

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 seem 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.

1 H Hydroge																	2 He Helium
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium											13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 S Sulfur	17 Cl Chlorine	18 Ar Argon
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon
55 Cs Cesium	56 Ba Barium	* 57-71 Lanthanides	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon
87 Fr Francium	88 Ra Radium	** 89-103 Actinides	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Uut Ununtrium	114 Fl Flerovium	115 Uup Ununpentium	116 Lv Livermorium	117 Uus Ununseptium	118 Uuo Oganesson
* Lanthanides			57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium
** Actinides			89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

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

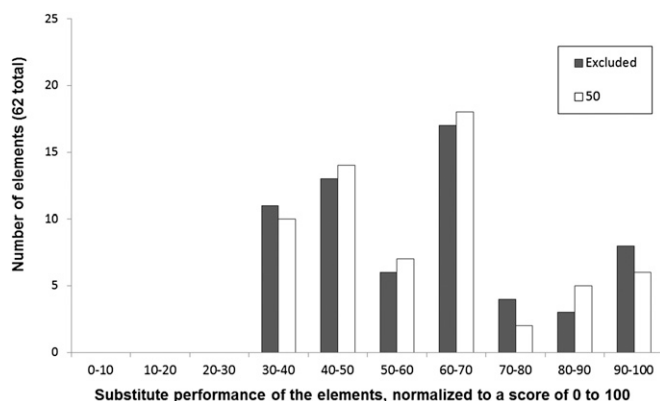


Fig. S2. Aggregated substitute performance scores for the 62 metals investigated showing distributions of substitute performance across all applications where white bars represent "other" categories set at a default value of 50 and black bars represent the exclusion of other categories. A substitute 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 \(DOCX\)](#)