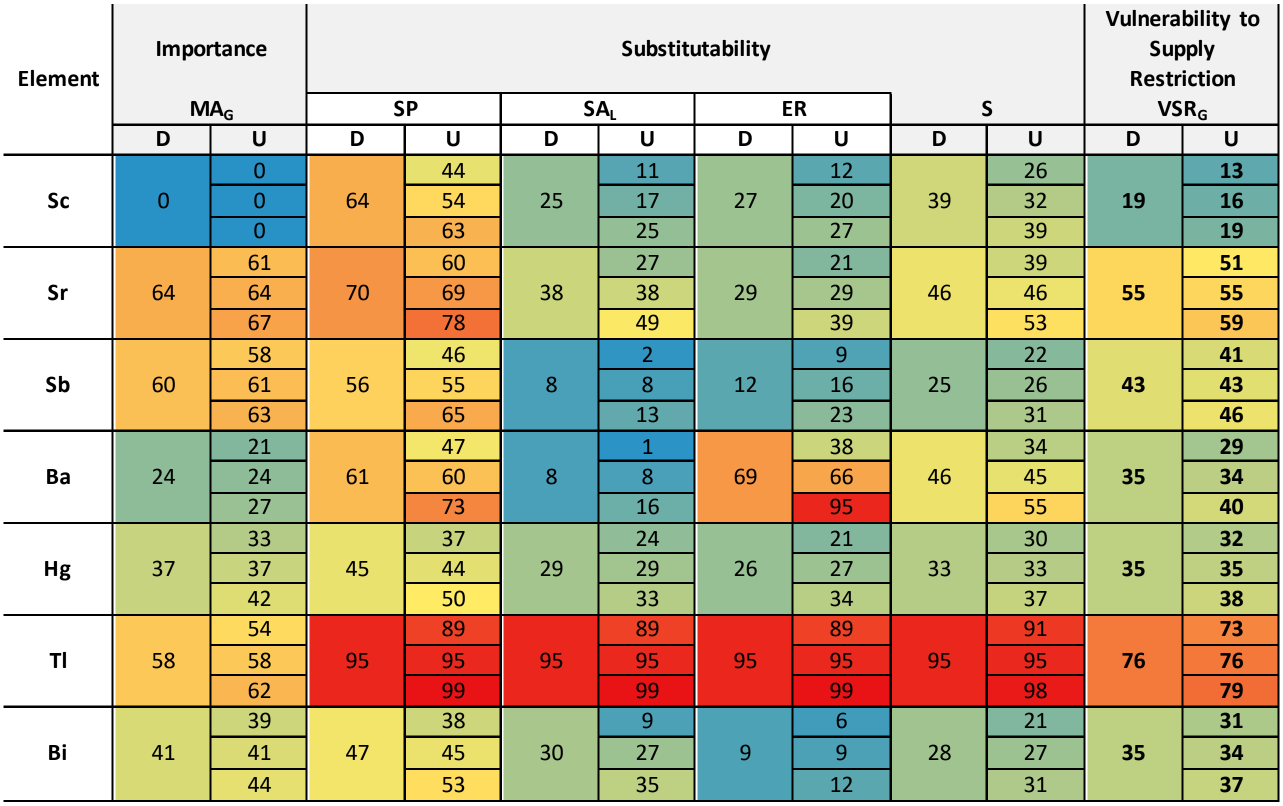
| Element | Human Health (supply source-weighted average points) | Ecosystems (supply source-weighted average points) | EI | |
|---|---|---|---|---|
| | | | D | U |
| **Sc** | 260 | 21.0 | **49** | **46** |
| | | | | **48** |
| | | | | **50** |
| **Sr** | 0.2 | 0.02 | **1** | **1** |
| | | | | **2** |
| | | | | **2** |
| **Sb** | 8.0 | 0.1 | **19** | **13** |
| | | | | **19** |
| | | | | **26** |
| **Ba** | 0.01 | 0.001 | **0** | **0** |
| | | | | **0** |
| | | | | **0** |
| **Hg** | 1300 | 1.1 | **62** | **47** |
| | | | | **59** |
| | | | | **71** |
| **Tl** | 22.0 | 1.4 | **28** | **27** |
| | | | | **28** |
| | | | | **29** |
| **Bi** | 2.7 | 0.2 | **12** | **11** |
| | | | | **13** |
| | | | | **14** |

Figure 2c. Vulnerability to Supply Restriction – National (United States)



| Element | Importance | | | | | | Substitutability | | | | | | | | | | Susceptibility | | | | | | VSR | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $MA_N$ | | NE | | I | | SP | | $SA_M$ | | ER | | IRR | | S | | IR | | GII | | SU | | $VSR_N$ | |
| | D | U | D | U | D | U | D | U | D | U | D | U | D | U | D | U | D | U | D | U | D | U | D | U |
| **Sc** | 0 | 0 | 0 | 0 | 0 | 0 | 52 | 30 | 51 | 41 | 25 | 12 | 44 | 31 | 43 | 32 | 100 | 66 | 29 | 16 | 64 | 45 | 36 | 29 |
| | | 0 | | 0 | | 0 | | 41 | | 47 | | 18 | | 38 | | 38 | | 83 | | 23 | | 56 | | 33 |
| | | 0 | | 0 | | 0 | | 51 | | 53 | | 25 | | 45 | | 44 | | 96 | | 29 | | 62 | | 35 |
| **Sr** | 100 | 96 | 0 | 0 | 50 | 48 | 76 | 69 | 74 | 68 | 53 | 47 | 62 | 56 | 66 | 63 | 100 | 84 | 29 | 23 | 64 | 56 | 60 | 57 |
| | | 99 | | 0 | | 50 | | 76 | | 74 | | 54 | | 62 | | 66 | | 96 | | 29 | | 62 | | 60 |
| | | 100 | | 0 | | 50 | | 82 | | 79 | | 61 | | 69 | | 70 | | 100 | | 36 | | 67 | | 62 |
| **Sb** | 100 | 94 | 1 | 1 | 51 | 48 | 59 | 49 | 46 | 40 | 14 | 7 | 39 | 11 | 39 | 30 | 86 | 72 | 29 | 23 | 57 | 50 | 49 | 44 |
| | | 99 | | 1 | | 50 | | 58 | | 46 | | 14 | | 18 | | 34 | | 86 | | 29 | | 58 | | 47 |
| | | 100 | | 1 | | 51 | | 67 | | 52 | | 21 | | 25 | | 38 | | 100 | | 36 | | 65 | | 50 |
| **Ba** | 71 | 65 | 1 | 0 | 36 | 33 | 62 | 50 | 44 | 40 | 72 | 38 | 7 | 5 | 46 | 37 | 79 | 66 | 29 | 23 | 54 | 47 | 45 | 41 |
| | | 71 | | 1 | | 36 | | 61 | | 45 | | 68 | | 7 | | 45 | | 79 | | 29 | | 54 | | 45 |
| | | 78 | | 1 | | 39 | | 74 | | 51 | | 98 | | 10 | | 54 | | 94 | | 36 | | 63 | | 49 |
| **Hg** | 89 | 82 | 0 | 0 | 44 | 41 | 34 | 24 | 59 | 57 | 17 | 15 | 100 | 100 | 53 | 50 | 0 | 0 | 29 | 23 | 14 | 11 | 37 | 35 |
| | | 89 | | 0 | | 45 | | 32 | | 59 | | 18 | | 100 | | 52 | | 0 | | 29 | | 14 | | 37 |
| | | 97 | | 0 | | 49 | | 41 | | 61 | | 22 | | 100 | | 55 | | 0 | | 36 | | 18 | | 39 |
| **Tl** | 94 | 87 | 0 | 0 | 47 | 44 | 95 | 89 | 95 | 89 | 95 | 89 | 95 | 89 | 95 | 91 | 100 | 84 | 29 | 23 | 64 | 56 | 69 | 65 |
| | | 94 | | 0 | | 47 | | 95 | | 95 | | 95 | | 95 | | 95 | | 96 | | 29 | | 62 | | 68 |
| | | 100 | | 0 | | 50 | | 99 | | 99 | | 99 | | 99 | | 98 | | 100 | | 36 | | 67 | | 70 |
| **Bi** | 79 | 73 | 1 | 0 | 40 | 37 | 49 | 40 | 55 | 52 | 9 | 6 | 9 | 7 | 30 | 28 | 97 | 81 | 29 | 23 | 63 | 54 | 44 | 41 |
| | | 79 | | 1 | | 40 | | 47 | | 55 | | 9 | | 10 | | 30 | | 94 | | 29 | | 62 | | 44 |
| | | 86 | | 1 | | 43 | | 55 | | 58 | | 12 | | 12 | | 32 | | 100 | | 36 | | 67 | | 46 |

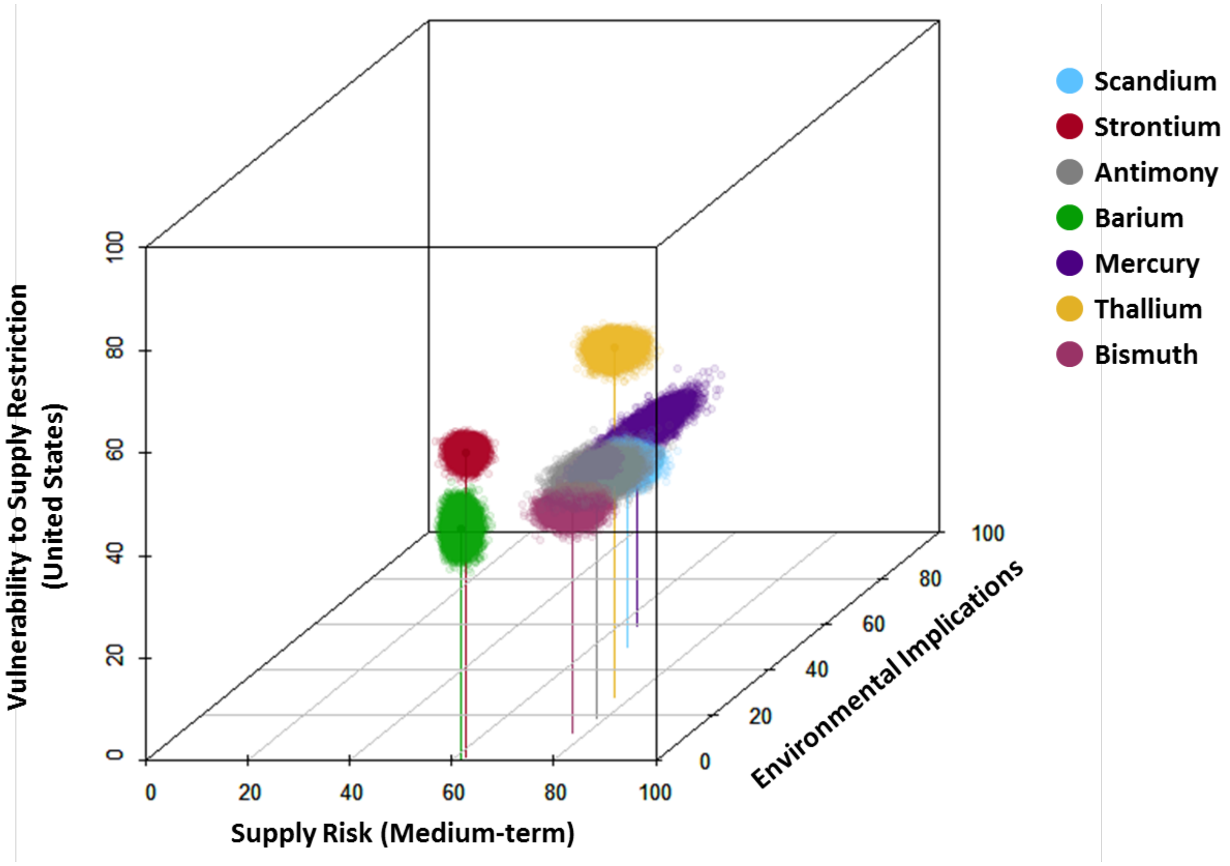
Figure 2d. Vulnerability to Supply Restriction – Global



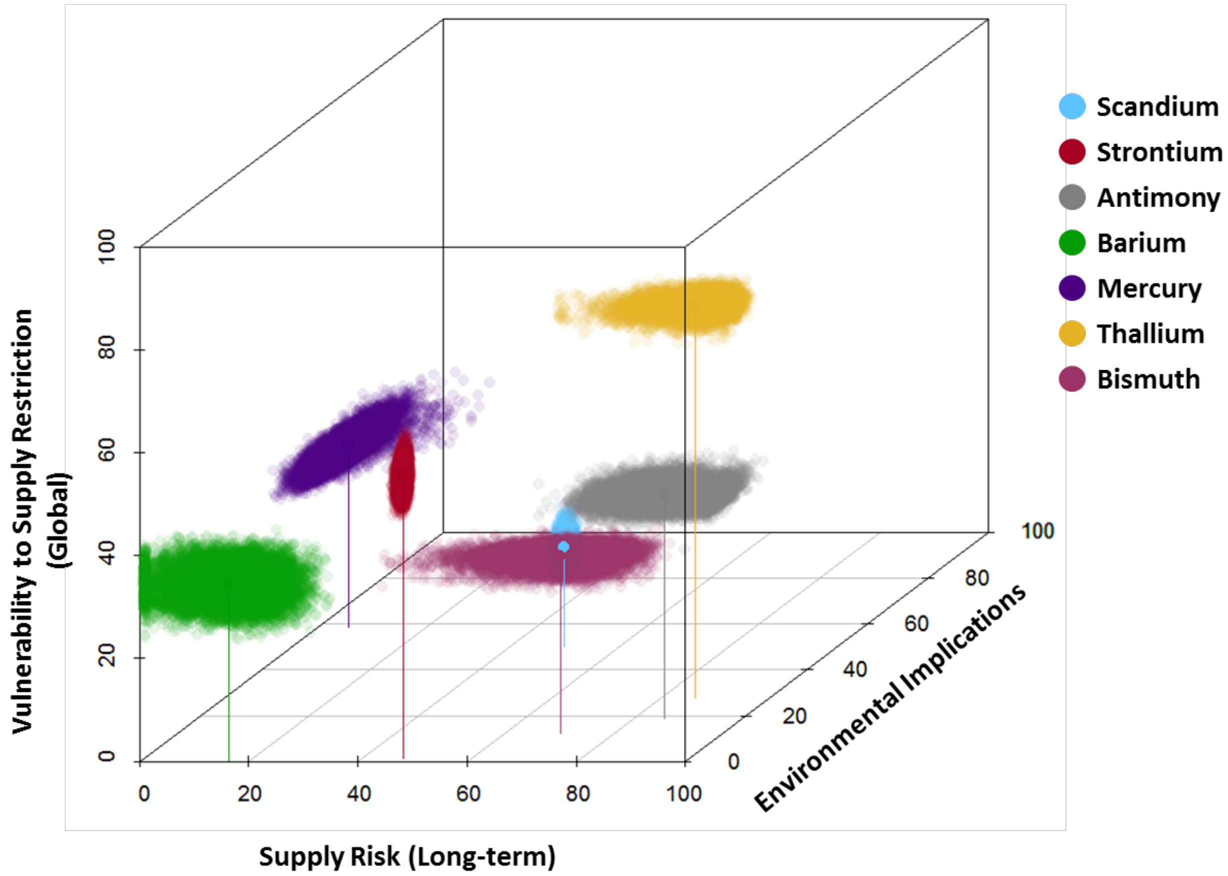
| **Element** | **Importance** | | **Substitutability** | | | | | | | | **Vulnerability to Supply Restriction** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **$MA_G$** | | **SP** | | **$SA_L$** | | **ER** | | **S** | | **$VSR_G$** | |
| | **D** | **U** | **D** | **U** | **D** | **U** | **D** | **U** | **D** | **U** | **D** | **U** |
| **Sc** | 0 | 0 | 64 | 44 | 25 | 11 | 27 | 12 | 39 | 26 | **19** | **13** |
| | | 0 | | 54 | | 17 | | 20 | | 32 | | **16** |
| | | 0 | | 63 | | 25 | | 27 | | 39 | | **19** |
| **Sr** | 64 | 61 | 70 | 60 | 38 | 27 | 29 | 21 | 46 | 39 | **55** | **51** |
| | | 64 | | 69 | | 38 | | 29 | | 46 | | **55** |
| | | 67 | | 78 | | 49 | | 39 | | 53 | | **59** |
| **Sb** | 60 | 58 | 56 | 46 | 8 | 2 | 12 | 9 | 25 | 22 | **43** | **41** |
| | | 61 | | 55 | | 8 | | 16 | | 26 | | **43** |
| | | 63 | | 65 | | 13 | | 23 | | 31 | | **46** |
| **Ba** | 24 | 21 | 61 | 47 | 8 | 1 | 69 | 38 | 46 | 34 | **35** | **29** |
| | | 24 | | 60 | | 8 | | 66 | | 45 | | **34** |
| | | 27 | | 73 | | 16 | | 95 | | 55 | | **40** |
| **Hg** | 37 | 33 | 45 | 37 | 29 | 24 | 26 | 21 | 33 | 30 | **35** | **32** |
| | | 37 | | 44 | | 29 | | 27 | | 33 | | **35** |
| | | 42 | | 50 | | 33 | | 34 | | 37 | | **38** |
| **Tl** | 58 | 54 | 95 | 89 | 95 | 89 | 95 | 89 | 95 | 91 | **76** | **73** |
| | | 58 | | 95 | | 95 | | 95 | | 95 | | **76** |
| | | 62 | | 99 | | 99 | | 99 | | 98 | | **79** |
| **Bi** | 41 | 39 | 47 | 38 | 30 | 9 | 9 | 6 | 28 | 21 | **35** | **31** |
| | | 41 | | 45 | | 27 | | 9 | | 27 | | **34** |
| | | 44 | | 53 | | 35 | | 12 | | 31 | | **37** |

Figure 3: Locations of the specialty metals group of elements in criticality space: (a) national level, for the United States (2008 epoch), and (b) global level (2008 epoch). The highest level of criticality is at 100, 100, 100 (back right top).

(a)



(b)


Scandium
Strontium
Antimony
Barium
Mercury
Thallium
Bismuth
Vulnerability to Supply Restriction (Global)
0
20
40
60
80
100
Supply Risk (Long-term)
0
20
40
60
80
100
Environmental Implications
0
20
40
60
80
100

# <heading level 1> References

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# <heading level 1> Appendix

## Criticality Analysis Structure, with List of Acronyms and Abbreviations

| **Axes, Components, and Indicators** | **Acronyms and Abbreviations** |
|---|---|
| **I. Supply Risk** | **SR** |
| *Medium-term* | $SR_M$ |
| a. Geological, Technological, and Economic | $GTE_M$ |
| i. Depletion Time | $DT_M$ |
| ii. Companion Metal Fraction | CF |
| b. Social and Regulatory | S&R |
| i. Policy Potential Index | PPI |
| ii. Human Development Index | HDI |
| c. Geopolitical | GP |
| i. Worldwide Governance Indicators – Political Stability & Absence of Violence/Terrorism | WGI-PV |
| ii. Global Supply Concentration | GSC |
| *Long-term* | $SR_L$ |
| a. Geological, Technological, and Economic | $GTE_L$ |
| i. Depletion Time | $DT_L$ |
| ii. Companion Metal Fraction | CF |
| **II. Environmental Implications** | **EI** |
| **III. Vulnerability to Supply Restriction** | **VSR** |
| *National* | $VSR_N$ |
| a. Importance | I |
| i. Material Assets | $MA_N$ |
| ii. National Economic Importance | NE |
| b. Substitutability | S |
| i. Substitute Performance | SP |
| ii. Substitute Availability | $SA_M$ |
| iii. Environmental Impact Ratio | ER |
| iv. Net Import Reliance Ratio | IRR |
| c. Susceptibility | SU |
| v. Global Innovation Index | GII |
| vi. Net Import Reliance | IR |
| *Global* | $VSR_G$ |
| d. Importance | I |
| i. Material Assets | $MA_G$ |
| e. Substitutability | S |
| vii. Substitute Performance | SP |
| viii. Substitute Availability | $SA_L$ |
| ix. Environmental Impact Ratio | ER |