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By-product recovery from US metal mines could reduce import reliance for critical minerals

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The US has sufficient geological endowment in active metal mines to reduce the nation's dependence on critical mineral imports. Demand is increasing for cobalt, nickel, rare earth elements, tellurium, germanium, and other materials used in energy production, semiconductors, and defense. This study uses a statistical evaluation of new geochemical datasets to quantify the critical minerals that are mined annually in US ores but go unrecovered. Ninety percent recovery of by-products from existing domestic metal mining operations could meet nearly all US critical mineral needs; one percent recovery would substantially reduce import reliance for most elements evaluated. Policies and technological advancements can enable by-product recovery, which is a resource-efficient approach to critical mineral supply that reduces waste, impact, and geopolitical risk.

Global demand is increasing considerably for materials such as cobalt, nickel, manganese, and lithium used in rechargeable batteries; copper for electricity transmission; rare earth elements for electric vehicle and wind turbine magnets; tellurium for solar panels; and germanium for semiconductors, defense, and aerospace (1). Some of these elements have only recently become technologically essential and have seen little mining in the past. Others such as copper have been mined intensively but are likely to require more additional production by 2050 than has ever been mined throughout human history (2).

The United States (US) Geological Survey designated 47 chemical elements and three minerals *critical* for the overall economy and national security (3), and the US Department of Energy identified 15 chemical elements and three materials that are *critical for energy technologies* (4). Geographically concentrated production of a mineral commodity is likely to lead to unstable supply, as in the example of cobalt, which is mostly produced in the Democratic Republic of Congo; or antimony, gallium, and germanium for which China has recently restricted export. Some critical minerals are mined as primary ores, such as lithium and nickel, whereas others such as gallium, germanium, indium, and tellurium are not found in high concentrations and are better suited to recovery as by-products of mining other commodities (5). Supply chain vulnerabilities for critical minerals have prompted new US policies to stimulate domestic mining (6, 7). Although there are efforts to develop new US mines for critical minerals such as nickel, cobalt, lithium, manganese, and graphite (6–8), many of these projects have led to environmental and social opposition (6–10). Even in the absence of conflict, the average

timeline for exploration, permitting, and development of a new mine in the US is 29 years (11).

This study quantifies the critical minerals that currently go unrecovered at active US mines, demonstrating that the US could reduce criticality and meet domestic demand through by-product recovery from existing mining operations. By-product recovery is defined as the production of additional minerals or elements during recovery of the main product, before those by-products enter the final waste stream. In analogy to household waste, by-products are recovered within the household during normal operations and are not discarded, rather than being recovered from a repository such as a landfill after having been discarded. Although the accumulated wastes from past US mining are a potential source of critical minerals, their volumes and geochemical compositions have not been systematically inventoried, and re-mining of closed or abandoned sites and tailings impoundments poses both engineering and regulatory challenges. Recovery of by-products is limited by technology, cost, and the pricing environment for the by-products; most sites do not implement additional processing and metallurgical steps that enable recovery of all the commodities contained in an ore body. By-products are typically only recovered when they generate a net profit, such as minor nickel and cobalt from platinum-palladium mines in Montana, or copper from proposed cobalt mining in Idaho. In a few cases, mining operations produce by-products for reasons other than profit, such as the reputational benefit gained by recovering tellurium and rhenium during copper mining in Utah. When by-products go unrecovered, they become constituents of mine waste such as tailings, where they may require storage and

environmental monitoring in perpetuity (12).

Quantifying critical mineral endowment

The critical mineral endowment of US mines has hitherto been difficult to assess. This endowment, or amount contained in the geological units, is an essential prerequisite for estimation of the by-product resource that could be potentially recovered from US mines. Many of the elements on the US critical minerals list were not routinely analyzed in the past, due to limited end-use as well as the analytical challenges presented by low concentrations. Although modern exploration and extraction operations conduct multi-element geochemical characterization of geological exploration targets and the ore that is fed to the mineral processing facility or “mill,” analytical costs constrain the number of elements routinely assayed. These factors have resulted in largely unknown concentrations and unknown total endowments of critical minerals at US mines until now.

This contribution presents results from two new databases: 1) annual main product commodity production of permitted mining operations on US federal land, compiled from public and proprietary company data, and 2) geochemistry of 70 elements analyzed across 26,838 ore samples, in the Critical Minerals in Ores database generated by the Critical Minerals Mapping Initiative (CMMI), released by the federal Geological Surveys of the US, Canada, and Australia in 2024 (13, 14). The latter dataset leverages new methodological developments in analytical geochemistry to analyze critical mineral concentrations at low detection limits. The ores represent samples of opportunity and do not necessarily capture the full range of geochemical heterogeneity across the ore body. However, broad sample coverage across deposits from a variety of ore types reveals linkages between critical mineral enrichment and the geological processes that lead to mineralization, enabling a predictive approach to critical mineral assessment based on ore deposit geology. The present study employs a statistical resampling approach to estimate the by-product endowment of 70 mineral commodities, using the by-product concentrations in ore samples for each geological deposit type and the masses of main product commodities mined annually at each site (Supplementary Materials).

The ratio R_B of each by-product B to the main product M was calculated on a per-sample basis for all samples of each deposit type in the CMMI database (i.e., main case). A conceptual, coarse cutoff grade was applied for comparison, eliminating CMMI samples below 20x crustal abundance for the main product (i.e., cutoff case) (Supplementary Materials). The resulting ratios were multiplied by a set production unit that is 1/10,000th of the total annual production of the main product commodity, based on 2023 values. This dataset was resampled 10,000 times, and the results were summed to

the total main product production, generating an estimate of P_B , the by-product endowment of each element in each deposit type. The resampling exercise was conducted 1000 times for the main case and the 20x crustal abundance cutoff case, in each case creating a distribution of P_B values. For each of 70 elements in each of the 17 deposit types in the main case and the cutoff case, the mean of 1,000 realizations of the resampling (mean of means) is presented as the mean P_B for that case. Each mean P_B represents the estimated total annual endowment that was mined but unrecovered, for each element in each deposit type (data S1). The 1,190 distributions (70 elements in 17 deposit types) vary widely and in many cases are non-normal, as indicated by Pearson’s median skew. To estimate the total by-product endowment of each element across all of the US mines in the dataset, the mean of means was summed across the deposit types. This sum of the mean of means is presented for each element in the main case and the cutoff case. Uncertainty for each element in each case was estimated by resampling the means from each deposit type 1000 times before summing across deposit types, resulting in a distribution of total values which was used to calculate the 2.5th, 5th, 95th, and 97.5th percentiles for each element (supplementary materials and data S1). The results are compared to statistics on domestic manufacturing demand, imports, global production, and end use, at a range of recovery scenarios from 1 to 90% recoverability for each element.

By-product endowment in US metal mines

The US has over 6,000 federally permitted mines, quarries, and mineral processing facilities. Most of these operations produce industrial materials such as sand, gravel, and cement. Of the 162 sites that produce metals, only about a third are active hard-rock mines. The remainder are inactive mines, in-situ recovery or placer operations, or processing facilities. Some of the active mine sites function together as combined operations and are considered as a single unit in this study, resulting in a total of 54 hard-rock metal mining operations (Fig. 1A and table S1). In decreasing order of total annual production in kilotons of main product, these mines produce iron, copper, zinc, rare-earth elements, nickel, molybdenum, silver, gold, and platinum-palladium as main products. Operations are by open-pit and underground methods (Fig. 1, B to E). The 54 sites are classified into 17 geological deposit types based on the mineral systems classification used in the CMMI database (15), with the most common being porphyry copper, low-sulfidation epithermal gold-silver, and Carlin-type gold (table S1). With the exception of iron, which is mined at concentrations of about 15% in iron ore, the main product metals are mined at average grades of <1 part per million to single-digit percents (data S2); the remainder of the rock is treated as waste.

By-products at US metal mines include elements that

occur in mineral phases that are distinct from the main product ore mineral (Fig. 1G) or in the same mineral as the main product. In the latter case, the by-product element can occur with the main product in the same zone of the mineral (Fig. 1, H to J) or in different zones of the mineral (Fig. 1, K to M). The mineralogical residence (department) of the element and the characteristics of the rock determine recoverability, including the processes, energy, reagents, and water required for mineral processing and extractive metallurgy.

Comparison to US imports, manufacturing demand, and global production

The total by-product endowment of active US metal mines is shown in Fig. 2, as the estimated amount of each element mined annually but not recovered. These unrecovered by-products exceed US imports and US manufacturing demand for most elements (Fig. 2). For many elements the by-product endowment also exceeds current global production or would constitute a significant share thereof (Fig. 2). For the main case, the data represent all rocks with detectable main product, and uncertainty is shown as 5th and 95th percentile error bars (Fig. 2). Uncertainties vary depending on the number of CMMI ore samples and the distributions of values in the ore samples. Any element with a main case mean value greater than imports also has a 5th percentile value greater than imports. The uncertainties are modest in comparison to expected uncertainties in mineral demand projections and embedded trade (1). The 20x crustal abundance cutoff case represents a hypothesis for the by-product endowment in the ores that are mined and processed over a reasonable range of ore grades (uncertainties are included in data S1).

The only critical minerals with low by-product endowment are platinum and palladium, for which the combined main-product production and by-product endowment are only about 20% of US manufacturing demand. The elements Os, Rh, and Ru could not be assessed because there were few mineralized CMMI samples with detectable values in the 17 deposit types. Fluorspar and graphite are minerals that could not be quantified using the elemental data in the CMMI dataset.

By-product contributions vary by deposit type

The by-product endowment varies by geological deposit type (Fig. 3). The data show how each deposit type contributes to the total share of the by-product endowment of that element. The data are useful to determine which deposit types should be targeted for by-product recovery of particular elements. The geological endowments are unequal across the 17 deposit types, even when accounting for varying shares of main product production. For example, although Superior-type banded iron formations are responsible for most of US mine production by kilotons, the deposit type contributes only a small

share of most by-product elements. Other deposit types with high production rates, such as copper porphyry deposits, contribute a large share of many by-products. Certain deposit types have the potential to produce a disproportionate share of some elements, such as Mn, Dy, Nd, Pr, and Ge in siliciclastic carbonate lead-zinc deposits; Co in Mississippi Valley type deposits; or As in Carlin-type deposits. Ultramafic PGE deposits contain most of the Cr and Ir; minor but undisclosed amounts of by-product Ni and Co are already recovered from those deposits. The potential economic value of the by-product commodities in today's market is compared to the economic value of the main products (Fig. 3B). In gross US dollars at average 2023 prices (16), Cu porphyry deposits represent the largest share of the US main product mining market, followed by Superior-type banded iron formations and Carlin-type gold. In gross US dollars at average 2023 prices, the by-product value is largest in siliciclastic carbonate deposits, followed by Cu porphyry, ultramafic PGE, low sulfidation epithermal, and Carlin-type gold.

Targets for recovery

Many elements in the CMMI dataset have not been systematically analyzed in the past, and very few have been targeted for recovery, so the by-product recoverability of most elements in most deposit types remains unknown. Instead of estimating the amount that is recoverable, the data are used to show the approximate percentage of recovery of each element that would be needed to replace imports (Fig. 4). For fifteen elements, less than 1% recovery is estimated to be needed to replace imports. For eleven elements, between 1 and 10% recovery is needed to replace imports. For thirteen elements, between 10 and 50% recovery is needed to replace elements. For five elements, 100% recovery would only partially replace imports. Focusing on the nine elements and REO that are currently produced as main products (Figs. 1A and 3), the data can be used to evaluate whether by-product recovery could supplement main-product mining to meet US manufacturing demand without imports. A combination of annual main-product mining and partial by-product recovery could enable domestic production sufficient to meet US manufacturing demand for copper, iron, molybdenum, silver, nickel, zinc, and REO. However, main-product mining combined with even 100% by-product recovery falls short of domestic manufacturing demand for gold, platinum, and palladium.

For most deposit types, recovery of <10% of the by-products would generate a larger gross US dollar value than the main products (Fig. 3B). These comparisons do not account for the costs in infrastructure, energy, water, or reagents, but they provide a first-order estimation of the potential value of unrecovered by-products in US mines. These data can be used to target sites and elements for which recovery should be studied and possibly attempted.

By-product resource compared to end use

The data for US imports (Figs. 2 and 4) represent the direct trade of mineral commodities, such as the purchase of cobalt, rather than embedded trade inherent in imports of consumer goods, such as batteries containing cobalt. Similarly, manufacturing demand (Fig. 2) represents the direct consumption of mineral commodities, but it does not include the domestic manufacturing of goods containing imported components, such as computer chips containing gallium. Current manufacturing demand also does not account for projected increases driven by the energy transition or adoption of other new technologies. Mineral demand models are highly varied, depending on the assumptions for key inputs such as future energy requirements, technology, population, and policy (1). To provide a simple comparison between by-product endowment and future needs, potential end-uses of the annual estimated P_B are calculated for four battery minerals used in NMC (nickel manganese cobalt) lithium-ion batteries, four rare earth elements used in direct-drive wind turbines, and five elements used in semiconductors and solar panels (Fig. 5). The unrecovered by-products could contribute meaningfully to renewable energy production: there are sufficient resources to produce more electric vehicle batteries, wind turbines, and solar panels than current demand.

Reducing uncertainty

The statistical approach used in this study provides the best available estimate of by-product endowment at US mine sites. The CMMI sample set is robust where it includes many samples from sites across various locations within a deposit type. Although deposit types with a small number of samples may be biased by particular regional characteristics, the by-product endowment of most elements is sufficiently to be meaningful regardless of regional bias. To reduce the uncertainties in the estimated P_B values (Fig. 3A and data S1), a systematic sampling program should be conducted to characterize the ore being mined and fed to the mill at each US mine site. Implementation of such a program may require government mandates or incentives, but it is an essential step toward unlocking the by-product resources in US mines. Such a program would provide real-time, site-specific characterization of geochemical and spatial variability in by-product element concentrations of the ores as they are mined, reducing potential uncertainty associated with the existing CMMI samples.

The results of this study can be used to guide the selection of by-product elements that are prospective at each deposit type. For the targeted elements, geometallurgical studies should be conducted to assess the deportment, or mineralogical residence, of each potential by-product element, as well as the textures and characteristics of the host rock and other associated minerals, all of which determine the possible approaches for recovery. Based on such data, new methods for

mineral processing and extractive metallurgy can be developed to enable recovery. Such new methods must also enable efficiencies in equipment and process design; energy; water; and reagents. Recovery methods must be tested at bench and pilot scale prior to commercial operation, in order to evaluate the recovery of individual or multiple by-product metals and the potential ways in which these additional processes could impede or enhance main product recovery. The cutoff cases demonstrate that more by-products could be obtained by mining at lower main-product grades (data S1), and the potentially significant value of those by-products (Fig. 3B) should be assessed relative to the cost of recovery.

Unlocking US by-product mineral resources

The US's vulnerable supply of critical minerals is not a function of domestic geological availability. The results presented here demonstrate that US metal mines already have sufficient mineral endowment to substantially reduce the nation's mineral criticality. If 90% recovery of by-products were enabled, existing US mines could supply sufficient quantities to eliminate imports of most minerals, meet domestic manufacturing demand, and enable economic growth in key sectors. Even 1% recovery would substantially reduce net import reliance for most critical minerals. Unrecovered, these by-products contribute to the country's growing industrial waste.

By-product recovery is a resource-efficient approach to mineral production, presenting the triple advantages of waste reduction; utilization of existing mine infrastructure and environmental footprint; and leveraging the energy and emissions already expended in mining to produce a wider range of needed materials. Recovery of multiple products from this processed material would represent a notable efficiency, since mining and particle size reduction during mineral processing constitute about 3.5% of the global energy budget (17). By-product recovery of all metals from an ore deposit constitutes a first step toward zero-waste mining, wherein all the constituents of the rock would ultimately be used. Removal of the metals creates a geochemically inert stream of leftover material that is more readily repurposed for construction and other applications than potentially toxic metal-bearing waste. In the near term, recovery of even a modest percentage of the calculated endowment would reduce the US's geopolitically vulnerable supply of critical minerals.

Unlocking the by-products from the rock that is already being mined will require significant advancements. Investment is needed in geometallurgical research and processing technologies, and in the mining and metallurgical engineering programs that are key to developing such advancements. A policy framework must be developed to incentivize research and implementation of by-product recovery. Strategic efforts should focus on (1) implementing a nationwide mill

sampling program to refine resource assessments, (2) improving the economics of by-product recovery through geo-metallurgical characterization and processing studies, and (3) incentivizing mining companies to adopt more comprehensive recovery practices. By embracing these measures, the US can transition toward a more resilient, sustainable, and self-sufficient mineral supply chain.

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SUPPLEMENTARY MATERIALS

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Materials and Methods

Table S1

References (23–82)

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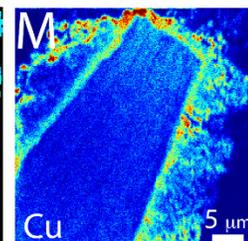
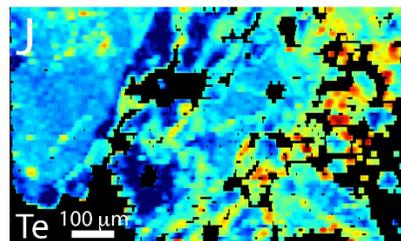
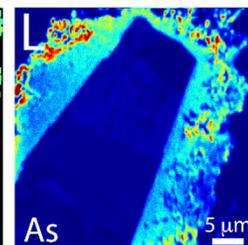
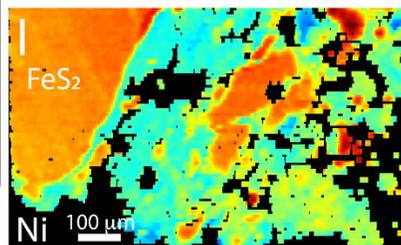
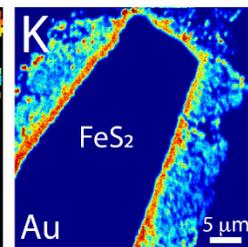
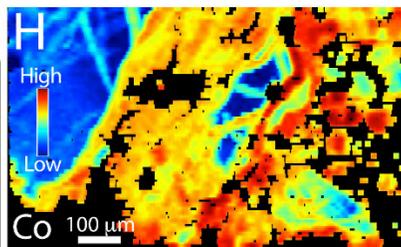
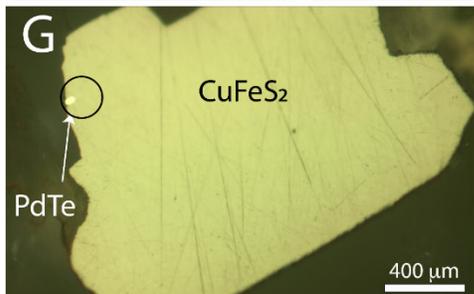
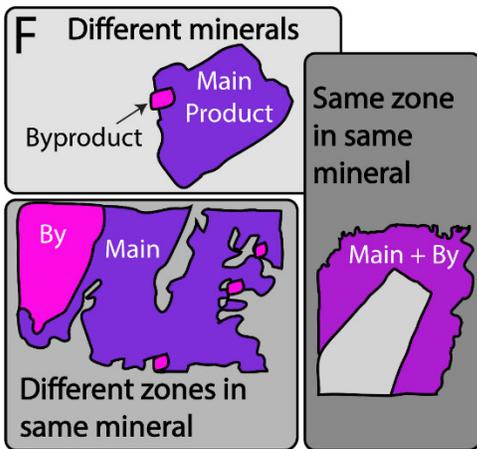
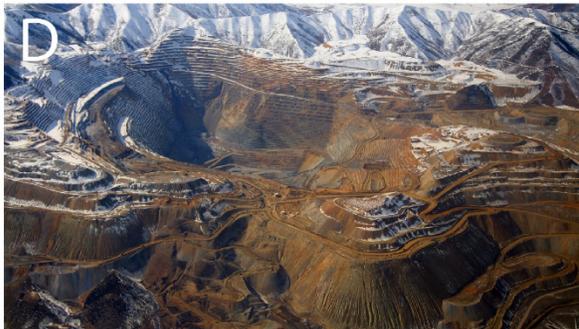
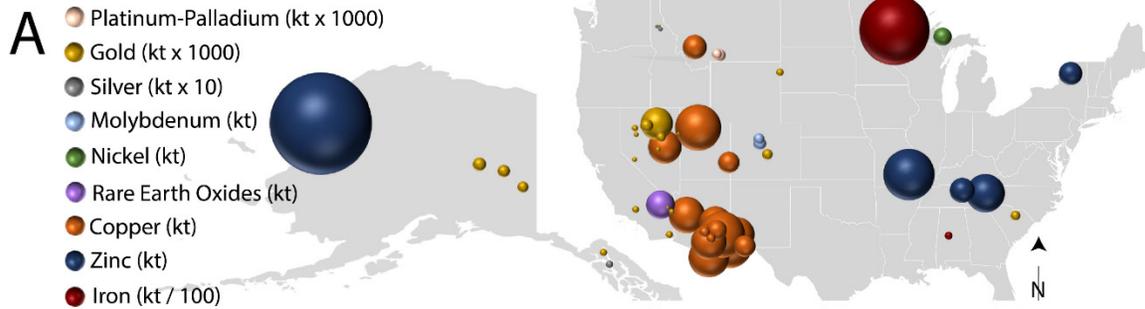


Fig. 1. Metal mining in the US and modes of by-product occurrence. (A) Sites considered in this study, shown as annual metric kilotons of main product (several iron mines are combined for visual clarity). (B) Open pit mining of gold from a Carlin-type deposit in Nevada. (C) Underground mining of nickel from an ultramafic intrusion deposit in Michigan (image courtesy of Lundin mining). (D) Open pit mining of copper from a porphyry deposit in Utah (Creative Commons image by D. Searles). (E) Underground mining of palladium and platinum from an ultramafic deposit in Montana (image courtesy of Sibanye Stillwater). (F) Schematic cartoon showing each mode of by-product occurrence. (G) By-product elements can occur in different minerals from the main product. Example of an ore sample and reflected light photomicrograph from a porphyry copper deposit where platinum and palladium are potential by-products (18). (H to J) By-product elements can occur in the same mineral as the host but in different mineralogical zones. Example of an ore sample and laser-ablation ICP-MS geochemical maps from a sedimentary-hosted cobalt deposit where nickel and tellurium are potential by-products (19). (K to M) By-product elements can occur in the same zone of the host mineral as the main product. Example of an ore sample and NanoSIMS geochemical maps from a Carlin-type gold deposit where arsenic and copper are potential by-products (20, 21). (H) to (M) share the same geochemical intensity scale.

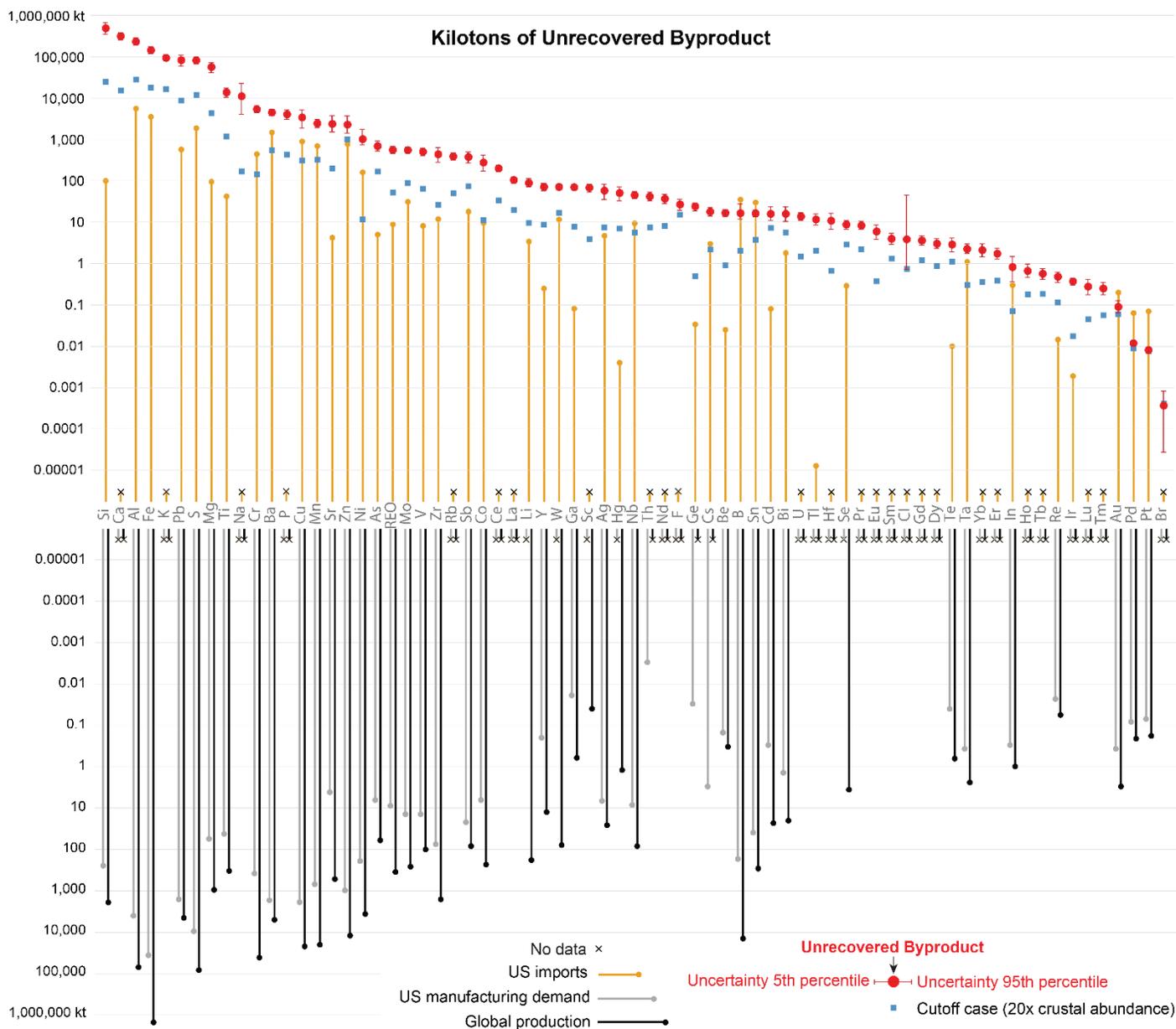


Fig. 2. Endowment of unrecovered by-product at US metal mines, presented as kilotons that were mined in 2023 but unrecovered. For each element, the datapoint represents the sum across all 17 deposit types, according to the main case (all CMMI data), as well as a 20x crustal abundance cutoff case that filters the CMMI data to main-product values similar to the ore grades mined (data S2). Uncertainties are shown graphically for the main case and presented in data S1, which also presents the 20x crustal abundance cutoff case and four alternative cutoff cases. Data are presented in comparison to 2023 US imports, global production, and US manufacturing demand (16); Si is presented in elemental form. Production, import, and consumption data are not available for some elements, such as the rare earths, which are summed and presented in oxide form (REO) for comparison to published statistics.

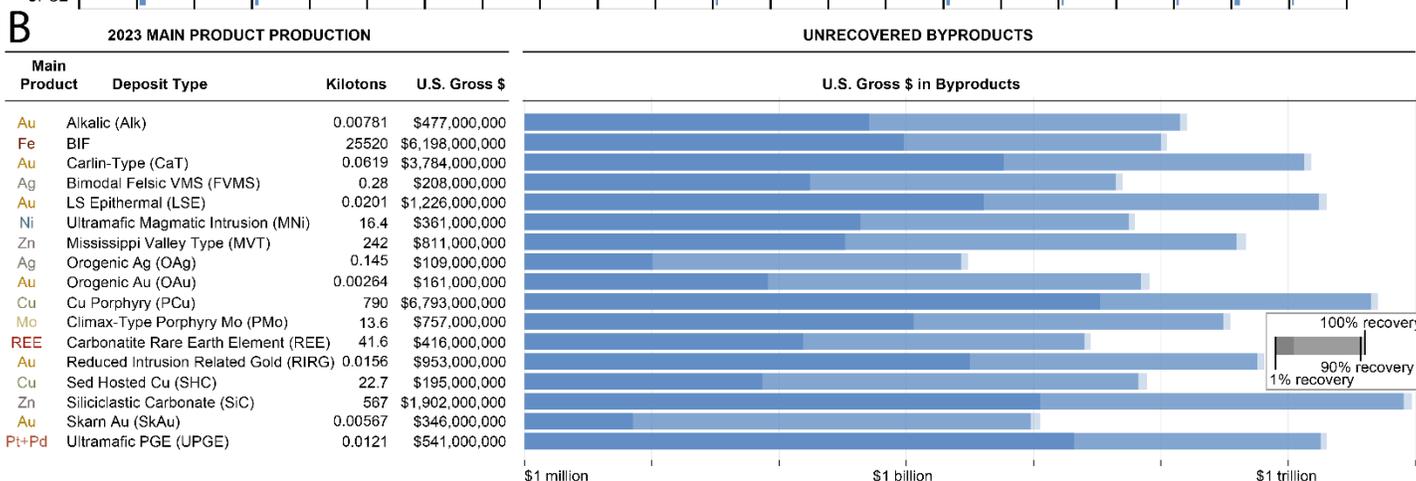
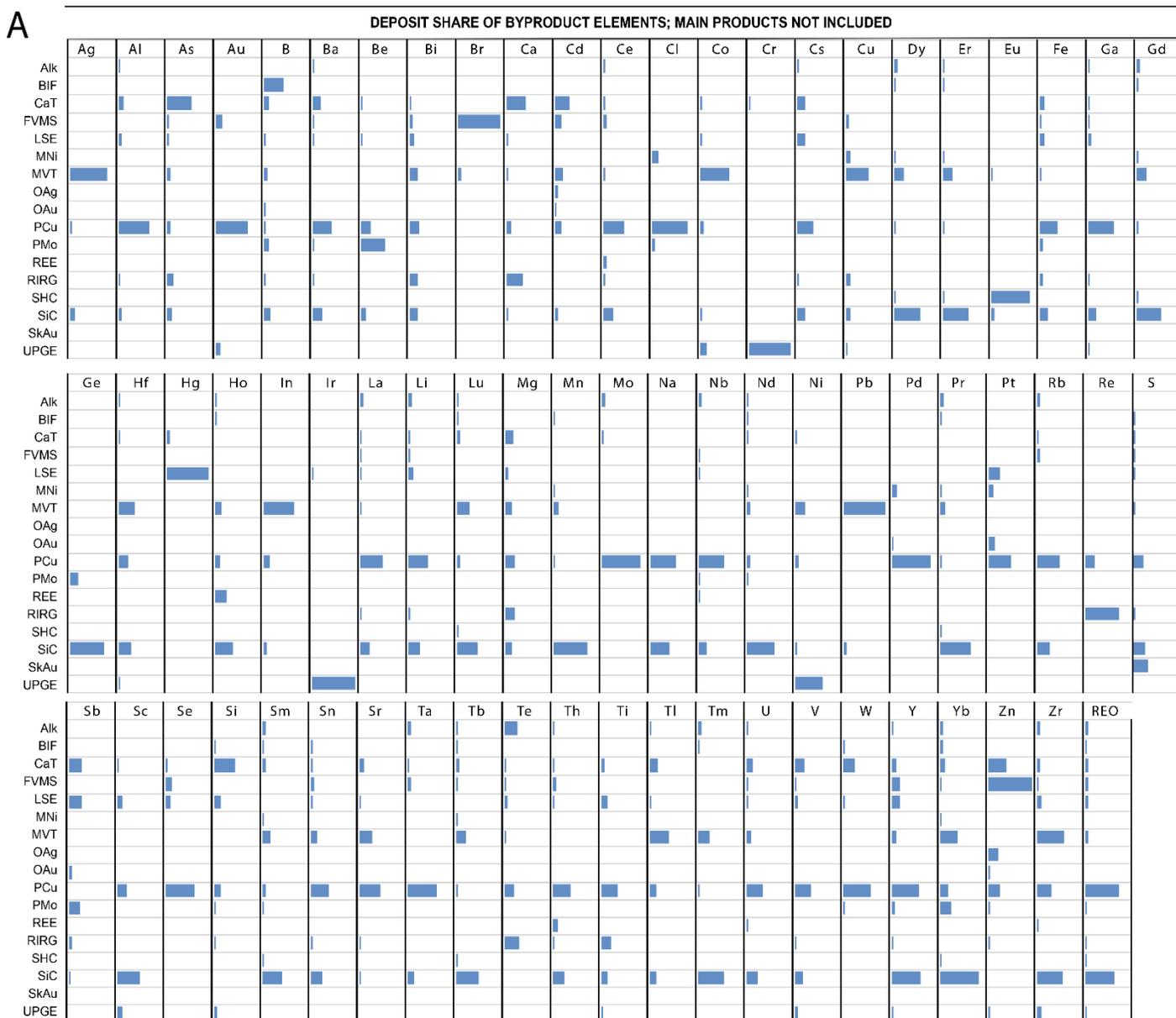


Fig. 3. Contributions of critical minerals by geological deposit type. (A) The data show the by-product endowment per deposit type as a fraction of total endowment of that by-product across all 17 deposit types; main product share is not included. (B) The gross US dollar value at average 2023 price is shown for main products mined in 2023 (left), as well as unrecovered by-products at a range of recoveries from 1 to 90% (right).

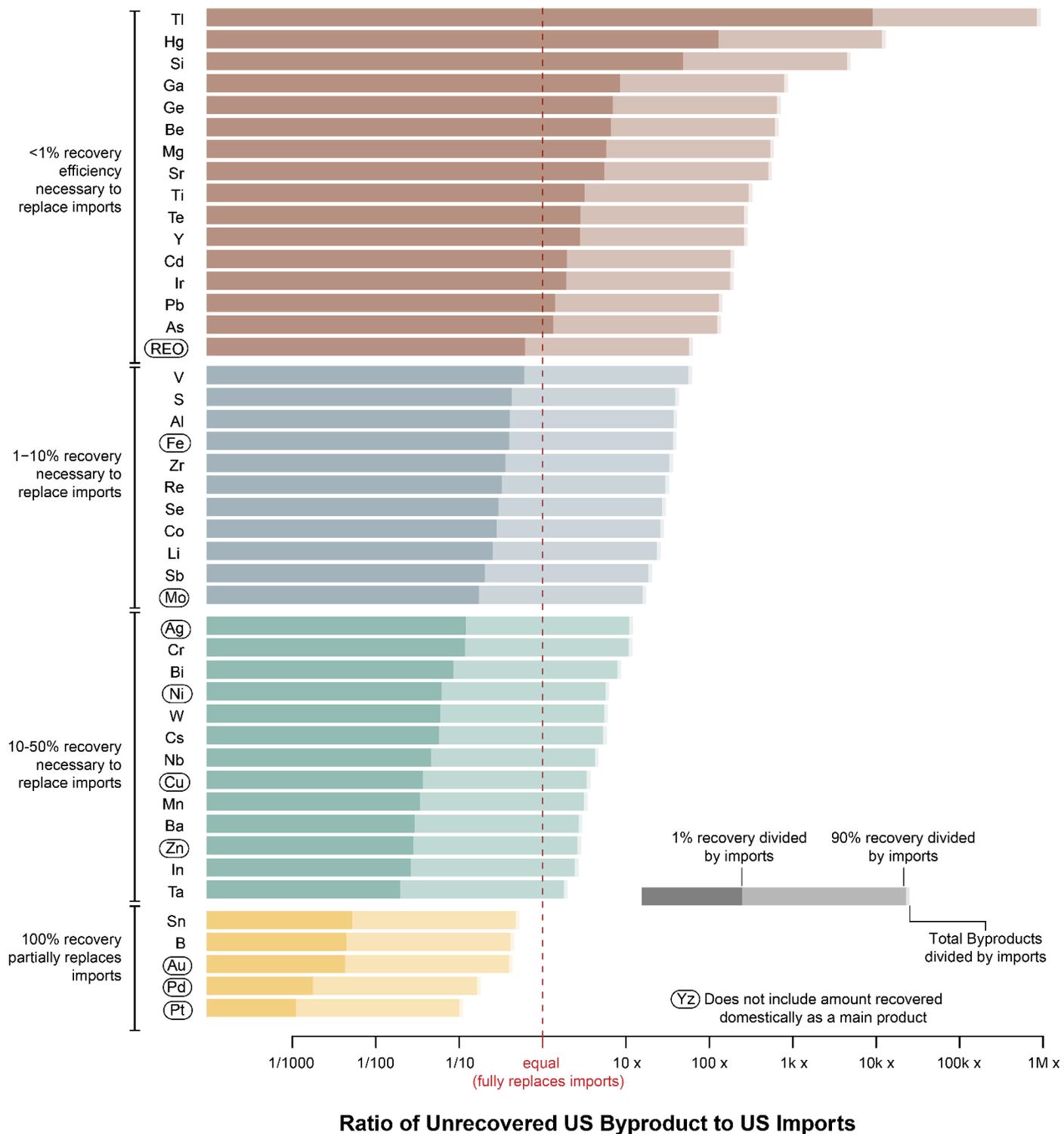


Fig. 4. By-product resource based on a range of recoverability. Each element is shown as a ratio over US imports (16). The elements are grouped in four bins based on the percentage of recovery necessary to replace imports. The amount recovered in 2023 as a main product is not included.

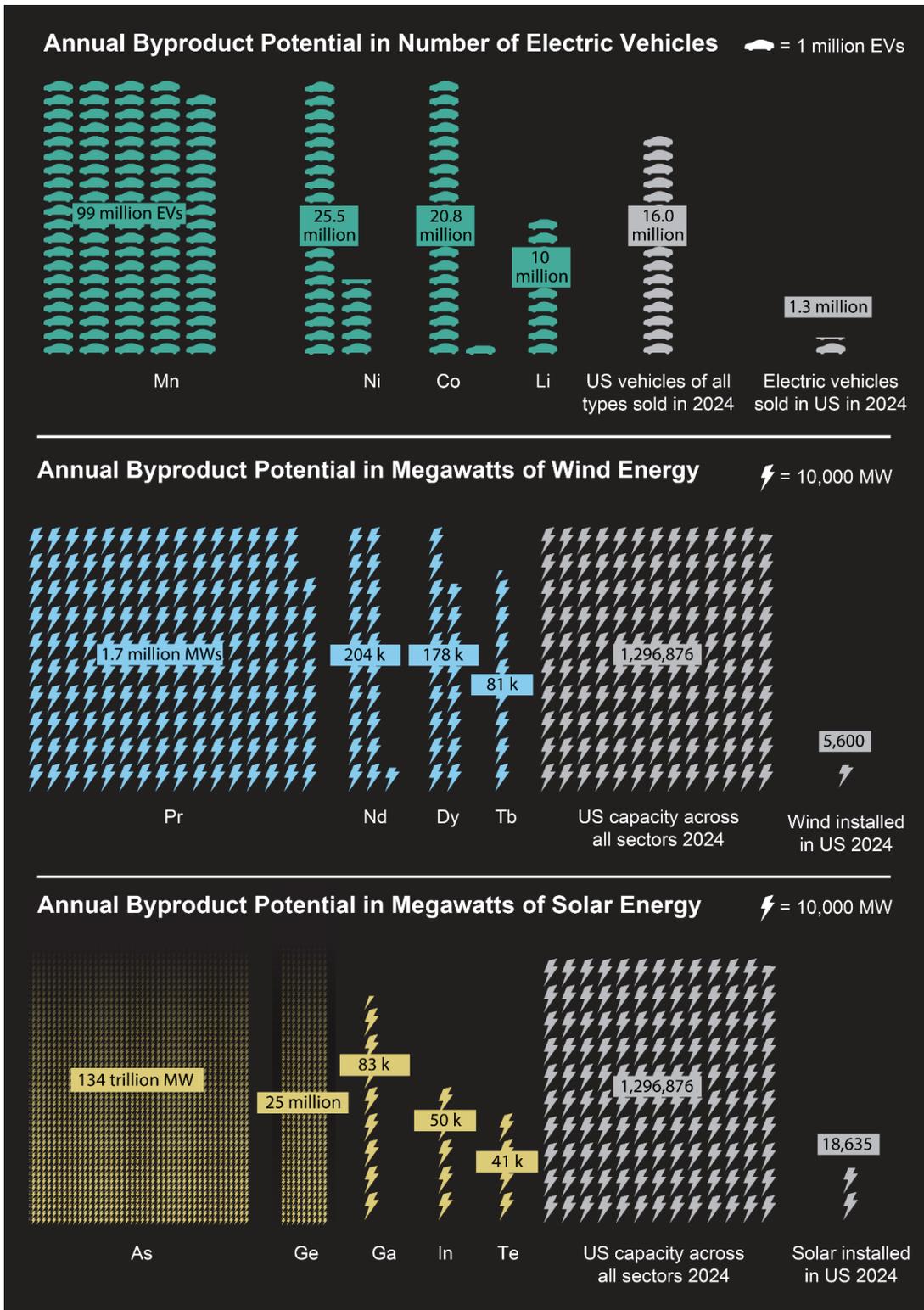


Fig. 5. Annual by-product resource from active US metal mines, presented as number of electric vehicles or megawatts of wind and solar energy [(4, 22) and supplementary materials].