INDUSTRIAL ECOLOGY

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By-product metals are technologically essential but have problematic supply

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The growth in technological innovation that has occurred over the past decades has, in part, been possible because an increasing number of metals of the periodic table are used to perform specialized functions. However, there have been increasing concerns regarding the reliability of supply of some of these metals. A main contributor to these concerns is the fact that many of these metals are recovered only as by-products from a limited number of geopolitically concentrated ore deposits, rendering their supplies unable to respond to rapid changes in demand. Companionality is the degree to which a metal is obtained largely or entirely as a by-product of one or more host metals from geologic ores. The dependence of companion metal availability on the production of the host metals introduces a new facet of supply risk to modern technology. We evaluated companionality for 62 different metals and metalloids, and show that 61% (38 of 62) have companionality greater than 50%. Eighteen of the 38—including such technologically essential elements as germanium, terbium, and dysprosium—are further characterized as having geopolitically concentrated production and extremely low rates of end-of-life recycling. It is this subset of companion metals—vital in current technologies such as electronics, solar energy, medical imaging, energy-efficient lighting, and other state-of-the-art products—that may be at the greatest risk of supply constraints in the coming decades.

INTRODUCTION

For the vast majority of human history, only a few metals, including iron, copper, tin, and lead, were in common use. These metals of antiquity are those that are typically found in relatively high concentrations of one-half weight percent or more in the continental crust (*1*) and produced in relatively high volumes. Although these major metals, along with several precious metals, still form the foundation of any developed economy, it is the set of other "minor" metals and metalloids of the periodic table that modern technology is increasingly dependent on to perform specialized functions. Unlike the major metals, these minor metals are typically found in relatively low concentrations of less than about 0.1%, in which case these metals seldom form viable deposits of their own, and instead occur interstitially in the ores of metals with similar physical and chemical properties (*2*). These minor metals are thus often recovered only as by-products during the processing of the major metals, their "host(s)." The availability of these "by-product" or "companion" metals is thus dependent not only on the mining production of their host metal(s) but also on whether the companion metals are recovered rather than being discarded without having been processed. This raises concern regarding their availability given their rapid deployment in a number of emerging electronic and solar energy applications (for example, gallium and indium), as alloying elements in high-temperature applications (for example, cobalt), and in technologies such as offshore wind (for example, several of the rare earth elements). Here, we present a comprehensive "companionality" evaluation for 62 metals, indicating for each the global percentage mined as a companion. We discuss related topics, such as the dynamic nature of companionality, further consideration of risk factors for companion metals, and an economic evaluation of companionality, all of which are important considerations when evaluating mineral supply and availability.

Our results formally represent in most cases a "snapshot in time" for year 2008, largely because much of the necessary data are reported with long time delays, especially for the lesser-used companion metals. Where possible, we have reviewed more recent data relevant to companionality and see only modest revisions. We therefore regard the results presented here as fully applicable to the present situation.

The degree of companionality varies greatly among different metals. In the case of indium, for instance, typical concentrations in the zinc host ore are only a few parts per million (*3*), too low to mine for indium itself. Thus, nearly all indium production occurs as a by-product of zinc (with much smaller amounts from tin and copper ores, also as a by-product) (*4*). In contrast, silver sometimes has deposits that are sufficiently rich to permit direct silver mining. More often, however, silver is a minor constituent in the ores of host metals, especially zinc, lead, copper, and gold, and it is from those ores that the majority of silver (about 71% of the total global production) is derived (*5*).

Companionality is intertwined with the complexities of supply and demand of metals. The supply of a companion metal is often not significantly influenced by changes in its demand. Rather, the production of companion metals is dependent on their host(s)' supply(ies), rendering companion metal supply to be relatively price inelastic (*6*).

Aspects of host/companion complexities have previously been addressed to some degree (*4*, *6*–*12*), and the risks associated with companionality have been incorporated to varying extents in several "metal criticality" assessments (*13*–*21*). However, no comprehensive quantification of the various aspects of companionality has yet been presented. The tasks of the present work are to address companionality in all its breadth and to determine whether specific hosts and/or companions pose previously unrecognized issues for material availability. Although the work is centered on metals, metalloids, such as selenium, are also common companions in the ores of host metals. For convenience, we use the term "metals" to refer, hereafter, to either metals or metalloids.

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RESULTS

Companionality estimates based on production quantities

A first step in characterizing companionality requires the quantification of its extent for each metal. This is accomplished by estimating the percentage of each metal's global primary production obtained as a companion. To do this, the various sources of each metal's primary production were examined and classified as being either one in which the metal was recovered as the main or target product (typically the metal that provided that largest revenue), in which case it was designated as the host, or not so recovered, in which case it was designated as a companion. Companionality values were derived for 62 metals and metalloids that are most commonly used in modern technology and are presented in Fig. 1 (with details in table S1). From this analysis, we find that 61%, or 38 of the 62 metals evaluated, have the majority (that is, >50%) of their global production obtained as a companion. This result suggests that companionality has a significant role to play when considering metal supply and availability (and, in turn, related topics, such as product design).

It should be noted that the information drawn upon for these computations can involve sparse data sets of varying quality. In addition, transparent markets do not exist for companion metals in the way that they do for major metals such as copper or nickel. Companion metal transactions between producers and brokers, and between brokers and users, are often entirely on a private contract basis. The result is that reporting on quantities of companion metals that are recovered and processed from each mining operation is uncommon, and recovery efficiencies for each process step are not made public. Hence, companionality is necessarily estimated on the basis of industry information (for example, mining company and industry association reports), private consultation, and a variety of literature sources (for example, U.S. Geological Survey publications, articles in scientific journals, and science and engineering encyclopedias). The results of this process should be regarded as informed estimates rather than precise determinations.

It is not simply the case that a large number of elements are companions: those that are companions tend to be situated near each other in the periodic table, because of similarities in their physical and chemical properties. The most evident groupings are in the second and third rows of the transition metals. It is interesting and important that metals increasingly used in electronic and solar energy applications (gallium, germanium, selenium, indium, and tellurium), those employed as alloying elements in high-temperature applications (cobalt, hafnium, and rhenium), and several rare earth elements (praseodymium, neodymium, terbium, dysprosium, and lutetium) important in offshore wind, lighting, and medical imaging are included in the companion metal groupings in the periodic table. We do not go into more detail as to the causes of these groupings, noting only that they are obviously related to the physical and chemical properties of the elements (and, in turn, to their co-occurrence in ore bodies), as well as to their crustal abundances (*6*). The central point from our perspective is that many of the metals so important to modern technology are available mostly or completely as companions. In many cases, their most likely substitutes are elements

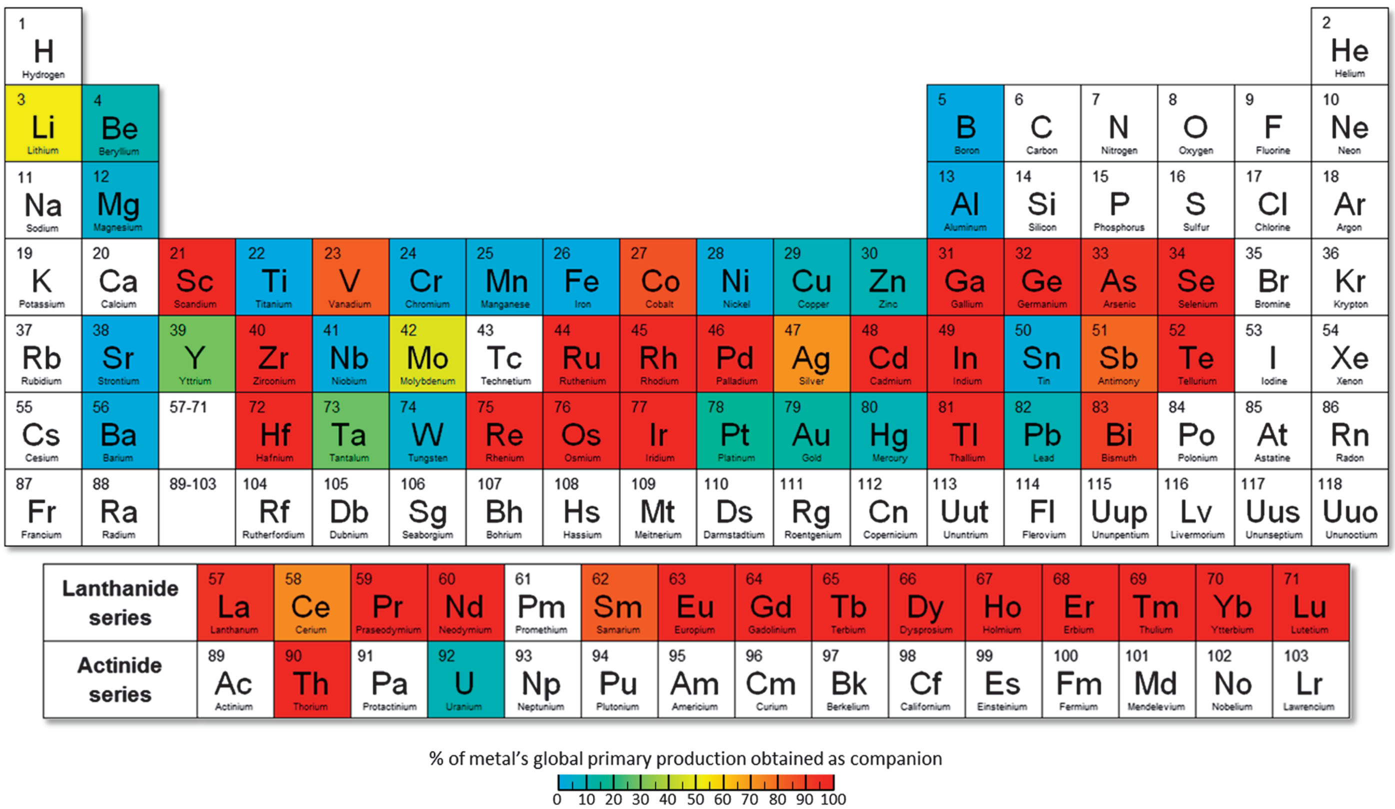


Fig. 1. The periodic table of companionality on a global basis for 2008. Metals that are mainly produced as hosts appear in blue, and those that are mainly produced as companions are in red. Details regarding data sources and assumptions are presented in the Supplementary Materials.

with similar physical and chemical properties, elements that are companions as well.

The primary production of a companion metal may primarily be associated with a single host or with multiple hosts at varying degrees. Most (≥90%) of selenium's and tellurium's supplies, for example, are associated with copper, whereas significant portions of silver's supply are associated with zinc, lead, copper, and gold. The host-companion relationships for several of the main hosts are illustrated in Fig. 2, with more complete information presented in table S1. This analysis suggests that although there are a few companion metals associated with multiple hosts, many more are primarily (that is, most of their primary production) associated with only one or two hosts. Similarly, although host metals may be hosts to multiple companions, they are often the principal host (that is, supply the majority of a companion's primary production) for only a few companions. For example, copper can be considered a host for some 18 elements, but it is the principal host only for selenium and tellurium, with molybdenum's supply from copper being just less than 50% in year 2008.

Dynamic companionality

The analysis presented in Figs. 1 and 2 is a snapshot of companionality in 2008, and it should be recognized that companionality is dynamic. That is, changes in production in different countries or in ore deposits within countries may change over time. Figure 3 illustrates this dynamism for cobalt, nickel, copper, molybdenum, silver, platinum, rhenium, and gold, where the contribution of each metal's supply is delineated by host over time. Variations in the host metals' contributions are more striking in some cases than in others over the time periods presented. In the case for molybdenum, for example, the percent of molybdenum supplied from copper-dominant ores has generally decreased relative to the percent supplied from molybdenum-dominant ores. Molybdenum's companionality has, thus, varied between 75 and 47% from 1985 to 2013. This is a reversal of trend that began in the 1960s when copper ores became a significant source of molybdenum (*22*). In contrast, the contributions of silver supply from lead/zinc-, copper-, gold-, and silver-dominant ores have changed little from 1998 to 2012. Variations in silver's companionality are thus minor, varying from 77 to 70% over that time period. Cobalt and rhenium have similarly unique situations, with each illustrating the interplay between the different deposits and their associated metals. For nickel, copper, platinum, and gold, the largest contributions are from ores in which they are the primary metal, a reflection of their status as host metals. In general, the contribution of other metals to the overall production of these host metals is small and changes little over time.

Additional risk factors: Geopolitically concentrated production and minimal end-of-life recycling

Another interesting aspect of companion metals is the degree to which their production is concentrated in a few countries and the degree to which they are currently recycled at end of life. These aspects are illustrated in Fig. 4 (with details in table S2), where companionality is plotted against country-level production concentration as measured by the Herfindahl-Hirschman index (HHI). The end-of-life recycling rates are indicated by the color of the symbols. HHI values for most (43 of 62) of the metals analyzed suggest that metal production is highly concentrated (that is, defined as a value of 2500 or greater) (*23*), meaning that the sources are predominantly in fewer than three or four countries. Overall, the HHI values seem to be clustered in two general areas, with exactly half centered on a value of 2500 and the other half having values greater than 5000, as illustrated in the upper histogram insert of Fig. 4.

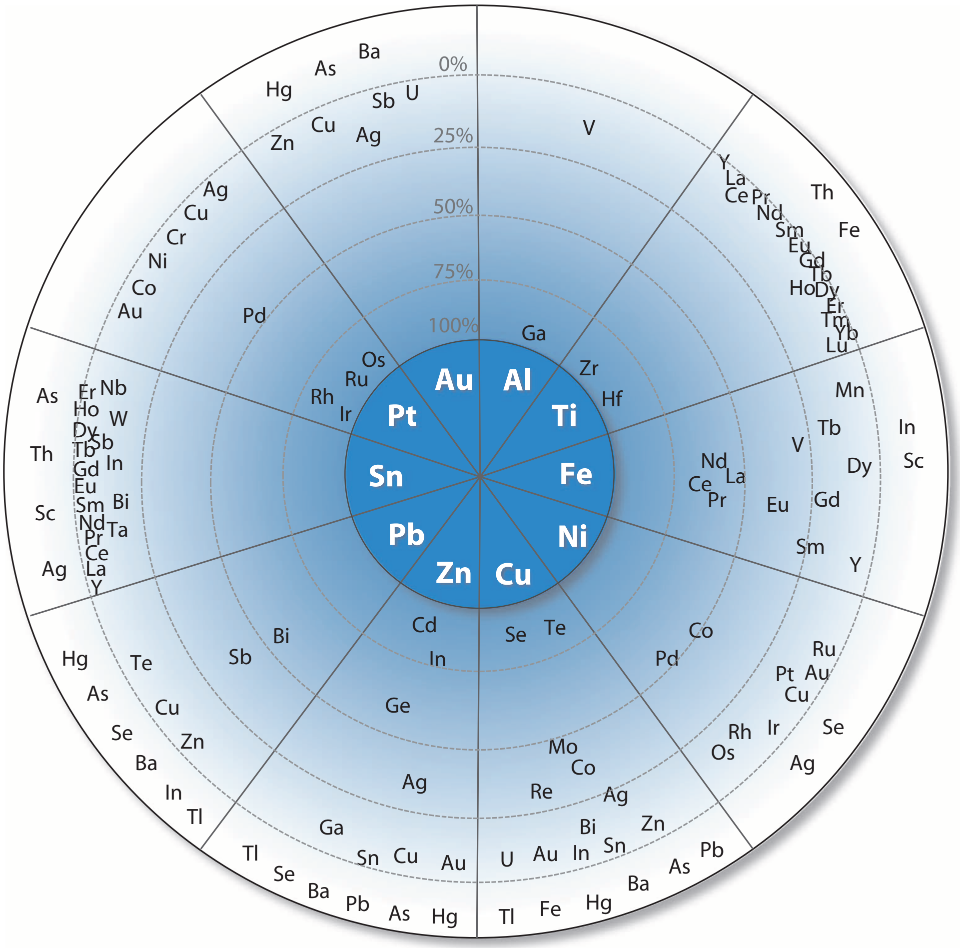


Fig. 2. The wheel of metal companionality. The principal host metals form the inner circle. Companion elements appear in the outer circle at distances proportional to the percentage of their primary production (from 100 to 0%) that originates with the host metal indicated. The companion elements in the white region of the outer circle are elements for which the percentage of their production that originates with the host metal indicated has not been determined. Data sources and assumptions for the assessment are given in the Supplementary Materials. Inspired by a diagram developed by (*10*).

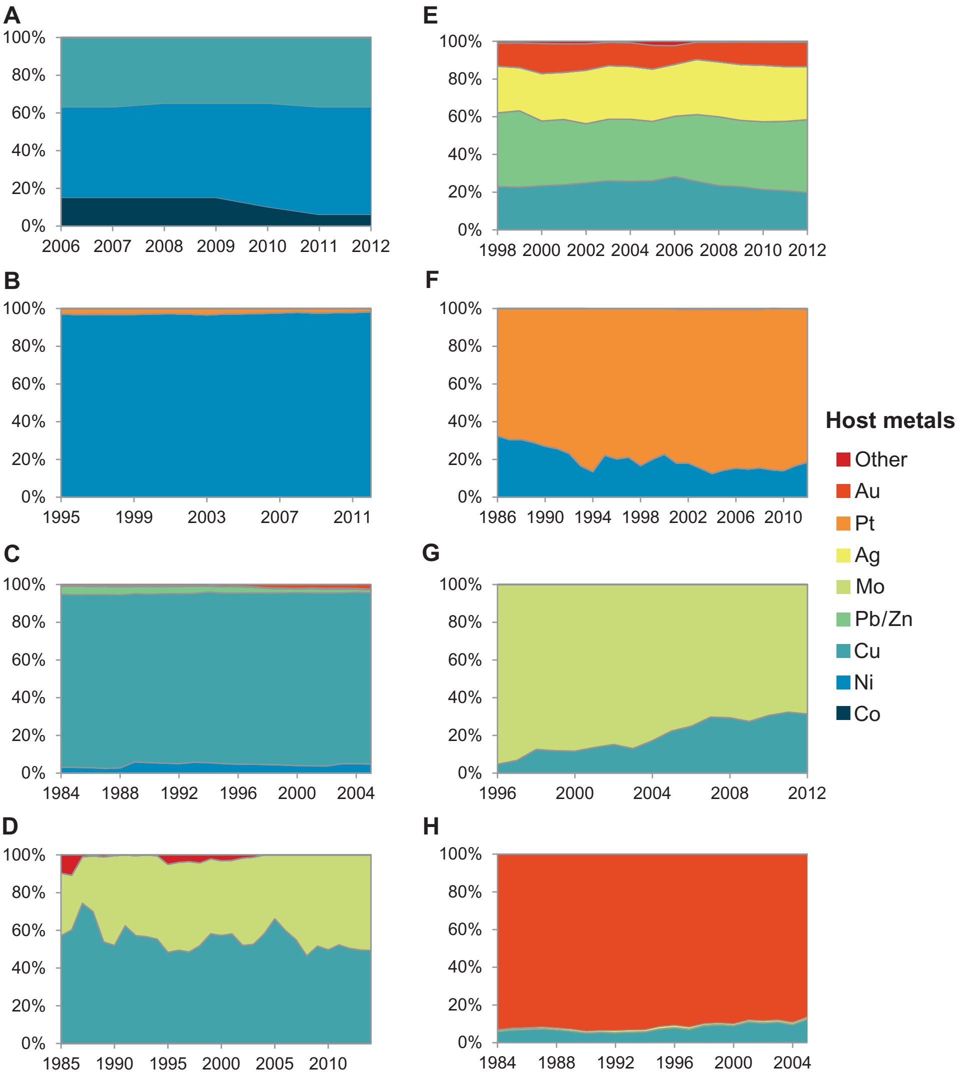


Fig. 3. Companionality dynamics. (**A** to **H**) Variations in host metal contributions (vertical axis) for cobalt (A), nickel (B), copper (C), molybdenum (D), silver (E), platinum (F), rhenium (G), and gold (H) as a percentage of total primary production over several years (horizontal axis). Data are from (*5*, *37*–*39*).

metals that are mainly obtained as hosts (that is, companionality of <50%) are recycled at end of life at rates of >50%.

The locations of the metals along both the dimensions of geopolitical production concentration and companionality (main chart of Fig. 4) fall in distinct clusters at the corners of this two-dimensional matrix. Moreover, the 17 metals in the lower-left quadrant with lower geopolitical production concentration (that is, HHI value <5000) and lower companionality (that is, <50%) are predominantly the metals that have high end-of-life recycling rates (that is, >50%). In contrast, the metals in the upper-right quadrant, with extreme geopolitical production concentration and companionality, tend to have lower end-of-life recycling rates (that is, <1%). It is these latter 18 metals—scandium, germanium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, osmium, thallium, bismuth, and thorium—that are potentially at the greatest risk for supply restriction with respect to the combination of these three factors.

Production of metals with extreme HHI values (that is, ≥5000) is potentially more vulnerable, because they could be constrained by market forces, geopolitics, or war more easily than metals whose sources are more widely dispersed. It is also striking that most (20 of 31) of the metals with extremely concentrated production are metals that are currently either not recycled at their end of life or recycled in extremely low rates of <1% (*24*). Unless major innovations occur in collection and processing of discarded products that contain these companion metals, most companion metals will be extracted and used only once.

From the perspective of companionality, there are also two distinct clusters at the upper and lower ends of the range. The right histogram insert of Fig. 4 shows that most (27 of 38) of the metals that are mainly obtained as companions (that is, companionality of ≥50%) are also metals that are currently either not recycled at their end of life or recycled in extremely low rates of <1%, whereas most (13 of 24) of the

An economic evaluation of companionality

The degree of companionality of any given metal is inherently dependent on the definition used in the analysis. We propose that companionality may, in general, be more precisely defined by understanding the underlying economic contributions of the metals in question, an assertion quite possibly best understood when highlighting the challenge in terming metals "coproducts" versus by-products. The distinction between coproducts versus by-products is a challenge, with analysts frequently using the terms interchangeably. Examples of what is commonly called coproducts are not uncommon and include lead and zinc, nickel and copper, tantalum and niobium, and the rare earth elements.

When mining metals together, the metal with the largest economic contribution may be considered the host, and those with smaller economic contributions, the companions. Metals with similar economic contributions may be considered coproducts. As an example case, an analyst suggests that a metal needs to contribute no more than 20% of revenue to be considered a by-product, and otherwise should be considered a coproduct (*25*).

Although this economically based categorization provides an intuitive basis for designating metals as either hosts or companions, it has rarely been applied across all production for all metals and often cannot be so applied because of data limitations. An exception is the case of the rare earth elements, for which such an analysis has been done (*26*). In that case, it was determined that in 2008, the rare earth elements were produced as companions in all production locations except the ion adsorption deposits in southern Chinese provinces, as well as deposits in Sichuan and Shandong. For these deposits, the companionality for the individual rare earth elements was based on their relative economic contribution, where an element with a larger economic contribution has a proportionally lower companionality value. Comparing those results to the more generalized analysis performed in Fig. 1, we note only minor changes to the companionality values for all the rare earth elements with the exception of yttrium, which would have a value of 84 instead of 29—a reflection of its dependency on other rare earth elements for economic recovery.

Although this type of economically based categorization is suggestive, it does not fully address the issue of what it means to be a companion metal. From our perspective, a companion metal is one that is financially dependent on other metals for recovery rather than merely co-occurring with the host. Specifically, can a metal be profitably mined on its own under the current cost structure? It is our assertion that whenever possible, companionality should be determined on the basis of whether the revenue contribution from a specific metal is sufficient to cover the entire cost of sales from the mine and subsequent beneficiation and refining processes. Because the revenue contribution for metals and operating costs varies by operation, the analysis needs to be conducted for each operation and then weight-averaged by the size of that operation to obtain a single, comparable value for each element. We arrive at the range of possible values from 0 for metals that are entirely self-sufficient to 100 for metals that are completely dependent on others by using the following equation:

$$\text{Companionality}_i = \frac{\sum_j\left(\left(100\cdot\left(1-\min\left(\frac{\text{Revenue}_{i,j}}{\text{Cost of sales}_j},1\right)\right)\right)\cdot\text{Sales volume}_{i,j}\right)}{\text{Sales volume}_i} \qquad (1)$$

for metal i and operation j, where cost of sales includes operating costs for mining, concentrating, smelting, and refining (for example, attributable labor, utilities, consumables, transportation, taxes, shared services, and royalty expenses) or attributable treatment costs, as well as depreciation, depletion, amortization, and changes in metal inventories. That is, "how dependent for profitable operation is metal i in mine j on the revenue of the other metals recovered from that operation?"

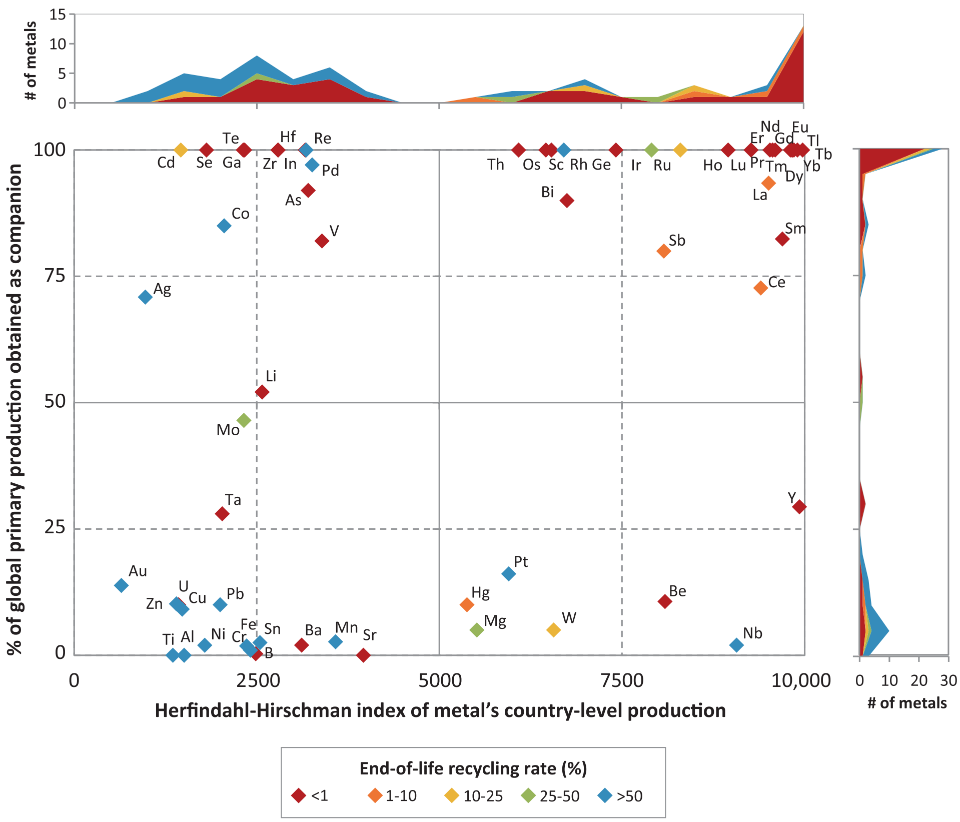


Fig. 4. Companionality, primary production concentration, and end-of-life recycling for 62 metals. Primary production concentration is measured by the HHI, which is calculated as the sum of the squares of the individual country production shares. Where data for multiple production stages (for example, mining, smelting, and refining) are reported, the production stage that yields the largest HHI value is used. Top and side inserts indicate distributions along respective axis. Data sources and assumptions for the assessment of companionality and production concentration are given in the Supplementary Materials (tables S1 and S2). End-of-life recycling rate ranges are obtained from (*24*).

An example will make this determination of host and companion clearer. Consider the platinum group elements, whose deposits are sometimes richest in platinum, sometimes in palladium, and sometimes in other metals. Figure 5 treats platinum group element sources in five different operations in five countries for 2008. For the South African and Zimbabwean mines, platinum is the largest revenue contributor. Revenues from platinum exceed the cost of sales, and so platinum is indeed a host in both of these mines because it is not dependent on any other metal for profitable production. No other metal in these two examples produces large enough revenues to cover the cost of sales, and so these metals may be considered companions to varying degrees, based on each metal's revenue contribution relative to that operation's cost of sales.

In the Russian example, in Fig. 5, nickel covers the entire cost of sales in 2008. Copper is the second largest contributor, but it alone would not have covered the cost of sales. The Canadian mine clearly has palladium as the metal that generates the most revenue and would normally be considered the host, but in this particular year, the mine was running a deficit, with the costs being greater than all revenue. At the U.S. mine, which was also running a deficit that year, palladium and platinum provided nearly equal revenues and would be considered coproducts.

To quantify a metal's companionality, we weight-averaged the ratio of the metal's

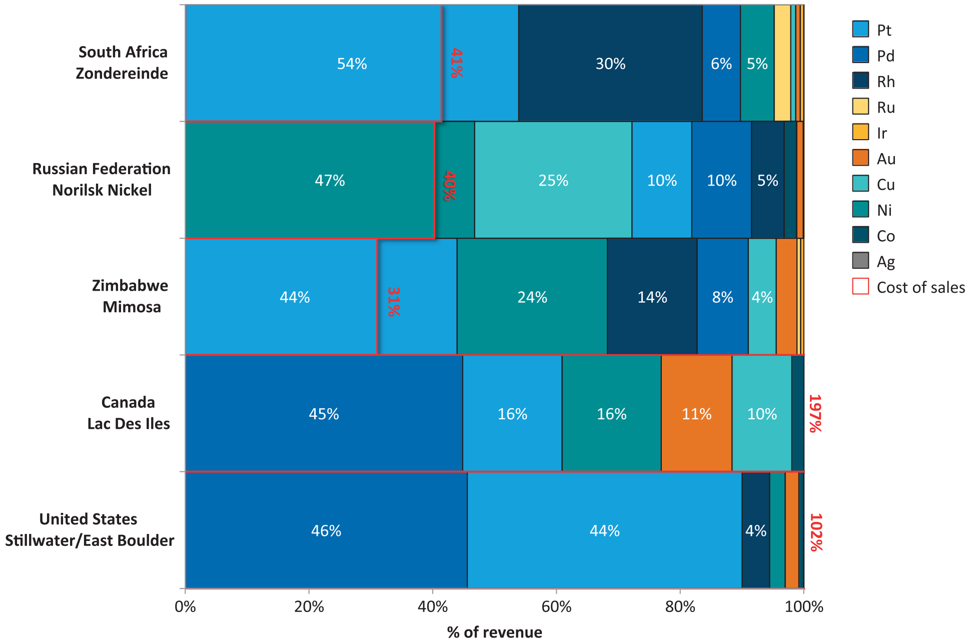


Fig. 5. Revenue contribution by metal (in descending order) for five mines producing platinum group elements. The red line marks the point at which revenues cover the cost of sales, thus defining dependency of the metals. For the Canadian and U.S. mines, costs of sales exceed revenues, as indicated by the red number at the right. Details regarding data sources (that is, company annual reports) and assumptions are noted in the Supplementary Materials.

revenue contribution relative to cost of sales for each mine by each mine's sales volume of that metal relative to its global sales across all operations. To illustrate this process, we performed this calculation for the platinum group elements using data from company annual reports (Fig. 6, with details in the Supplementary Materials) and find the companionality for platinum, palladium, rhodium, ruthenium, and iridium to be 17, 80, 48, 95, and 99, respectively. Comparing these results to the more generalized analysis performed in Fig. 1, we again note only minor changes to the companionality values for platinum (16 versus 17), palladium (80 versus 97), ruthenium (95 versus 100), and iridium (99 versus 100). Only for rhodium do the results change significantly (48 versus 100), reflecting the potential for rhodium to be nearly self-sufficient in 2008 due to its high price. We imagine that similar circumstances may be found for other metals with large enough economic contributions. In most cases, however, the identified companions likely provide only a small contribution to the overall revenue and are unlikely to cover a significant portion of the cost of sales. As previously mentioned, this companionality determination is completed for 2008, but revenues and costs can differ significantly over time. As a consequence, our results are a snapshot in time that highlights the nature of the interdependency of these metals.

DISCUSSION

Unappreciated companionality constraints

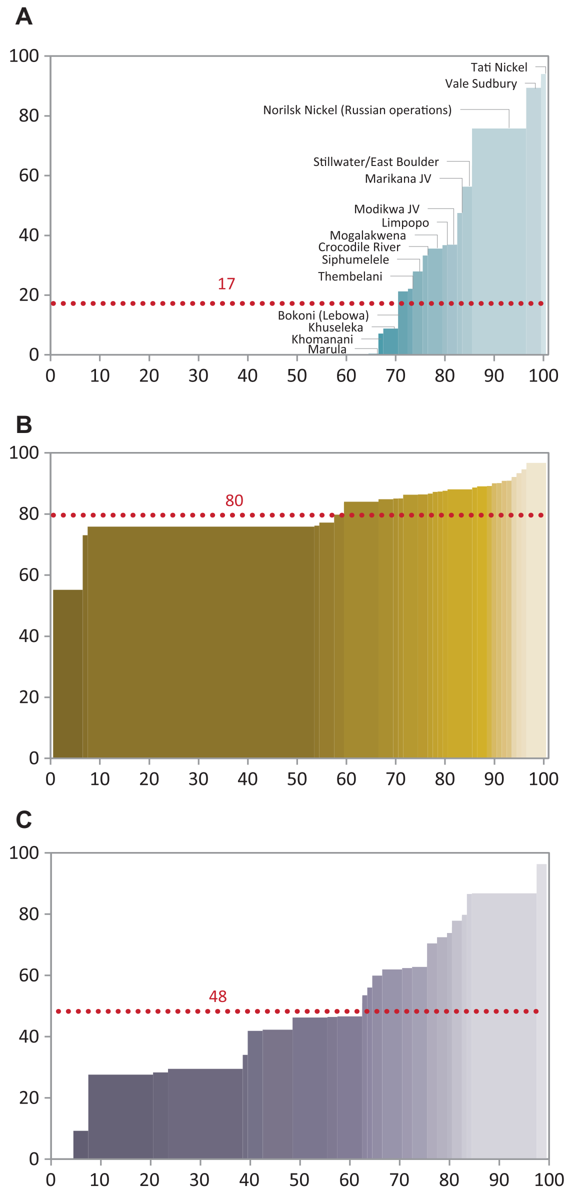
One aspect of companionality of note is that when a metal is obtained largely or completely as a companion, its production is often unable to respond quickly to rapid changes in demand and, as a result, its price can fluctuate widely. This is because the production of companion metals is strongly influenced by the production of its host(s). The situation can be exacerbated by marked differences in market demands of the companions and their hosts, as exemplified again by examining the platinum group elements. As we have shown, ruthenium is obtained almost entirely as a companion, and so its primary production is largely responsive to the changes in the production of its main host, platinum. In late 2006, demand for ruthenium expanded rapidly, owing to its increased use in hard disk drives and due to purchases by speculative buyers. Unable to expand ruthenium production at a rate greater than that of its host metals, ruthenium demand had to be partially fulfilled by above-ground stocks that had accumulated during previous years (*27*). This did not, however, prevent the price of ruthenium from rising rapidly to US$870 per troy ounce by mid-February 2007, a 9-fold increase from the previous year and a 29-fold increase from a low point in 2003 (*28*). The market eventually stabilized, only to see the situation repeat itself in 2010, reflecting the relative inelasticity of supply and the lack of a long-term solution. Similar incidents of mismatched supply and demand of the host and companion metals are not uncommon (*11*).

Toxicity can also influence companion metal supply. A principal example in this case is lead, widely used in vehicle batteries. Lead is being partially replaced by other battery technologies as hybrid and electric vehicles grow in popularity (*29*), but a decrease in lead mining over time has the potential to imperil supplies of antimony and bismuth, for which lead is the main host. A similar situation may occur with thallium, a toxic companion of zinc (*30*). Because of regulatory complexities related to the processing of toxic metals, a zinc miner may well choose not to invest in thallium recovery, and constrained thallium supplies could occur as a result.

A different situation exists with cadmium, a metal widely used in a range of batteries but with some other applications being phased out as a consequence of cadmium's toxicity (*31*). Cadmium is a companion of zinc, and about half of all zinc is used as an anticorrosion plating for steel. If zinc-plated steel demand is high, so will be the demand for zinc, and cadmium will be extracted from ore bodies regardless of demand. Cadmium may not be recovered during host metal processing, but increased above-ground cadmium stocks will result and may need to be stored and monitored over time. Thorium as a companion of rare earth elements is a similar example.

The path forward

If primary production of companion metals becomes constrained, what options exist? One is certainly enhanced end-of-life recycling. Figure 4 shows that end-of-life recycling for most companion metals is low to nonexistent. Increasing recycling is a challenge, however, because companion metals are frequently used in small amounts in complex mixtures of materials (for example, electronics), where collection



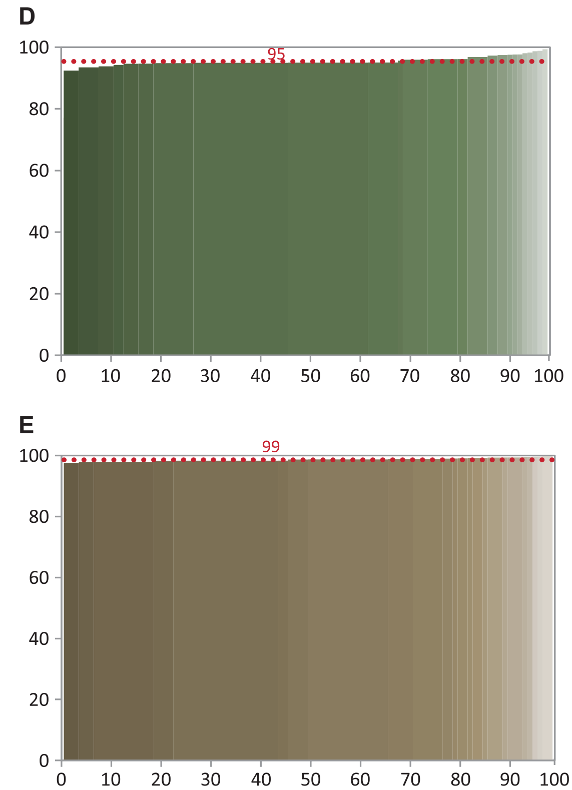


Fig. 6. Economic companionality assessment. (**A** to **E**) 2008 companionality of platinum (A), palladium (B), rhodium (C), ruthenium (D), and iridium (E) calculated on the basis of each metal's revenue contribution relative to the cost of sales on an operation-by-operation basis for 36 operations (column height) displayed in ascending order. Column widths are proportional to each operation's sales contribution as percent of global sales. Sales-weighted averages for each metal are represented by horizontal lines.

and separation can be difficult. Hence, if increased end-of-life recycling of companion metals becomes a priority, recycling will need to be better enabled at the product design stage.

Substitution of another material in place of a companion metal is also, in theory, a way to reduce demand. In some cases (for example, nickel for palladium in multilayer ceramic capacitors), this approach has proven possible. However, frequently, the best substitute for a companion metal is another companion metal, often from the same host, because of similar physical and chemical properties (*32*, *33*). Thus, although substitution opportunities may exist in some cases, a transition to radically different technologies that use completely different metals is much more likely than substitution to change companion metal use.

Perhaps the most promising way to increase companion metal supply, if desired, is to increase the recovery rate of companions from the host metal ores. For a variety of technological and financial reasons, along with varying companion metal demand, these rates are typically quite low. Although information on process efficiencies is generally proprietary, we find that recovery efficiencies for some companion metals can be as low as 10% (*11*, *34*). Improving these rates would require capital expenditure, and the companion metal demand may provide insufficient return on investment, at least in the short run.

Consider the situation of the companion metal indium mined with one of its hosts, zinc. Demand for indium expanded significantly over the past few decades, especially with increased demand for flat panel displays that use indium tin oxide; the primary production of indium thus increased a staggering 1675% from 1975 to 2012 (*35*). As noted previously, the vast majority of indium is recovered as a companion of zinc. Unlike indium, zinc primary production increased a modest 231% over the same time period (*35*). This was possible because of enhanced recovery of indium from zinc-dominant ore (*36*). If such disparities in the demand of the host and companion were to continue, the recovery of indium from zinc ores would need to be improved or a greater portion of indium demand would need to be fulfilled from other sources (for example, tin-, lead-, and copper-dominant ores).

It is undeniable that the widespread use of companion metals has resulted in markedly improved performance in many product sectors. Sustaining those uses may become a challenge going forward because of the dependence of companion metal supplies on the production of host metals. Product designers should consider companion metal use only upon consideration of the supply and demand situation. It is likely that improving end-of-life recycling of companion metals together with developing processes that more efficiently extract companion metals from their host ores will be required in the future. As it now stands, much of modern technology depends on metals whose supplies are uncertain and whose market transactions are largely opaque; in concert, this produces a supply situation that may prove difficult to sustain.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/1/3/e1400180/DC1
Table S1. Companionality of the metals of the periodic table.
Table S2. Country-level production concentration.
Table S3. 2008 reported or estimated metal sales by platinum group element–producing operation.
Table S4. Platinum group element ore grade distributions, as reported in literature or company reports.
Table S5. Estimated elemental distribution of platinum group elements based on mix of ore body milled.
Table S6. Revenue contribution by metal and cost of sales as a percentage of revenue by operation.
Table S7. Companionality estimates for platinum group elements by operation and for overall production.
References (*40–153*)

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