Supporting Information

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SI Text

This work covers each of 62 elements of the periodic table. We list them in atomic number order in situations where we discuss more than one. For the convenience of readers, we reproduce here as Fig. S1 the periodic table with atomic numbers included. Our list of elements includes those designated as transition metals (to atomic number 80) on the figure, all posttransition metals except polonium, all metalloids except silicon, lithium, beryllium, magnesium, and selenium. For convenience, we refer to all of these as metals.

For each of these metals, we determined their uses, the distribution of the element's total use into those several uses, the best substitute (if any) for each use, and the performance of that substitute. The last factor is characterized on an ordinal basis as exemplary, good, adequate, or poor; the four designations are in the analysis at 12.5, 37.5, 62.5, and 87.5 (i.e., the respective medians of the ranges 0–25, 25–50, 50–75, and 75–100). Table S1 provides the complete information together with citations.

For most metals, the data available for the fractions that enter each use are based on the total amount that enters the fabrication and manufacturing stage (frequently called apparent consumption or demand). They are typically either first or principal uses (e.g., galvanizing) or end uses (e.g., construction). The justification for not selecting a uniform type of use is that each metal is unique, and sometimes it makes more sense to select a substitute for a first use and, other times, for an end use. To avoid confusion, we term these uses applications.

A primary substitute was determined for each application through the assimilation of research and expert opinion for each application and its potential for substitution. The primary substitutes should be thought of as substitutes for the case that the metals of focus are not available at all (not even at high prices), rather than as a determination of whether or not substitution will occur. In cases where an application is too diverse to determine a single primary substitute, in cases in which a primary substitute is not well developed, and in cases in which a completely different technology is the substitute, we assign a designation of no substitute. This ultimately results in a higher overall substitutability potential score.

One aspect of Table S1 deserves particular mention: a designation of "other" appears in the application column for many of the metals. A characteristic of metal use in technology is, of course, that there typically are a few main uses and a larger number of low-volume specialized uses. The latter cannot be tracked from available statistics and are highly variable, so their inclusion in the table is to round out total metal use to 100% rather than to provide detailed information. As a result, except in the cases of iron and iridium, in which substitute performance for other uses can be pretty clearly determined, we exclude the other portion of Table S1 in determining overall substitute performance.

As it turns out, this omission does not seems to be too important. The average percent of other applications across all of the metals is only about 13% of total flow into all uses. Additionally, if we were to include the other entries under the perhaps reasonable supposition that reasonable substitutes would exist for some uses but not others (i.e., substitutability = 50% in those cases), the distribution of elements with moderate to high substitutability changes little, as can be seen in Fig. S2. Moreover, there is no change at all to the main text result that none of the 62 metals has exemplary substitutes for all of its major applications whether or not other uses are included. Numerically, $S < 35$ for all metals, whether or not other uses are included.

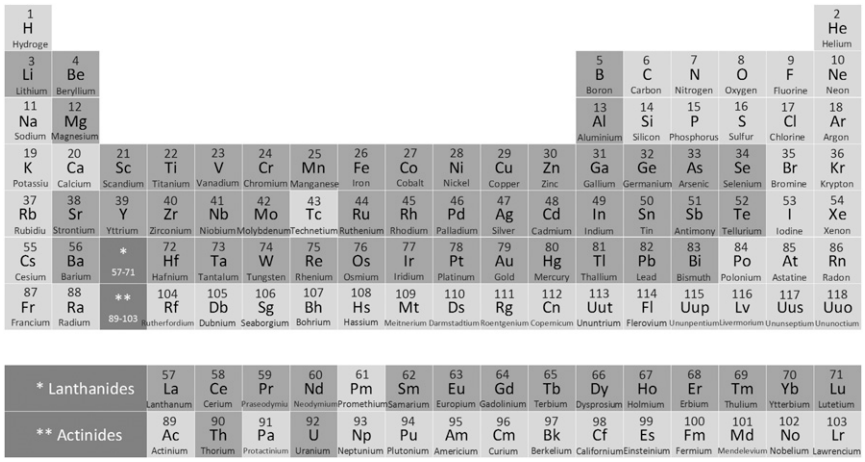

Fig. S1. Periodic table of the elements, with the 62 metals investigated in this study shaded a darker color.

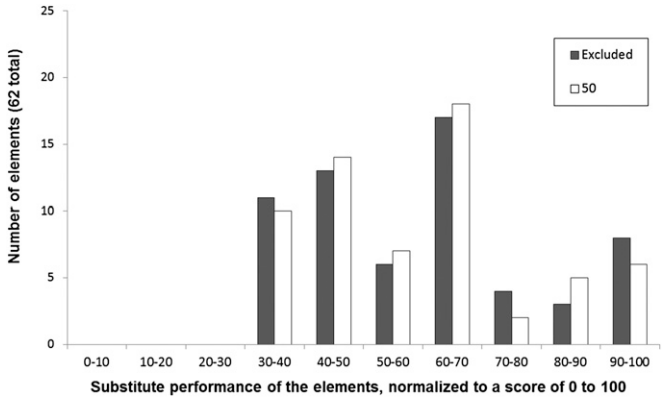

Fig. S2. Aggregated substitute performance scores for the 62 metals investigated showing distributions of substitute performance across all applications where white bars represent "other" categories set at a default value of 50 and black bars represent the exclusion of other categories. A substitute performance score of 100 indicates extremely poor substitute performance or lack of substitutes, whereas a score of 0 indicates excellent substitute performance.

Other Supporting Information Files

Table S1 (DOCX)